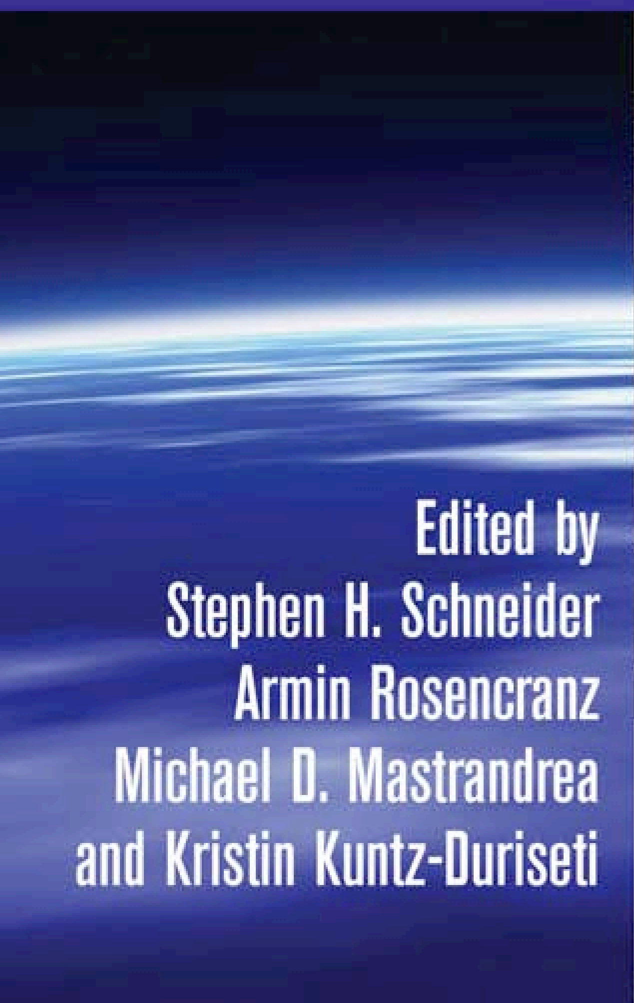
Climate Change Science and Policy



Edited by
Stephen H. Schneider
Armin Rosencranz
Michael D. Mastrandrea
and Kristin Kuntz-Duriseti

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Dedicated to a generation of our students who, over the years, have been the inspiration—and the guinea pigs—for the evolution of this book.

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ACKNOWLEDGMENTS

In January 2006, Steve Schneider and Armin Rosencranz concluded that their earlier volume, *Climate Change Policy* (Island Press, 2002), was no longer current. In light of the many developments in climate change science and policy and the broad recognition that anthropogenic carbon loading of the atmosphere is having increasingly severe global consequences, a new and comprehensive book on the subject was needed. Schneider and Rosencranz invited their former student and recent PhD, Michael Mastrandrea, to join them in coediting such a volume.

The editors are indebted to a number of people who played critical roles in bringing this project to fruition. First and foremost is Kristin Kuntz-Duriseti, who had coauthored one of Schneider's chapters in the 2002 edition and who worked with authors to edit each chapter down to its essence for the final version. Kristin's work was so impressive that the three original editors asked her to join the project as a fourth editor.

Sixteen graduate students in Armin Rosencranz's climate change policy class at the University of Maryland's School of Public Policy—Sanjana Ahmad, Andre Aquino, Russ Conklin, Jonathan Dorn, Kate Durant, Dan Emerine, Jerry Hinkle, Christina Hodgson, Marisa London, Mandy Ma, Lisa McGoldrick, Julia Miller, Margaret Spearman, Rodolfo Tello, Brian Turnbaugh, and Elizabeth Vonhof—also carefully reviewed and evaluated earlier drafts of each chapter.

The editors also received countless hours of help in formatting and preparing the final chapters and artwork. Vikram and Sanjay Padval were the helpers on the formatting. The helpers on the artwork, who often needed to find original and high-resolution sources, were Lee Love-Anderegg and Sarah Jo Chadwick. Lee and Sarah spent countless hours binding all the loose strings together, and their work was essential to the completion of the book. Lee also played a critical role working with Kristin on final chapter edits.

Chapter authors are the heroes of this publication. They patiently and cooperatively revised and updated their material at least twice and often three times in order to make the book as up to date and as relevant as it could be.

It has been a pleasure to work again with Todd Baldwin at Island Press. With his help, we have sought to make this book complete, authoritative, and readable. We editors are responsible for any lacunae that the reader may find.

Stephen H. Schneider
Armin Rosencranz
Michael Mastrandrea
Kristin Kuntz-Duriseti

Introduction

John P. Holdren

The popular term *global warming* is a misnomer. It implies something uniform, gradual, mainly about temperature, and quite possibly benign. What is happening to global climate is none of those. It is occurring with uneven effects across geographic, economic, and social divisions. It is rapid compared with ordinary historic rates of climatic change, as well as rapid compared with the adjustment times of ecosystems and human society. It is affecting a wide array of critically important climatic phenomena besides temperature, including precipitation, humidity, soil moisture, atmospheric circulation patterns, storms, snow and ice cover, and ocean currents and upwellings. And its effects on human well-being are and undoubtedly will remain far more negative than positive. A more accurate, albeit more cumbersome, label for this phenomenon is *global climatic disruption*.

The disruption that the world is experiencing has been documented in thousands of scientific reports covering dozens of climatic phenomena in hundreds of locations around the globe. While natural processes affect climate and climate change on time scales both short and long, overwhelming scientific evidence supports the conclusion that the human influences on climate, growing steadily since the beginning of the Industrial Revolution, have become the dominant driver of the exceptionally rapid climatic change experienced during the last half century. The largest of these human influences is the atmospheric buildup of the heat-trapping gas carbon dioxide, which civilization emits in immense quantities through combustion of the coal, oil, and natural gas that fuel 80 percent of world energy use and through deforestation occurring largely in the tropics.

These fundamental conclusions about the problem of climate change are solid. They are based on:

- Basic and uncontroversial understandings of how energy interacts with the gases that make up the atmosphere and how the Earth's water and carbon cycles work.
- Temperature readings by global networks of thermometers spanning 125 years, as well as similarly long-running and wide-ranging measurements of other climate variables.

- The records of earlier climates preserved in tree rings, corals, ocean sediments, and layered ice cores.
- Complex and detailed computer models of the motions of atmosphere and oceans showing that the sum of human and natural influences as we understand them explains with high fidelity the pattern of observed changes in global climate that has been observed.

Subject to somewhat greater uncertainties (which are two-sided and thus not a rational basis for complacency) are projections of how global climatic disruption will evolve in the future. There is, after all, a range of possibilities for the future trajectories of population, economic activity, and technology—and thus of the emissions of carbon dioxide and other climate-altering substances emanating from the activities of civilization—and for any given emissions scenario there is a set of uncertainties, expanding as one moves further into the future, arising from imprecision in our predictions of how emissions will affect atmospheric concentrations, how concentrations will affect average temperatures, and how changes in average temperatures will affect the spatial and temporal patterns of hot and cold, wet and dry, and storm and calm that constitute the actual climate.

It is known with very little doubt, however, that the average surface temperature of the Earth has already gone up about 0.8 degree Celsius above its level in 1750 and would eventually go up about another 0.5 degree even if all the climate-altering gases and particles in the atmosphere could be "frozen" at today's concentrations (due to the long time lag for the ocean to reach equilibrium with the altered atmospheric energy transport those climate-altering substances cause). It is also known with considerable confidence that, under a middle-of-the-road emissions trajectory going forward—not the highest plausible and also not the lowest—the global average temperature increase is likely to reach something like 2 degrees Celsius above the 1750 figure by 2050 and 3 to 4 degrees Celsius above it by 2100.

These increases may sound small to those not steeped in climate change science, but they are frightening to nearly all of those who are, for two reasons: (1) the changes in mid-continents (where agriculture is concentrated) are typically twice the global average change, and those in the far north are 3 to 4 times the global average (with huge impacts on tundra, permafrost, northern forests, and sea ice); and (2) small changes in global-average surface temperature correspond to large changes in the climatic *patterns* that strongly influence human affairs and the fate of ecosystems. The last time the Earth was 2 degrees Celsius warmer was 130,000 years ago, when the climate was markedly different from today's and sea level was 4 to 6 meters higher. The last time the Earth was 3 to 4 degrees Celsius warmer was 30 million years ago, when the climate was drastically different and sea level was 20 to 30 meters higher.

Climate change is already causing harm *now*. Major floods, droughts, heat waves, and wildfires have been on the rise all around the world, in patterns largely predicted by climate models for a world heating up as ours is. The evidence that the disruption is also driving an increase in the power of hurricanes and typhoons is becoming compelling. Coral reefs are being roasted by rising sea-surface temperatures and pickled by the increased ocean acidity that is caused by uptake of some of the excess carbon dioxide from the atmosphere. The World Health Organization estimated in

2002 that global climate change was responsible for 150,000 premature deaths worldwide already in the year 2000; the number would be much higher today.

Faced with the challenges posed by this human-driven disruption of global climate, civilization has only three options:

1. Mitigation, meaning measures to reduce the pace and magnitude of the changes in climate that will occur (e.g., emissions reductions, afforestation and reforestation, improved soil management, geo-engineering to create cooling effects to offset warming by heat-trapping gases).
2. Adaptation, meaning measures to minimize the harm done by the climate changes that do occur (e.g., developing heat- and drought-resistant crop strains, strengthening defenses against diseases favored by a warming world, building more dams to contain floods and dikes to cope with rising sea level).
3. Suffering the impacts that mitigation and adaptation don't avoid.

Society is already doing some of each: we are mitigating; we are adapting; and we are suffering. The open question is what the future mix will be.

Neither mitigation alone nor adaptation alone will do. No amount of effort at mitigation can stop climate change in its tracks; the disruption is certain to grow before it can be stabilized and perhaps rolled back. Adaptation, for its part, becomes more costly and less effective the larger the climatic changes to which we are trying to adapt. And there are some impacts for which no meaningful adaptation is possible. Many low-lying regions will not adapt to 2 or 3 meters of sea-level rise; they will be submerged. Nor will we adapt to the likely loss of the world's coral reefs and their rich biodiversity; we will just do without them, permanently impoverished by their absence. Clearly, minimizing suffering will require a strategy incorporating a great deal of both mitigation and adaptation.[1]

Specifying the degree of climate change that should be avoided has been a vexing issue. The 1992 UN Framework Convention on Climate Change, which under international law is the "law of the land" in all 191 countries that have ratified it (including the United States), called for "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." The convention did not define what would constitute "dangerous anthropogenic interference," however, and the climate-science-and-policy literature has been increasingly populated ever since with articles proposing definitions of varying degrees of complexity and sophistication.

I find this question a sterile part of the debate. In my personal opinion the world is already experiencing "dangerous anthropogenic interference" by any ordinary understanding of the meaning of the word "dangerous." The question now, in my view, is whether we can avoid *catastrophic* anthropogenic interference with the climate system.

How much mitigation will be needed to avoid catastrophe? The probability of crossing a tipping point into potentially unmanageable degrees of climatic change rises rapidly for increases in global average surface temperature more than 2 to 2.5 degrees Celsius above the 1750 level.[2] The European Union reached agreement in 2002 that not exceeding a 2-degree-Celsius increase should be society's goal. Taking into account uncertainties about the exact sensitivity of global average surface temperature to greenhouse gas concentrations, one finds that achieving a 50 percent chance of not exceeding 2 degrees Celsius above the 1750 level requires stabilizing the atmospheric concentrations of climate-altering substances at the equivalent of 450 parts per million by volume of carbon dioxide. A 50 percent chance of not exceeding 2.5 degrees Celsius requires stabilizing at 500 parts per million by volume CO_2-equivalent.

As a number of the chapters in this book explain in greater detail, translating these concentration targets into corresponding emissions trajectories leads to the conclusion that global emissions of carbon dioxide from fossil fuel burning and deforestation must peak and begin to decline no later than 2015 to 2025 (depending on which target is chosen and on what the trajectories of the other climate-altering substances are). Achieving such a large deflection from "business as usual" will be a large challenge, however. The quantity of civilization's carbon dioxide emissions is immense—well over 30 billion tons per year from fossil fuel burning and tropical deforestation combined. Today, 75 to 80 percent of this is coming from burning the fossil fuels—coal, oil, and natural gas—that still supply 80 percent of the world's energy. The offending pollutant is emitted in volumes too large and from sources too diverse to be captured cheaply, and the fossil fuel–dominated global energy system is too big and too costly to be changed quickly. The CO_2 emissions coming from tropical forestation will also not be easy to reduce, because the forces driving this deforestation are deeply embedded in the economics of food, fuel, timber, trade, and development.

Although the challenge is large, there is a wide array of effective emission-reduction options; employing enough of them in parallel could give a reasonable chance of avoiding catastrophe. Many of these—particularly those focused on increasing the efficiency of energy end-use in buildings, transport, and manufacturing—can be undertaken at negative cost (that is, at a profit), because the value of the energy saved more than pays for them. Some others, such as measures to reduce soot emissions from inefficient engines, would be seen to be profitable propositions for society as a whole if their co-benefits in improved public health or other "public goods" were taken into account. Still others would at least be relatively inexpensive if their social benefits were subtracted from their costs—for example, reforestation, afforestation, and avoided deforestation (forest preservation).

It's very unlikely that emissions can be reduced as much as needed using only the profitable and inexpensive options, however. While one can imagine technological breakthroughs that might expand the scope for inexpensive reductions, the timing of the need means we cannot wait. Most important, we need to outfit the new coal-burning power plants scheduled to be built in the next twenty years to capture and sequester their carbon dioxide. Measures as costly as that will only be embraced if a high price is placed on greenhouse-gas emissions or if regulations require them. That's why government action is essential to move mitigation forward at an adequate pace.

There is every indication from the most careful studies that have been conducted to date that the cost of a portfolio of measures adequate to the task—comprising profitable, inexpensive, and costlier alternatives together—would probably not reduce world GDP in 2050 by more than a percent or two, nor reduce GDP in 2100 by more than twice that, which would represent one or two years' growth at the generally forecasted rates. In other words, the citizens of the world would need to wait until 2101 or 2102 to be as rich as they otherwise would have been in 2100. This seems to me to be a small price to pay for a large reduction in the probability of climatic catastrophe with a far bigger negative impact on future GDPs.

The most important conclusions about global climatic disruption—that it's real, that it's accelerating, that it's already doing significant harm, that human activities are responsible for most of it, that there is a growing danger of its becoming unmanageable, and that there is much that could be done to reduce the danger at affordable cost—have not been concocted by environmental extremists or enemies of capitalism. They are based on an immense edifice of painstaking studies published in the world's leading peer-reviewed scientific journals. They have been vetted and documented in excruciating detail by the largest, longest, costliest, most international, most interdisciplinary, and most thorough formal review of a scientific topic ever conducted—the now nearly twenty-year-long, multi-thousand-participant study by the Intergovernmental Panel on Climate Change organized under the auspices of the World Meteorological Organization and the UN Environment Programme.[3] They have been attested to by the leadership of the academies of science of Brazil, Canada, China, France, Germany, India, Italy, Japan, Russia, the United Kingdom, and the United States (in a joint statement issued in 2005); the American Geophysical Union; the American Association for the Advancement of Science; and the national meteorological offices of every country that has one. They are endorsed by all three winners of the only Nobel Prize ever awarded for atmospheric science.

The science of global climate disruption and its impacts, the technology of remedies, the economics of damage and evasive action, and the policy issues that must be resolved if the available insights from science, technology, and economics are to be integrated into an effective program of action have already been the topics of several long shelves' worth of books and book-length reports. Why another book now, and why the particular book that is before you?

This book's audience, in my view, is a broad one: students in interdisciplinary courses on climate change for upper-division undergraduate and graduate courses; graduate students and more senior researchers who work on one part or another of the science, technology, economics, or politics of the climate change problematique and seek a an authoritative but still accessible introduction to the parts they have not focused on in their own work; natural and social scientists who haven't worked on the climate problem, but want to survey the subject in a way that moves them efficiently up the learning curve; and journalists, policy makers, and members of the wider public who have the appetite and capacity for mastering the level of technical detail needed to understand—really understand—what global climate disruption is, where it is headed, what can be done, and how. No other book that I'm aware of offers this one's combination, for these purposes, of comprehensiveness, authoritativeness, currency, and readability.

To those who might ask whether the 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change hasn't already met this need, I would answer, in part, that the three main volumes—the full reports of IPCC Working Groups I, II, and III—are too much (at 2,823 large-format pages of fine print), while the Summaries for Policymakers and even the Technical Summaries are too little.[4] The book before you is the "Goldilocks Solution"—the amount of intellectual sustenance on climate change that is "just right."

In addition, there is the matter of coverage of the most recent developments. The multilayered review and consultative process followed by the IPCC dictated a December 2005 cutoff for science findings to be covered in an assessment issued in early to mid-2007. The climate change field is fast-moving—not only in its scientific but also in its technological and policy dimensions—and many important developments too recent to be treated by the 2007 IPCC documents are covered here.

One of the primary uses of this volume, in my view, will be to equip its most industrious readers with all they need to recognize and to rebut the misunderstandings and misrepresentations being propagated by climate change deniers, who continue to receive attention in the media disproportionate to their numbers, their qualifications, or the merit of their arguments. The attention and credence they receive are a menace, insofar as it delays the development of the political consensus that will be needed before society embraces remedies that are commensurate with the magnitude of the climate change challenge.

It is often said that there are three stages of denial in relation to issues at the science-society interface:

1. They tell you you're wrong, and they can prove it: "Climate isn't changing in unusual ways" or "Human activities are not the cause of climate change."

2. They tell you you're right, but it doesn't matter: "OK, the Earth's climate is changing, and humans are playing a role, but the damages will be small and there may even be some benefits."

3. They tell you it matters, but it's too late to do anything about it: "Yes, climate disruption is going to do some real damage, but it's too late, too difficult, or too costly to avoid that, so we'll just have to hunker down and suffer."

Individual deniers often move over time from stage 1 to 2 and from 2 to 3 as evidence becomes harder to ignore or refute. The very few deniers with any credentials in climate change science have virtually all shifted in the past few years from stage 1 to 2; jumps from 2 to 3 and even from 1 to 3 are becoming more frequent.

All three positions are deeply wrong, and the reasons why they are wrong are nowhere as clearly, comprehensively, and authoritatively laid out as in this book. The intellectual terrain it covers is vast and sometimes demanding, but it will repay the effort of all those able and willing to traverse it. May many do so.

Notes

1. The international Sigma Xi/UN Foundation Scientific Expert Group (SEG) on Climate Change and Sustainable Development, which provided its recommendations on mitigation and adaptation opportunities to the UN Commission on Sustainable Development and the Secretary General in February 2007, stated the dual mitigation-adaptation challenge concisely in the subtitle of its report: "Avoiding the Unmanageable and Managing the Unavoidable." Scientific Expert Group on Climate Change (SEG), 2007: Confronting Climate Change: Avoiding the Unmanageable and Managing the Unavoidable. Rosina M. Bierbaum, John P. Holdren, Michael C. MacCracken, Richard H. Moss, and Peter H. Raven, eds. Report prepared for the United Nations Commission on Sustainable Development. Sigma Xi, Research Triangle Park, NC, and the United Nations Foundation, Washington, DC, 144 pp.

2. Ibid.

3. See the Web site of the Intergovernmental Panel on Climate Change, www.ipcc.ch.

4. IPCC, 2007a: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, M. Marquis, K. Averyt, M. M. B. Tignor, H. L. Miller, Jr., and Z. Chen, eds., Cambridge University Press, Cambridge, UK.

IPCC, 2007b: *Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, eds., Cambridge University Press, Cambridge, UK.

IPCC 2007c: *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer, eds., Cambridge University Press, Cambridge, UK.

Impacts of Climate Change

Chapter 1

Climate Change Science Overview

Michael D. Mastrandrea and Stephen H. Schneider

Introduction

This chapter outlines the current state of scientific knowledge regarding the climate system and the effects of human activities on climate. Although uncertainty remains regarding knowledge about climate, the basic processes that cause climate change are scientifically well established, and human activities have been identified with very high confidence as the main driver of most observed climate-induced trends during the last several decades. Conclusions such as these are based on the vast preponderance of accumulated scientific evidence. To understand complex systems science like the study of climate change, it is essential to distinguish such conclusions from hypotheses that can be "falsified" by one or even several lines of argument that seem to contradict the mainstream consensus. This is how simple science used to be done—for example, testing whether the liquid in a tube is acidic or basic. One piece of litmus paper can falsify a wrong preliminary hypothesis. While it can take decades to reconcile incomplete elements of complex systems analysis, rarely will a few contrary results entirely overthrow a consensus built on decades of consistent lines of evidence.

Throughout this chapter, many research findings we refer to are taken from the multiply-peer-reviewed, government-approved Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, which present the best approximation of a worldwide consensus on climate change science every five to six years. One important feature of IPCC reports is the quantified assessment of the likelihood of each major conclusion, and the explicit assignment of the authors' confidence in the underlying science to back up each conclusion. This practice clearly separates out aspects that are well established from those that are better described by competing explanations and from those best labeled as speculative. This contrasts markedly from most of the media and political debates in which well-established conclusions are often conflated with speculative ones, and public confusion results. Box 1.1 presents the likelihood and confidence definitions from the 2007 IPCC Fourth Assessment Report (AR4).[1]

Box 1.1

The IPCC defines the likelihood of an outcome or a result as: Virtually certain (greater than 99 percent probability of occurrence), extremely likely (greater than 95 percent), very likely (greater than 90 percent), likely (greater than 66 percent), more likely than not (greater than 50 percent), unlikely (less than 33 percent), very unlikely (less than 10 percent), and extremely unlikely (less than 5 percent).

The IPCC defines the level of confidence in the correctness of the science underlying a conclusion as: Very high confidence (at least a 9 out of 10 chance of being correct), high confidence (about an 8 out of 10 chance), medium confidence (about a 5 out of 10 chance), low confidence (about a 2 out of 10 chance), and very low confidence (less than a 1 out of 10 chance).

The Global Temperature Record

Modern temperature records date back to the mid-nineteenth century, when thermometers became accurate and widespread enough to allow scientists to calculate a meaningful global average temperature. These records show (figure 1.1) that the Earth's average surface temperature has increased by about 0.75 degree Celsius (around 1.4 degrees Fahrenheit) since the mid-nineteenth century (with an uncertainty of about a tenth of a degree Celsius).[2]

Year-to-year variation in temperature cannot override this long-term upward trend in global average temperature. Unfortunately, short-term variability in the temperature record is often inappropriately used to "refute" long-term climatic trends. Climate, however, refers to the state of atmospheric conditions over decades or longer, while weather refers to shorter-term variations in atmospheric conditions. Thus, the IPCC description of the warming trend of past century or so as "unequivocal" is indeed appropriate, and even decadal-scale exceptions do not disprove this long-term fact.

Looking back into history can tell us more about how the current anthropogenic (or human-caused) changes compare to naturally induced changes in the past, both in magnitude and in rate. Paleoclimatologists use proxy variables that vary with temperature to approximate temperature records that stretch back hundreds, thousands, and even millions of years (see figure 1.2). These proxies consider diverse factors such as tree rings, the extent of mountain glaciers, changes in coral reefs, and pollen in lake beds. Although there is considerable uncertainty in temperature, the averaged trend over the last 1,000 years is a gradual temperature decrease over the first 900 years, followed by a sharp upturn in the twentieth century (shown also in figure 1.1). The question is, Why?

In particular, there are three typical explanations of observed global mean surface air temperature trends: (1) natural internal variability, in which energy exchanges among atmosphere, oceans, ice sheets, and ecosystems cause random, unpredictable background noise; (2) natural forcings in the Earth's radiative energy input from volcanic dust veils or solar energy fluctuations; and (3) anthropogenic

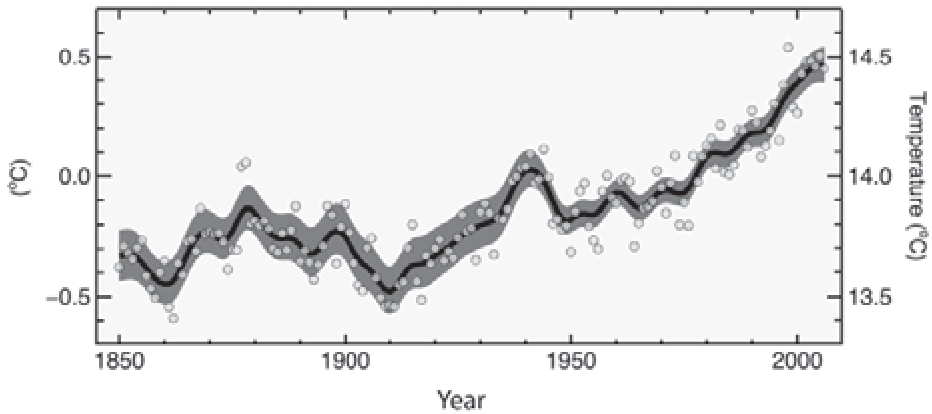

FIGURE 1.1. Observed global average temperature record (since 1850), shown relative to the average for 1961–1990 (vertical axis on the left), as well as in absolute terms (vertical axis on the right). Smoothed black line represents decadal average values, circles represent yearly values. Shading represents uncertainty in observations. Source: Intergovernmental Panel on Climate Change (IPCC), 2007(a), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon et al., eds., Cambridge University Press: Cambridge, United Kingdom.

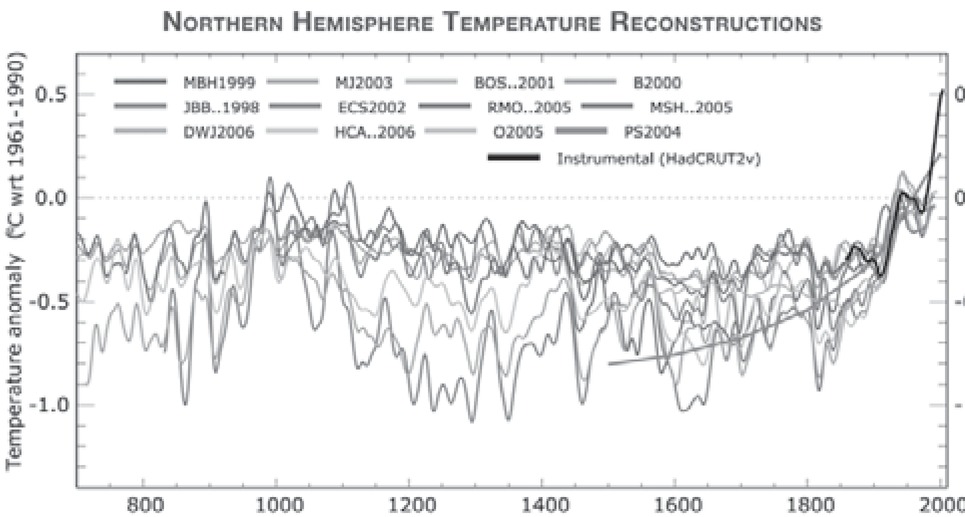

FIGURE 1.2. Records of northern hemisphere temperature variation during the last 1,300 years relative to the 1961–1990 average using multiple proxy records. Observed temperature record since 1850 shown in black. Source: Intergovernmental Panel on Climate Change (IPCC), 2007(a), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon et al., eds., Cambridge University Press: Cambridge, United Kingdom.

forcings, such as increased greenhouse gases, altered atmospheric aerosols (e.g., dust and smoke), and land-use changes.

A Natural Climate Variation?

Is it possible that natural variability and natural forcings of the Earth's climate could produce the temperature record of figures 1.1 and 1.2? Using a variety of methods to detect the human "fingerprint" on observed warming trends, scientists are finding overwhelming evidence that the answer to this question is "no" (see chapter 2).

Scientists can also use computer models of the climate system (see below) to investigate the contribution of natural and human factors to the observed warming. Figure 1.3 shows a comparison of the global average surface temperature record for the twentieth century (black line) with two sets of climate model simulations of this time period. The gray lines represent simulations that are driven only by estimates of purely natural forcings—solar variability and volcanic activity (see Solar Variability and Aerosols below). The range of simulations indicates an estimate of the degree of uncertainty in the model calculations. The estimated temperature variation due to natural forcing alone does not show an overall warming trend and is clearly a poor fit to the actual surface temperature record, especially in the second half of the century when temperatures made a significant upturn. The lighter lines represent simulations that also incorporate anthropogenic factors—emissions of greenhouse gases and aerosols. The fit between these simulations and the observed record is far better; they strongly suggest that the temperature changes observed in the twentieth century, particularly the rise of the past few decades, cannot be explained without anthropogenic greenhouse gas emissions as a significant causal factor.

Taken together, these and many other fingerprint analyses provide very strong evidence that the observed changes in climate over at least the past several decades are anthropogenic.[3] This has led the IPCC to conclude that most of the warming observed over the last fifty years is attributable to human activities and, in addition, that the influences of anthropogenic climate change are now identifiable on warming ocean temperatures, changes in the life cycles of plants and animals (see chapter 3), atmospheric circulation patterns, and the increasing intensity of some extreme weather events.[4]

Keeping the Earth Warm

What ultimately determines climate and specifically the Earth's temperature? That question is at the heart of climate science and of the issues surrounding anthropogenic climate change.

About half of the light energy from the sun penetrates the atmosphere and is absorbed by the Earth's surface. The surface warms and reemits some of the energy as infrared radiation. Certain naturally occurring gases and particles—greenhouse gases—absorb 80 to 90 percent of the infrared radiation emitted at the surface and radiate heat in all directions, both up to space and back down toward the surface, warming the surface further. This feedback cycle between the Earth's surface and the atmospheric greenhouse gases continues until the infrared radiation released to space is in balance with the sources of radiant energy.

Because the atmosphere functions, in a crude sense, like the heat-trapping glass of a

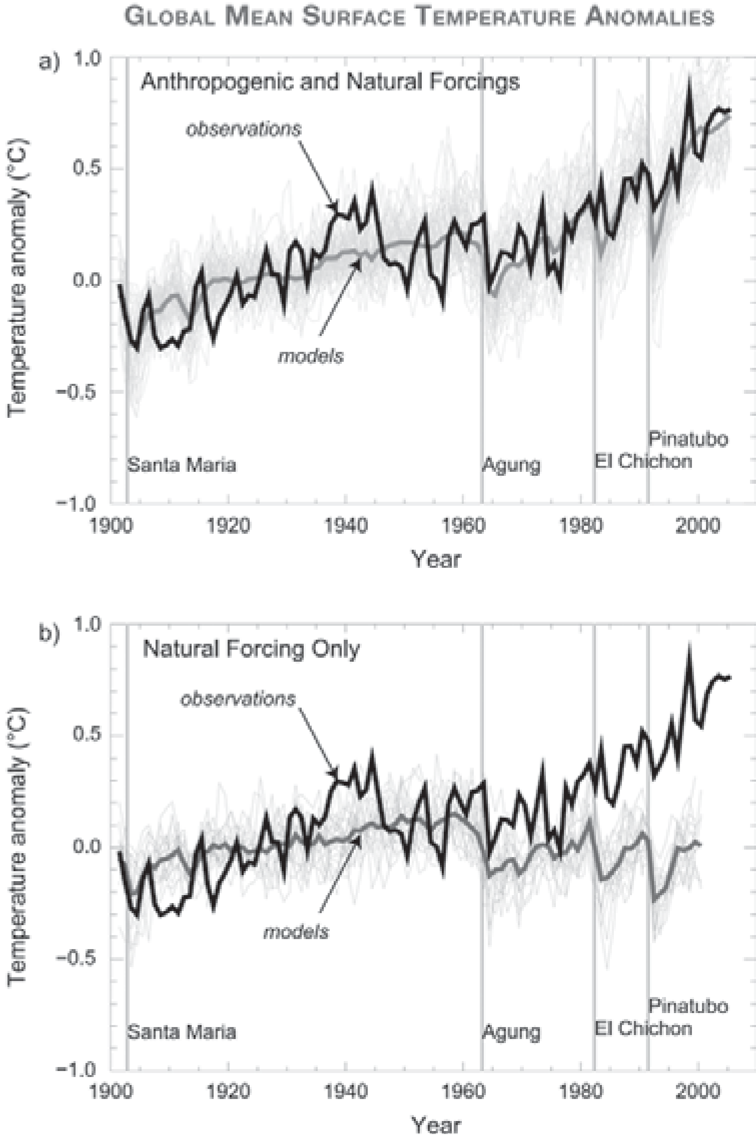

FIGURE 1.3. Observed changes in surface temperature compared with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906–2005 (black lines) relative to the corresponding average for 1901–1950. Gray lines depict model estimates; the ranges of estimates reflect model uncertainty. Gray lines use only natural forcings due to solar activity and volcanoes (dark gray line is multimodel average). Gray lines use both natural and anthropogenic forcings (dark gray line is multi-model average). Major volcanic eruptions are shown in both panels, corresponding to temporary cooling episodes. Source: Intergovernmental Panel on Climate Change (IPCC), 2007(a), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon et al., eds., Cambridge University Press: Cambridge, United Kingdom.

greenhouse, this heating process has earned the nickname "greenhouse effect." The natural greenhouse effect from gases and clouds effectively raises the Earth's surface temperature by 33 degrees Celsius (59 degrees Fahrenheit), which supports life as we know it on the Earth. However, increasing concentrations of atmospheric greenhouse gases due to human activities are intensifying the greenhouse effect and further increasing the Earth's temperature.

Greenhouse Gases Past and Present

Human activities add to the atmospheric concentrations of a number of naturally occurring greenhouse gases and introduce other potent greenhouse gases that are not naturally occurring. Increasing concentrations of the greenhouse gas carbon dioxide (CO_2) due to human activities, primarily the burning of fossil fuels but also deforestation and other land-use changes, have contributed most to the intensification of the greenhouse effect. As shown in figure 1.4, before the Industrial Revolution, CO_2 concentrations were relatively stable for roughly 10,000 years, varying between 260 and 280 parts per million (ppm). In the last 150 years, atmospheric CO_2 concentrations have increased by more than 35 percent, from around 280 to around 380 ppm. The reality of this CO_2 increase is well documented and is well-established science.

Carbon dioxide entering the atmosphere does not just sit there. Huge quantities of carbon circulate between the atmosphere, the ocean, and land ecosystems. As the burning of fossil fuels and carbon dioxide emissions have increased, flows of carbon from the atmosphere into the ocean and into land ecosys-

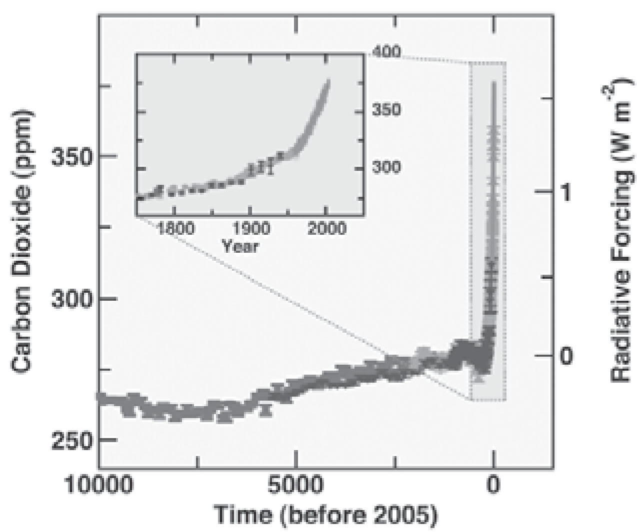

FIGURE 1.4. Atmospheric concentrations in parts per million (ppm) of carbon dioxide during the last 10,000 years and since 1750 (inset panel). Measurements from ice cores (different shades for different studies) and atmospheric samples. Corresponding radiative forcing is shown on the right side.

tems have also increased, but by a smaller amount. Currently, about half of the annual anthropogenic carbon dioxide emissions are taken up by ocean and land ecosystems. However, scientists have observed a decrease in the fraction of anthropogenic emissions absorbed by ocean and land ecosystems, and expect that fraction to continue to decrease as these "sinks" become saturated.[5]

How are scientists able to estimate the concentrations of these gases in the atmosphere for thousands of years in the past? Ice cores bored in Greenland and Antarctica provide estimates of both temperature and atmospheric greenhouse gases going back hundreds of thousands of years. So far, Antarctic ice cores have yielded a continuous record of the past 740,000 years.[6] Variations in ice density associated with seasonal snowfall patterns provide a way to determine the age of specific points in some ice cores. By measuring the ratio of the hydrogen isotope deuterium (D) to hydrogen in the ice, scientists can calculate a proxy for the temperature at the time each layer of ice formed. By analyzing air bubbles trapped in this ancient ice, scientists can even measure the composition of the Earth's past atmosphere. The result of such an ice core analysis, shown in figure 1.5, gives dramatic evidence that temperature (measured by variations in deuterium; D) and greenhouse gas concentrations, particularly carbon dioxide,

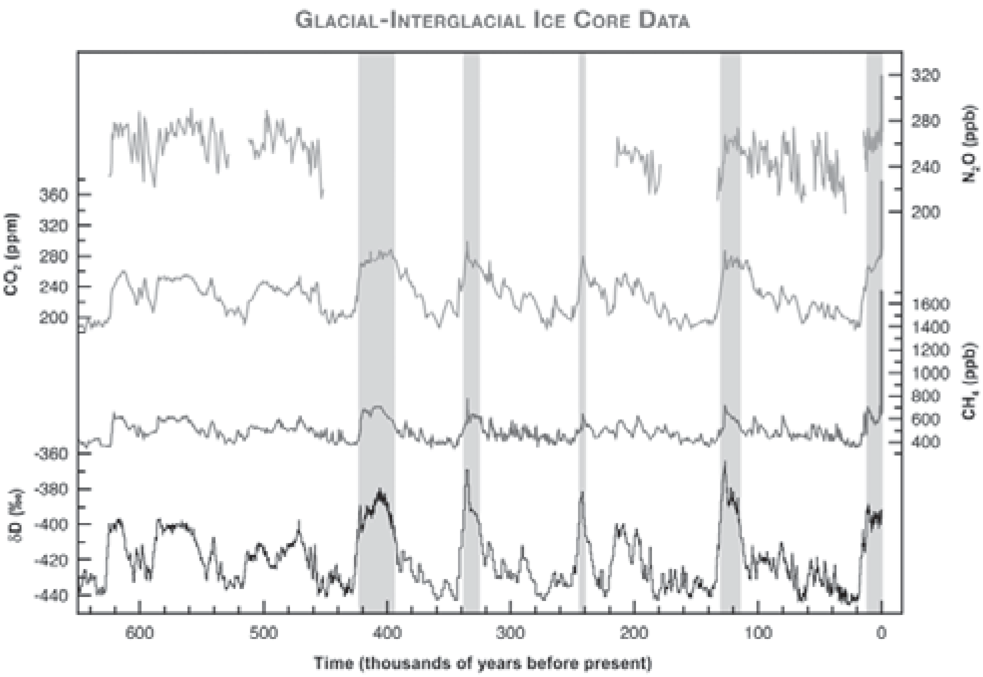

FIGURE 1.5. Variations of deuterium (δD; bottom line) in Antarctic ice core records, a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2; line second from top), methane (CH_4; line second from bottom), nitrous oxide (N_2O; top lines) in air trapped within these ice cores and from recent atmospheric measurements. Data cover 650,000 years, and the shaded bands indicate previous interglacial warm periods.

are correlated over the long term. Although greenhouse gases are not the sole trigger for climate change historically—other factors like variations in the Earth's orbit are likely to initiate and end ice ages—greenhouse gases amplify processes that accelerate ice age formation and eventual deglaciation. The data support the mechanistic understanding of the role of greenhouse gases in climate changes and their ability to cause current and future climate changes as human activities increase atmospheric greenhouse gas concentrations.

The maximum CO_2 concentration in the ice core record of the past 650,000 years is less than 300 ppm. The present-day concentration of around 380 ppm is far above anything the Earth has seen, probably, for millions of years. Figure 1.5 shows the recent rise in CO_2 and other greenhouse gases relative to the rest of the ice core data. Clearly, the anthropogenic increase in CO_2 concentration is unprecedented in both its size and its rapidity over this time period. We have made truly dramatic changes in the Earth's atmosphere over the past century or so, and we are already observing impacts of climate change around the world that will continue to grow. To begin to predict the extent of these changes, we must examine *all* of the important influences human activities have on the climate system.

Greenhouse Gases and Radiative Forcing

Climatologists characterize the effect of a given atmospheric constituent by its radiative forcing, the rate at which it alters absorbed solar or outgoing infrared energy. Water vapor is the most important greenhouse gas, but is not directly influenced much by human activities—only indirectly as a feedback process amplifying warming from the anthropogenic greenhouse gases. Carbon dioxide is the most important of the anthropogenic greenhouse gases, but other gases play a significant role, too. On a molecule-to-molecule basis, most other greenhouse gases are far more potent absorbers of infrared radiation than is CO_2, but they are released in much smaller quantities so their overall effect on climate is smaller. The second most prevalent anthropogenic greenhouse gas is methane. One methane molecule is roughly thirty times more effective at absorbing infrared than is one CO_2 molecule. Although CO_2 concentration increases tend to persist in the atmosphere for centuries or longer, methane typically disappears in decades, making its warming potential relative to that of CO_2 lower on longer timescales. Currently, the radiative forcing from anthropogenic methane is slightly less than one-third that of CO_2.

Other anthropogenic greenhouse gases include nitrous oxide and gases solely created through industrial processes, such as halocarbons used in refrigeration. Halocarbons include chlorofluorocarbons (CFCs), which are also the leading cause of stratospheric ozone depletion. Newer halocarbons do not cause severe ozone depletion but are still powerful greenhouse gases. They are hundreds to thousands of times more potent than carbon dioxide, molecule to molecule, and remain in the atmosphere for centuries to millennia, but appear in much lower concentrations than carbon dioxide and methane. Together, nitrous oxide and halocarbons account for approximately the same level of radiative forcing as methane. A number of other trace gases contribute a small amount of additional forcing. All the gases mentioned so far are well mixed, meaning that they last long enough to be distributed in roughly even concentrations throughout the troposphere, the lowest 10 kilometers of the atmosphere.

Finally, ozone (O_3), familiar because of the "ozone hole" and its depletion by anthropogenic CFCs, is also a greenhouse gas. Ozone in the troposphere near the surface is a potent component of smog, resulting largely from motor vehicle emissions. Tropospheric ozone contributes about one-fourth the radiative forcing of CO_2, although unlike the well-mixed gases, tropospheric ozone tends to be limited to industrialized regions, and it is of great concern for health effects as well as climatic influences.

The cooling of the stratosphere from added greenhouse gases has an effect on ozone, both by temperature-dependent atmospheric chemistry, which might slightly increase ozone levels in the tropical stratosphere, and by cooling of the polar stratosphere, which causes more high-altitude clouds that increase ozone destruction. Thus, there are many processes around the globe leading to climate and ozone changes arising from increasing the concentrations of greenhouse gases in the atmosphere above their natural levels.

Aerosols

Fuel combustion, and to a lesser extent agricultural and other industrial processes, produce emissions that create particulate matter. Coal-fired power plants burning high-sulfur coal, in particular, emit gases that become sulfate aerosols and reflect incoming solar energy, producing a cooling effect. Natural aerosols that produce a cooling effect are also created during volcanic eruptions and the evaporation of seawater, as well as from emissions of hydrocarbons in forested areas like the Great Smoky Mountains—hazes that are largely from biological emissions. Conversely, diesel engines and some biomass burning produce black aerosols such as soot, which absorb the sun's energy and, depending on circumstances, can warm the climate.

Aerosol particles also affect radiative forcing indirectly. For example, they act as "seeds" for the condensation of water droplets to form clouds, affecting the color, size, and number of cloud droplets, and, in aggregate, likely offset some greenhouse warming. The IPCC estimates that the negative radiative forcing resulting directly from all anthropogenic aerosols (e.g., aerosol hazes) offsets about one-third of the positive forcing from greenhouse gases, with indirect effects (e.g., the change in cloud optical properties resulting from pollutant aerosols) offsetting, in aggregate, roughly another third.[7] However, there is considerable uncertainty regarding these figures (especially the indirect effects), which may be much larger or much smaller than these central estimates, although still likely to be a net negative forcing. Unfortunately, the uncertainty in aerosol radiative forcing complicates the assessment of "climate sensitivity": the amount the Earth's surface warms for a given increase in forcing—typically a doubling of CO_2 over pre-industrial levels. The climate sensitivity is an important parameter in projecting future climate change.

Solar Variability

Another important influence on the climate system not affected by human activities is the variation in the sun's energy output. Variations caused by the twenty-two-year sunspot cycle are typically estimated to amount to only about 0.1 percent of solar output and are too small and occur too rapidly to explain a significant climatic effect like the late-twentieth-century warming in figure 1.2. However, long-term solar variations, either from variability in the sun itself or from changes in the Earth's orbit and tilt, have substantially affected the Earth's climate over tens of thousands of years. Accurate, satellite-based measurements of solar output are available for only a few decades. To estimate past variations in solar activity, scientists use proxies such as the level of the isotope beryllium-10 in ice cores. Beryllium-10 is generated by cosmic rays entering the atmosphere, and its level in ice goes down when the sun is active and the "solar wind" of energetic electrons and protons repels more of these cosmic rays, and vice versa. The IPCC estimates that current solar forcing is equivalent to about one-tenth of the forcing from CO_2, which contributes somewhat to observed global climate change but is far below what is needed to fully account for the warming of recent decades. There are many hypotheses suggesting that various solar effects have generated climate change, but none are considered likely explanations of the recent climate warming.[8]

Radiative Forcing: The Overall Effect

Figure 1.6 summarizes our current knowledge of radiative forcing caused by green-

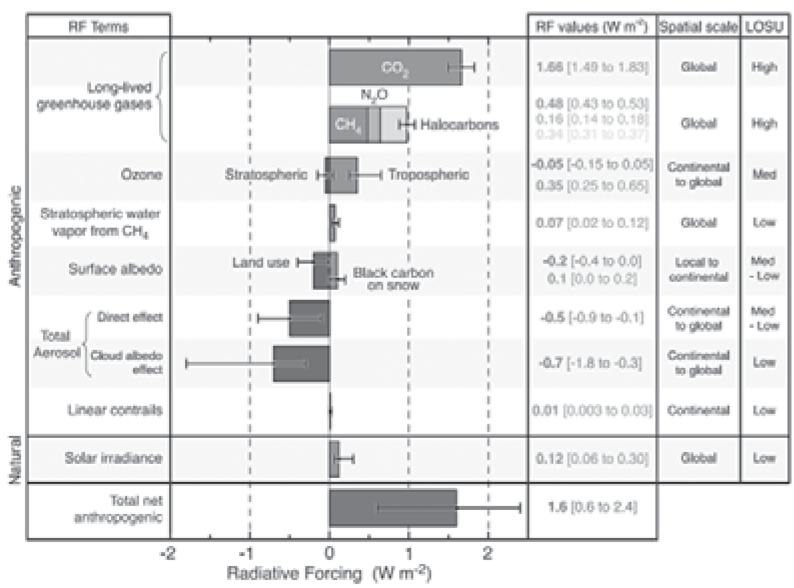

FIGURE 1.6. Global-average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other important processes and components. The total net anthropogenic RF is also shown, which requires combining uncertainty estimates from the component terms and cannot be obtained by simple addition. For each, the bracketed range represents a 90 percent confidence interval (5 percent likelihood that the value could be above or below the range). Typical geographical extent (spatial scale) of the RF and the Working Group I authors' assessed level of scientific understanding (LOSU) are also reported. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature.

house gases, aerosols, land-use changes, solar variability, and other effects since the start of the industrial era.[9] The bottom bar presents an estimate of the total net current anthropogenic forcing. An important point to remember is that the individual forcings in the top panel have different levels of persistence and uncertainty. For example, different greenhouse gases remain in the atmosphere for different periods, as discussed previously. Therefore, the total net forcing is not a simple sum of the individual components. Comparing the top (CO_2) and bottom (total) forcing bars in figure 1.6, scientists estimate that total current forcing is roughly equal to the positive forcing from carbon dioxide.

Feedback Effects

Knowing the radiative forcing caused by changes in atmospheric constituents would be sufficient to project future climate, if there were no additional climatic effects beyond the direct change in energy balance. But a change in climate caused by simple forcing can have significant effects on atmospheric, geological, oceanographic, biological, chemical, and even social processes. These effects, in turn, can further change the climate. If that additional change is in the same direction as its initial cause, then the effect is called a positive or amplifying feedback. If that additional change is in the opposite direction, then it is a negative or dampening feedback. In reality, numerous feedback effects complicate the assessment of climate change. Here we list just a few feedback processes to give a sense of their variety and complexity.

Albedo is a planet's reflectance of solar radiation. The Earth's albedo is about 0.31, meaning that 31 percent of solar radiation is reflected back to space. A decrease in that number means that more radiation is absorbed. As the amount of radiation absorbed increases, global temperature also increases. One consequence of rising temperatures is the melting of snow and ice, which can already be observed in many parts of the world in the form of melting and receding mountain glaciers and decreasing snowpacks. Such melting eliminates a highly reflective surface and exposes the darker land or water beneath the ice. The result is a decreased albedo, increased solar energy absorption, and additional warming. This is a positive feedback.

Rising temperature also results in increased evaporation of water from the oceans into the atmosphere. Because water vapor is itself a greenhouse gas, this effect results in still more warming and is thus a positive feedback. Most assessments suggest that the overall effect of increased water vapor with global warming is a positive feedback that causes a temperature increase some 50 percent higher than would occur in the absence of this feedback mechanism.[10] But increased water vapor in the atmosphere can also mean more widespread cloudiness. More cloudy areas raise the Earth's albedo by reflecting more incoming solar radiation. This reflection results in less energy absorbed by the Earth-atmosphere system, a negative feedback if the increased cloud amount was caused by some positive forcing. On the other hand, more clouds mean greater absorption of outgoing infrared radiation from the Earth's surface. Furthermore, more evaporation or surface heating could mean increases in cloud top heights that would add to the greenhouse effect. Both of the latter processes are positive feedbacks. The net effect of increasing cloud amount depends on latitude and season, but averaged annually over the globe it is often estimated to be a positive feedback.[11] However, uncertainty in the *net* cloud feedback—including changing cloud amount, top height, and microphysical properties like number, color, or size of droplets—makes it difficult to precisely estimate how sensitive the climate is to increasing greenhouse gas concentrations (see chapter 15).[12]

As mentioned above, huge amounts of carbon are continuously cycled among the atmosphere, ocean, land, and terrestrial biosphere as part of the global carbon cycle. In fact, a significant fraction of anthropogenic emissions are removed from the atmosphere by oceanic and terrestrial uptake. Increasing atmospheric greenhouse gas concentrations influence these processes in many ways.

For example, CO_2 dissolves in water. As CO_2 in the atmosphere increases, more CO_2 dissolves into surface waters, which is a negative feedback on CO_2 concentrations in the climate system. Some of this oceanic dissolved CO_2 is taken up by phytoplankton (tiny plants) and other organisms that are capable of photosynthesizing and thus converting it to organic material. Zooplankton (small marine animals) graze on the phytoplankton. When these phytoplankton and zooplankton die, their bodies sink, along with other organic matter, transporting the carbon to the deep ocean. Much of the carbon is redissolved along the way, but some reaches the ocean floor and is buried, becoming sediment. This small fraction becomes very significant to the carbon cycle over long timescales. Warmer water can hold less CO_2 than colder water, so as temperature increases, the uptake of atmospheric CO_2 will slow, which is a positive feedback. Scientists estimate that oceanic processes currently take up about one-fourth of CO_2 from fossil fuel burning, but this uptake may slow in the future as warming inhibits overturning of surface waters with the deep ocean, and as ocean acidification and increasing temperature reduce the rate of CO_2 uptake (see chapter 5).

In the terrestrial biosphere, increased atmospheric CO_2 stimulates plant growth, and plants in turn remove CO_2 from the atmosphere, which is a negative feedback. On the other hand, warmer soil temperatures stimulate microbial action that releases CO_2 from the decomposition of dead organic matter, which is a positive feedback. Scientists estimate that terrestrial processes currently take up about one-tenth of CO_2 emissions from fossil fuel burning, the so-called land sink. This represents a larger sink from plant growth partially offset by emissions from land-use change, such as deforestation. What will happen to this sink in the future is highly uncertain. Several studies simulating future climate indicate that this sink may become a source of additional emissions later this century even if deforestation decreases, primarily due to increased release of carbon from soils as temperatures warm beyond a degree or two Celsius.[13]

There are even social feedbacks. For example, rising temperature causes more people to install and use air conditioners. If the resulting increase in electrical consumption resulted in more fossil fuel-generated atmospheric CO_2, that would be another positive feedback. Increasing temperatures and climate impacts, combined with assessments of future risks, may encourage more stringent policies to reduce emissions, which will in turn reduce further intensification of those impacts, a negative social feedback also known as climate mitigation policy.

Accounting for all significant feedback effects entails not only identifying important feedback mechanisms, but also developing a quantitative understanding of how those mechanisms work. Such understanding often includes research at the boundaries of disciplines, including meteorology, atmospheric chemistry, oceanography, biology, and geology; social sciences such economics and sociology; and research on technological development.

Climate Models

Uncertainty in future greenhouse gas emissions and in scientific understanding of the response of the climate system to their influence makes projecting future climate change a complex task. The most sophisticated tools we have are global models of the climate system. Not only can they reproduce global temperature records, as shown in figure 1.3, but the best model results reproduce, although not completely, the detailed geographic patterns of temperature, precipitation, and other climatic variables seen on a regional scale, and can project changes in those patterns given scenarios for future greenhouse gas emissions.

A climate model is a set of mathematical statements describing physical, biological, and chemical processes that determine climate. What must go into a climate model depends on what one wants to learn from it. A few simple equations can give a reasonable range of estimates of the average global warming in response to specified greenhouse forcings. Our estimate above that the Earth's global average temperature in the absence of the greenhouse effect would be colder by about 33 degrees Celsius was based on a simple climate model. In that case, the Earth's surface is treated as a single point, with a simple height-varying atmosphere and no distinction between land and oceans. Simple models have the advantage that their predictions are easily understood on the basis of well-known physical laws. Furthermore, they produce results quickly and can, therefore, be used to test a wide range of assumptions by changing parameters of the model. More advanced are "multibox" models that treat land, ocean, and atmosphere as separate "boxes" and include flows of energy and matter between these boxes. More sophisticated multibox models may break the atmosphere and ocean into several layers or the Earth into several latitude zones.

Most sophisticated are the complex computer models known as general circulation models (GCMs). Such detailed models can only be run effectively on a limited number of supercomputers around the world. These divide the Earth's surface into a grid that can represent with reasonable accuracy the actual shape of the Earth's land masses and, to a lesser extent, mountains. The atmosphere above and ocean below each surface grid cell are further divided into layers, making the basic unit of the model a small, three-dimensional cell. Properties such as temperature, pressure, and humidity are averaged within each cell. Equations based in physics, chemistry, and biology regulate the various quantities within a cell, and other equations describe the transfer of energy and matter between adjacent cells. The newest models also include processes such as the cycling of carbon between the atmosphere, land, and ocean, the response of the Earth's vegetation to changing conditions and its feedbacks to the climate system, atmospheric chemistry, and the functioning of the cryosphere. Figure 1.7, panel A, displays the typical geographic resolution of the grid representing northern Europe at the time of each of the four IPCC assessment reports and the improvement in resolution (i.e., grid-box size) over this period. Panel B displays the progression in climate models since the 1970s in terms of the processes and com-

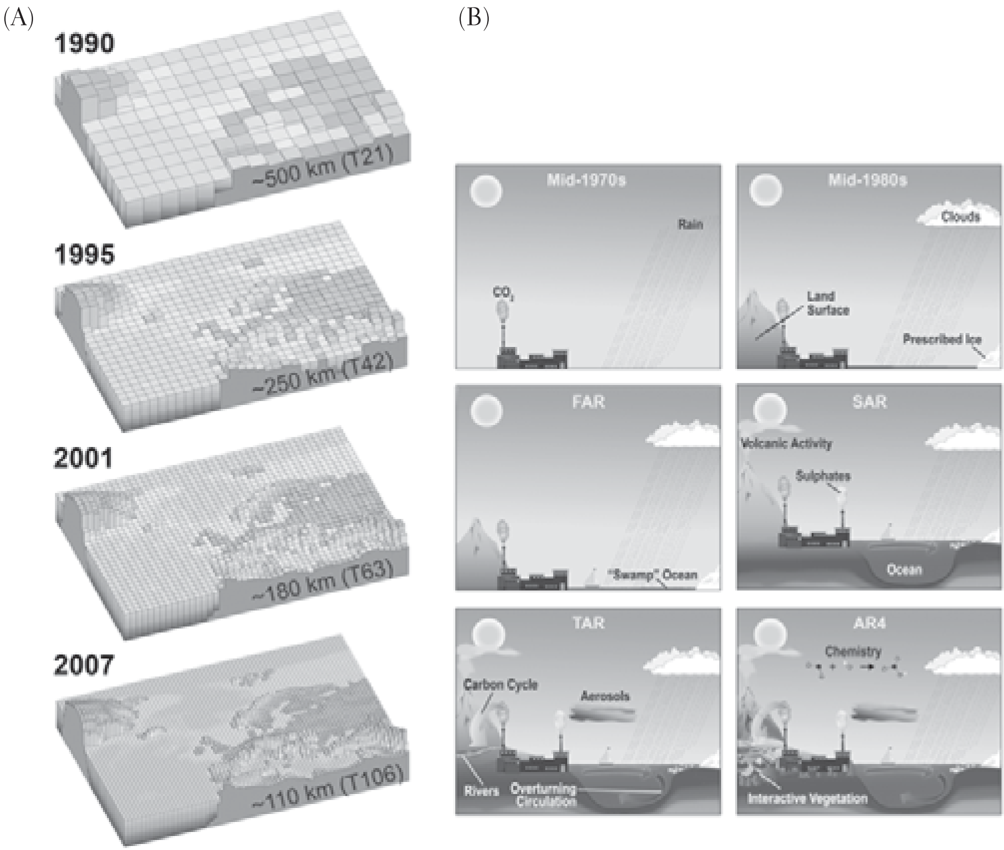

FIGURE 1.7. Panel A: Geographic resolution of GCMs at the time of each of the IPCC assessment reports. Vertical resolution in both atmosphere and ocean models is not shown, but has increased as well, beginning typically with a single-layer "slab" ocean and ten atmospheric layers in 1990 and progressing to about thirty levels in both atmosphere and ocean in 2007. Panel B: The complexity of climate models has increased during the last few decades. The series of pictures displays different features of the modeled world and when they were incorporated. Source: Intergovernmental Panel on Climate Change (IPCC), 2007(a), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon et al. (eds.), Cambridge University Press: Cambridge, United Kingdom.

ponents of the climate system that GCMs incorporate.[14]

Even with the rapid expansion of computational power, the best global climate models are currently limited to a geographic grid-box resolution of roughly 100 kilometers horizontally and 1 kilometer vertically. But climatically important phenomena occur on smaller scales, such as clouds or the substantial thermal differences between cities and surrounding areas. Because all physical, chemical, and biological properties are averaged over a single grid cell, it is impossible to represent these phenomena *explicitly* within a model. But they can be treated *implicitly* with what is called a parametric representation, or "parameterization." A parameterization connects small-scale processes to grid-box averages with semi-empirical rules designed to capture the major interactions between explicitly modeled grid-scale variables and sub-grid-scale processes. For example, a grid cell half covered by scattered clouds might be parameterized as a uniform blockage of somewhat less than half the incoming sunlight. Such an approximation manages not to ignore clouds altogether but doesn't quite handle them correctly. One can imagine that the effects of full sunlight penetrating to the ground in some parts of a grid box while other parts are in full shade might be different from those of a uniform light overcast, even with the same total energy reaching the ground averaged over the grid box.[15]

Model Validation

How can modelers be confident in their model results? How do they know that they have taken into account all climatologically significant processes and that they have satisfactorily parameterized processes whose scales are smaller than their models' grid cells? The answer lies in a variety of model validation techniques, most of which attempt to reproduce known climatic conditions in response to known forcings.

Major volcanic eruptions inject enough dust into the stratosphere to exert a global cooling influence that lasts several years. Such eruptions typically occur once a decade or so, and they constitute natural experiments that can be used to test climate models. The climatic effects of the largest recent major eruption, Mount Pinatubo in 1991, were forecast by a number of climate modeling groups to cool the planet by several tenths of a degree Celsius for a few years. That is indeed what happened.

Seasonality provides another natural experiment for testing climate models. Winter predictably follows summer, averaging some 15 degrees Celsius colder than summer in the northern hemisphere and 5 degrees Celsius colder in the southern hemisphere (the southern hemisphere variation is smaller because a much larger portion of that hemisphere is water, with a high heat capacity that moderates seasonal temperature variations). Climate models do an excellent job of reproducing the timing and magnitude of the seasonal temperature variations, although the absolute temperatures themselves may not be completely accurate.

Still another way to gain confidence in a model's future climate projections is to model past climates. Starting in 1860 with known climatic conditions, for example, can the model reproduce a reasonable simulation of the temperatures observed during the twentieth century? The "experiments" of figure 1.3 discussed previously provide clear evidence that the answer is "mostly yes" and also help modelers understand what physical processes are significant in determining past climate trends.

Climate models certainly have room for improvement. For example, models are less accurate in representing climatic variations involving precipitation and other aspects of the hydrologic cycle. While temperature changes are driven by large-scale forcing such as greenhouse gas heat-trapping or continental-scale aerosol cooling, precipitation is influenced by complex local/regional processes like the nature of the land surface, proximity to topographical features (e.g., mountains), and temperature differences across the region. All of those interacting smaller-scale processes and drivers are more difficult to include accurately in models. Nevertheless, today's climate models can reproduce recognizable simulations of regional patterns of temperature, precipitation, and other climatic variables. These pattern-based comparisons of models and reality provide further confirmation of the models' broad-scale validity. No one model validation experiment alone is enough to give us high confidence in future climate projections. But considered together, results from the wide range of experiments probing the validity of climate models give considerable confidence that these models are treating the essential climate-determining processes with reasonable accuracy—certainly for temperature trends at continental scales, and with some skills for regional trends and/or precipitation changes in certain regions like high latitude continents and Mediterranean climates of the subtropics.[16] Furthermore, researchers have linked grid-box-scale changes in temperature with observed changes in the lifecycles of plants and animals during the last fifty years (see chapter 3).[17]

Conclusion

We have given a thumbnail sketch of the science of global climate change. The greenhouse effect and its intensification by human-induced emissions of greenhouse gases are well understood and solidly grounded in basic science. Likewise, observed warming is now unequivocal, and many impacts of that warming can already be observed around the world. Nevertheless, the future effects of climate change are characterized by deep uncertainty, compounded by the global scale of the problem and the fact that climate change is not just a scientific topic but also a matter of public and political debate. There are two general sources of uncertainty in projecting future climate change: what we do and how the natural climate system responds. Policy decisions can strongly influence the first source of uncertainty (future emissions), but will have little influence on the second source (climate response to emissions). We cannot know precisely what the severity of impacts will be for a specific trajectory for future emissions, but we can confidently say that the severity will be reduced if emissions are reduced. In very general terms, climate policy is about managing risk: assessing the potential impacts of climate change, judging how likely it is that various impacts will occur, and determining how our policy choices will affect those risks.

Notes

1. Intergovernmental Panel on Climate Change (IPCC), 2007(a), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon et al., eds., Cambridge University Press: Cambridge, United Kingdom, pp. 22–23.
2. Ibid.
3. Ibid.
4. Ibid. See also IPCC, 2007(b), *Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC*, M. Parry et al., eds., Cambridge University Press: Cambridge, United Kingdom.
5. Denman, K. L. et al., 2007: Couplings between Changes in the Climate System and Biogeochemistry. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* S. Solomon et al., eds., Cambridge University Press, Cambridge, United Kingdom; P. Canadell et al., 2007: Contri-

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7. IPCC, 2007(a) op. cit.

8. M. Lockwood and C. Fröhlich, 2008: Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature. II. Different reconstructions of the total solar irradiance variation and dependence on response time scale. *Proceedings of the Royal Society* A 464, 1367–85; E. Bard and M. Frank, 2006: Climate change and solar variability: What's new under the sun? *Earth and Planetary Science Letters* 248, 1–14.

9. IPCC, 2007(a) op. cit.

10. Ibid.

11. B. J. Soden and I. M. Held, 2006: An assessment of climate feedbacks in coupled ocean atmosphere models. *Journal of Climate* 19, 3354–60.

12. S. H. Schneider, 1972: Cloudiness as a global climatic feedback mechanism: The effects on the radiation balance and surface temperature of variations in cloudiness. *Journal of the Atmospheric Sciences* 29, 1413–22.

13. P. M. Cox et al., 2000: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* 408, 184–87.

14. For a detailed discussion of these models, see IPCC, 2007(a) op. cit.

15. S. H. Schneider and R. E. Dickinson, 1976: Parameterizations of fractional cloud amounts in climate models: The importance of modeling multiple reflections. *J. Appl. Meteorol* 15, 1050–56.

16. IPCC, 2007(a) op. cit.

17. T. I. Root, D. MacMynowski, M. D. Mastrandrea, and S. H. Schneider, 2005: Human-modified temperatures induce species changes: Joint attribution. *Proceedings of the National Academy of Sciences* 102, 7465–69.

Chapter 2

Progress in Detection and Attribution Research

B. D. Santer and T. M. L. Wigley

1. Introduction

In 1988, the Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization and the United Nations Environment Programme. The goals of this panel were threefold: to assess available scientific information on climate change, to evaluate the environmental and societal impacts of climate change, and to formulate response strategies. The IPCC's first major scientific assessment, published in 1990, concluded that "unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more."[1]

Six years later, the IPCC's second scientific assessment reached a more definitive conclusion regarding human impacts on climate, and stated that "the balance of evidence suggests a discernible human influence on global climate."[2] This cautious sentence marked a paradigm shift in scientific understanding of the nature and causes of recent climate change. The shift arose for a variety of reasons. Chief among these was the realization that the cooling effects of anthropogenic sulfate aerosols had partially obscured the warming signal arising from increasing atmospheric concentrations of greenhouse gases (GHGs).[3] A further major area of progress was the increasing use of so-called fingerprint studies, which involve detailed statistical comparisons of modeled and observed climate change patterns.[4,5,6] Fingerprinting relies on the fact that each climate forcing mechanism (e.g., changes in solar irradiance, volcanic dust, sulfate aerosols, or GHG concentrations) has a unique pattern of climate response (see figure 2.1). Fingerprint studies have greatly enhanced our ability to diagnose cause and effect relationships in the climate system.

The third IPCC assessment was published in 2001, and went one step further than its predecessor. It made an explicit statement about the magnitude of the human effect on climate, and concluded that "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."[7] This conclusion was based on improved estimates of natural climate variability, better reconstructions of temperature fluctuations during the last millen-

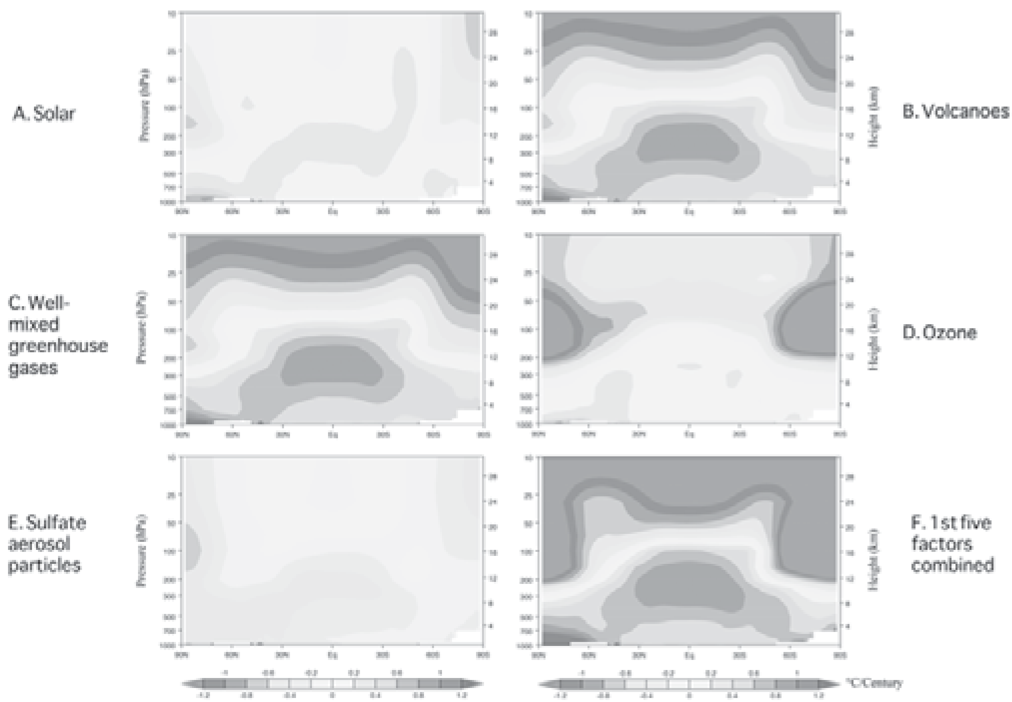

Figure 2.1. Zonally averaged temperature changes as a function of latitude (from 90°N–90°S) and height (from 1000 hPa to 10 hPa). Results are from single forcing experiments (A through E) with historical changes in five individual forcings, and from an experiment with simultaneous changes in all five forcings (F). All experiments were performed with the coupled atmosphere-ocean Parallel Climate Model (PCM).[8] Temperature changes are expressed as linear trends in degrees Celsius per century, and were calculated over the period from 1890 to 1999. All results are ensemble means (averages over four individual realizations).

nium, continued warming of the climate system, refinements in fingerprint methods, and the use of results from more (and improved) climate models, driven by more accurate and complete forcing estimates.

This gradual strengthening of scientific confidence in the reality of human influences on global climate continued in the IPCC AR4 report, which stated that "warming of the climate system is unequivocal," and "most of the observed increase in global average temperatures since the mid-twentieth century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations"[9] (meaning >90% probability that the statement is correct). The AR4 justified this increase in scientific confidence on the basis of ". . . longer and improved records, an expanded range of observations and improvements in the simulation of many aspects of climate and its variability."[10] In its contribution to the AR4, IPCC Working Group II concluded that anthropogenic warming has had a "discernible influence" not only on the physical climate system, but also on a wide range of biological systems.[11]

The fundamental conclusion that human activities have significantly altered not only the chemical composition of Earth's atmosphere, but also the climate system, has been corroborated by other independent bodies, such as the U.S. National Academy of Sciences[12], the Science Academies of eleven nations[13], and the first Synthesis and Assessment Product of the U.S. Climate Change Science Plan.[14]

Despite the overwhelming evidence of pronounced anthropogenic effects on climate, important uncertainties remain in our ability to quantify the human influence. The experiment that we are performing with the Earth's atmosphere lacks a suitable control: we do not have a convenient "undisturbed Earth," which would provide a reference against which we could measure the anthropogenic contribution to climate change. We must therefore rely on numerical models and paleoclimatic evidence [15] to estimate how the Earth's climate might have evolved in the absence of any human "forcing" (see figure 2.2). Such sources of information will always have significant uncertainties.

In the following, we provide a personal perspective on recent developments in the field of detection and attribution (D&A) research—that is, research directed toward detecting significant climate change, and attributing it to a specific cause or causes.[16,17,18,19]

2. Recent Progress in D&A Research

Physical Consistency and Robustness of D&A Results

The IPCC and National Academy findings that human activities are affecting global-scale climate are based on multiple lines of evidence:

- Our continually improving physical understanding of the climate system and the human and natural factors that cause climate to change.
- Evidence from paleoclimate reconstructions, which enables us to place the warming of the twentieth century in a longer-term context.[21,22]
- The qualitative consistency between observed changes in many different aspects of the climate system and model predictions of the changes that should be occurring in response to human influences.[23,24]
- Evidence from rigorous quantitative fingerprint studies, which compare modeled and observed patterns of climate change.

This Chapter focuses on fingerprint evidence. The underlying strategy in fingerprint studies is to search for a model-predicted pattern of climate change (the "fingerprint") in observational data. The fingerprint can be estimated in different ways, but is typically derived from a model experiment in which one or more human factors are varied according to the best-available estimates of their historical changes. Different statistical techniques are then applied to quantify the level of agreement between the fingerprint and observations and between the fingerprint and model estimates of climate noise. This enables researchers to make rigorous tests of competing hypotheses[25] regarding the possible causes of recent climate change.[26,27,28,29]

While early fingerprint work dealt almost exclusively with changes in near-surface or atmospheric temperature, more recent studies have applied fingerprint methods to a range of different variables, such as ocean heat

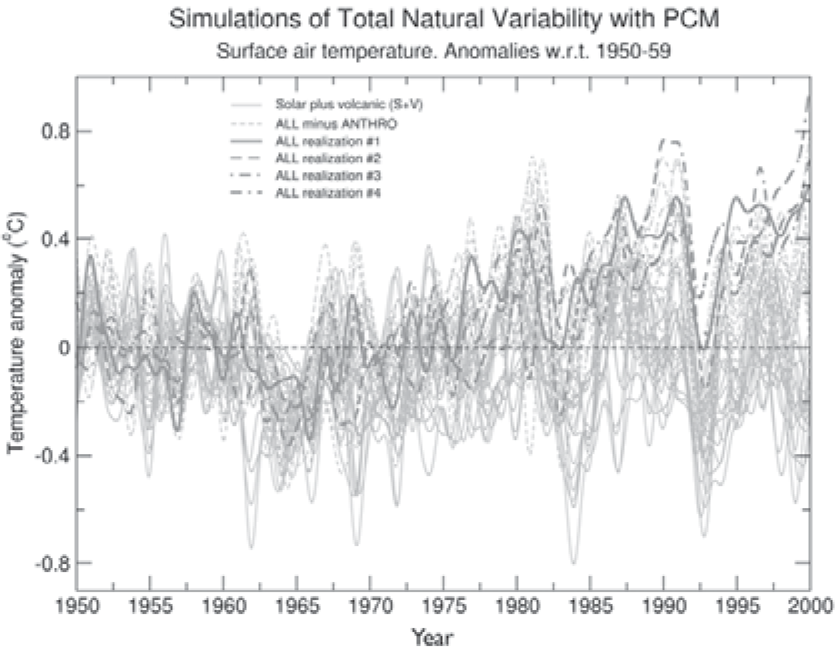

FIGURE 2.2. Simulations of climate change and "total" natural variability using the Parallel Climate Model.[20] Results are for global-mean, monthly-mean near-surface temperature changes. Total natural variability reflects both the effects of processes internal to the climate system and the forced temperature variations caused by changes in solar energy output and volcanic aerosols. The brown lines represent thirty-two individual realizations of total natural variability. Natural variability estimates are derived in two different ways: by adding temperature responses from experiments with individual changes in solar and volcanic forcing (S+V), or by subtracting the temperature response to anthropogenic forcings (ANTHRO) from models runs with combined anthropogenic and natural forcings (ALL). The red lines are four different realizations of the ALL experiment. Each ALL realization has the same anthropogenic and natural forcings, but starts from a slightly different initial state of the climate system in 1890. The effects of anthropogenic forcing begin to emerge from the noise of natural variability by the late twentieth century. All anomalies were defined relative to climatological monthly means computed over 1950 to 1959.

content[30,31], sea-level pressure[32], tropopause height[33], zonal-mean precipitation[34], and atmospheric moisture.[35] The general conclusion is that natural climate variability alone cannot explain the observed climate changes during the second half of the twentieth century. The best statistical explanation of the observed climate changes invariably involves a large human contribution. These results are robust to the processing choices made by different groups, and show a high level of physical consistency across different climate variables. For example, observed atmospheric water vapor increases[36] are physically consistent with increases in ocean heat content[37,38] and near-surface temperature.[39]

There are a number of popular misconceptions about fingerprint evidence. One misconception is that fingerprint studies consider global-mean temperatures only, and thus provide a very poor constraint on the relative contributions of human and natural factors to observed changes.[40] In fact, fingerprint studies rely on information about the detailed spatial structure (and often the combined space-time structure) of observed and simulated climate changes. Complex patterns provide much stronger constraints on the possible contributions of different factors to observed climate changes.[41,42,43]

Another misconception is that model-based estimates of natural internal climate variability ("climate noise") are accepted uncritically in fingerprint studies, and never tested against observations.[44] This is demonstrably untrue. Many fingerprint studies explicitly test whether model estimates of climate noise are realistic, at least on annual and decadal timescales where observational data are of sufficient length to obtain reliable estimates of observed noise.[45,46,47,48]

2.2. The MSU Debate: A Resolution?

For more than a decade, scientists critical of "fingerprint" studies have argued that tropospheric temperature measurements from satellites and weather balloons (radiosondes) show little or no warming of the troposphere over the last several decades, while climate models indicate that that the troposphere should have warmed markedly in response to increases in greenhouse gases (figure 2.1C). This apparent discrepancy between climate model estimates and observations has been used to cast doubt on the reality of a "discernible human influence" on the climate system.[49]

It is unquestionable that satellites have transformed our scientific understanding of the weather and climate of planet Earth. Since 1979, Microwave Sounding Units (MSUs) on polar-orbiting satellites have measured the microwave emissions of oxygen molecules in the atmosphere, which are proportional to atmospheric temperatures. Measurements of microwave emissions made at different frequencies can be used to obtain information about the temperatures of broad atmospheric layers. Most attention has focused on estimates of the temperatures of the lower stratosphere and mid- to upper troposphere (T_4 and T_2, respectively) as well as on a retrieval of lower tropospheric temperatures (T_{2LT}).[50]

The first attempts to obtain climate records from MSU data were made by scientists at the University of Alabama in Huntsville (UAH).[51,52,53] Until recently, the UAH group's analysis of the MSU data suggested that the tropical lower troposphere had cooled since 1979. Concerns regarding the reliability of the MSU-based tropospheric temperature trends were dismissed with the argument that weather balloons also suggested cooling of the tropical troposphere[54], and constituted a completely independent temperature monitoring system.[55,56]

Throughout most of the 1990s, only one group (the UAH group) was actively working on the development of temperature records from MSU data. In 1998, the Remote Sensing Systems (RSS) group in California identified a problem in the UAH data related to the progressive orbital decay and altitude loss over the lifetimes of individual satellites. This introduced a spurious cooling trend in the UAH data.[57] The RSS findings suggested that the lower troposphere had warmed over the satellite era.

The UAH group subsequently discovered two new corrections that approximately compensated for the cooling influence of orbital degradation. The first new correction was related to the effects of orbital drift on the sampling of Earth's diurnal temperature cycle. The second (the so-called instrument body effect) was due to variations in measured microwave emissions arising from changes in the temperature of the MSU instrument itself, caused by changes in the instrument's exposure to sunlight.[58]

Additional research cast doubt on the UAH results. Three separate groups found that the mid- to upper troposphere had warmed markedly during the satellite era[59,60,61,62,63,64], in contrast to the UAH results.[65,66] The UAH group, however, continued to claim close correspondence between their own MSU-based estimates of tropospheric temperature trends and trends derived from radiosondes.[67] This raised critical questions regarding the quality of radiosonde temperature measurements. Were weather balloons an unambiguous "gold standard"?

Recent research indicates that the answer to this question is "no." The temperature sensors carried by radiosondes have changed over time, as has the shielding that protects the sensors from direct solar heating. Solar heating of the sensors can affect the temperature measurements themselves. The introduction of progressively more effective shielding results in less solar heating, thus imparting a non-climatic cooling trend to the daytime measurements.

Sherwood et al.[68] discovered this effect by comparing the radiosonde-based temperature trends based on nighttime ascents (with no solar heating effects) and daytime launches. The former showed pronounced tropospheric warming, while the latter did not. These results were independently confirmed by Randel and Wu.[69] Accounting for the influence of solar heating yielded tropospheric temperature trends that were in better agreement with RSS estimates than with UAH results.[70]

Two papers shed further light on these issues. The first paper was by the RSS group, and described a new MSU retrieval of lower tropospheric temperatures.[71] RSS obtained substantially larger T_{2LT} trends than UAH.[72] Mears and Wentz[73] attributed most of these differences to an error in UAH's method of adjusting for drift in the time of day at which satellites sample the Earth's daily temperature cycle. This error was acknowledged by Christy and Spencer.[74] When the UAH group remedied this problem, however, their lower tropospheric trends increased by much smaller amounts than expected on the basis of the RSS analysis.[75]

The second paper addressed the physics that governs changes in atmospheric temperature profiles. It compared the relationship between surface and tropospheric temperature changes over a wide range of observational and climate model datasets.[76] The focus was on the deep tropics (20°N–20°S), where the UAH and RSS tropospheric temperature trends diverged most markedly. The intent was to investigate whether the simple physics that governs the vertical structure of the tropical atmosphere could be used to constrain the uncertainties in satellite-based trends.

This "simple physics" involves the release of latent heat when moist air rises due to convection and condenses to form clouds. Because of this heat release, tropical temperature changes averaged over large areas (and averaged over sufficient time to damp day-to-day "weather noise") are generally larger in the lower and mid-troposphere than at the surface. This "amplification" behavior is well-known from basic theory[77], observations[78], and climate model results.[79]

The UAH amplification results were puzzling. For month-to-month fluctuations in tropical temperatures, UAH T_{2LT} anomalies were 1.3 to 1.4 times larger than surface temperature anomalies, consistent with models, theory, and other observational datasets. But for decade-to-decade temperature changes, the UAH T_{2LT} trends were smaller than surface trends, implying that the troposphere *damped* surface warming. In contrast, model amplification results were consistent across all timescales considered, despite large differences in model structure, parameterizations, and forcings. The RSS data also showed similar amplification of surface warming on different timescales.

These results have at least two possible explanations.[80,81] The first is that the UAH data are reliable, and different physical mechanisms control the response of the tropical atmosphere to "fast" and "slow" surface temperature fluctuations. Such time-dependent changes in the physics seem unlikely given our present understanding, and mechanisms that might explain such changes have yet to be identified.

A second explanation is that significant inhomogeneities remain in the UAH tropospheric temperature records, leading to residual cooling biases in the UAH long-term trend estimates. This is both a simpler and more plausible explanation given the consistency of amplification results across models and timescales, our theoretical understanding of how the tropical atmosphere should respond to sustained surface heating[82], and the currently large uncertainties in observed tropospheric temperature trends.[83]

The extraordinary claim that the tropical troposphere had cooled since 1979 has not survived rigorous scrutiny. We have learned that uncertainties inherent in satellite estimates of tropospheric temperature change are far larger than originally believed, and now fully encompass the model results.[84] There is no longer a fundamental discrepancy between modeled and observed estimates of tropospheric temperature changes.[85]

2.3. *Detecting Anthropogenic Effects at Sub-Global Scales*

Because regional-scale climate changes will determine societal impacts, many recent D&A studies have shifted their focus from global to regional scales. One fundamental problem in regional D&A work is that climate noise typically becomes larger when averaged over increasingly finer scales.[86]

To illustrate this, figure 2.3 shows surface temperature changes in an "unforced" control run and in simulations of twentieth-century climate change. Results are averaged over the globe, the Northern Hemisphere, and the Western U.S. It is obvious that averaging over the entire globe produces the largest reduction in climate noise. Signal and noise are generally most easily separable in the global results, although in regions with large signals, the signal-to-noise ratio may actually increase as the spatial scale decreases.[87]

As attention shifts to smaller scales, it becomes more important to obtain reliable information about climate forcings. Some of these forcings are both uncertain and highly variable in space and time.[88,89] Examples include human-induced changes in land surface properties[90] or in the concentrations of carbon-containing aerosols.[91,92] Neglect or inaccurate specification of these forcings can hamper the identification of an anthropogenic fingerprint.

Despite such problems, and despite the