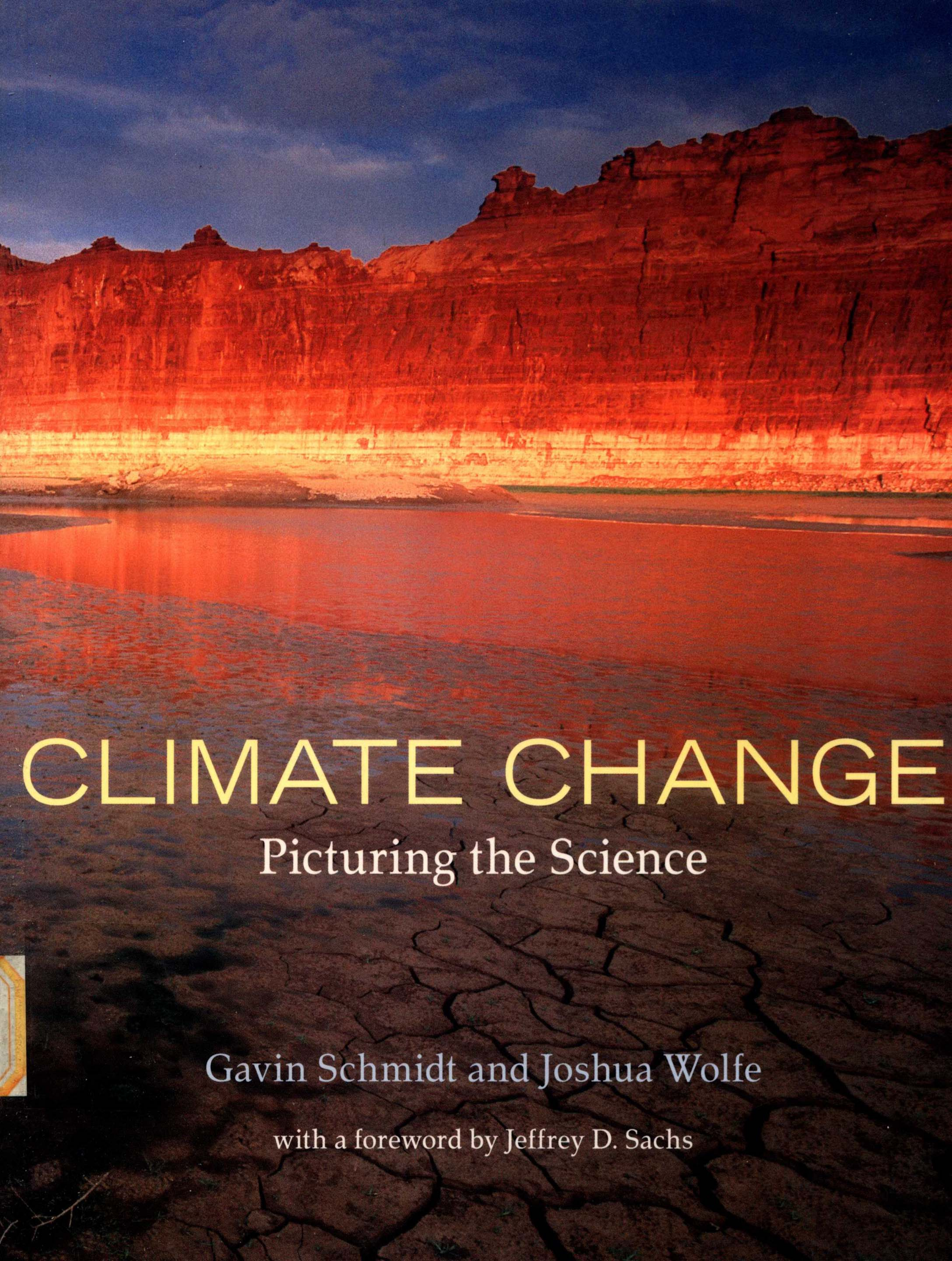


CLIMATE CHANGE

Picturing the Science

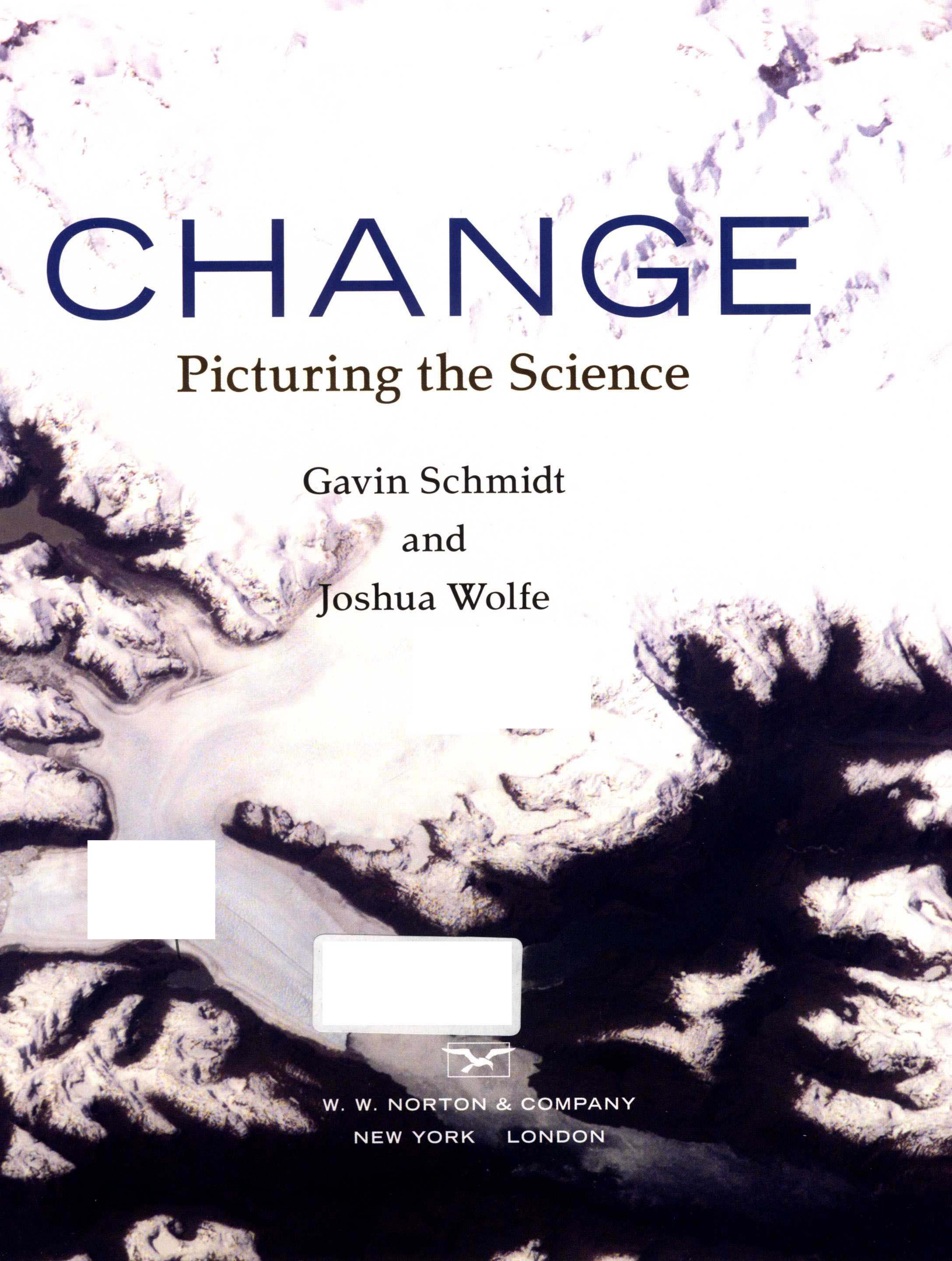
Gavin Schmidt and Joshua Wolfe

with a foreword by Jeffrey D. Sachs

CHANGE

Picturing the Science

Gavin Schmidt
and
Joshua Wolfe



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FRONTISPIECE: The Brüggen Glacier in southern Chile is one of the largest outflow glaciers from the southern Patagonian ice field. Unlike most glaciers worldwide, it advanced significantly from 1945 to 1994. Since then, the glacier has mostly stabilized. NASA EARTH SCIENCES AND IMAGE ANALYSIS LABORATORY, JOHNSON SPACE CENTER

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FOREWORD

Heading off the worst of human-induced climate change will require global cooperation. No single country or region can solve the climate crisis on its own. Moreover, governments around the world will act only when their citizens understand the magnitude of the challenge, the risks of continuing with business as usual, and the options for action. An informed public, therefore, is essential for the world to find effective solutions for one of the most harrowing and complex challenges facing humanity. Yet with a challenge so complex, so encompassing, and with so much inherent uncertainty, finding a path to public understanding and responsible action is a vast challenge in its own right.

Climate Change: Picturing the Science is a tour de force of public education. It is simply the best available collection of essays by climate scientists on the nature of human-induced climate change, the ways scientists have come to understand and measure the risks that it poses, and the options that we face. I am, of course, hugely proud that it is largely (though by no means wholly) the work of scientists at Columbia University's Earth Institute, a unique cross-faculty initiative by the university to bring science to bear on the global challenges of sustainable development. This book is an exemplar of what public education in the twenty-first century can and should accomplish.

The editors, climatologist Gavin Schmidt and photographer Joshua Wolfe, have produced a collection of essays of uniformly outstanding quality, supported by photographs of beauty and insight. Each chapter offers a scientifically rich, yet remarkably jargon-free, account of one crucial aspect of the climate change challenge. Several essays, including the one by Peter deMenocal and Tim Hall and the one by Gavin Schmidt, describe the underlying human and natural processes that lead to human-induced climate change, explaining the direct effects of greenhouse gases and the ways these effects may be amplified by various positive feedbacks in the climate system. These and the accompanying essays that describe how climatologists measure and verify climate change are told vividly by scientists who have been at the very forefront of these challenges.

Several powerful essays explain why human-induced climate change matters, and matters urgently. A scintillating essay by Shahid Naeem describes how climate change is already impacting the entire biosphere—the thin film of life covering the Earth—with a remarkably complex range of effects that can threaten the basic functioning of ecosystems and deprive them of their resilience and productivity and their ability to provide services—such as food, fresh water, and a safe environment—to humanity. The essay also makes clear the pervasive threats to the very survival of millions of other species as well. Another beautifully written chapter by Adam Sobel takes on the complex issue of extreme weather events, describing how and why climate change is likely to increase the frequency of droughts, floods, heat waves, and high-intensity tropical cyclones in some parts of the world. An essay by Stephanie Pfirman documents the changes already under way in the Arctic and Antarctica, with ramifications that will threaten human societies and biodiversity far beyond the Arctic itself. In all of these chapters, powerful photographs help to illuminate a complex and compelling story.

After these careful, precise, and yet highly accessible accounts of the underlying science, the collection then turns to the choices facing humanity. What do we know about the prospects for future climate change if we stay on the current business-as-usual trajectory, or if humanity adopts an alternative path based on new technologies for energy use, agriculture, and patterns of urbanization and land use? What are the likely costs and benefits of alternative public policy choices? What time horizons are involved? And what can one individual do to contribute to global solutions?

The essayists avoid glib solutions and stay true to the science, with all of its uncertainties and incomplete answers. Yes, we must make choices, but no, we cannot know with utter precision the costs and benefits (and for whom) of these alternatives. Gavin Schmidt explains clearly the hows and whys of climate scenarios, which summarize the likely outcomes of alternative policy choices. Frank Zeman explains how new ways of producing and deploying commercial energy—by replacing fossil fuels with renewable sources, by economizing on energy use through improved technologies for automobiles and buildings, or by capturing and safely storing the carbon dioxide emitted by fossil fuel power plants and factories—can dramatically reduce the buildup of greenhouse gases in the atmosphere, thereby reducing the human impact on climate change. A concluding essay by David Leonard Downie, Lyndon Valicenti, and Gavin Schmidt describes how this massive challenge must, in the end, be addressed by an equally massive effort at global problem solving, a "preventative planetary care" requiring an unprecedented level of global cooperation. The essay brings us up to date with the global efforts to reach consensus within the framework of international law, notably the UN Framework Convention on Climate Change, and the accompanying globally agreed protocols needed to implement the convention.

There are no shortcuts to addressing a challenge that is global, pervasive, profound, and long term. Global citizens must grasp the challenge, master its intricacies, and take responsibility, for our own generation and those to come. Recent years have seen a dramatic increase in global awareness and concern. *Climate Change: Picturing the Science* provides another vital impetus for understanding and therefore for action. For this reason, the book elicits enormous admiration for the science of climatology as well as enormous hope that humanity, based on a deeper awareness of the science and public policy of climate change, will rise to the challenge of protecting human well-being and the beauty and rich diversity of the Earth.

Jeffrey D. Sachs
New York
June 16, 2008

PREFACE

In interactions on the Web or at public talks and exhibitions, we have found a hunger among the public for more context and information about climate change that is not being satisfied by newspapers, television, or the occasional documentary. Elsewhere, photographers have begun documenting the effects of current climate change and have created images that bring home the depth and immediacy of the problem. Stemming from a 2005 gallery exhibition, "Photographers' Perspectives on Global Warming," in New York, this book is a marriage (it is hoped a happy one) between the image makers and the investigators. We have selected images on their intrinsic merit, and we have used the text to provide the background necessary to understand what is being seen and discussed. This is not a textbook, nor just a collection of pretty pictures. Instead, our aim is to provide an accessible summary of the state of the science and a visual record of what it means.

Interest in human-induced climate change as a public issue has a long and varied history. It goes back at least to Swedish chemist Svante Arrhenius's first calculation of the effect of increasing greenhouse gases on temperature in the late nineteenth century. It was recognized as an environmental problem by President Johnson as early as 1965. NASA scientist James Hansen's testimony to Congress in the summer of 1988 made newspaper headlines, while the Rio Earth Summit in 1992 and the 2006 release of Al Gore's film documentary *An Inconvenient Truth* have heightened public concerns. In previous decades, the issue rose in the public consciousness temporarily, only to be subsumed as more immediate concerns vied for media attention. Scientifically, however, the study of climate change has proceeded at a steady pace, and evidence of human modification of the climate has been mounting rapidly.

With the 2007 publication of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, a group of scientists sponsored by the United Nations and the World Meteorological Organization, the case for global warming has become "unequivocal," with a "very likely" dominant role for humans causing it.

But what lies behind these definitive statements? Where are the key observations and theoretical insights that climate scientists rely on? Are there remaining issues? What does climate change portend? These are questions now asked daily at the water cooler, in the newsroom, and in Congress.

The scope of climate change is truly vast, and no one author can do justice to its varied aspects. Accordingly, we have brought together experts on atmospheric science, oceanography, paleoclimatology, the polar regions, technology, and politics to each address their realm of expertise.

On a similar note, the photographers on this project also have diverse backgrounds. While they all work in documentary photography, largely for magazines, their specialties range from wildlife and nature to portraits and scientific imagery. Unfortunately, there are spatial and temporal limits to what a photographer can capture. The fascinating patterns of ocean circulation or the scale of Arctic ice melt are beyond the reach of traditional photography. So, for many of these subjects we use some of the exceptional imagery now obtained from space. Some photographs were taken from the NASA space shuttle, and some from the orbiting satellites that are more commonly used for weather forecasting or research.

Additionally, we have a number of first-person accounts from people at the front lines of climate research that clearly demonstrate how the field has transcended its origin as a dry academic discipline.

In putting this book together, we hope to impress, educate, intrigue, and maybe motivate. Please let us know if we have succeeded.

Gavin Schmidt
Joshua Wolfe
New York, 2008

CLIMATE CHANGE

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INTRODUCTION

Gavin Schmidt and Joshua Wolfe

Whether the weather be cold or whether the weather be hot,
We'll weather the weather whatever the weather,
Whether we like it or not.

—Anonymous

Climate is what you expect, weather is what you get.

—Mark Twain

In writing a book about climate change, it's probably a good idea to start with what we mean by *climate*. A common definition—"weather conditions prevailing over an area or over a long period"—reflects the situation of forty years ago, when climatology solely referred to a very necessary, but rather dull, study of daily temperature and rainfall statistics, and their collation into averages. This definition, however, does little justice to the expansive modern concept of a climate system that incorporates the oceans, atmosphere, biosphere, and polar regions and describes the multiple interactions between these distinct physical entities. While the weather in the atmosphere or the eddies in the ocean are quite variable and even chaotic from day to day, the average conditions in a given location are relatively stable and can be explained and understood in physically consistent ways.

Climate, then, is the average condition of all these environmental components over a period of time. The period needs to be long enough, say thirty years, to smooth out some of the variability associated with the weather day to day and year to year. However, the average condition alone is not enough to define the climate. We also need a description of the variability over the same period—the frequencies of a cold winter or strong rainstorm, or the magnitude of the seasonal cycle—which is also part of a region's climate. The climate can be thought of as all the statistics of the weather (or of the sea ice, or the ocean, or the biosphere), but not the particular sequence of events in any one season or year.

If climate is the sum of our expectations, *climate change* is an alteration in those expectations. However, climate change is not limited to alterations in the global mean temperature or rainfall. For example, global warming describes the ongoing rise in mean surface temperatures across the planet, but global climate change encompasses not only global warming but also the occurrence of drought and the shifts in ocean currents or atmospheric winds. Although climate change cannot be seen in any one particular storm, heat wave, or cold snap, it is found within the changing frequency of such events.

We take for granted the ways in which we have adapted to the current climate. After all, the climate as we know it has been relatively stable for hundreds of years. The kinds of crops that are grown, the capacity of storm drains, and the distance that we allow between a building and the shoreline all depend heavily on the expectation that patterns in rainfall, temperature, and sea level will continue as in the past. This expectation has served us well up to now. But how well will it serve us in the future?

Has the Earth's climate changed before? Yes! The planet has seen many different climate changes in the past. Some 700 million years ago, geological evidence indicates that our planet may have been completely glaciated, a condition referred to as "snowball Earth." During the extremely hot Cretaceous period 100 million years ago, dinosaurs ruled a world in which the polar regions were ice-free and heavily forested. More recently, during the last major ice age that ended only about 20,000 years ago, much of Europe and North America was covered with ice that was kilometers thick.

Why did the Earth's climate change in the past, before we humans had any measurable impact on it? Those changes were driven by slow movements of the continents that changed the ocean currents, by asteroid impacts that filled the atmosphere with smoke and dust, and by wobbles in the Earth's orbit that made the summers warmer and the winters colder. These factors (among others) led to dramatic extinctions and spurts of evolution. However, since the time agriculture was invented, animals were domesticated, and our earliest cities were built, all of human civilization has existed in the relatively stable climate of the Holocene epoch, which started around 10,000 years ago. No farmers were displaced when the now-petrified forests of Axel Heiberg Island in the high Arctic first succumbed to the ice some 50 million years ago. No human cities were drowned when sea levels rose 120 meters (400 feet) at the end of the last ice age. What makes climate change different this time is that, over hundreds of years, our modern industrial society has adapted, albeit imperfectly, to the current conditions. Our climate has influenced where we have built our cities, where we plant our crops, how we travel, what we eat, and sometimes, how we die.

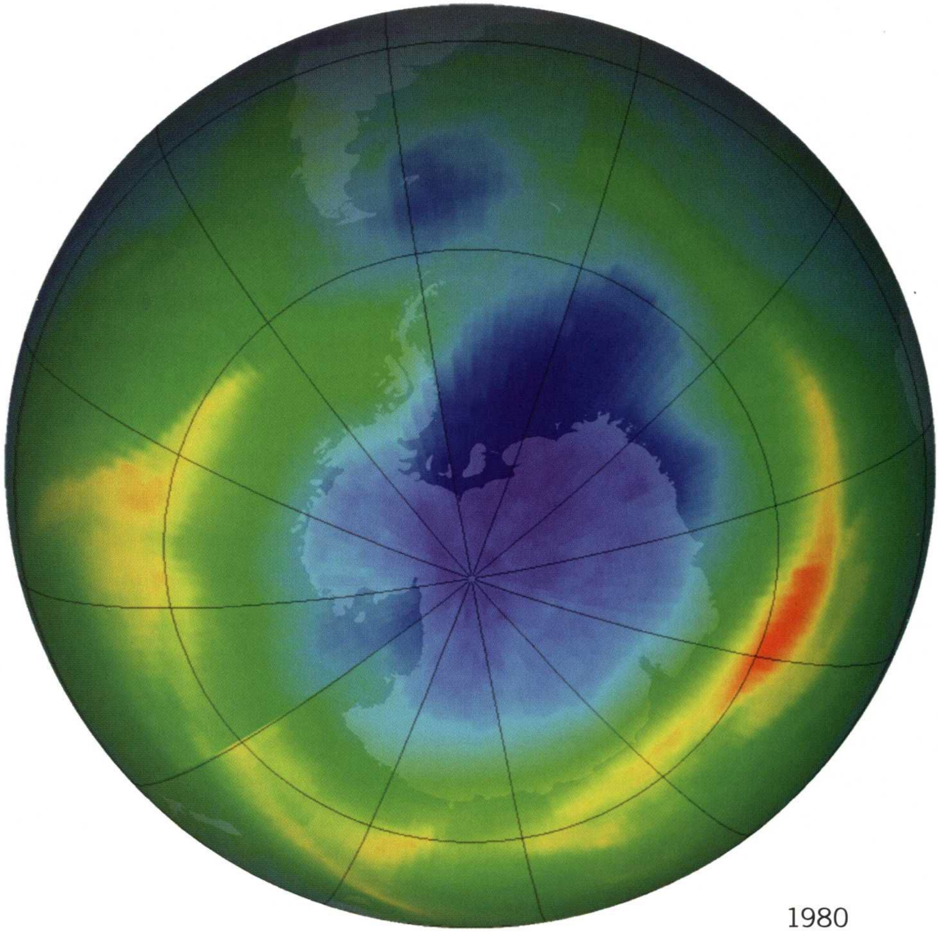
Throughout our planet's 4.5 billion years of existence, Earth as a whole has been indifferent to its average temperature. Life on Earth, as it has for several billion years, will eventually adapt to any new situation. But for our particular species, with its huge investment in the status quo, that fact is probably not too comforting. The issue of climate change today is not that the current climate is somehow ideal or perfect, but that it is the one we are used to. Given enough time, we could probably adapt to almost anything. But could we adapt if the climate changed quickly? Would we have enough time?

A medical analogy is illustrative. A doctor can examine our symptoms, try to diagnose our condition, and suggest treatments if the prognosis is not favorable. The success of modern medicine shows clearly that, even when medical knowledge is not perfect, it can still be useful. This is also true for climate scientists studying the Earth—the science is imperfect, but still useful. Drawing from that analogy, we have organized this book into three parts that describe the symptoms of climate change, the diagnosis and prognosis, and suggestions for potential cures and treatments.

The symptoms of climate change can be seen on land, in the oceans, in the stratosphere, at the poles, and near the equator. They can be seen in temperatures, rainfall, winds, plant and animal behavior, and in observations at the local level as well as in images derived from satellites in orbit around the Earth. Diagnosing what the symptoms mean is a job for theorists and modelers who attempt to place these changes in a consistent physical framework. The details are not perfectly described—ambiguities will always exist. But the overall conclusions are robust: much of what is happening is clearly the result of human activity.

Since human activity is not about to cease, or even stop growing, the diagnosis that humans are impacting climate has real consequences. If we take a business-as-usual approach and change very little, those consequences are likely to be serious. Even with significant effort to reduce human impacts, we have no guarantee that dangerous interference with the climate won't occur. Given the nature of the problem and the diverse and complex sources of greenhouse gases, no one simple solution will be possible. But the set of solutions that will be most effective and efficient is still unclear.

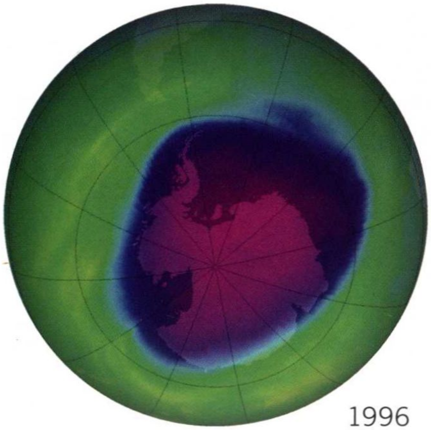
In many ways the problem of human-induced climate change is unique: it is global, it will affect the planet for decades to centuries, and it is complex, imperfectly understood, and has the potential for truly dramatic consequences. However, human civilization may have solved one other environmental problem that shares all of these characteristics, albeit on a smaller scale: stratospheric ozone depletion. This story has both connections to, and lessons for, the climate change problem.

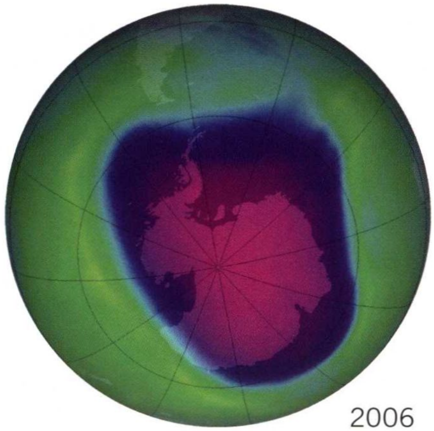


1980

FIXING AN OZONE HOLE

Fifteen to thirty-five kilometers above the Earth's surface, the ozone layer in our stratosphere is made of the "good" ozone that protects life on our planet from the Sun's powerful and dangerous ultraviolet rays. Our atmosphere's shielding layer of ozone exists due to a delicate balance between ozone production from solar ultraviolet rays and ozone loss through the Earth's atmospheric chemistry. In the 1930s, chemists invented a new class of compounds that could be used as a coolant in refrigerators and air conditioners. These compounds, collectively called chlorofluorocarbons (CFCs), consisted of chlorine and fluorine atoms attached to a central carbon atom, forming a large and stable molecule. They were chemically inert, cheap, and apparently harmless, and so had immediate commercial appeal. CFC production increased exponentially over the next four decades. Then in 1973 James Lovelock discovered that almost all of the CFCs ever produced were still sitting in the atmosphere. The CFCs weren't being removed by any natural process. Sci-





entists soon realized that because of the long life of these compounds, significant amounts of CFCs would make their way up to the stratosphere. There, subjected to the intense ultraviolet radiation, the CFC molecules would break down, releasing chlorine atoms. Chlorine on its own is extremely reactive, and when placed in contact with the ozone layer, as Sherwood Rowland, Mario Molina, and Paul Crutzen suggested, it would catalyze ozone destruction while not being used up itself. This research, which later won the Nobel Prize, was soon confirmed. Concern for the health of the ozone layer grew.

As with the climate change issue, there was uncertainty about what ozone depletion meant. Was it a problem at all? How large would it be? How difficult to fix? The problem spurred enormous amounts of research into the details of stratospheric chemistry to see if the basic mechanism would still be important once a host of other factors were brought in. Models were developed to project what would happen. CFC producers funded disinformation to try to downplay the problem. Some even claimed that CFCs couldn't possibly reach the stratosphere, because CFCs were heavier than air. This claim persisted even after CFCs had already been measured there! (In fact, the atmosphere is so turbulent that all the long-lived gases are well mixed from the surface up to a height of 80 kilometers [50 miles]).

Observations soon confirmed that the models were reasonable and the ozone layer was thinning; however, progress on fixing the problem was slow. In 1985, while international efforts to control CFCs were just getting under way, observations from Antarctica indicated that, instead of the expected gradual decline in ozone, very large and dramatic declines were occurring in the Antarctic region. A "hole" in the ozone layer had in fact developed in the early 1980s, but the measurements were so out of line they had initially been dismissed as a suspected error with the sensor. This phenomenon had not been predicted by any of the models. Scientists soon discovered that the ozone hole was related to small ice particles that form at very cold temperatures in the polar winter vortex. In the spring, these

OPPOSITE AND LEFT: The evolution of the Antarctic ozone hole. Ozone depletion is enhanced above the South Pole because of the existence of polar clouds, which only form in very cold conditions. The ice crystals within these clouds provide extra surface area for the chemical destruction of ozone by the chlorine derived from CFCs. In 1980, a diminuation in polar ozone was barely noticeable. By 1996 it was very noticeable indeed. The ozone hole in 2006 was the largest yet seen, covering some 23 million square kilometers (10.6 million square miles). Now that CFCs have been controlled and are no longer increasing in concentration, ozone recovery is expected to start in the next few years. The amount of natural year-to-year variability will make it difficult to be sure the ozone layer is on the mend for a decade or so. NASA EARTH OBSERVATORY ice crystals provide surfaces where more of the damaging chlorine atoms could be released.

After the discovery of the ozone hole, international efforts to reduce CFCs redoubled. By 1987, the Montreal Protocol on Substances That Deplete the Ozone Layer was negotiated. Since then, 191 nations have signed the protocol in an exceptional example of international cooperation. This treaty led to the eventual phasing out of all CFC production, first in the developed world and then in developing countries. Concentrations of CFCs have since started to fall. Although the CFC decrease has not yet produced a reduction in the size of the ozone hole, recovery is expected within the next few decades.

The ozone story is connected to climate change in a number of ways. First, CFCs, in addition to depleting ozone, also are significantly more powerful greenhouse gases than carbon dioxide on a molecule-per-molecule basis (see Chapter 6). Second, changes in stratospheric ozone themselves have climate impacts: globally, ozone depletion has had a small cooling effect on the climate, and the ozone hole specifically is implicated in changes in wind patterns around the Antarctic (Chapter 1). Finally, the reactions that govern polar ozone destruction are affected by colder temperatures, and as the stratosphere cools because of increases in carbon dioxide (this might seem paradoxical, but see Chapter 6 for details), this cooling is likely to push the recovery of the ozone hole back a decade or so. (Occasionally, the two stories have become jumbled in the popular mind, and the question "Isn't global warming caused by the sun coming in through the hole in the ozone layer?" is sometimes asked—the answer is no.)

Apart from these physical connections, the issues of ozone depletion and climate change are connected on political and practical levels. Most importantly, at no time was the science of ozone depletion ever certain. There were (and are) always unanswered questions. Yet the knowledge we did have demonstrated that a problem and a solution existed. Then, as now, extreme exaggerations of the costs of fixing the problem were commonplace. In dealing with the solutions, individual efforts to boycott aerosol sprays using CFCs as a propellant were important in raising awareness. But significant action only occurred within the context of international agreements and with the participation of the major CFC-producing businesses such as DuPont in the United States and ICI in the United Kingdom. Finally, do not forget that the models did not predict the ozone hole. In that case, the models were incomplete and they unknowingly underestimated the scale of the problem. Keep this in mind when reading the prognosis in Chapter 8.

Overall, the lesson learned from the ozone problem is positive. Despite scientific uncertainty, despite reluctance from vested interests, and despite the global equity