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The scientific consensus on climate change:

How do we know we're not wrong?

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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 the year that global warming "got respect."[1]

Many scientists felt that respect was overdue: as early as 1995, the Intergovernmental Panel on Climate Change (IPCC) had concluded that there was strong scientific evidence that human activities were affecting global climate. By 2001, IPCC's Third Assessment Report stated unequivocally that human activities are having detectable effects on the earth's atmosphere and hydrosphere. Prominent scientists and major scientific organizations have all ratified the IPCC conclusion. Today, all but a tiny handful of climate scientists are convinced that Earth's climate is heating up, and that human activities are a significant cause.

Yet many Americans continue to wonder. A recent poll report in *Time* magazine found that only just over half (56%) of Americans think that average global temperatures have rise despite the fact that virtually all climate scientists think that it has.[2] More startlingly, a majority of Americans believe that scientists are still divided about the issue! In some quarters, these doubts have been invoked to justify the American refusal to join the rest of the world in addressing the problem.

This book deals with the question of climate change and its future impacts, and by definition predictions are uncertain. 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. Several chapters in this book have already addressed that question—explaining how some harmful affects are already occurring, how we can assess the likely extent of future harms, and why it is reasonable to act now to prevent a worst-case scenario from coming true.

This chapter addresses a different question: Might the scientific consensus be wrong? If the history of science teaches anything, it's humility: there are numerous historical examples where expert opinion turned out to be wrong. At the start of the 20th 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 could not drift. Moreover, in any scientific community there are always some 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, but how do we know it's not wrong?

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, 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 very difficult for outsiders to understand.

Climate science is a little different. Because of the political importance of the topic, scientists have been unusually motivated 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), already discussed in previous chapters. Created in 1988 by the World Meteorological Organization and the United Nations Environment Programme, the IPCC's *raison d'être* is to evaluate the state of climate science as a basis for informed policy action, primarily on the basis of peer-reviewed and published scientific literature.[3] The IPCC has issued three assessments. The most recent, IPCC 2001, states unequivocally that the consensus of scientific opinion is 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."[4]

The IPCC is a somewhat unusual scientific organization: created not to foster new research, but to compile and assess existing knowledge on a politically charged issue. Perhaps its conclusions have been skewed by these political concerns? Perhaps, but IPCC is by no means alone it its conclusions, and its results have been repeatedly ratified by other scientific organizations.

In the past several years, 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." [5] 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." [6]

Other U.S. scientific groups agree. 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."[7] 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."[8] 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."[9] Climate scientists agree that global warming is real, and substantially attributable to human activities.

The drafting of these kinds of reports and statements is 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.[10]

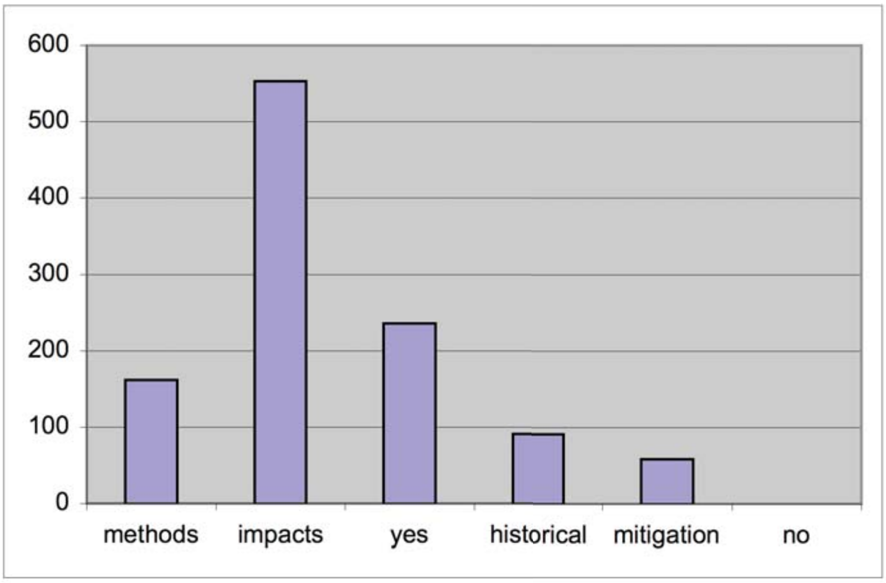
One way to test that hypothesis is by analyzing the contents of published scientific papers, which contains the views that are considered sufficiently supported by evidence that they merit publication in expert journals. After all, any one can *say* anything, but not anyone can get research results published in a refereed journal.[11] 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 very small: a handful, a dozen, perhaps a hundred at most, in part because the total number of scientists in the world was very small.[12] Moreover, because professional science was a very 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 19th or early 20th 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, there are hundreds of thousands of scientists publishing over a million scientific papers each year.[13] The American Geophysical Union alone boasts 41,000 members in 130 countries. The American Meteorological Society has 11,000, and the IPCC reports involved the participation of many hundreds of scientists from scores of countries.[14] 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 1 shows the results of an analysis of 928 abstracts, published in refereed journals during the period 1993 -2003, produced by a Web of Science Search using the keyword phrase "global climate change."[15] 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 paleo-climate change, and 6) those proposing mitigation strategies. How many fell into category (2)? That is to say, 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.



Not one paper in the sample provided scientific data to refute the consensus position.

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 some cases, 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% of the papers dealt with methods, and slightly less than 10% dealt with paleo-climate 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 paleo-climatology and to the development of methods for measuring and evaluating global temperature and climate. Such papers are essentially neutral: 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% of the papers explicitly endorsed the consensus position, and an additional 5% proposed mitigation strategies. In short, the basic reality of anthropogenic global climate change is no longer a subject of scientific debate.[16]

Some readers will be surprised by this result, and wonder about the reliability of a study that failed to find any arguments against the consensus position, when such arguments clearly exist. After all, anyone who watches the evening news or trolls the internet knows that there is 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, and 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 some of the changes that are now occurring are clearly deleterious to both human communities and ecosystems.[17] Humans are losing their homes and hunting grounds, and plants and animals are losing their habitat, because of global warming.[18]

Second, to say that global warming is real and happening now is not the same as agreeing about what will happen in the future. Much of the 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 on the reality of human-induced climate change, but debate continues on tempo and mode.

Third, there is the question of what kind of dissent still exists. The analysis of the published literature presented here was done by sampling, using a keyword phrase that was intended to be fair, accurate, and neutral: "Global climate change" (as opposed to, for example, global warming, which might be viewed as biased.) The *total* number of papers published over the last ten years having anything at all to do with climate change is probably over 10,000, and no doubt some of the authors of the other 9000-plus papers have expressed skeptical or dissenting views. *But the fact that the sample turned up no dissenting papers at all demonstrates that any remaining professional dissent is now exceedingly minor.*

This suggests something suggested elsewhere in this book: that the mass media has paid a great deal of attention to a handful of dissenters in a manner that is greatly disproportionate with their representation in the scientific community. The number of climate scientists, who actively do research in the field, but disagree with the consensus position, is, evidently, very, very, small.

This is not to say that there are not a significant number of contrarians, but to point out that most of them are not actually climate scientists, and therefore have little (or no) basis to claim to be experts on the subjects upon which they so boldly pronounce. Some contrarians, like the physicist Frederick Seitz, were once active scientific researchers, but have long since retired. (And Seitz never actually did research in climate science; he was a solid-state physicist). Others, like the novelist Michael Crichton, are not scientists at all. 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 for the most 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 materials 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, along with several colleagues, published a paper entitled, "Modeling climatic effects of anthropogenic carbon dioxide emissions: unknowns and uncertainties." [19] This paper has been has been widely cited by contrarians as an important example of a legitimate dissenting scientific view, published in a peer-review journal.[20] But the issue actually under discussion in the paper 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 this: "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."[21]

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 the 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. [22]

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?[23] There are several reasons. First, it is important to distinguish between scientific and political uncertainty. 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 is uncertain. It's important to distinguish between 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, much less 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 with little training in how to communicate to broad audiences, and even less in how to defend scientific work against determined and well-financed contrarians. 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. Some even 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.[24] This places scientists in a double-bind: the demands of objectivity 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 and George Marshall Institutes have been active for some time in trying to communicate a message that is at odds with the consensus scientific view.[25] These organizations have successfully garnered a great deal of media attention for the very tiny number of scientists who disagree with the mainstream view, and for non-scientists, like novelist Michael Crichton, who nevertheless pronounce loudly on the scientific issues at stake. [26]

This message of scientific uncertainty has been reinforced by the public relations campaigns of certain corporations with a strong stake in the issue. [27] The most well known example is Exxon-Mobil, who in 2004 ran a highly visible advertising campaign on the Op-Ed page of *The New York Times*. These carefully worded advertisements, written and formatted to look like Op-Ed pieces—and *called* Op-Ed pieces by Exxon Mobil—suggested that climate science was far too uncertain to warrant action upon it.[28] One advertisement concluded that the uncertainties and complexities of climate and weather means that "there is an on-going need to support scientific research to inform decisions and guide policies."[29] Of course there is! But our scientists have concluded that existing research warrants decisions and policies *today*.[30]

In any scientific debate, past or present, one can always find intellectual outliers, individuals who diverge from the consensus view. Even after plate tectonics was resoundingly accepted by earth scientists in the late 1960s, there were a handful of persistent resisters who clung to the older views, as well as a handful of idiosyncratics who 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 advisor to Presidents Lyndon Johnson and Richard Nixon; they both continued to reject plate tectonics until their dying day, which for MacDonald was in 2002. Does that mean 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.

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, and that HIV causes AIDS. You can always find someone, somewhere, to disagree, but these conclusions represent our best current understandings and therefore our best basis for reasoned action.[31]

How do we know we're not wrong?

Might the consensus on climate change be wrong? Yes, it could 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 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 some climate change deniers have suggested that climate scientists do not follow the scientific method (because they rely on models, rather than laboratory experiments), so their results are suspect. Both of these views are wrong.

Contrary to popular opinion, there is no scientific method (singular). Despite heroic efforts by historians, philosophers and sociologists, there is no answer to what the methods and standards of science really are (or even what they should be). There is no methodological litmus test for scientific reliability, 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 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.[32] 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 and the 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 have no way to prove that it will rise again tomorrow.

Nevertheless, common sense tells us that the sun is extremely *likely* to 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 increase since the industrial revolution about 0.6-0.7 C.[33] The empirical signal is clear, even if not all the details are clear.

How reliable are the very early records? How do you average the data to be representative of the globe as a whole, even though much of the early data comes from only a few places, mostly in Europe? Scientists have spent quite a bit of time addressing these questions; most have satisfied themselves that the empirical signal is clear. But even if scientists doubted the older records, the more recent data show a strong increase in temperatures over the past thirty to forty years, just when the amount of carbon dioxide and other greenhouses gases in the atmosphere was growing dramatically. [34]

Moreover these records—based on measurements with instruments, such as thermometers—are corroborated by independent evidence from tree rings, ice cores, and coral reefs. A recent paper by Jan Esper at the Swiss Federal Research Center and colleagues at Columbia University, shows, for example, that tree-rings can provide a reliable, long-term record of temperature variability, one that largely agrees with the instrumental records over the past 150 years.[35]

While many scientists are happy simply to obtain consistent results—often no trivial task—others may deem it important to find some means to test whether their conclusions are right. This has led to the view 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." In this view, scientists develop hypotheses and then test them. Every hypothesis has logical consequences—deductions—and one can try to determine whether the deductions are correct. If they are, it supports the hypothesis. If they are not, then one must revise or reject the hypothesis. It's 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 Dr. Ignaz Semmelweis, who in the 1840s deduced the importance of hand washing to prevent the spread of infection. [36] Semmelweis had noticed that a great number of 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 this. Nor did women who gave birth at another hospital clinic where they were attended by midwives. Semmelweis was deeply troubled by this.

In 1847, a friend of Semmelweis, Dr 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 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, the infection rate would decline. They did and it did, 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. As we've already noted in several previous chapters, scientific concern over the effects of increased atmospheric CO_2 is based on physics: the fact that CO_2 is a greenhouse gas. In the early 20th century, Swedish chemist Svante Arrhenius predicted that increasing carbon dioxide from the burning of fossil fuels would lead to global warming, and by the mid century, a number of other scientists, including G.S. Callendar, Roger Revelle, and Han Suess, concluded that the effect might soon be quite noticeable, leading to see level rise and other global changes. 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."[37] This prediction has come true.[38]

Another prediction fits the category of something unusual that you might not even think of without the relevant theory. In 1980, Princeton climatologist Suki Manabe predicted that the effects of global warming would be strongest first in the polar regions—'polar amplification.' This was not an induction from observations, but a deduction from theoretical principles: the notion of ice-albedo feedback. The reflectivity of a material is is called its albedo. Ice has a high albedo, reflecting sunlight back into space much more effectively than grass, dirt or water, and one reason polar regions are as cold as they are is that all the snow and ice is very effective in reflecting solar radiation back into space. But if the snow starts to melt, and bare ground (or water) is exposed, the reflection effect will diminish. Less ice means less reflection, which means more solar heat is absorbed, leading to yet more melting, in a positive feedback loop. So once warming begins, it effects will be more pronounced in polar regions than in temperate ones. The Arctic Climate Impact Assessment concluded in 2004 that this prediction has also come true. [39]

Falsificationism

Ignaz Semmelweis is among the famous figures in the history of science, as his work foreshadows the germ theory of disease and the saving of millions of human lives. 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 hand-washing was effective not because it removed the cadaveric material, but because it removed the germs associated with that material.

The story illustrates the fundamental problem with the hypothetico-deductive model, one that philosophers have labeled the "fallacy of affirming the consequent." If I make a prediction, and it comes true, it does not prove that my hypothesis was correct; my prediction may have come true for other reasons. The others 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, but you can prove it false--a view known as "falsificationism." [40]

How does climate science hold up to this modification? Can climate models be refuted? Falsification is a bit of a problem for all 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. For this reason, many models are tested by seeing if they can accurately reproduce past events. In principle this should be an excellent test—a climate model that failed to reproduce past temperature records might be considered falsified—but in reality, it doesn't quite work that way.

Climate models are very complex, and they involve many variables—some of which are well measured, others which 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 the most best model you can. But the problem is obvious: calibration can make models refutation-proof: the model doesn't get rejected, it gets revised. If model results were the only basis for current scientific understanding, that *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 U.K. Hadley Centre for Climate Prediction and Research. Figure 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 pre-industrial levels, and the model Earth allowed to adjust. The results in black are the climateprediction.net runs; the results in red come from runs made by professional climate scientists at the Hadley Centre.[41]

Figure 2 General Circulation Model Ensemble produced by climateprediction.net

The figure shows the change in globally averaged surface temperature with time after carbon dioxide values in the atmosphere are doubled. The black lines show the results of 2579 15-year simulations of climate*prediction*.net runs by members of the general public using their own personal computers. The red lines show comparable results from 127 30-year simulations completed by the Hadley Centre on the Met Office's supercomputer.

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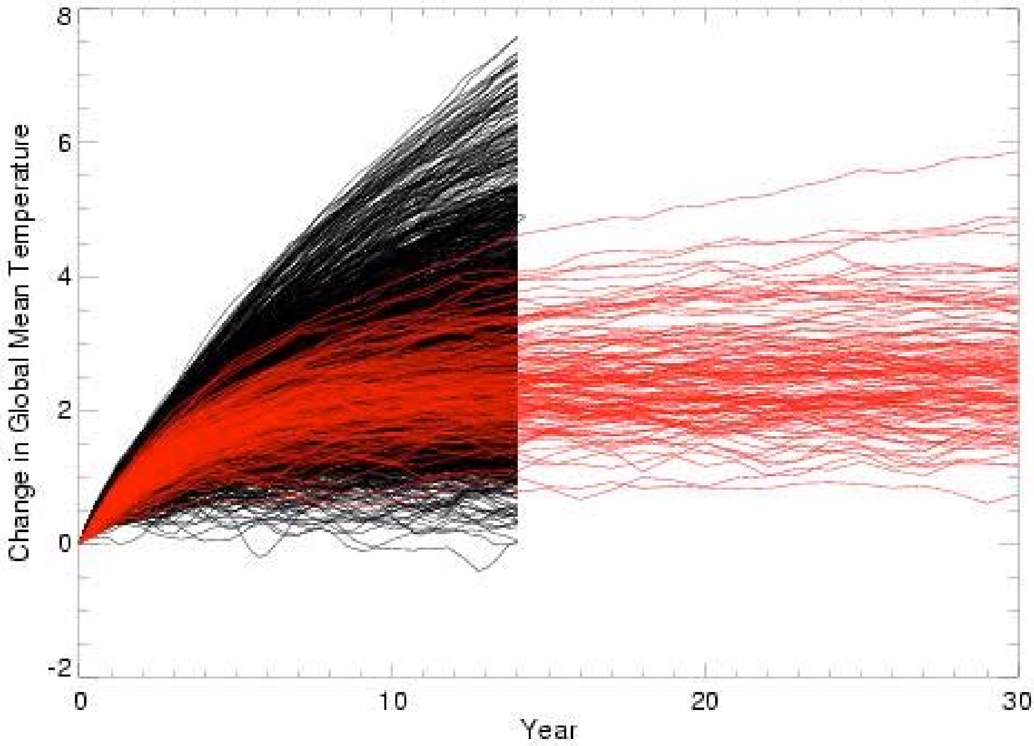

What does an ensemble like this show? Well, for one thing, that no matter how many times you run the model, you almost always get the same qualitative result: our Earth will warm. The unanswered question is how much and how fast—in other words, tempo and mode.

The models vary quite a bit in their tempo and mode, but nearly all fall within a range of temperature range of 2-8^o C 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 Figure 2. If the model runs had been were allowed to continue out to thirty years, as the Hadley Centre 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 pre-industrial level? The answer depends largely on how much carbon dioxide 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 pre-industrial levels. Most experts believe that unless major steps are taken quickly, atmospheric CO_2 levels will go well above that. 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 very few exceptions, the models are warming, and some of them are warming very fast.

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 would be wrong. 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. [42] This is one reason why 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). Climate models give us a tool for exploring scenarios and interactions, but you *don't* need a climate model to know that global warming is a real problem.

If climate science stands with or without climate models, then is there any information that would show that climate science is wrong? Sure. 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 carbon dioxide, 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 even worse than we'd supposed.

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.[43] Perhaps that is the strongest argument of all. Contrarians have repeatedly tried to falsify the consensus, and they have repeatedly failed.

Consilience of Evidence

Most philosophers and historians of science agree that there is no iron-clad 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 its use is generally credited to the English philosopher William Whewell, who defined it this way: "The consilience of inductions takes place when one class of facts coincides with an induction obtained from another different class."[44] 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 only need to show 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, bore hole data, and coral reefs, all point to the same conclusion: things are getting warmer overall. Keith Briffa and Timothy Osborn of the Climate Reearch 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.[45] All seven analyses agree: temperatures increased dramatically in the late 20th 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 20th 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 not proof, but explanation. Not just any explanation, however, but the best explanation consistent with the evidence.[46] Certainly, it is possible that a malicious or mischievous deity placed fossils throughout the geological record to trick us into believing organic evolution, 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."[47]

Of course, "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 virtually by definition can not 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 *scientific*, in the sense of being 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. To be sure, 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 no, it's not the best explanation. In fact, it's not even a *good* explanation—because it is inconsistent with so much of what we know.

Should we believe that the global increase in atmospheric carbon dioxide has had negligible effect, even though basic physics indicates that it should? Should one believe that the correlation between increased CO_2 and increased temperature is just a weird coincidence? If there were no theoretical reason to relate them, and if Arrhenius and Callendar and 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 every reason 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 wishful thinking: that this is just a natural cycle in which humans have played no role, and global warming will go away on its own in due course.

And that sums up the problem. Denying that global warming is real is precisely that: denial. It is denial that humans have become geological agents, changing the most basic physical processes of our Earth. 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 in comparison with the vastness of geological time; that human activities were insignificant in comparison with the force of geological processes. And once, perhaps, 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, indeed, become geological agents. We have changed the chemistry of our atmosphere, causing sea level to rise, ice to melt, and the climate to change. There is no reason to think otherwise, except denial.

[1]John Roach. 2004. "2004: The year global warming got respect." *National Geographic*, (December 29), http://news.nationalgeographic.com/news/2004/12/1229_041229_climate_change_consensus.html (accessed February 24, 2005).
[2] Time. 2006. "Poll: Americans See a Climate Problem." *Time.com,* (March 26), http://www.time.com/time/nation/article/0,8599,1176967,00.html (accessed May 1, 2006). Contrast this with the results of the Intergovernmental Panel on Climate Change Third Assessment Report, which states unequivocally that average global temperatures have risen: http://www.ipcc.ch/
[3] Intergovernmental Panel on Climate Change. 2005. About IPCC. (February 7) http://www.ipcc.ch/about/about.htm (accessed March 1, 2005).
[4] James J. McCarthy, Osvaldo F. Canziani, Neil A. Leary, David J. Dokken, and Kasey S. White, eds. 2001. *Climate change 2001: impacts, adaptation and vulnerability***:** *contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change***.** Cambridge: Cambridge University Press.
[5]National Academy of Sciences Committee on the Science of Climate Change. 2001. *Climate change science: an analysis of some key questions*. Washington D.C.: National Academy Press.
[6] Ibid, on p. 3.
[7] American Meteorological Society. 2003. Climate change research: issues for the atmospheric and related sciences. *Bulletin of the American Meteorological Society* 84, (February 9), http://www.ametsoc.org/policy/climatechangeresearch_2003.html (accessed on May 1, 2006).
[8] American Geophysical Union Council. 2003b. Human impacts of climate. *American Geophysical Union- Science and Policy,* (December 12), http://www.agu.org/sci_soc/policy/climate_change_position.html (accessed March 1, 2005).
[9]Paul Harrison and Fred Pearce. 2000. *AAAS Atlas of Population and Environment.* Berkeley, California: University of California Press. Also available online at http://www.ourplanet.com/aaas/pages/atmos02.html (accessed on May 1, 2006).
[10] And one must acknowledge that in any area of human endeavor, leadership may diverge from the views of the led. A recent opinion poll, reported in *The New York Times*, suggests that 50% of American Catholics have no problem with married priests, despite the Church's official and uncompromising position against it. Science, in this respect, at least, appears to be different from religion. Robin Toner aqnd Janet Elder. 2002. "Scandals in the Church: American Catholics; Catholics

Back Strong Steps on Abuse, Poll Finds." *The New York Times* May 3, 2002 (Late Edition – Final) A1.

[11] Indeed, 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, David Deming. 2005. "How 'Consensus' On Global Warming Is Used To Justify Draconian Reform." *Investor's Business Daily* March 18, 2005. A16.

[12] Derek de Solla Price. 1986. *Little science, big science--and beyond*. New York: Columbia University Press.

[13] An email inquiry to the Thomson Scientific Customer Technical Help Desk. Produced this reply "We index the following number of papers in Science Citation Index
2004 --> SCIE --> 1'057,061 papers
2003 --> SCIE --> 1'111,398 papers

[14]Intergovernmental Panel on Climate Change. 1990. *Scientific assessment of climate change: the policymakers' summary of the report of Working Group I to the Intergovernmental Panel on Climate Change.* Geneva: World Meteorological Organization/United Nations Environment Programme.

[15] The analysis begins in 1993, because that is the first year for which the data base consistently published abstracts. Some abstracts initially compiled were deleted from our analysis because, although the authors had put "climate change" in their key words, on reading it became clear that the paper had, in fact, nothing to do with that subject.

[16] This is consistent with the analysis of historian Spencer Weart, who concluded that scientists achieved consensus in 1995. See Spencer R. Weart. 2003. *The discovery of global warming*. Cambridge, Massachusetts: Harvard University Press.

[17] Artic Council. 2004. Arctic Climate Impact Assessment. http://www.acia.uaf.edu/ (accessed March 14, 2005).

[18] These impacts are also discussed in Elizabeth Kolbert. 2006. *Field Notes from a Catastrophe.* New York: Bloomsbury, and Tim Flannery. 2006. *The Weather Makers: How Man Is Changing the Climate and What It Means for Life on Earth.* New York: Atlantic Monthly Press.

[19] W. Soon, S. Baliunas, S. B. Idso, K. Y. Kondratyev, and E. S. Posmentier. 2001. Modeling Climatic Effects of Anthropogenic Carbon Dioxide Emissions: Unknowns and Uncertainties. *Climate Research* 18: 259-275.

[20] In emails that I received after publishing my essay in *Science*, this paper was frequently invoked.

[21] Soon et al, 2001. See also, W. Soon, S. Baliunas, S. B. Idso, K. Y. Kondratyev, and E. S. Posmentier. 2002. Modeling Climatic Effects of Anthropogenic Carbon Dioxide Emissions: Unknowns and Uncertainties Reply to Risbey. *Climate Research* 22: 187-188.

[22] See for example, Leonard A. Smith, 2001 Proceedings of the National Academy of Sciences, 99 (suppl.1): 2487-2492.

[23] And we do. According to Time magazine, a recent Gallup poll reported that "64% of Americans think scientists disagree with one another about global warming." Time, March 26, 2006; see Time. 2006. Poll: Americans See a Climate Problem. *Time.com,* (March 26), http://www.time.com/time/nation/article/0,8599,1176967,00.html (accessed May 1, 2006).

[24] This is not just an abstract concern. One possible implication is that they are no longer objective, either. This is not an abstract worry: 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 NIH, the American Cancer Society, or other non-profit 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, vs. simply trying ones best to communicate the results of ones research clearly and in plain English.

[25] For the role of think-tanks in the misinformation campaigns, see Ross Gelbspan. 1997. *The Heat is On: The High Stakes Battle over Earth's Threatened Climate*. Reading, MA: Addison-Wesley, and Ross Gelbspan. 2004. *Boiling Point: How Politicians, Big Oil and Coal, Journalists, and Activists are Fueling the Climate Crisis-and What we Can do to Avert Disaster*. New York: Basic Books.

[26] Maxwell T. Boykoff, and Jules M. Boykoff. 2004. Balance as bias: global warming and the US prestige press. *Global Environmental Change* 14: 125-136.

[27] It is important to note that some petroleum companies, such as BP and Shell, have refrained from participating in misinformation campaigns. See John Browne. 1997. Climate change: the new agenda. Presentation, May 19, in Stanford, California. Brown began his 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." (p 3).
For an analysis of diverse corporate responses, see Sybille Van den Hove, Marc Le Menestrel, and Henri-Claude de Bettignies. 2003. The oil industry and climate change: strategies and ethical dilemmas. *Climate Policy* 2: 3-18.

[28] For an analysis of one particular ad, "Weather and Climate" see Environmental Defense. 2005. Too Slick: Stop ExxonMobil's Global Warming Misinformation Campaign. http://actionnetwork.org/campaign/exxonmobil?source=edac2 (accessed March 14, 2005). An interesting development in 2003 was that that ISS, Institutional Shareholders Services, Inc. advised Exxon-Mobil Shareholders to ask the company to explain its stance on climate change issues and to divulge financial risks that could be associated with it. See Reuters. 2003. ISS in favor of ExxonMobil global warming proposals. *Planet Ark* (May 19, 2003), http://www.planetark.com/dailynewsstory.cfm/newsid/20824/story.htm (accessed March 14, 2005).

[29] Environmental Defense. 2005. Too Slick: Stop ExxonMobil's Global Warming Misinformation Campaign.

http://actionnetwork.org/campaign/exxonmobil?source=edac2 (accessed March 14, 2005). Assertions of uncertainty have also been made by leading officials in government; see for example Eric Pianin. 2002. Group meets on global warming: Bush officials say uncertainties remain on cause, effects. *Washington Post*, December 4, Southeast edition. and Andrew C. Revkin, and Katharine Q. Seelye. 2003. Report by EPA leaves out data on climate change. *The New York Times*, June 19, (Midwest edition) A1.

[30] These efforts to generate an aura of uncertainty and disagreement have had an effect. This issue has been studied in detail by academic researchers; one example may suffice to make the point, see for example, Maxwell T. Boykoff, and Jules M. Boykoff. 2004. Balance as bias: global warming and the US prestige press. *Global Environmental Change* 14: 125-136.

[31] Oreskes, 2004.

[32] Reliable, is of course, a term of judgment. By reliable I mean provided a basis for action that 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.

[33] Intergovernmental Panel on Climate Change. 1990. *Scientific assessment of climate change: the policymakers' summary of the report of Working Group I to the Intergovernmental Panel on Climate Change.* Geneva: World Meteorological Organization/United Nations Environment Programme; James P. Bruce, Hoesung Lee, and Erik F. Haites, eds. 1996. *Climate change 1995: economic and social dimensions of climate change*. Cambridge: Cambridge University Press; Robert T. Watson, Marufu C. Zinyowera, and Richard H. Moss, eds. 1996. *Climate change, 1995: impacts, adaptations and mitigation of climate change: scientific-technical analyses*. Cambridge: Cambridge University Press; James J. McCarthy, Osvaldo F. Canziani, Neil A. Leary, David J. Dokken, and Kasey S. White, eds. 2001. *Climate change 2001: impacts, adaptation and vulnerability**:** contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change***.** Cambridge: Cambridge University Press; J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, x. Dai, K. Maskell, and C.A. Johnson, eds. 2001. *Climate change 2001: the scientific basis: contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press; Bert Metz, Ogunlade Davidson, Rob Swart, and Jiahua Pan, eds. 2001. *Climate change 2001: mitigation: contribution of Working Group III to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press; Robert T. Watson, ed. 2001. *Climate change 2001: synthesis report*. Cambridge: Cambridge University Press; National Academy of Sciences Committee on the Science of Climate Change, 2001; and Spencer R. Weart, 2003. *The discovery of global warming*. Cambridge, Massachusetts: Harvard University Press.

[34] James J. McCarthy, Osvaldo F. Canziani, Neil A. Leary, David J. Dokken, and Kasey S. White, eds. 2001. *Climate change 2001: impacts, adaptation and*

vulnerability: *contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press; J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, x. Dai, K. Maskell, and C.A. Johnson, eds. 2001. *Climate change 2001: the scientific basis: contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press; Bert Metz, Ogunlade Davidson, Rob Swart, and Jiahua Pan, eds. 2001. *Climate change 2001: mitigation: contribution of Working Group III to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press; Robert T. Watson, ed. 2001. *Climate change 2001: synthesis report*. Cambridge: Cambridge University Press.

[35] Jan Esper, Edward R.Cook, and Fritz H. Schweingruber. 2003. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* 295: 2250-2253.

[36] Charles C. Gillispie, ed. 1975. Semmelweis. In *Dictionary of scientific biography*. Vol. 12. New York: Scribner. The classic user of Semmelweis to illustrate scientific method is Carl Hempel. See Carl Hempel. 1965. *Aspects of scientific explanation, and other essays in the philosophy of science*. New York: Free Press; Carl Hempel. 1966. *Philosophy of natural science.* Englewood Cliffs, New Jersey: Prentice-Hall.

[37] Roger Revelle. 1965. "Atmospheric Carbon Dioxide, Appendix Y4 of Restoring the Quality of Our Environment, a Report of the Environmental Pollution Panel." *President's Science Advisory Committee, The White House*, pp. 111-133.

[38] On Arrhenius, Callendar, Revelle and Suess, see Fleming, 1998 and Weart, 2003. On the actual increase in sea level rise, see McCarthy et al., 2001; Houghton, et al., 2001; Metz et al., 2001; Watson, 2001.

[39] On Manabe, see Manabe and Stouffer, 1980 and 1994. For a recent discussion of how different models predict polar amplification, see Holland and Bitz, 2003. For the evidence of polar amplification taking place, see Artic Council, 2004

[40] Popper, 1959.

[41] Stainforth, 2005.

[42] Smith. 2004.

[43] This is most evident by comparing the three IPCC assessments: 1990, 1995 , 2001: Intergovernmental Panel on Climate Change, 1990; Bruce et al., 1996; Watson et al., 1996; McCarthy et al., 2001; Houghton, et al., 2001; Metz et al., 2001; Watson, 2001. See also Weart, 2003.

[44] Gillispie, 1981; the idea has recently been popularized by biologist E.O. Wilson, see Wilson, 1998.

[45] Briffa and Osborn, 2002.

[46] The most comprehensive treatment of this view is Lipton, 1991, reprinted 2004.

[47] Lipton, 2004, on 56.