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To My Father

If the Lord Almighty had consulted me before embarking on the Creation, I would have recommended something simpler.

Alfonso X of Castille
(Alfonso the Wise)

CONTENTS

PREFACE

WE ARE GAMBLING that the benefits of our industrial and agricultural activities—increasing standards of living for the rich and poor alike—will outweigh possible adverse consequences of an unfortunate by-product of our activities, an increase in the atmospheric concentration of greenhouse gases that could lead to global climate changes associated with global warming. Some experts are warning that we are making very poor bets; others assure us that the chances of global warming are so remote that the outcome will definitely be in our favor. We conduct opinion polls, but the matter remains unresolved because scientific differences, unlike political disagreements, cannot be settled by means of referenda. This impasse is disquieting because the issue is of vital importance to each of us; it concerns the habitability of our planet. To what extent are we interfering with the processes that maintain the benign conditions under which a glorious diversity of fauna and flora is flourishing? How should we proceed in the face of contradictory answers from the experts?

In our attempts to cope with this complex planet, we could learn from our success in coping with another immensely complex system, the human body. In the same way that public awareness of the manner in which the human body functions facilitates effective health care, so public awareness of the processes that maintain benign conditions on our remarkable planet will facilitate effective environmental policies. Earth's habitability is too important a matter to be left entirely to experts, especially when they contradict each other for reasons that are ideological rather than scientific. Everyone ought to participate in discussions of environmental policies and to that end should have a rudimentary understanding of the processes that make this a habitable planet.

Everyone already has considerable familiarity with the phenomena that contribute to Earth's habitability. They are the things people write poetry about: clouds, rain, wind, weather, the oceans. Although we find those phenomena endlessly fascinating and full of mystery, we nonetheless tend to view their scientific aspects in simplistic terms. For example, some people believe that summer is warmer than winter for the "obvious" reason that the Earth is closer to the sun in summer than in winter. They are reluctant to accept that very dense gases such as chlorofluorocarbons (CFCs) can rise into the stratosphere and harm the ozone layer. The most common and serious error is the assumption that scientists should always be capable of precise predictions. The expectation that more accurate scientific information will soon be available can result in a continual deferral of action to deal with environmental problems until there is a crisis. The likelihood of a calamity will decrease once everyone realizes that many natural phenomena, even seemingly mundane ones such as clouds and winds, are so complex that scientific results concerning them have inevitable uncertainties. To appreciate that scientists can nonetheless provide valuable information to help us cope better with our environmental problems, we need some familiarity with a new discipline known as the Geosciences or Earth Sciences.

The Geosciences integrate traditional disciplines such as geology, biology, meteorology, and oceanography in order to address scientific questions about Earth's habitability. This subject has such an enormous scope that any one book can deal at most with a few of its facets. This book focuses on Earth's climate and its sensitivity to perturbations, those that occurred in the past—that resulted in the Ice Ages, for example—and those we are currently introducing, which could cause global warming. The main goal is to give insight into the science of the intricate processes that make this planet habitable in order to shed light on controversial environmental issues. Part One, which concerns general issues, starts with a chapter examining the principal reason for controversies: uncertainties in scientific results that cause a blurring of the distinction between science and policy. Chapter 2 describes briefly how scientists explore complex phenomena by studying simpler, idealized situations to obtain results that can be of enormous practical value even when precise predictions are precluded. Part Two examines some of the physical and chemical processes that make this a habitable planet. The topics include interactions between light and air molecules that enable the atmosphere to be a shield that protects us from dangerous ultraviolet rays and also a blanket that keeps the surface warm by providing a greenhouse effect (chap. 3); the dependence of Earth's great diversity of climatic zones on the global redistribution of heat and moisture by means of convection and clouds (chaps. 4, 5), winds that range from gentle sea breezes to the mighty Jet Streams (chap. 6), and chaotic weather patterns (discussed in chapter 7 along with a description of computer models that predict weather and climate). Chapters 8 and 9 concern oceanic currents and interactions between the ocean and atmosphere that cause phenomena such as El Niño and La Niña. Part Three describes how the interplay between the various processes discussed in Part Two determines Earth's response to various perturbations: the intensification of sunlight over the past few billion years (chap. 10); the periodic fluctuations in the distribution and intensity of sunlight on Earth that cause the cycles of seasons and of Ice Ages (chap. 11); our introduction of CFCs into the atmosphere and the resulting ozone hole over Antarctica (chap. 12); and the current increase in the atmospheric concentration of greenhouse gases that could lead to global climate changes (chap. 13).

Henry David Thoreau cautioned that "men are never tired of hearing how far the wind carried men and women, but are bored if you give them a scientific account of it." This book nonetheless attempts to explain to laymen the fascinating science of phenomena associated with our weather and climate. It is based on notes I prepared for an introductory course I teach at Princeton University. To accommodate those with little affinity for mathematics, the main part of the text is essentially void of equations and should be accessible to anyone interested in weather, climate, and related environmental issues. The Appendixes are intended for those who use the book as a text for an introductory course. It assumes familiarity with simple algebra and revisits some of the scientific arguments of the previous three parts, providing technical details plus exercises and suggestions for further reading.

I owe thanks to many people. My home institutions, the Department of Geosciences of Princeton University and the Geophysical Fluid Dynamics Laboratory of NOAA, provide an ideal environment for the study of weather and climate. I am grateful to friends, colleagues, and students who shared their expertise, commented on the manuscript, and generously offered advice and encouragement. I am indebted to Leo Donner, Kevin Hamilton, Rob Hargraves, Peter Heaney, Isaac Held, Philippe Hisard, Gabriel Lau, George Mellor, and Lori Perliski for critical readings of various chapters. For insights into good writing and good pedagogy I thank Harriet Bryan, Jim, Karen, and Majory Wunsch. Dan Feiveson, Jessica Godfrey, Barbara Winter, and Cathy Raphael contributed the splendid figures and computer graphics. My research has been supported by NOAA (grant NA56GP0226) and NASA (contract UCLA-NASA-NAG5–2224). Dr. G. Kukla, the American Meteorological Society, Cambridge University Press, the University of Washington Press, and *Science* generously gave permission to reproduce certain figures.

PART ONE

1

BETWEEN THE IDEA AND THE REALITY

WE ARE IN A RAFT, gliding down a river, toward a waterfall. We have a map but are uncertain of our location and hence are unsure of the distance to the waterfall. Some of us are getting nervous and wish to land immediately; others insist that we can continue safely for several more hours. A few are enjoying the ride so much that they deny that there is any imminent danger although the map clearly shows a waterfall. A debate ensues but even though the accelerating currents make it increasingly difficult to land safely, we fail to agree on an appropriate time to leave the river. How do we avoid a disaster?

To decide on appropriate action we have to address two questions: How far is the waterfall, and when should we get out of the water? The first is a scientific question; the second is not. The first question, in principle, has a definite, unambiguous answer. The second, which in effect is a political question, requires compromises. If we can distinguish clearly between the scientific and political aspects of the problem, we can focus on reaching a solution that is acceptable to all. Unfortunately, the distinction between science and politics can easily become blurred. This invariably happens when the scientific results have uncertainties.

Suppose that we have only approximate, not precise estimates of the distance to the waterfall. Rather than leave it at that—rather than accept that we can do no better than predict that we will arrive at the waterfall in thirty minutes plus or minus ten minutes—some people will minimize the distance and insist that we will arrive in twenty minutes or less, while others will maximize the distance, stating confidently that we won't be there for forty minutes or more. Do these people disagree for scientific reasons? (Some may have more confidence in their instruments than others do.) Or do their different opinions simply reflect the difference between optimists and pessimists?

To cope with this problem, we usually start by addressing the uncertainties in the scientific results. After all, everyone knows that science, in principle, can provide precise answers. One of the first scientists to be acclaimed by the public for his accurate predictions was Isaac Newton:

> Nature and Nature's law lay hid in night
> God said, Let Newton be! and all was light.
> *(Alexander Pope, "Epistle XI. Intended for Sir Isaac Newton in Westminster Abbey")*

Since Newton's accomplishments in the seventeenth century, scientists have continued to impress the public with remarkably accurate predictions that have led to inventions that continue to transform our daily lives. If, today, the results concerning a certain scientific problem have uncertainties, then, surely, it is only a matter of time before scientists present us with more accurate results. It is therefore easy to agree on a postponement of difficult political decisions regarding certain environmental problems on the grounds that we will soon have more precise scientific information. This could prove disastrous should we suddenly find ourselves at the edge of the waterfall. We recently had such an experience.

The current fisheries crisis, which is most severe off the shores of New England and eastern Canada where many species of fish have practically disappeared, started a decade after scientists first warned that overfishing could cause a dangerous reduction in fish stock. The scientists sounded a timely alert, but poor judgment on the part of policymakers contributed to this disaster. That is not how policymakers view the matter. Some complain of the scientists' "penchant for speaking in terms of probabilities and confidence intervals" and propose that, in future, scientists make "more confident forecasts . . . to catch the attention of regulators." As is often the case in environmental problems, we arrived at an impasse because of the reluctance of scientists to give definitive answers and the unwillingness of policymakers to make difficult political decisions. United States Congressman George Brown, former chairman of the House Committee on Science, Space and Technology, wonders whether there is a conspiracy between these two groups, the scientists who are assured a continuation of funds to improve their predictions, and the politicians who avoid difficult decisions that can cost them their jobs.

The fisheries crisis exemplifies a type of environmental problem with which we have had ample experience, and which the biologist Garret Hardin describes as "a tragedy of the commons."

> Picture a pasture open to all. It is to be expected that each herdsman will try to keep as many cattle as possible on the commons. Such an arrangement may work reasonably satisfactorily for centuries because

> tribal wars, poaching, and disease keep the numbers of both men and beast well below the carrying capacity of the land. Finally, however, comes the day of reckoning, that is, the day when the long-desired goal of social stability becomes a reality. At this point, the inherent logic of the commons remorselessly generates tragedy.
>
> As a rational being, each herdsman seeks to maximize his gain. Explicitly or implicitly, more or less consciously, he asks, "What is the utility to me of adding one more animal to my herd?"

The benefit of one more animal goes entirely to the herdsman. When it is sold, he receives all the proceeds. The disadvantage, the additional overgrazing, is shared by all. It is clearly to the advantage of the herdsman to acquire another animal. The other herdsmen reason similarly. The result is ruin for all.

The creation of private ownership is one attempt to avoid a tragedy of the commons. The landowner, out of self-interest, will prevent the land from being ruined. His interests do not necessarily coincide with ours so that we place restrictions on some of his actions. For example, he has to observe regulations concerning the disposal of sewage and toxic wastes because the water below his land and the air above it, fluids that can move pollutants off his property, remain part of the commons.

Given that, in the past, we successfully avoided many tragedies of the commons, why did we fail to avoid a fisheries crisis? Part of the reason is the novelty of the phenomenon; a decline in fish stock on a global scale is without precedent (although we have decreased the whale population significantly). Whereas we readily accept regulations that minimize damage that might occur during disasters with which we have experience (e.g., building codes that maximize public safety during an earthquake), we often oppose regulations that amount to precautionary measures to mitigate potential environmental disasters for which there are no precedents. If such disasters should occur in relatively small regions, they will serve as painful lessons on the need for regulations. If, however, a potential disaster has a global scale, we cannot afford to learn our lesson in such an expensive manner. Finding ways to avoid global disasters is a matter of urgency because the rapid growth in our numbers, and in our technological prowess, is increasing the likelihood of such disasters.

The English curate Thomas Robert Malthus (1766–1834) anticipated some of the problems that are likely because of the steady rise in the human population. In 1798 he predicted that, because our numbers are increasing at a rate that far exceeds the rate at which arable land increases, we are heading for a "gigantic inevitable famine." His forecast proved wrong, at least in the case of Britain and other rich countries, because he failed to anticipate the extent to which scientific and technological advances would increase the productivity of the inhabitants of those countries. The rising standards of living in the rich countries led to social changes that decreased the number of children born per family, thus stabilizing the populations. Presumably, the poor nations, by raising their standard of living, will in due course also halt the growth of their populations. Perhaps the present rapid rise in the world population is a temporary phenomenon, to be followed by a period of declining populations, whereafter the world population will stabilize at a relatively low number that our planet can accommodate comfortably. We all wish for such an end but, unless we are careful, the journey could prove very treacherous. We will face serious problems should the poor nations copy the current industrial and agricultural practices of the rich because, at present, the cost of a high standard of living is an enormous, adverse impact on the environment. The damage has been reversed, or at least mitigated in a few cases—certain rivers, once so polluted that they occasionally caught fire, are now clean and safe for fish—but other escalating environmental problems go essentially unattended. The fisheries crisis is one example. Another worrisome development is the rapid accumulation of greenhouse gases in the atmosphere. Rich countries may have limited the rate at which their populations grow, but they are increasing the rate at which they inject greenhouse gases into the atmosphere.

Toward the end of the nineteenth century, the Swedish chemist Svante August Arrhenius (1859–1927) alerted the world that our industrial activities, which are causing the increase in the atmospheric concentration of greenhouse gases, could result in global climatic changes. Nobody paid much attention to his predictions because of considerable uncertainties. For example, in the absence of instruments with which to monitor atmospheric carbon dioxide levels, many scientists assumed that oceanic absorption of that gas would prevent its accumulation in the atmosphere. During the past century, scientists have reduced the uncertainties significantly. There is now indisputable evidence that the atmospheric concentrations of several greenhouse gases, not only carbon dioxide, have indeed been increasing rapidly since the start of the Industrial Revolution. Mathematical models of Earth's climate now provide details of the global climate changes, including global warming, that we should expect. Furthermore, recent studies of past climates on Earth, which tell us about the response of this planet to perturbations, enable us to gauge the likely consequences of the perturbations that we are introducing. Empirical and theoretical evidence (reviewed in chap. 13) leave no doubt that the growth in the atmospheric concentration of greenhouse gases, if continued indefinitely, will cause global climatic changes. There is, however, considerable disagreement about the timing of those changes. Some experts paint alarming pictures of sea level that will soon rise to inundate New York, London, Tokyo, and other coastal cities; of pests and diseases that will spread into new territory; and of fertile farmlands that will soon become drought-stricken. Other experts assure us that our industrial and agricultural activities pose no immediate threat, that there is no likelihood of global warming in the foreseeable future. Do these contradictory statements reflect uncertainties in the scientific results, or are they expressions of ideological differences? Here we have another example of an impasse created by uncertainties in scientific results, and a reluctance to make difficult political decisions. The difficulty stems from our reluctance to accept that, although accurate predictions are, in principle, possible on the basis of the laws of physics, such forecasts may be impossible in practice because scientists—especially those who study complex environmental problems—deal with idealizations of reality. They too have to accept that

> Between the idea
> and the reality
> Between the motion
> and the act
> Falls the Shadow
>
> *(T. S. Eliot, "The Hollow Men")*

During the century since Arrhenius first sounded an alert, scientists have decreased the uncertainties in his forecasts considerably and are likely to continue doing so. However, there will always be shadows cast by inevitable uncertainties. We therefore have to ask ourselves whether we can continue to defer action much longer, given that the problem we face is similar to that of the gardener in the following riddle.

A gardener finds that his pond has one lily pad on a certain day, two the next day, four the subsequent day and so on. After 100 days the pond is completely filled with lily pads. On what day was the pond half full?

Answer: Day 99

Suppose that the gardener, once he realizes what is happening, quickly enlarges the pond to twice its size. On what day will the new pond be completely filled?

Answer: Day 101

The riddle illustrates how any problem involving explosive growth requires action at a very early stage, long before there are clear indications of impending trouble. In the case of the debate about global warming, in which some people insist that we are close to day 1 while others are adamant that we are close to day 100, the riddle indicates that, far more important than a precise answer that brings the debate to an end, is recognition of the special nature of the problem, its geometric growth. With such problems, it is far wiser to act sooner rather than later. To defer action is to court disaster.

A major impediment to progress on novel environmental problems, such as global warming or the depletion of fish stock, is the unrealistic expectation of precise predictions endorsed unanimously by the scientific community. This expectation reflects ignorance of the trial-and-error methods by which scientists reduce uncertainties in their results. Scientists continually subject any proposed solution to tests and do not hesitate to modify (or even abandon) a solution should it prove inadequate. Sound scientific results that have logic and clarity as their hallmark are often achieved by making many missteps along a tortuous road. (The irony is similar to that of poets who labor arduously to produce poems that flow effortlessly.) In our attempts to cope with our environmental problems, we should adopt a similar approach of trial and error. Rather than implement comprehensive programs that decree a rigid course of action to reach grand, final solutions, we should promote adaptive programs whose evolution is determined by the results from those programs and by new scientific results that become available. It will then be easier to take action when there is no scientific consensus, and it will be possible to correct mistakes at an early stage before scarce resources have been wasted. By adopting this approach, we are doing remarkably well in our efforts to minimize damage to Earth's protective ozone layer.

Because they recognize that the atmosphere is a commons whose protection is their responsibility, the nations of the world agreed in the Montreal Protocol of 1987 that each would limit its production of the chlorofluorocarbons (CFCs) that contribute to the depletion of the ozone layer. This was a remarkable decision because it was made before there was clear evidence that CFCs are harmful to the ozone layer; at the time, scientists had only warned that CFCs could pose a serious threat. The diplomats who negotiated the Montreal Protocol accepted the uncertainties in the scientific predictions and proceeded to take action. They wisely agreed on regulations that are subject to periodic reviews in order to accommodate new scientific results. The initial regulations called for a reduction in the production of CFCs. When the original predictions concerning the effect of CFCs on the atmosphere proved erroneous—scientists at first underestimated the harmful effects of CFCs (see chap. 12 for details)—the regulations were made more stringent, and the nations decided to cease production of CFCs.

Progress in science depends on the continual testing of results and explanations. Such skepticism makes it highly unlikely that scientists will ever unanimously recommend a solution to a problem that is so complex that the results have inevitable uncertainties. For a specific problem, the available evidence at a certain time may favor one particular explanation—e.g., overfishing for the disappearance of fish—but because of uncertainties, other possibilities—such as poor sampling of the fish population—cannot be excluded. A continual refinement of measurement and theories reduces uncertainties causing the spectrum of scientific opinions to converge. As long as there is some uncertainty, however, a few dissenting voices will persist. These contrariants, although they are wrong most of the time, are valuable because they force a continual reexamination of scientific methods and results. On a few rare occasions, they are even right. A prominent example concerns the idea of continental drift. With the exception of a few dissenters, the geological community rejected this notion for many decades, but in the end the dissenters proved right. Today the majority of geologists accept that continents drift.

The evidence accumulated over the past 100 years—especially the rapid scientific progress over the past few years—has convinced most scientists that the current rapid increase in the atmospheric concentration of greenhouse gases will lead to global climatic changes. There are, of course, a few dissenters, who would probably be skeptical even if the scientific issues were of strictly academic interest and concerned another planet, Mars, for example. That the issues are not strictly of academic interest but also have political aspects complicates matters enormously and dramatically alters the role of the skeptics, who become the focus of considerable attention for reasons unrelated to the merits of their scientific arguments. By focusing attention on the small group of dissenters, those who wish a continual deferral of action create the false impression that there is little agreement in the scientific community. To appreciate what is happening, the public needs to become familiar with the methods and results of scientists, especially the reasons for inevitable uncertainties that preclude precise predictions with which everyone agrees.

Scientists can contribute to the mitigation of potential disasters even when they are unable to make precise predictions. Consider the case of earthquakes. Their time of occurrence cannot be predicted, but it is possible to anticipate how Earth's surface will move should an earthquake occur and hence to build structures capable of surviving earthquakes. To ensure public safety, states enforce building codes that are in accord with the recommendations of earthquake engineers. The public, familiar with the disasters that earthquakes can cause, readily accepts those regulations. We need to recognize the need for regulations even in the case of environmental disasters for which there are no precedents. To avoid disasters such as the depletion of fish stock off the northeastern coast of the United States, we can demand of scientists more confident forecasts that "catch the attention of the regulators," but it would be wiser to accept that we have to act in spite of uncertainties, in spite of the inevitable shadow between the idea and the reality.

We cope successfully with some environmental problems but not with others. We sensibly agreed to limit the release of CFCs into the atmosphere, but we failed to act in time to avoid a fisheries crisis. We have yet to do something about the accumulation of greenhouse gases in the atmosphere. While we inject those gases into the atmosphere at an accelerating rate, we defer a decision on how soon to make a transition to environmentally sound technologies because of uncertainties in the scientific predictions and even bigger uncertainties about the cost of the transition. We are rushing toward dangerous rapids and possibly a waterfall but are reluctant to act because we do not know precisely how much time we have left before we are in serious trouble. In discussions about the appropriate time to leave the river, we should keep in mind that a step as drastic as leaving the river promptly and trekking across unknown terrain is but one option. It may be wiser to start by leaving the swift, accelerating part of the stream and moving where the flow is slow. Coping with uncertainties is not a novel challenge. All of us—businessmen, politicians, military strategists—routinely make decisions on the basis of uncertain information, usually after we have familiarized ourselves with the available facts. We who are privileged to live on this benign planet should at least attempt to understand it so that we can assess the likely consequences of our actions.

2

IS OUR PLANET FRAGILE OR ROBUST?

IN THE BEGINNING, swarms of rocks and swirls of gas circled the Sun. Gravity, the force that attracts objects to each other, gradually transformed this stony rubbish into something rich and strange: nine sparkling planets that wander across the skies as if they were independent of the stars. All are wondrous worlds—Saturn is adorned with rings, Jupiter with several moons—but only Earth, one of the smaller and less spectacular planets, a fragile blue dot when seen from afar, is blessed with a miracle, a glorious diversity of flora and fauna. Only our planet is habitable.

Earth has been habitable for most of its long history, even in its youth when the Sun was far fainter than it is today. At the birth of the solar system, some 4.5 billion years ago, the intensity of sunlight was approximately 30% less than at present. If the Sun were suddenly to become as faint as it originally was, temperatures on Earth would drop so much that all the water would freeze. The geological record nonetheless indicates that our planet has had plentiful water in liquid form, and hence has maintained a moderate range of temperatures, practically since birth. This paradox of the faint Sun but warm Earth—a clear indication that ours is a resilient planet, capable of maintaining benign conditions in spite of adversities—is a blessing to our species, *Homo sapiens*, because today we thrive on conditions that could have evolved only on a planet that has favored life for billions of years. It is as if elaborate preparations preceded the advent of mankind.

We are the beneficiaries of gradual evolutionary processes that unfolded to the rhythms of cyclic phenomena including the repeated buildup and erosion of mountains and the periodic opening and closing of ocean basins. Today our varied landscape, its spectacular mountains, vast plains, lush tropical jungles, and barren deserts, is but a snapshot of a continually changing panorama. *Homo sapiens* has been present for such a brief period, a million years or so, that we have witnessed only one possible arrangement of the continents. Our predecessors, however, have seen many changes because life, in one form or another, has been present on this planet practically since its birth.