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CHAPTER 1

Understanding Climate Science

Richard Wolfson and Stephen H. Schneider

This book is a survey of climate change policy. But developing, advocating, and implementing viable policies is impossible without some understanding of the science that underlies the climate change debate. This chapter provides just such an understanding. Whether or not you become involved formally in teaching about climate change, you will gain a sufficiently high level of expertise to help others grasp the subject at the level needed by an informed citizenry. This chapter has two explicit goals. The first is to educate you in the science of climate change. The second is to equip you as a citizen for a role in educating the broader public—including government officials and others charged with making policy—so that their decisions may be firmly grounded in the most current scientific knowledge of climate change.

Implicit here is a third, broader goal: to provide a concrete example of the policymaking context for a complex sociotechnological problem marked by conflicting claims of experts and the use of science to justify very different political ends. Whether the issue is genetically engineered food, missile defense, energy policy, or climate change, the burden on you, the informed citizen, is the same. You need to be literate enough about the nature of the debate and the underlying science to have your views counted in the political process. It is through the political process that society decides whether to take a given risk and determines who will be most exposed to the potential dangers. If the decision is to avert risk, then society decides how to do so and who should pay. Although each issue has its own particular scientific aspects, the associated policy processes have many common elements. This book will help you become more environmentally and scientifically literate not only on issues of climate change but also on a host of issues whose understanding is essential to full citizenship in the democratic process of the twenty-first century.

Is Earth's Climate Changing?

The Global Temperature Record

Modern temperature records, derived from thermometers sufficiently accurate and geographically dispersed to permit computation of a global average temperature, date back to the mid-nineteenth century. Extracting a global average from the data is complicated by many factors ranging from the growth of cities, with their "heat island" warming of formerly rural temperature measuring stations, to such mundane effects as changes in the types of buckets used to sample seawater temperature from ships. Early data suffer from a dearth of measurements and a bias toward the more developed regions of the planet. But climatologists understand how to account for these complications, and essentially all agree that Earth's average temperature increased by approximately 0.6°C since the mid-nineteenth century (we'll use Celsius temperatures throughout this book; 1°C is 1.8°F, so a rise of 0.6°C is about 1°F). Figure 1.1 shows the global temperature record as a plot of the yearly deviations from the 1961–1990 average temperature.[1]

A glance at Fig. 1.1 shows that Earth's temperature is highly variable, with

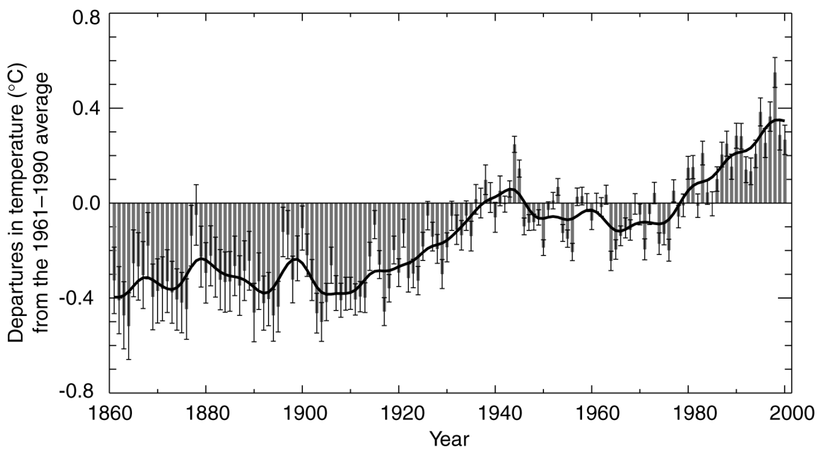

FIGURE 1.1. Variation in Earth's average global temperature from 1860 to 1999. Data are taken from global networks of thermometers, corrected for a variety of effects, and combined to produce a global average for each year. Wider, solid bars represent temperature deviations for each year, relative to the 1961–1990 average temperature, and narrow gray bars show uncertainties in the yearly temperatures. Black curve is a best fit to the data. (Adapted from IPCC, 2001a.)

year-to-year changes often masking the overall rise of approximately 0.6°C. Nevertheless, the long-term upward trend is obvious. Especially noticeable is the rapid rise at the end of the twentieth century. Indeed, all but 3 of the 10 warmest years on record occurred in the 1990s, with 1998 marking the all-time record high through 2000. There is good reason to believe that the 1990s would have been even hotter had not the eruption of Mt. Pinatubo in the Philippines put enough dust into the atmosphere to cause global cooling of a few tenths of a degree for several years. Looking beyond the top 10 years, Fig. 1.1 shows that the 20 warmest years include the entire decade of the 1990s and all but 3 years from the 1980s as well. Clearly the recent past has seen substantial surface warming.

A Natural Climate Variation?

Could the warming shown in Fig. 1.1, especially of the past few decades, be a natural occurrence? Might Earth's climate undergo natural fluctuations that could result in the temperature record of Fig. 1.1? Increasingly, we are finding that the answer to that question is "no." We would be in a better position to determine whether the temperature rise of the past century is natural if we could extend the record further back in time. Unfortunately, direct temperature measurements of sufficient accuracy or geographic coverage simply don't exist before the mid-1800s. But by carefully considering other quantities that do depend on temperature, climatologists can reconstruct approximate temperature records that stretch back hundreds, thousands, and even millions of years.

Figure 1.2 shows the results of a remarkable study, completed in 1999, that attempts to push the Northern Hemisphere temperature record back a full thousand years.[2] In this work, climatologist Michael Mann and colleagues performed a complex statistical analysis involving 112 separate indicators related to temperature.[3] These included such diverse factors as tree rings, the extent of mountain glaciers, changes in coral reefs, sunspot activity, volcanism, and many others. The resulting temperature record of Fig. 1.2 is a "reconstruction" of what one might expect had thermometer-based measurements been available. Although there is considerable uncertainty in the millennial temperature reconstruction, as shown by the error band in Fig. 1.2, the overall trend is most consistent with a gradual temperature decrease over the first 900 years, followed by a sharp upturn in the twentieth century. That upturn is a compressed representation of the thermometer-based temperature record shown in Fig. 1.1. Among other things, Fig. 1.2 suggests that the 1990s was the warmest decade not only of the twentieth century but of the entire millennium. Taken in the context of Fig. 1.2, the temperature rise of last century clearly is an unusual occurrence.

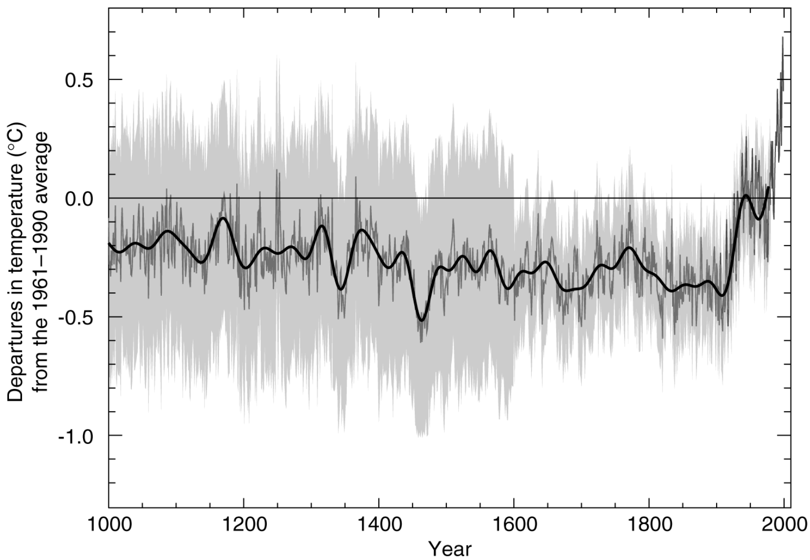

FIGURE 1.2. Reconstruction of the 1,000-year temperature record for the Northern Hemisphere. Black curve is a best fit to the millennial temperature record; gray is the 95% confidence interval, meaning that there is a 95% chance that the actual temperature falls within this band. Date from the mid-nineteenth century on are from the thermometer-based temperature record of Fig. 1.1. (Adapted from Mann et al. as shown in IPCC, 2001a.)

But is it unnatural? Mann et al. approached that question by correlating their temperature reconstruction with several factors known to influence climate, including solar activity, volcanism, and humankind's release of heat-trapping gases (greenhouse gases; more on this later in the chapter). They found that solar variability and volcanism were the dominant influences in the first 900 years of the millennium but that much of the twentieth-century variation could be attributed to human activity. Given the indirect, statistical nature of the study, this result can hardly be taken as conclusive evidence that humans are to blame for twentieth-century global warming. But the Mann et al. result does provide independent corroboration of computer climate models that also suggest a human influence on climate.

Climate Science: Keeping a Planet Warm

How can human activity affect Earth's climate? What ultimately determines climate, and specifically Earth's temperature? That question is at the heart of climate science and of the issues surrounding human-induced climate change and policies to prevent, ameliorate, or mitigate its effects.

Energy Balance

What keeps a house warm in the winter? After all, heat is continually flowing out through the walls and roof, through the windows and doors. So why doesn't the house get colder and colder? Because some source—a gas furnace, a heat pump, a woodstove, sunlight, an oil burner, electric heaters—supplies heat at just the right rate to replace what's being lost. In other words, the house is in energy balance: Energy enters the house at the same rate at which it's being lost. Only under that condition of energy balance will the house temperature remain constant.

The same idea holds for Earth and other planets. Energy, essentially all of it in the form of sunlight, arrives at Earth. In turn, Earth loses energy to the cold vacuum of space. When there's a balance between the incoming sunlight and the energy lost to space, then Earth's temperature remains constant (Fig. 1.3).

Why should there be a balance? Because the rate at which Earth loses energy depends on its temperature. That loss rate is given by a well-known and fundamental law of physics stating that all objects lose energy to their surroundings in the form of radiation. The higher the temperature, the greater the loss rate. Suppose Earth were to be so hot that it loses energy at a greater rate than the incoming sunlight supplies it. Then there is a net loss of energy, so the planet cools. As

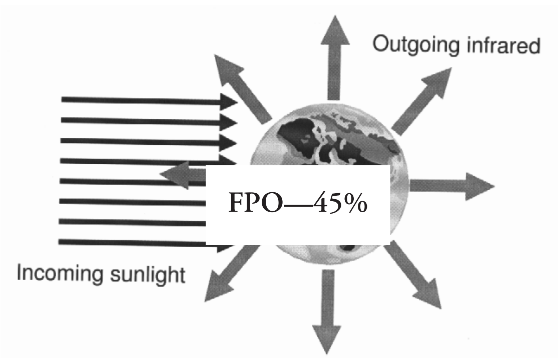

FIGURE 1.3. A simplified picture of Earth's energy balance, showing incoming sunlight delivering energy to Earth. To maintain a constant temperature, Earth radiates energy to space at the same rate. Because Earth is cooler than the Sun, it radiates not visible light but infrared energy. Note that sunlight impinges with full intensity on an area equal to that of a cross-section through Earth's center. But Earth radiates from its entire surface, the area of which is four times its cross-sectional area. That is why the average sunlight intensity, for purposes of energy balance, is one-fourth the direct intensity measured by satellites. This simple diagram neglects the complicating effects of Earth's atmosphere, reflection, and other processes.

it cools, the energy loss rate drops. Eventually the loss becomes equal to the energy supplied in the incoming sunlight, and at that point Earth is in energy balance at a fixed, lower temperature. If the planet is too cool, so it loses energy at a lower rate than the incoming sunlight supplies it, then Earth experiences a net energy gain and heats up. As it heats, the loss rate goes up until it just balances the incoming sunlight. Again, Earth achieves energy balance at a fixed, higher temperature.

What is that fixed temperature? Knowing the rate at which solar energy reaches Earth and knowing the mathematical form of the law for the energy loss, it's a simple matter to equate the two and solve for the temperature. The result, for Earth, is a predicted global average temperature of about –18°C, or about 0°F. That may sound quite cold, and it is, for reasons we'll explore shortly.

Our estimate of a –18°C global average temperature is based on the simplest possible climate model. The model assumes that Earth is a single point, characterized by a single temperature. Ignored are variations with latitude, longitude, and altitude. Also ignored are the tilt of Earth's axis and the resulting seasonal climate variations. So are the existences of separate land and ocean areas, and of the atmosphere, and of air and water currents that transport heat across the planet. Despite these simplifications, the model nevertheless provides a reasonable estimate of Earth's global average temperature as would be seen by a space traveler passing by the planet.

The Greenhouse Effect

Our simple energy balance model predicts a temperature that, though not absurd, seems cold. Too much of Earth's surface is well above freezing for a global average of –18°C or 0°F to be right. In fact, Earth's average surface temperature is about 15°C (59°F), some 33°C higher than the simplest model predicts. Why the discrepancy?

The answer lies in the atmosphere, and to understand it one needs to know more about how objects lose energy. Not only is the energy loss rate dependent on temperature, but so is the specific form of the energy being lost. Any object surrounded by a vacuum loses energy by radiation—more precisely, electromagnetic radiation. Electromagnetic radiation includes visible light, the radio and microwaves used in communication, the invisible infrared and ultraviolet (UV) "light" that lie just outside the visible range, and the penetrating X rays and gamma rays. All these forms of radiation are essentially the same; they differ only in the frequency of the electromagnetic vibrations or, equivalently, in their wavelength (distance between wave crests). Radio waves have the lowest frequency and longest wavelength, followed by microwaves, infrared, visible light, ultraviolet, X rays, and gamma rays.

Here's the climatologically important point: The hotter an object, the higher the frequency and shorter the wavelength of the dominant radiation it emits. The Sun, at 6,000°C, emits primarily visible light. Some bizarre astrophysical objects are so hot they emit primarily X rays. A hot stove burner glows a dull red and emits a mix of infrared and visible light. Your own body emits primarily infrared radiation, which sensitive instruments can detect for use in medical diagnosis. Similarly, infrared cameras image buildings to determine where heat loss occurs. And Earth itself, a cooler object, emits primarily infrared radiation, as shown in Fig. 1.3. For energy balance, the rate at which the planet loses energy in the form of infrared radiation must equal the rate at which it receives solar energy in the form of sunlight.

The gases that make up Earth's atmosphere are largely transparent to visible light. That's obvious because we can see the Sun, Moon, and stars from the ground. Therefore, much of the incident sunlight penetrates the atmosphere to reach the surface (we'll get more specific about this shortly). Once absorbed, this solar energy warms the atmosphere, and particularly the surface, which then re-emits the energy as infrared radiation. But the atmosphere is not so transparent to infrared. Certain naturally occurring gases absorb infrared radiation and limit its ability to escape from Earth. These gases—and cloud particles also—re-emit some of the infrared downward. As a result, Earth's surface warms further, emitting infrared radiation at a still greater rate, until the emitted radiation is again in balance with the incident sunlight. But because of the atmosphere with its infrared-absorbing and re-emitting gases, the resulting surface temperature is higher than it would be otherwise. That is what accounts for the 33°C difference between our simple prediction and Earth's actual surface temperature.

Because the atmosphere functions roughly like the heat-trapping glass of a greenhouse, this excess heating has earned the name *greenhouse effect*, and the gases responsible are called greenhouse gases. The most important natural greenhouse gas is water vapor, followed by carbon dioxide and, to a lesser extent, methane. (The greenhouse analogy is not such a good one; a greenhouse traps heat primarily by preventing the wholesale escape of heated air, with the blockage of infrared playing only a minor role.) We'll explore the role of the greenhouse effect in Earth's energy balance in more detail shortly.

The 33°C warming caused by natural greenhouse gases and particles in the atmosphere is the natural greenhouse effect, and it makes our planet much more habitable than it would be otherwise. What we're concerned about now is the *anthropogenic* greenhouse effect arising from additional greenhouse gases emitted by human activities. Such emissions add to the blanket of heat-trapping gases, further increasing Earth's temperature. Before we turn to the details, though, it's important to recognize that the basic greenhouse phenomenon is well understood and solidly grounded in basic science.

A Tale of Three Planets

We can't carry out controlled experiments with Earth's greenhouse effect because we have only one Earth and because such experiments would take decades or longer for definitive results. (Of course, we are in the midst of an *uncontrolled* experiment with Earth's climate as we pour greenhouse gases into our atmosphere.) But our two neighbor planets, Mars and Venus, conveniently provide us with natural greenhouse "experiments." Mars, somewhat farther from the Sun than Earth, should be correspondingly cooler. A simple energy balance calculation neglecting Mars's atmosphere suggests a surface temperature around –60°C. In fact, Mars's temperature is only a little warmer, at about –50°C. That's because Mars's atmosphere is so thin that it provides very little greenhouse warming. Venus, on the other hand, is closer to the Sun, and the simple calculation suggests a surface temperature around 50°C. But Venus's surface temperature is a much hotter: 500°C. Why? Because Venus's atmosphere is very thick and is composed primarily of the greenhouse gas carbon dioxide (CO_2). Consequently, Venus has a "runaway" greenhouse effect that greatly increases its temperature. Earth lies, physically and climatologically, between Venus and Mars. Our atmosphere is 100 times denser than Mars's, but the dominant gases (nitrogen and oxygen) do not absorb significant amounts of infrared radiation. In Earth's atmosphere the greenhouse gases occur in trace amounts, less than 0.1 percent for CO_2 and up to a few percent (varying with humidity) for water vapor. Thus we have a modest greenhouse warming of about 33°C, compared with Mars's 10°C and Venus's dramatic 450°C. This comparison with our neighbor planets confirms our basic scientific understanding of the greenhouse effect and increases confidence in our ability to calculate quantitatively the warming caused by changes in atmospheric greenhouse gases.

Incidentally, Earth's atmosphere is unique in another important way. Unlike the atmospheres of Mars and Venus, which result from geophysical processes, Earth's present atmosphere is strongly biologically controlled. More than 3 billion years ago, the first photosynthetic organisms began emitting oxygen, at that time just a byproduct, and to them a toxic one at that. Later organisms evolved to use the new atmospheric oxygen in a higher-energy metabolic process that ultimately made possible the rapid mobility of animal species. Today's atmospheric composition—about 80 percent nitrogen, 20 percent oxygen, and traces of other gases including CO_2—is significantly regulated by biogeochemical cycles that include plant photosynthesis and respiration by both plants and animals. Without life, atmospheric oxygen would disappear in the geologically short time of a few million years.

Earth's Energy Balance

The simplest way to understand the greenhouse effect is to consider greenhouse gases as a moderately insulating blanket that traps heat. Just as a blanket covers your body and keeps you warm, so the greenhouse gases blanket Earth and keep it warmer than it would be without those gases. Adding more greenhouse gases—as humans have been doing since the industrial revolution—is like making the blanket thicker. For the general public, that explanation is sufficient to capture the essence of the phenomenon and to show why anthropogenic greenhouse gas emissions should lead to climate change. Even for elementary school students, the greenhouse effect at this level is eminently comprehensible. We emphasize again that this picture of the greenhouse effect is solidly grounded in basic physics and confirmed by observations of Venus, Earth, and Mars.

However, the level of this book calls for a more sophisticated understanding of the greenhouse effect, including a detailed look at Earth's energy balance. On average, the rate at which solar energy arrives at the top of Earth's atmosphere is nearly 1,368 watts on every square meter oriented at right angles to the incident sunlight. (For several decades this figure has been accurately monitored by satellites; it varies by about 0.1 percent over the 22-year solar activity cycle and has been speculated to vary by up to 0.5 percent over century-long timescales.) Accounting for Earth's spherical shape and the fact that only the daytime half the planet faces the Sun results in an average solar energy incident on the planet of 342 watts per square meter (W/m^2). For energy balance, Earth must return energy to space at exactly this rate. Figure 1.4 shows the details of how this happens.[4] (Numbers given in Fig. 1.4 and in the text discussion are approximate, and some are uncertain by as much as 10 percent.) Of the incident sunlight energy, some 31 percent is reflected back into space, most of it by clouds but some by ice, snow, deserts, and other light-colored surfaces. This reflected energy is never converted to heat, so it plays essentially no role in climate. That leaves some 235 W/m^2 that is absorbed by the Earth–atmosphere system and must be returned to space. Incidentally, a change in the 31 percent reflectance figure—resulting, for example, from ice melting in response to global warming—could have significant climatic effects.

Another 20 percent or so of the incident solar energy is absorbed in the atmosphere, directly heating it. The remainder—nearly 50 percent—reaches and warms the surface. The warm surface warms the atmosphere, which, in turn, cools by emitting infrared radiation. This helps to explain why air tem-

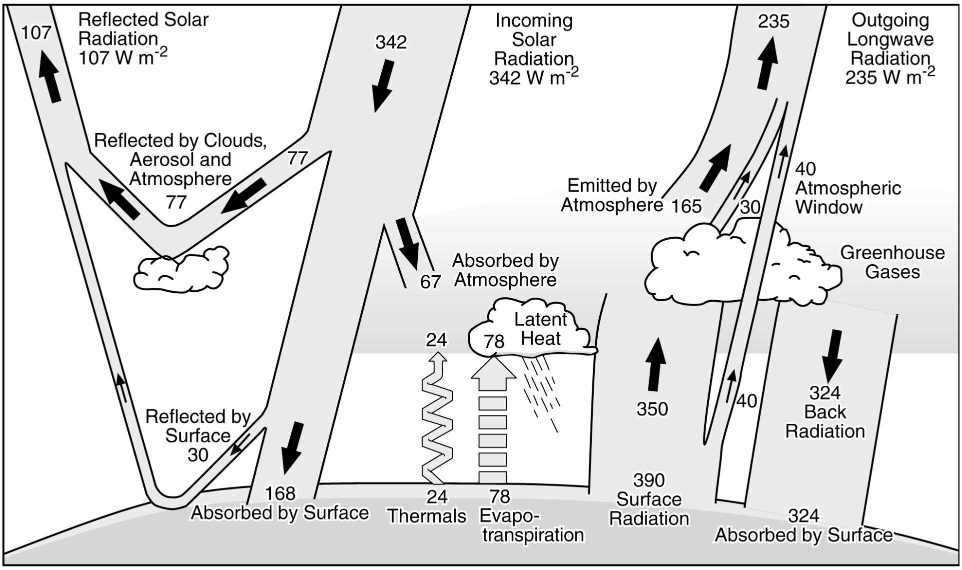

FIGURE 1.4. Details of Earth's energy balance. Numbers are in watts per square meter of Earth's surface, and some may be uncertain by as much as 10%. The greenhouse effect is associated with the absorption and reradiation of energy by atmospheric greenhouse gases, resulting in a higher downward flux of infrared radiation from the atmosphere to the surface and therefore in a higher surface temperature. Note that the total rate at which energy leaves Earth (107 W/m^2 of reflected sunlight plus 235 W/m^2 of infrared [long-wave] radiation) is equal to the 342 W/m^2 of incident sunlight. Thus Earth is in energy balance. (From Kiehl & Trenberth, 1997.)

perature usually decreases with altitude. Figure 1.4 shows that some heat is transported into the atmosphere by bulk air motions, which physically raise warm air from the surface and, more importantly, carry evaporated water and the latent energy it contains. When this water recondenses to form clouds, energy is released to the air. This energy transport process is what powers hurricanes, for example. The atmosphere, warmed by direct heating and by heating from the surface, in turn radiates energy to space to help maintain energy balance. In the absence of greenhouse gases, the surface would also radiate a significant amount of infrared energy directly to space. But clouds and greenhouse gases block much of this outgoing infrared, instead absorbing the energy and thus heating the atmosphere. The atmosphere, in turn, radiates the absorbed energy in all directions, again in the form of infrared radiation. Some escapes to space, but some heads downward, further warming the surface. The result, in the steady state depicted in Fig. 1.4, is a warmer surface that produces a larger flow of infrared radiation upward, not quite balanced by the smaller but still substantial flow downward from the atmosphere overhead. The difference between the upward and downward energy flows, in the steady state, is just the right amount to maintain energy balance between absorbed solar radiation, evaporation, thermal energy lost via rising plumes of heated air, and the net infrared radiation balance. So Earth is in nearly perfect energy balance but with a surface temperature significantly higher than it would be in the absence of greenhouse gases. This scientific theory is firmly established.

Past Climates

Just how much will increasing greenhouse gas concentrations affect climate? We can get clues by looking at past climates. The last 140 years, as shown in Fig. 1.1, have been a period of significant warming. Also, as Fig. 1.5 shows, atmospheric carbon dioxide has increased by more than 30 percent during the same period.[5] The reality of this CO_2 increase is unquestioned, and virtually all climatologists agree that the cause is human activity, predominantly the burning of fossil fuels and to a lesser extent deforestation and other land use changes, along with industrial activities such as cement production. (Although water vapor is the predominant greenhouse gas, its concentration is affected only indirectly by human-induced warming. Carbon dioxide, therefore, is the most important anthropogenic greenhouse gas that results directly in global warming, although we'll later take a look at some other significant heat-trapping gases.)

Note the units and numbers in Fig. 1.5. The unit of atmospheric CO_2

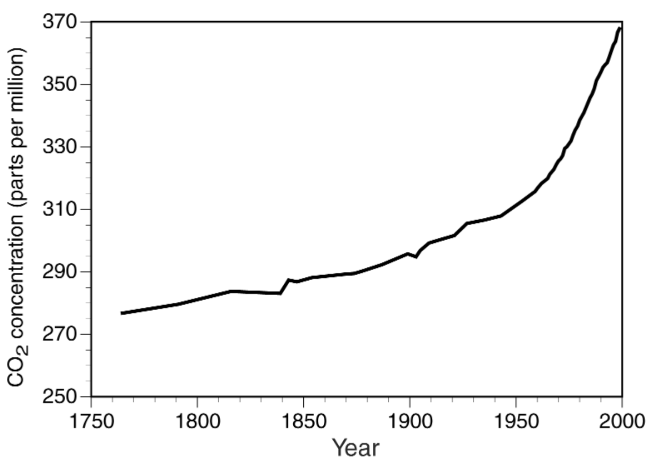

FIGURE 1.5. Atmospheric carbon dioxide has increased by more than 30% since preindustrial times. (Data are from Neftel et al., 1994, and Keeling & Whorf, 2000.)

concentration is the part per million (ppm). This describes the number of volume units of CO_2 in a million units of air. For example, the CO_2 concentration of some 370 ppm at the start of the twenty-first century means that out of every million liters of air, 370 of them are carbon dioxide. This level of 370 ppm is up from about 280 ppm at the beginning of the industrial era.

Figures 1.1 and 1.5 taken together show contemporaneous increases in global temperature and carbon dioxide concentration, both occurring during an era of rapid industrialization. So are anthropogenic CO_2 emissions a direct cause of recent warming? As the study summarized in Fig. 1.2 suggested, it looks increasingly like the answer is "yes." But the connection between the past 140 years' warming and the coincident rise in CO_2 is not so obvious. For example, global temperature actually declined in the period after World War II, a time of rapid industrialization when CO_2 concentrations began an especially rapid increase. On the other hand, temperature rises should lag CO_2 increases, so we shouldn't expect to find that recent temperature and CO_2 are instantaneously correlated. Moreover, there are other factors that can influence climate fluctuations or trends, and all of these are confounded in the data shown in Figs. 1.1 and 1.5. Separating the anthropogenic "signal" of climate change from the "noise" of natural fluctuations can be a tricky process.

We can get a better understanding of the temperature–CO_2 relationship by looking much further back in time. Ice cores bored from the Greenland and Antarctic ice sheets provide estimates of both quantities going back hundreds of thousands of years. Variations in ice density associated with seasonal snowfall patterns provide a year-to-year calibration of the time associated with a given point in the ice core. CO_2 measurement is easy: Analysis of air bubbles trapped in ancient ice gives an indication of CO_2 concentration. Temperature inference is a bit more subtle and usually is accomplished by comparing the ratio of two different forms (isotopes) of oxygen whose uptake in evaporation, and therefore concentration in precipitation and thus in the ice itself, is sensitive to temperature. The result of an ice core analysis, shown in Fig. 1.6, gives dramatic evidence that temperature and carbon dioxide concentration are correlated over the long term.[6]

Are the CO_2 variations in Fig. 1.6 the cause of the temperature changes? That's not clear from the graph alone. Sometimes a CO_2 increase precedes a warming, but sometimes not. In fact, climatologists suspect a feedback process whereby a slight increase in temperature, probably caused by subtle changes in Earth's orbit, results in an increase in atmospheric CO_2 through a variety of mechanisms such as the release of CO_2 dissolved in the oceans. The increased atmospheric CO_2, in turn, leads to greenhouse warming, amplifying the initial temperature increase. The result is a nearly simultaneous and substantial increase

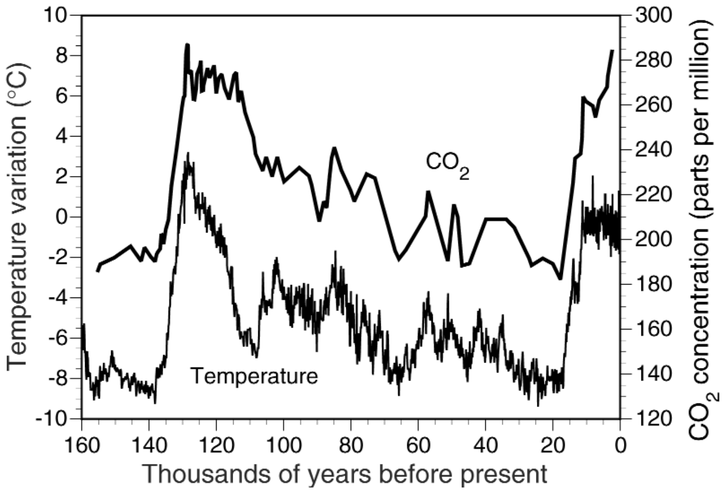

FIGURE 1.6. Atmospheric carbon dioxide (upper curve) and temperature variation (lower curve) over the past 160,000 years, from ice cores taken at Vostok, Antarctica. The record shows long stretches of low temperature (ice ages) separated by brief, warm interglacial periods. The correlation between CO_2 and temperature is quite obvious. Note also the small change, averaging perhaps 6°C, between the present warm climate and the recent ice age. Data do not extend to the present, but stop well before the industrial era. (CO_2 data are from Petit et al., 2000; temperature data from Jouzel et al., 1987, as reproduced in the Carbon Dioxide Information Analysis Center.)

in both CO_2 and temperature. Eventually orbital changes trigger a modest temperature decrease, and again feedback mechanisms amplify the decrease, driving down both CO_2 and temperature. Some paleoclimatologists believe that an initial cooling causes a drying of the continents, which therefore produce more windblown dust. This dust contains minerals needed by phytoplankton in the oceans. As dust settles on the ocean surface, it fertilizes these tiny oceanic organisms. The phytoplankton, in turn, increase their productivity by drawing down atmospheric CO_2, thus making the move toward an ice age even more rapid and deep. Such biotic feedback mechanisms illustrate how complex the actual climate system is and help us to understand why in the policy debates to be presented later, many claims will be made by advocates incompletely selecting bits of this complex story to suit certain value positions. (More on that in later chapters.) But despite the complexity, there is still much regularity in the record. The pattern of varying temperature and carbon dioxide concentration shown in Fig. 1.6 is believed to repeat on a timescale of roughly every 100,000 years over most of the past million years, at least in part as a result of periodic changes in Earth's orbit and inclination of its polar axis.

Note that Fig. 1.6 shows brief periods of warmth punctuated by much longer, cooler ice ages. They are characterized by dramatically different climatic conditions, with ice sheets 2 kilometers thick covering what is now Canada, the northeastern United States, and northwestern Europe and engulfing high mountain plateaus all around the world. Today we enjoy the warmth of an interglacial period, but not long ago, geologically speaking, conditions were very different.

What sort of global temperature change characterizes the contrast between an ice age and our present interval of warmth? A look at Fig. 1.6 shows that change to be on the order of 6°C (11°F). You can quibble by a few degrees, but it's certainly no more than 10°C and, on average, quite a bit less. This point is crucial because climate models driven by standard assumptions about population, land use, and energy consumption project a warming over the next century of 1.5°C to 6°C. The difference between the higher and lower ends of this range has substantial implications for sea level rise, extreme weather, redistribution of species ranges, and other impacts. Policymakers and the general public often ask how a few degrees can matter all that much. Figure 1.6 provides one startling answer: Downward changes on the same order as the largest projected warming are enough to make the difference between our current climate and an ice age. A few degrees, sustained in time and taken over the entire globe, can make a big difference.

A second important point follows from comparing Figs. 1.6 and 1.5. Note in Fig. 1.6 that the maximum CO_2 concentration in the ice core record of the past 160,000 years (and probably for at least millions of years) is under 300 ppm. This does not include the very recent past, but only the preindustrial period. Now look at Fig. 1.5, with its present-day concentration of 370 ppm—far above anything Earth has seen, probably, for millions of years. Figure 1.7

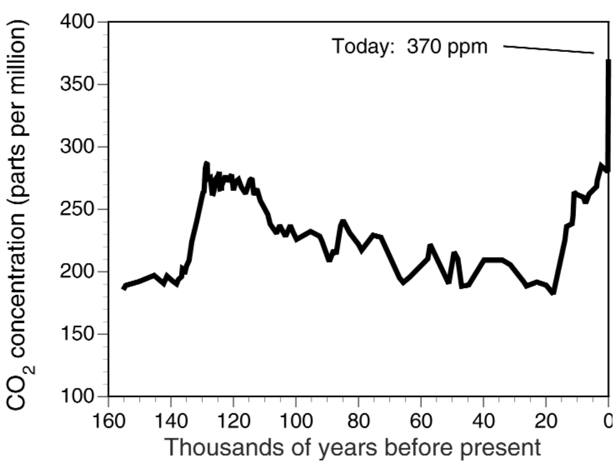

FIGURE 1.7
The CO_2 record of Fig. 1.6, with data to 1999 included. The CO_2 rise of Fig. 1.5 shown here as a dramatic jump to levels not seen on Earth for hundreds of thousands (and probably millions) of years.

shows the effect of adding the recent rise in CO_2 to the ice core data. Clearly the anthropogenic increase in CO_2 concentration is unprecedented in both its size and its rapidity. We have made truly dramatic changes in Earth's atmosphere over the past century or so, and we can almost certainly expect significant climate change to result.

Projecting Future Climate: Greenhouse Gases and Feedbacks

We know that human activities have increased the concentration of atmospheric carbon dioxide. Given the many decades of inertia built into social and industrial systems, they will almost certainly continue to do so for at least decades to come. We know that much of the extra CO_2 remains in the atmosphere for centuries. We also understand the molecular properties of CO_2 and can therefore predict how much infrared radiation over how long a period a given injection of CO_2 should absorb. If that were the whole story, it would be a simple matter to predict Earth's future climate.

However, anthropogenic carbon dioxide is not the whole story. Although CO_2 is the most significant anthropogenic greenhouse gas, accounting for some 60 percent of the enhanced infrared blockage, a host of other greenhouse gases also result from human activities. Another major complication in predicting future climate is feedback effects, whereby human-induced greenhouse warming may cause other processes that either exacerbate or dampen the warming. Finally, other human activities—most notably the emission of particulate pollution from cars and fossil-fueled power plants—can result in regional cooling that may mask or reduce the effects of greenhouse warming. To project future climate confidently, we must take these and many other effects into account. Unfortunately, not all uncertainties can now be, or soon will be, resolved, adding further to confusion in the public policy debate (see the discussion in Chapter 2).

Greenhouse Gases and Radiative Forcing

Although carbon dioxide is the most important of the anthropogenic greenhouse gases in terms of its direct effect on climate, other gases play a significant role, too. On a molecule-to-molecule basis, most other greenhouse gases (except water vapor) are far more potent absorbers of infrared radiation than is carbon dioxide, but they are released in much lesser quantities, so their overall effect on climate is smaller. 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. Currently anthropogenic CO_2 produces a radiative forcing estimated at about 1.5 watts for every square meter of Earth's surface (all forcings cited in this section are from the Intergovernmental Panel on Climate Change [IPCC] Third Assessment Report).[7] Relative to the 235 W/m^2 of solar energy that is absorbed by Earth and its atmosphere, the CO_2 forcing is a modest perturbation of the overall energy balance. Very crudely, one can think of that 1.5 W/m^2 of CO_2 forcing as having roughly the same effect as would an increase in the incoming sunlight energy by an average of 1.5 W on every square meter. The global warming resulting from a specified amount of radiative forcing, after the climate has settled into a new equilibrium state, is called climate sensitivity. If we knew the climate sensitivity and the concentration of all atmospheric constituents that affect radiative forcing, then we could more credibly predict future global warming.

Another anthropogenic greenhouse gas is methane (CH_4), produced naturally and anthropogenically when organic matter decays anaerobically (that is, in the absence of oxygen). Such anaerobic decay occurs in swamps, landfills, rice paddies, land submerged by hydroelectric dams, the guts of termites, and the stomachs of ruminants such as cattle. Methane is also released by oil and gas drilling, coal mining, volcanic eruptions, and the warming of methane-containing compounds on the ocean floor. One methane molecule is roughly 30 times more effective at blocking infrared than is one CO_2 molecule, although this comparison varies with the timescale involved and the presence of other pollutants. Whereas CO_2 concentration increases tend to persist in the atmosphere for centuries or longer, the more chemically active methane typically disappears in decades, making its warming potential relative to that of CO_2 lower on longer timescales. Currently methane accounts for about 0.5 W/m^2 of anthropogenic radiative forcing, about one-third that of CO_2.

Other anthropogenic greenhouse gases include nitrous oxide, produced from agricultural fertilizer and industrial processes, and the halocarbons used in refrigeration. (A particular class of halocarbons—the chlorofluorocarbons—is also the leading cause of stratospheric ozone depletion. Newer halocarbons do not cause severe ozone depletion but are still potent greenhouse gases.) Together, nitrous oxide and halocarbons account for roughly another 0.5 W/m^2 of radiative forcing. A number of other trace gases contribute roughly 0.05 W/m^2 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 lowest 10 km of so of the atmosphere.

Another greenhouse gas is ozone (O_3), familiar because of its depletion by anthropogenic chlorofluorocarbons. Ozone occurring naturally in the stratosphere (some 10–50 km above the surface) absorbs incoming ultraviolet radiation and protects life from UV-induced cancer and genetic mutations, hence the concern about ozone depletion and in particular the polar "ozone holes." Unfortunately, ozone depletion and global warming have become confused in the public mind, even among political leaders and some environmental policymakers. But the two are very distinct problems. The ozone depletion problem is not the same as the global warming problem! Ozone depletion eventually will come under control because of the 1987 Montreal Protocol, an international agreement that bans the production of the chlorinated fluorocarbons that destroy stratospheric ozone. Whether similar agreements can be forged for climate-disturbing substances is what the current debate—and this book—are about.

Because ozone is a greenhouse gas, there are some direct links between greenhouse warming and anthropogenic changes in atmospheric ozone. Ozone in the lower atmosphere—the troposphere—is a potent component of photochemical smog, resulting largely from motor vehicle emissions. Tropospheric ozone contributes roughly another 0.35 W/m^2 of radiative forcing, although unlike the well-mixed gases, tropospheric ozone tends to be localized where industrialized society is concentrated. In the stratosphere, the situation is reversed. Here the anthropogenic effect has been ozone depletion, resulting in a negative forcing of approximately –0.15 W/m^2. Thus stratospheric ozone depletion, on its own, would cause a slight global cooling. Taken in the context of the more substantial positive forcings of other gases, though, the effect of stratospheric ozone depletion is a slight reduction of the potential for global warming, an effect that will diminish as the ozone layer gradually recovers under the Montreal Protocol's ban on chlorofluorocarbons. The net effect of all anthropogenic ozone (both tropospheric and stratospheric) probably amounts to a slight positive forcing. The net forcing to date from all anthropogenic gases probably is about 3 W/m^2 and is expected to become much larger if business-as-usual development scenarios are followed in the twenty-first century.

Aerosols

Fuel combustion, and to a lesser extent agricultural and industrial processes, produce not only gases but also particulate matter. Coal-fired power plants burning high-sulfur coal, in particular, emit gases that become sulfate aerosols that reflect incoming solar radiation and thus results in a cooling trend. Natural aerosols from volcanic eruptions and the evaporation of seawater also produce a cooling effect. However, diesel engines and some biomass burning produce black aerosols such as soot, which can warm the climate. Recent controversial estimates suggest that these could offset much of the cooling from sulfate aerosols, especially in polluted parts of the subtropics.[8] The IPCC estimates the total radiative forcing resulting directly from all anthropogenic aerosols very roughly at about –1 W/m^2. However, this figure is much less certain than the radiative forcings caused by the greenhouse gases. Furthermore, aerosol particles also exert an indirect effect in that they act as "seeds" for the condensation of water droplets to form clouds. Thus the presence of aerosols affects the size and number of cloud droplets. An increase in sunlight reflected by these aerosol-altered clouds may result in a cooling due to the associated –2 W/m^2 of radiative forcing. Similarly, soot particles mixed into clouds can make the droplets absorb more sunlight, producing some warming. Taken together, aerosols add an element of uncertainty into anthropogenic radiative forcing of about 1 W/m^2 and complicate attempts to discern an anthropogenic signal of climatic change from the noise of natural climatic fluctuations.

Solar Variability

Variation in the Sun's energy output affects Earth's climate. Variations caused by the 22-year solar activity cycle amount to only about 0.1 percent and are too small and occur too rapidly to have a significant climatic effect. Long-term solar variations, either from variability at the Sun itself or from changes in Earth's orbit and inclination, have substantially affected Earth's climate over geologic time. Although accurate, satellite-based measurements of solar output are available for only a few decades, indirect evidence of solar activity allows us to estimate past variations in solar energy output.[9] Such evidence suggests that solar forcing since preindustrial times amounts to about 0.3 W/m^2—enough to contribute somewhat to the observed global warming but far below what is needed to account for the warming of recent decades. However, there is some speculation that magnetic disturbances from the Sun can influence the flux of energetic particles impinging on Earth's atmosphere, which in turn affect stratospheric chemical processes and might thus indirectly alter the global energy balance. These speculations have led some to declare the warming of the past century to be wholly natural, but this notion is discounted by nearly all climatologists for two reasons: first, there is no demonstrated way in which solar energetic particles can have a large enough effect to account for the recent warming and, second, because it is unlikely that such solar magnetic events happened only in the past few decades and not over the past 1,000 years. But in the political world, scientific evidence cited by advocates of a solar explanation for recent climate change often is accorded equal credibility—until assessment groups such as the IPCC are convened to sort out such claims and to weigh their relative probabilities. That is why we report primarily the IPCC assessments rather than the claims of a few individual scientists.

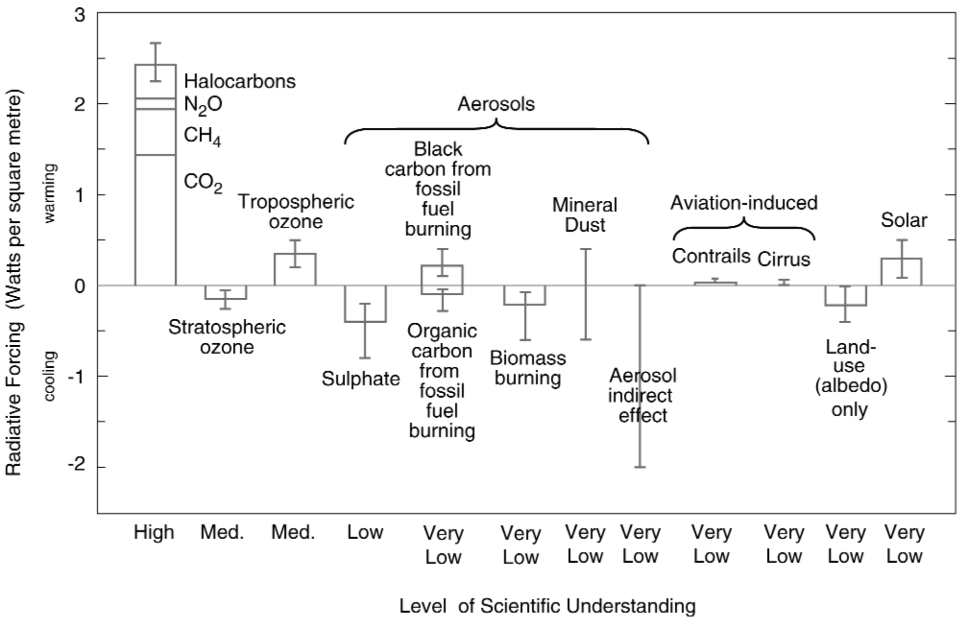

FIGURE 1.8. Radiative forcings caused by anthropogenic greenhouse gases, particulate emissions (aerosols), and other processes. Vertical bars indicate relative uncertainties, and the overall level of scientific understanding of and confidence in these processes is listed below the graph. (From IPCC, 2001.)

Radiative Forcing: The Overall Effect

Figure 1.8 summarizes our current understanding of radiative forcings caused by greenhouse gases, aerosols, land use changes, solar variability, and other effects since the start of the industrial era. The negative forcings from some of these anthropogenic changes might appear sufficient to offset the warming caused by anthropogenic greenhouse gases. This implication is misleading, however, because the effects of aerosols are short-lived and geographically localized compared with the long-term, global effects of the well-mixed greenhouse gases. The most advanced climate models, to be discussed shortly, are driven by a range of plausible assumptions for future emissions of all types and make it clear that the overall effect of human activity is almost certainly a net positive forcing.

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 alter the climate. If that further alteration is in the same direction as its initial cause, then the effect is called a positive feedback. If the further alteration tends to counter the initial change, then it is a negative feedback. In reality, numerous feedback effects greatly complicate the full description of climate change. Here we list just a few to give a sense of their variety and complexity.

Ice-albedo feedback is an obvious and important feedback mechanism. Albedo is a planet's reflectance of incident sunlight. Figure 1.4 showed that Earth's albedo is about 0.31, meaning that 31 percent of incident sunlight is reflected back to space. A decrease in that number would mean more sunlight absorbed which would increase global temperature. One likely consequence of rising temperature is the melting of some ice and snow, which would eliminate a highly reflective surface and expose the darker land or water beneath the ice. The result is a decreased albedo, increased energy absorption, and additional heating. This is a positive feedback.

Rising temperature also results in increased evaporation of water from the oceans. That means more water vapor in the atmosphere. Because water vapor is itself a greenhouse gas, this effect results in still more warming and is thus a positive feedback. But increased water vapor in the atmosphere might mean more widespread cloudiness, which reflects sunlight and thus raises the albedo, resulting in less energy absorbed by the Earth–atmosphere system. The result is a negative feedback, tending to counter the initial warming. On the other hand, clouds also absorb outgoing infrared, resulting in a warming—a positive feedback. There are actually a number of processes associated with clouds, some of which produce warming and some cooling. These effects vary with the type of cloud, the location, and the season. Our limited understanding of cloud effects is one of the greatest sources of uncertainty in global climate sensitivity and thus in climate projections. However, the best estimates suggest that the overall effect of increased water vapor is a positive feedback that causes a temperature increase 50 percent higher than would occur in the absence of this feedback mechanism.[10]

Some feedbacks are biological. For example, increased atmospheric CO_2 stimulates plant growth, and plants in turn remove CO_2 from the atmosphere. This is a negative feedback. On the other hand, warmer soil temperatures stimulate microbial action that releases CO_2—a positive feedback effect. Drought and desertification resulting from climate change can alter the albedo of the land by replacing dark plant growth with lighter soil and sand. Greater reflection of sunlight results in cooling, so this is a negative feedback. But here, as so often with the climate system, the situation is even more complex. If sand is wet, as on a beach, then it is darker and therefore absorbs more sunlight than dry sand. Yet dry sand is hotter. The resolution of this conundrum is that the wet sand is cooler because of the cooling effects of evaporation, but the Earth is warmed by the wet sand because the evaporated water condenses in clouds elsewhere and puts the heat back into the overall system. Thus cooling or warming of the Earth–atmosphere system does not always imply cooling or warming of the Earth's surface at that location. Feedbacks can be a very complicated business.

There are even social feedbacks. For example, rising temperature causes more people to install air conditioners. The resulting increase in electrical consumption means more fossil fuel–generated atmospheric CO_2—again giving a positive feedback.

Accounting for all significant feedback effects entails not only identifying important feedback mechanisms but also developing a quantitative understanding of how those mechanisms work. That understanding often includes research at the boundaries of disciplines such as atmospheric chemistry and oceanography, biology and geology, even economics and sociology.

With positive feedback, there is a danger of runaway warming, whereby a modest initial warming triggers a positive feedback that results in additional warming. That, in turn, may increase the warming still further. This feedback could lead to extreme climate change. That is what has happened on Venus, where the thick, CO_2-rich atmosphere produced a runaway greenhouse effect that gives Venus its abnormally high surface temperature. Fortunately, we believe that the conceivable terrestrial feedbacks, at least under Earth's current conditions, are incapable of such dramatic effects. But that only means we aren't going to boil the oceans away; it doesn't preclude potentially disruptive climatic change.

Climate Modeling

Our earlier estimate that Earth's global average temperature in the absence of the greenhouse effect would be about –18°C was based on a simple climate model—a mathematical statement describing physical conditions that govern climate. In that case the statement was a single equation setting equal the temperature-dependent rate of energy loss and the rate of incoming solar energy. More generally, a climate model is a set of mathematical statements describing physical, biological, and chemical processes that determine climate. The ideal model would include all processes known to have climatological significance and would involve enough spatial and temporal detail to resolve phenomena occurring over limited geographic regions and in short times. Today's most comprehensive models approach this ideal but they still entail many compromises and approximations. Often less detailed models suffice, and in general the climate modeling enterprise involves comparisons between models with different levels of detail and sophistication. Computers are necessary to solve all but the simplest models.

What must go into a climate model depends on what one wants to learn from it. A few simple equations can give a decent estimate of the average global warming in response to specified greenhouse forcings. If we seek to model the long-term sequence of ice ages and interglacial warm periods (as shown in Fig. 1.6), our model must include explicitly the effects of all the important components of the climate system that act over timescales of a million years or so. These include atmosphere, oceans, the cryosphere (sea ice and glaciers), land surface and its changing biota, and long-term biogeochemical cycles as well as forcings from varying solar input associated with long-term variations in Earth's orbit and changes in the Sun itself. If we want to project climate over the next century, many of these long-term processes can be left out of our model. On the other hand, if we want to explore climate change on a regional basis or variations in climatic change from day to night, then we need models with more geographic and temporal detail. Computational limits impose trade offs between spatial and temporal scales.

This last point bears further emphasis in light of an unfortunately common misimpression among the general public. It is widely believed that meteorologists' inability to predict weather accurately beyond about 10 days bodes ill for any attempt at long-range climate projection. That misconception misses the differences of scale stressed in the preceding paragraph. In fact, it is impossible, even in principle, to predict credibly the small-scale details of local weather beyond about 10 days, and no amount of computing power or model sophistication is going to change that. This is because the atmosphere at small scales is an inherently chaotic system in which the slightest perturbation here today can make a huge difference in the weather a thousand miles away and a month hence. But large-scale climate shows little tendency to chaotic behavior (at least on decadal timescales), and appropriate models therefore can make reasonable climate projections decades or even centuries forward in time—provided, of course, that we have credible emission scenarios to drive the models.

A Hierarchy of Models

The simplest models involve just a few fundamental equations and a host of simplifying assumptions. For example, our basic global energy balance model treated Earth as a single point, with no 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 tweaking parameters of the model. In our simple energy balance model, for example, we could have studied the effect of different radiative forcings by subtracting a given forcing from the outgoing energy term to mimic the effect of infrared blockage.

More advanced are "multibox" models that treat land, ocean, and atmosphere as separate "boxes," and include flows of energy and matter between these boxes. Two-box models may ignore the land–ocean distinction and just treat Earth and its atmosphere separately. Three-box models handle all three components but do not distinguish different latitudes or altitudes. Still more sophisticated multibox models may break atmosphere and ocean into several layers or Earth into several latitude zones.

Most sophisticated are the large-scale computer models known as general circulation models (GCMs). These divide Earth's surface into a grid that, in today's highest-resolution models, measures just a few degrees of latitude and longitude on a side. At this scale, a model can represent with reasonable accuracy the actual shape of Earth's land masses. The atmosphere over and ocean below each surface cell are further divided into some 10–40 layers, making the basic unit of the model a small three-dimensional cell. Properties such as temperature, pressure, humidity, greenhouse gas concentrations, sunlight absorption, chemical activity, albedo, cloud cover, and biological activity are averaged within each cell. Equations based in physics, chemistry, and biology relate the various quantities within a cell, and other equations describe the transfer of energy and matter between adjacent cells. In some cases separate specialized models are developed for the atmosphere and the oceans and then linked together in a coupled atmosphere–ocean general circulation model (AOGCM).

GCMs are time-consuming and expensive to run, and their output can be difficult to interpret. Therefore, GCMs often are used to calibrate or to set empirical parameters (those not determined only from fundamental scientific principles) for simpler models that can then be used in specific studies. Thus the entire hierarchy of models becomes useful, indeed essential, for making progress in understanding climate.

Parameterization and Sub–Grid-Scale Effects

Even the best GCMs are limited to cell sizes roughly the size of a small country, such as Belgium. But climatically important phenomena occur on smaller scales.

Examples include clouds, which are far smaller than a typical grid cell, or the substantial thermal differences between cities and the surrounding countryside. Because all physical 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.

Modelers use parametric representations, or parameterizations, in an attempt to include sub–grid-scale effects in their models. For example, a cell whose sky was half covered by fair-weather cumulus clouds might be parameterized by a uniform blockage of somewhat less than half the incident sunlight. Such a model manages not to ignore clouds altogether but doesn't quite handle them correctly. You can imagine that the effects of full sunlight penetrating to the ground in some small regions, while others are in full cloud shadow, might be different from those of a uniform light overcast, even with the same total energy reaching the ground. Developing and testing parameterizations that reliably incorporate sub–grid-scale effects is one of the most important and controversial tasks of climate modelers.

Transient Versus Equilibrium Models

Whether or not we manage to reduce anthropogenic greenhouse gas emissions, the atmospheric CO_2 concentration is likely to reach twice its preindustrial value (that is, CO_2 will reach some 560 parts per million) sometime in the present century. Although it may continue to rise well beyond that, a CO_2 concentration twice that of preindustrial times probably is the lowest level at which we have any hope of stabilizing atmospheric CO_2, barring a major breakthrough in low-cost, low–carbon-emitting energy technologies. For that reason, and because a doubling of atmospheric CO_2 from its preindustrial concentration provides a convenient benchmark, climate models often are run with doubled CO_2. The results can be summarized as a global average temperature rise for a doubling of CO_2, and this quantity is taken as a measure of the models' climate sensitivity. Most current models show a climate sensitivity of 1.5 to 4.5°C; that is, they predict a global average temperature rise of 1.5 to 4.5°C for a CO_2 concentration twice that of preindustrial times.

Until recently, most modeling groups did not have sufficient computer power to project future climate in response to the gradual increase in CO_2 concentration that will actually occur. Instead, they simply specified a doubled CO_2 concentration and solved their model equations once to determine the resulting climate. Physically, these equilibrium simulations give a projected climate that would result eventually if CO_2 were instantaneously doubled and then held fixed forever. In contrast, transient simulations solve the model equations over and over at successive times, allowing concentrations of greenhouse gases to evolve with time. The result is a more realistic projection of a changing climate. Transient simulations exhibit less immediate temperature rise because of the delay associated with the warming of the thermally massive oceans. In fact, the transient climate sensitivity—the warming at the instant CO_2 doubles during a transient calculation—typically is about half the equilibrium climate sensitivity (see Table 9.1 of IPCC, 2001a). That reduced rise can be deceptive because the full equilibrium warming must eventually occur, even if it is delayed for decades or more.

Transient simulations are essential in attempting to model climate records like that shown Fig. 1.1 in response, for example, to the CO_2 increase of Fig. 1.5. Recent advances in transient modeling have helped climatologists understand the role of anthropogenic gases in global warming by successfully reproducing the climate of the recent past in response to known anthropogenic and natural forcings.

Model Validation

How can modelers be more 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 occur somewhat randomly, but typically once a decade or so, and they constitute natural experiments that can be used to test climate models. The last major eruption, of the Philippine volcano Mt. Pinatubo in 1991, was forecast by a number of climate modeling groups to cool the planet by several tenths of a degree Celsius. That is indeed what happened. Figure 1.9 shows a comparison between actual observed global temperature variations and those predicted by a climate model, for a period of 5 years after the Mt. Pinatubo eruption.[11] A few tenths of a degree is small enough that the observed variation might be a natural fluctuation. However, earlier eruptions including El Chichón in 1983 and Mt. Agung in 1963 were also followed by a marked global cooling of several tenths of a degree. Studying the climatic effects of a number of volcanic eruptions shows a clear and obvious correlation between major eruptions and subsequent global cooling.[12] Furthermore, a very simple calculation shows that the negative forcing of several watts per square meter produced by volcanic dust is consistent with the magni-

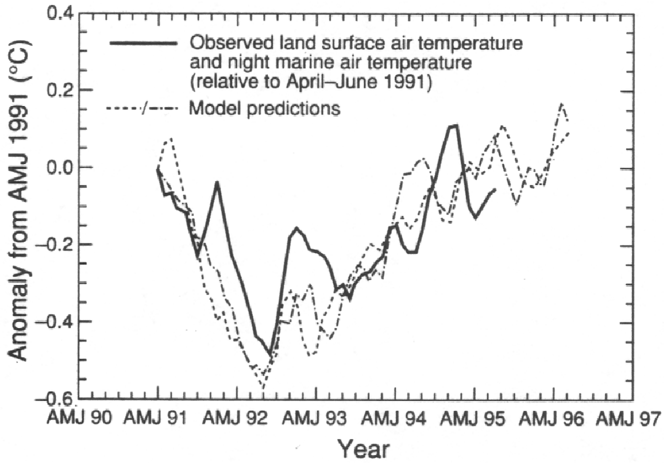

FIGURE 1.9. Predicted and observed changes in global temperature after the 1991 eruption of Mt. Pinatubo in the Philippines. Solid curve is derived from measured air temperatures over land and ocean surfaces. Broken curves represent climate model runs with slightly different initial conditions. In both cases the models included the effect of dust injected into the atmosphere by the volcanic eruption. (From Hansen et al., 1992, as adapted from IPCC, 2001a.)

tude of cooling after major volcanic eruptions. Taken together, all this evidence suggests that climate models do a reasonably good job of reproducing the climatic effects of volcanic eruptions.

Seasonality provides another natural experiment for testing climate models. Winter predictably follows summer, averaging some 15°C colder than summer in the Northern Hemisphere and 5°C colder in the Southern Hemisphere. (The Southern Hemisphere variation is smaller because a much larger portion of that hemisphere is water, whose high heat capacity moderates seasonal temperature variations.) Climate models do an excellent job reproducing the timing and magnitude of the seasonal temperature variations, although the absolute temperatures they predict may be off by several degrees in some regions of the world. The models are less good at reproducing other climatic variations, especially those involving precipitation and other aspects of the hydrologic cycle. Of course, reproducing the seasonal temperature cycle alone does not guarantee that models will describe accurately the climate variations resulting from other driving factors such as increasing anthropogenic greenhouse gas concentrations. However, the fact that GCMs reproduce seasonal variations so well is an assurance that the models' climate sensitivity is unlikely to be off by a factor of 10 or more, as some greenhouse contrarians assert.

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 the temperature variation shown in Fig. 1.1? This approach not only provides some model validation but also helps modelers understand what physical processes may be significant in determining past climate trends. Figure 1.10 shows three different attempts, using the same basic climate model, to reproduce the historical temperature record of Fig. 1.1.[13] In the model runs of Fig. 1.10a, only estimates of solar variability and volcanic activity—purely natural forcings—were included in the model. The projected temperature variation, represented by a thick band indicating the degree of uncertainty in the model calculations, does not show an overall warming trend and clearly is a poor fit to the actual surface temperature record. The runs of Fig. 1.10b include only forcing caused by anthropogenic greenhouse gases and aerosols (e.g., the CO_2 record of Fig. 1.5, along with other known greenhouse gases and particulate emissions). This clearly does a much better job, especially in the late twentieth century, but deviates significantly from the historical record around midcentury. Finally, Fig. 1.10c shows the results from runs that include both natural and anthropogenic forcings. The fit is excellent, and it suggests that we can increase our confidence in this model's projections of future climate. Furthermore, the model runs of Fig. 1.10 taken together strongly suggest that the temperature rise of the past few decades is unlikely to be explained without invoking anthropogenic greenhouse gases as a significant causal factor. Thus the "experiments" of Fig. 1.10 illustrate one way of attempting to pry an anthropogenic climate signal from the natural climatic noise. In other words, Fig. 1.10 provides substantial circumstantial evidence of a discernible human influence on climate and supports the IPCC report's conclusion that "most of the warming observed over the last 50 years is attributable to human activities."[14]

Today's climate models provide geographic resolution down to the scale of a small country. Not only can they reproduce global temperature records, as shown in Fig. 1.10, but the best model results approach, although with less accuracy, the detailed geographic patterns of temperature, precipitation, and other climatic variables. These pattern-based comparisons of models and reality provide further confirmation of the models' essential 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. Therefore, we can expect from them moderately realistic projections of future climate, given credible emission scenarios. That said, we still expect variations in the projections of different models. And

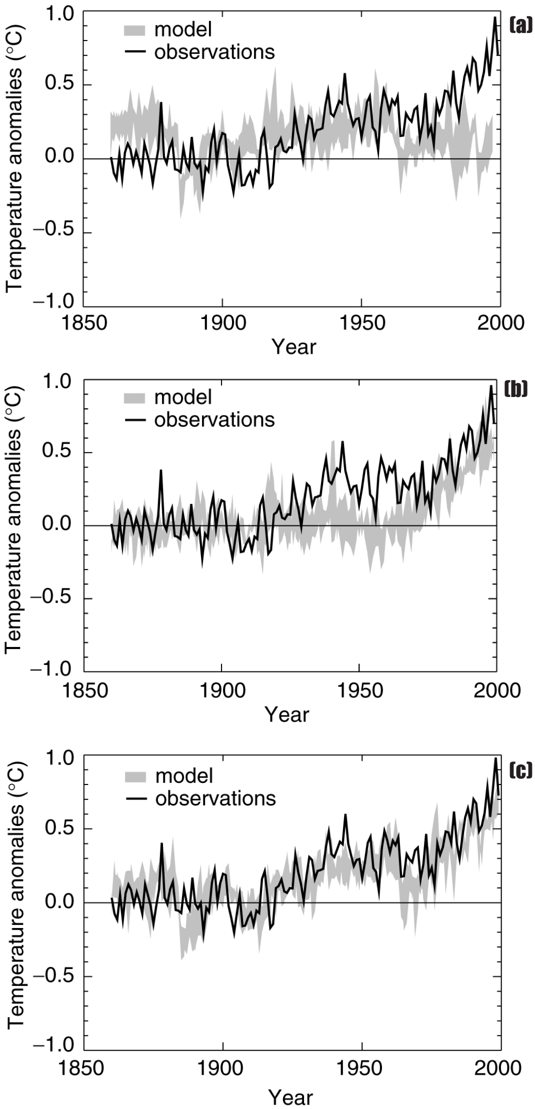

FIGURE 1.10. Attempts to model Earth's temperature from the 1860s using different model assumptions. In all three graphs, the solid curve is the observed surface temperature record of Fig. 1.1. Gray bands represent model projections. In each graph the bands encompass the results of four separate model runs. In (a), only natural forcings—volcanism and solar variability—are included. Clearly this simulation lacks the upward trend in the observed temperature record, suggesting that the temperature rise of the last century and a half is unlikely to have a purely natural explanation. Simulation (b), including only anthropogenic forcings, does much better, especially with the rapid temperature increase of the late twentieth century. Simulation (c), combining both natural and anthropogenic forcings, shows the best agreement with observations. (From IPCC, 2001a.)

because future greenhouse gas emissions depend on human behavior, future projections will differ depending on what assumptions modelers make about the human response to global warming. The uncertainties in projections of human behavior cause about as much spread in estimates of future warming as do uncertainties about the sensitivity of the climate system to radiative forcings. We probably will have to live with this frustrating situation for some time (see Chapter 2).

Consequences of Global Warming

The 1.5°C to 6°C global average temperature rise projected for the current century may seem modest, but as we noted, it could imply quite serious impacts. What might be the consequences? The most sophisticated climate models speak to a wide variety of possible impacts from global warming. Recall that a 6°C temperature drop means the difference between Earth's present climate and an ice age. Fortunately, it does not appear that a comparable rise will have consequences as devastating as two-kilometer thick ice sheets over populated areas of the Northern Hemisphere. But that doesn't mean the consequences of a few degrees' global warming will not be substantial and disruptive.

Global warming, obviously, means higher temperatures. But just how will the temperature rise be distributed in time and in space? We've been looking mostly at the global average temperature rise, characterized by a single number, but in fact global warming will vary substantially from one geographical region to another, and it will have different effects on night and day, winter and summer, land and sea.

Climate models provide rough consensus on many temperature-related projections. In general, projected temperature rises are greatest in the polar regions, and they affect the polar winter more dramatically than the summer. Similarly, nighttime temperatures are projected to rise more than daytime temperatures. Land temperatures are projected to rise more than oceans for the most part, influencing the patterns of monsoons and life-giving rains (and deadly floods) that they engender. Other obvious temperature-related consequences include increases in the maximum-observed temperatures and more hot days, increases in minimum temperatures and fewer cold days, and longer growing seasons owing to earlier last frosts and later first frosts. All these trends have already been seen in the climate change of the past few decades, and all are projected to continue through the present century. Climatologists' assessed confidence in these projections ranges from "likely" (two–thirds to 90 percent probability) to "very likely" (90 to 99 percent probability). Table 1.1 summarizes these and other effects of global warming, and gives the IPCC's quantitative estimates of the probability of each effect (see Chapter 2 for more explanation of what these probabilistic estimates really mean).[15]

The broadest impacts of direct temperature effects on human society are likely to be in agriculture and water supplies. However, health effects, including the spread of lowland tropical diseases vertically upward to plateaus and mountains and horizontally into temperate regions, may also be significant depending on the effectiveness of adaptive measures to reduce the threat. Natural ecosystems may also respond adversely to global warming. With temperatures chang-

TABLE 1.1. Projected Effects of Global Warming During the 21st Century

Projected Effect	*Probability Estimate*	*Examples of Projected Impacts with High Confidence of Occurrence (67–95% probability) in at Least Some Areas*
Higher maximum temperatures, more hot days and heat waves over nearly all land areas	Very likely (90–99%)	•Increased deaths and serious illness in older age groups and urban poor •Increased heat stress in livestock and wildlife •Shift in tourist destinations •Increased risk of damage to a number of crops •Increased electric cooling demand and reduced energy supply reliability
Higher minimum temperatures, fewer cold days, frost days and cold waves over nearly all land areas	Very likely (90–99%)	•Decreased cold-related human morbidity and mortality •Decreased risk of damage to a number of crops, and increased risk to others •Extended range and activity of some pest and disease vectors •Reduced heating energy demand
More intense precipitation events	Very likely (90–99%) over many areas	•Increased flood, landslide, avalanche, and mudslide damage •Increased soil erosion •Increased flood runoff increasing recharge of some floodplain aquifers •Increased pressure on government and private flood insurance systems and disaster relief
Increased summer drying over most mid-latitude continental interiors and associated risk of drought	Likely (67–90%)	•Decreased crop yields •Increased damage to building foundations caused by ground shrinkage •Decreased water resource quantity and quality •Increased risk of forest fire
Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities	Likely (67–90%) over some areas	•Increased risks to human life, risk of infectious disease epidemics and many other risks •Increased coastal erosion and damage to coastal buildings and infrastructure •Increased damage to coastal ecosystems such as coral reefs and mangroves
Intensified droughts and floods associated with El Niño events in many different regions	Likely (67–90%)	•Decreased agricultural and rangeland productivity in drought- and flood-prone regions •Decreased hydro-power potential in drought-prone regions

Projected Effect	*Probability Estimate*	*Examples of Projected Impacts with High Confidence of Occurrence (67–95% probability) in at Least Some Areas*
Increased Asian summer monsoon precipitation variability	Likely (67–90%)	•Increase in flood and drought magnitude and damages in temperate and tropical Asia
Increased intensity of mid-latitude storms	Uncertain (current models disagree)	•Increased risks to human life and health •Increased property and infrastructure losses •Increased damage to coastal ecosystems

Source: IPCC 2001b.

ing much more rapidly than in most natural sustained climatic shifts, temperature-sensitive plant species may find themselves unable to migrate fast enough to keep up with the changing climate. Even though their suitable habitat may shift only a few hundred miles, if plant species cannot reestablish themselves fast enough then they—and many animal species that depend on them—will go at least locally extinct. This is not just theory. Recent analyses of over 1,000 published studies have shown that, among other impacts, birds are laying eggs a few weeks earlier, butterflies are moving up mountains, and trees are blooming earlier in the spring and dropping their leaves later in the fall. In her capacity as a lead author for IPCC Working Group II, Terry Root led a group that combed recent literature to conclude that the most consistent explanation for these observed changes in environmental systems over the past few decades is global warming, and it appears that there is a discernible impact of regional climate change on wildlife and other environmental systems.[16] This opinion was first assessed and then echoed by the Working Group II, Third Assessment Report of the IPCC (2001b). Whether the regional climatic changes that seem to be driving these impacts are themselves manifestations of anthropogenic causation is more controversial. However, given that the responses observed are in about 80 percent of the cases in the direction expected with warming, Root and Schneider argue that global warming is the most consistent explanation.

Rising temperature also means rising sea level. A popular misconception holds that this is because of melting arctic ice. Actually, ice now floating on the oceans has almost no direct effect on sea level if it melts. Glaciers and the large ice sheets covering Greenland and Antarctica are a different story, as meltwater from these sources does increase sea level. But the bulk of sea-level rise observed to date or expected in the next century comes from the simple thermal expansion of seawater—the same process that drives up the liquid in a mercury or alcohol-based thermometer. Determining a global average level for the world ocean is difficult, but measurements suggest that sea level rose some 10–20 cm (4–8 inches) during the twentieth century. Climate models suggest that the rate of rise should increase as much as fourfold through the current century, resulting in a rise most likely near half a meter (about 20 inches). This may not seem like much, but it adds to the highest tides and to the surges associated with major storms (whose intensity is also expected to increase—see Table 1.1). Given that much of the world's population lives close to sea level, even a half-meter rise could have serious consequences in some regions, particularly those such as Bangladesh, which possess minimal resources and infrastructure to adapt to rising seas and higher storm surges. However, slow processes such as glacial melting would go on for many centuries, even after greenhouse gas emissions had long been replaced with non-emitting alternative energy systems. Thus, if humans use a substantial fraction of remaining fossil fuels and dump the greenhouses gases produced from their combustion into the atmosphere, then sea level is expected to go on rising, perhaps by several meters or more, over the thousand years that would follow the end of the fossil fuel era.[17]

Other weather-related projections include increased frequency of intense precipitation events, more heat waves in which the temperature remains at high levels for an extended time, fewer cold waves, more summer droughts, and more wet spells in winter. The intensity of tropical cyclones (hurricanes and typhoons) is likely to increase, although it is less clear whether the frequency or average locations of these storms will change. Hail and lightning are also likely to become more frequent. The large-scale Pacific Ocean fluctuation known as the El Niño/Southern Oscillation could become more persistent, which would have a substantial climatic impact on the Americas and Asia. All these projected changes will impact agriculture and may increase flooding and erosion, with concomitant effects on health and on the insurance industry. As shown in Table 1.1, confidence in this group of consequences ranges from medium (likelihood between one–third and two–thirds) to high (greater than two out of three chances). Keep in mind, however, that the probabilities given in Table 1.1 are not based on conventional statistical analysis because they refer to future events that do not follow past patterns—and obviously, the future hasn't occurred yet. Rather, these are *subjective* odds based on scientific judgment as sound as current understanding permits. Not surprisingly, that subjective element encourages some participants in the political process to attempt to discount these probability estimates (see Chapter 2 for more discussion on uncertainties and methods to deal with them).

Finally, there is the remote possibility of dramatic changes such as alterations in large-scale patterns of ocean circulation or the disintegration of the West Antarctic Ice Sheet. These could occur because the climate system is inherently nonlinear, meaning that a small change in some conditions can produce a disproportionately large change in others. A change in the Gulf Stream—part of the so-called ocean thermohaline circulation—could eventually—hundreds of years hence after anthropogenic greenhouse gases had dissipated—leaving northwest Europe with a chilly climate. Climate models predict with high confidence that the thermohaline circulation will weaken over the present century. But they also suggest, fortunately, that wholesale disruption is very unlikely at least before the year 2100. However, the models also warn that what humans do in the twenty-first century can precondition what the ocean currents will do in the twenty-second century and beyond. Potentially irreversible events could be built into the long-term planetary future even if those of us living in the twenty-first century are spared the experience of those effects.[18, 19] Similarly, recent studies suggest that the West Antarctic Ice Sheet is likely to remain stable for the foreseeable future, which is a very good thing because its breakup would result in a rise in sea level by some 6 meters (about 20 feet). But that "unlikely possibility" is not ruled out and looms as a potential threat that we need to check for periodically as we advance our understanding of the climate system and its potential for surprises.

We have given a brief description of the anticipated consequences of global warming in the present century. But even if we humans get our greenhouse gas emissions under control—not a likely occurrence in the near future—global temperature will continue to rise toward a new equilibrium value that will take at least many decades—more likely centuries—to become established. The effects of global warming, in particular sea-level rise, will almost certainly continue to increase beyond the end of the twenty-first century, and they may well become far more dramatic over the following centuries.

There is one final note on the issue of climatic impacts. In the above example of Bangladesh suffering from sea-level rises or more intense storms, we mentioned that adaptation would be difficult. This is much less so for a richer, more technologically advanced country such as the Netherlands. In fact, as is illustrated in Table 1.2 (in which IPCC 2001b authors summarize a comprehensive list of potential climate-change impacts for most regions of the world and economic sectors), a consensus is building in the scientific community that the damages that climatic changes might inflict on societies will depend in part on the adaptive capacities of those future societies, which in turn depend on their resource bases and technological and infrastructure capabilities.[20] This suggests, as Table 1.2 notes, that damages may be asymmetrically felt across the developed/developing country divide. The scenario where the northern rich countries

TABLE 1.2. Regional Adaptive Capacity, Vulnerability, and Key Concerns[a,b] (relevant sections of the Technical Summary of IPCC 2001b for each example are given in square brackets)

Region	
Africa	•Adaptive capacity of human systems in Africa is low due to lack of economic resources and technology, and vulnerability high as a result of heavy reliance on rain-fed agriculture, frequent droughts and floods, and poverty. [5.1.7] •Grain yields are projected to decrease for many scenarios, diminishing food security, particularly in small food-importing countries (*medium to high confidence*[c]). [5.1.2] •Major rivers of Africa are highly sensitive to climate variation; average runoff and water availability would decrease in Mediterranean and southern countries of Africa (*medium confidence*[c]). [5.1.1] •Extension of ranges of infectious disease vectors would adversely affect human health in Africa (*medium confidence*[c]). [5.1.4] •Desertification would be exacerbated by reductions in average annual rainfall, runoff, and soil moisture, especially in southern, North, and West Africa (*medium confidence*[c]). [5.1.6] •Increases in droughts, floods, and other extreme events would add to stresses on water resources, food security, human health, and infrastructures, and would constrain development in Africa (*high confidence*[c]). [5.1] •Significant extinctions of plant and animal species are projected and would impact rural livelihoods, tourism, and genetic resources (*medium confidence*[c]). [5.1.3] •Coastal settlements in, for example, the Gulf of Guinea, Senegal, Gambia, Egypt, and along the Southern–East African coast would be adversely impacted by sea-level rise through inundation and coastal erosion (*high confidence*[c]). [5.1.5]
Asia	•Adaptive capacity of human systems is low and vulnerability is high in the developing countries of Asia; the developed countries of Asia are more able to adapt and less vulnerable. [5.2.7] •Extreme events have increased in temperate and tropical Asia, including floods, droughts, forest fires, and tropical cyclones (*high confidence*[c]). [5.2.4] •Decreases in agricultural productivity and aquaculture due to thermal and water stress, sea-level rise, floods and droughts, and tropical cyclones would diminish food security in many countries of arid, tropical, and temperate Asia; agriculture would expand and increase in productivity in northern areas (*medium confidence*[c]). [5.2.1] •Runoff and water availability may decrease in arid and semi-arid Asia but increase in northern Asia (*medium confidence*[c]). [5.2.3] •Human health would be threatened by possible increased exposure to vector-borne infectious diseases and heat stress in parts of Asia (*medium confidence*[c]). [5.2.6]

Region	
Asia (*cont.*)	•Sea-level rise and an increase in the intensity of tropical cyclones would displace tens of millions of people in low-lying coastal areas of temperate and tropical Asia; increased intensity of rainfall would increase flood risks in temperate and tropical Asia (*high confidence*[c]). [5.2.5 and Table TS-8] •Climate change would increase energy demand, decrease tourism attraction, and influence transportation in some regions of Asia (*medium confidence*[c]). [5.2.4 and 5.2.7] •Climate change would exacerbate threats to biodiversity due to land-use and land-cover change and population pressure in Asia (*medium confidence*[c]). Sea-level rise would put ecological security at risk, including mangroves and coral reefs (*high confidence*[c]). [5.2.2] •Poleward movement of the southern boundary of the permafrost zones of Asia would result in a change of thermokarst and thermal erosion with negative impacts on social infrastructure and industries (*medium confidence*[c]). [5.2.2]
Australia & New Zealand	•Adaptive capacity of human systems is generally high, but there are groups in Australia and New Zealand, such as indigenous peoples in some regions, with low capacity to adapt and consequently high vulnerability. [5.3 and 5.3.5] •The net impact on some temperate crops of climate and CO_2 changes may initially be beneficial, but this balance is expected to become negative for some areas and crops with further climate change (*medium confidence*[c]). [5.3.3] •Water is likely to be a key issue (*high confidence*[c]) due to projected drying trends over much of the region and change to a more El Niño-like average state. [5.3 and 5.3.1] •Increases in the intensity of heavy rains and tropical cyclones (*medium confidence*[c]), and region-specific changes in the frequency of tropical cyclones, would alter the risks to life, property, and ecosystems from flooding, storm surges, and wind damage. [5.3.4] •Some species with restricted climatic niches and which are unable to migrate due to fragmentation of the landscape, soil differences, or topography could become endangered or extinct (*high confidence*[c]). Australian ecosystems that are particularly vulnerable to climate change include coral reefs, arid and semi-arid habitats in southwest and inland Australia, and Australian alpine systems. Freshwater wetlands in coastal zones in both Australia and New Zealand are vulnerable, and some New Zealand ecosystems are vulnerable to accelerated invasion by weeds. [5.3.2]
Europe	•Adaptive capacity is generally high in Europe for human systems; southern Europe and the European Arctic are more vulnerable than other parts of Europe. [5.4 and 5.4.6]

(*continues*)

TABLE 1.2. *Continued*

Region	
Europe (*cont.*)	•Summer runoff, water availability, and soil moisture are likely to decrease in southern Europe, and would widen the difference between the north and drought-prone south; increases are likely in winter in the north and south (*high confidence*[c]). [5.4.1] •Half of alpine glaciers and large permafrost areas could disappear by end of the 21st century (*medium confidence*[c]). [5.4.1] •River flood hazard will increase across much of Europe (*medium to high confidence*[c]); in coastal areas, the risk of flooding, erosion, and wetland loss will increase substantially with implications for human settlement, industry, tourism, agriculture, and coastal natural habitats. [5.4.1 and 5.4.4] •There will be some broadly positive effects on agriculture in northern Europe (*medium confidence*[c]); productivity will decrease in southern and eastern Europe (*medium confidence*[c]). [5.4.3] •Upward and northward shift of biotic zones will take place. Loss of important habitats (wetlands, tundra, isolated habitats) would threaten some species (*high confidence*[c]). [5.4.2] •Higher temperatures and heat waves may change traditional summer tourist destinations, and less reliable snow conditions may impact adversely on winter tourism (*medium confidence*[c]). [5.4.4]
Latin America	•Adaptive capacity of human systems in Latin America is low, particularly with respect to extreme climate events, and vulnerability is high. [5.5] •Loss and retreat of glaciers would adversely impact runoff and water supply in areas where glacier melt is an important water source (*high confidence*[c]). [5.5.1] •Floods and droughts would become more frequent with floods increasing sediment loads and degrade water quality in some areas (*high confidence*[c]). [5.5] •Increases in intensity of tropical cyclones would alter the risks to life, property, and ecosystems from heavy rain, flooding, storm surges, and wind damages (*high confidence*[c]). [5.5] •Yields of important crops are projected to decrease in many locations in Latin America, even when the effects of CO_2 are taken into account; subsistence farming in some regions of Latin America could be threatened (*high confidence*[c]). [5.5.4] •The geographical distribution of vector-borne infectious diseases would expand poleward and to higher elevations, and exposures to diseases such as malaria, dengue fever, and cholera will increase (*medium confidence*[c]). [5.5.5] •Coastal human settlements, productive activities, infrastructure, and mangrove ecosystems would be negatively affected by sea-level rise (*medium confidence*[c]). [5.5.3] •The rate of biodiversity loss would increase (*high confidence*[c]). [5.5.2]

Region	
North America	•Adaptive capacity of human systems is generally high and vulnerability low in North America, but some communities (e.g., indigenous peoples and those dependent on climate-sensitive resources) are more vulnerable; social, economic, and demographic trends are changing vulnerabilities in subregions. [5.6 and 5.6.1] •Some crops would benefit from modest warming accompanied by increasing CO_2, but effects would vary among crops and regions (*high confidence*[c]), including declines due to drought in some areas of Canada's Prairies and the U.S. Great Plains, potential increased food production in areas of Canada north of current production areas, and increased warm-temperate mixed forest production (*medium confidence*[c]). However, benefits for crops would decline at an increasing rate and possibly become a net loss with further warming (*medium confidence*[c]). [5.6.4] •Snowmelt-dominated watersheds in western North America will experience earlier spring peak flows (*high confidence*[c]), reductions in summer flows (*medium confidence*[c]), and reduced lake levels and outflows for the Great Lakes–St. Lawrence under most scenarios (*medium confidence*[c]); adaptive responses would offset some, but not all, of the impacts on water users and on aquatic ecosystems (*medium confidence*[c]). [5.6.2] •Unique natural ecosystems such as prairie wetlands, alpine tundra, and cold-water ecosystems will be at risk and effective adaptation is unlikely (*medium confidence*[c]). [5.6.5] •Sea-level rise would result in enhanced coastal erosion, coastal flooding, loss of coastal wetlands, and increased risk from storm surges, particularly in Florida and much of the U.S. Atlantic coast (*high confidence*[c]). [5.6.1] •Weather-related insured losses and public sector disaster relief payments in North America have been increasing; insurance sector planning has not yet systematically included climate change information, so there is potential for surprise (*high confidence*[c]). [5.6.1] •Vector-borne diseases—including malaria, dengue fever, and Lyme disease—may expand their ranges in North America; exacerbated air quality and heat stress morbidity and mortality would occur (*medium confidence*[c]); socioeconomic factors and public health measures would play a large role in determining the incidence and extent of health effects. [5.6.6]
Polar	•Natural systems in polar regions are highly vulnerable to climate change and current ecosystems have low adaptive capacity; technologically developed communities are likely to adapt readily to climate change, but some indigenous communities, in which traditional lifestyles are followed, have little capacity and few options for adaptation. [5.7] •Climate change in polar regions is expected to be among the largest and most rapid of any region on the Earth, and will cause major physical, ecological, sociological, and economic impacts, especially in the Arctic, Antarctic Peninsula, and Southern Ocean (*high confidence*[c]). [5.7]

TABLE 1.2. *Continued*

Region	
Polar (*cont.*)	•Changes in climate that have already taken place are manifested in the decrease in extent and thickness of Arctic sea ice, permafrost thawing, coastal erosion, changes in ice sheets and ice shelves, and altered distribution and abundance of species in polar regions (*high confidence*[c]). [5.7] •Some polar ecosystems may adapt through eventual replacement by migration of species and changing species composition, and possibly by eventual increases in overall productivity; ice edge systems that provide habitat for some species would be threatened (*medium confidence*[c]). [5.7] •Polar regions contain important drivers of climate change. Once triggered, they may continue for centuries, long after greenhouse gas concentrations are stabilized, and cause irreversible impacts on ice sheets, global ocean circulation, and sea-level rise (*medium confidence*[c]). [5.7]
Small Island States	•Adaptive capacity of human systems is generally low in small island states, and vulnerability high; small island states are likely to be among the countries most seriously impacted by climate change. [5.8] •The projected sea-level rise of 5 mm per year for the next 100 years would cause enhanced coastal erosion, loss of land and property, dislocation of people, increased risk from storm surges, reduced resilience of coastal ecosystems, saltwater intrusion into freshwater resources, and high resource costs to respond to and adapt to these changes (*high confidence*[c]). [5.8.2 and 5.8.5] •Islands with very limited water supplies are highly vulnerable to the impacts of climate change on the water balance (*high confidence*[c]). [5.8.4] •Coral reefs would be negatively affected by bleaching and by reduced calcification rates due to higher CO_2 levels (*medium confidence*[c]); mangrove, sea grass beds, and other coastal ecosystems and the associated biodiversity would be adversely affected by rising temperatures and accelerated sea-level rise (*medium confidence*[c]). [4.4 and 5.8.3] •Declines in coastal ecosystems would negatively impact reef fish and threaten reef fisheries, those who earn their livelihoods from reef fisheries, and those who rely on the fisheries as a significant food source (*medium confidence*[c]). [4.4 and 5.8.4] •Limited arable land and soil salinization makes agriculture of small island states, both for domestic food production and cash crop exports, highly vulnerable to climate change (*high confidence*[c]). [5.8.4] •Tourism, an important source of income and foreign exchange for many islands, would face severe disruption from climate change and sea-level rise (*high confidence*[c]). [5.8.5]

Source: IPCC 2001b.

[a] Because the available studies have not employed a common set of climate scenarios and methods, and because of uncertainties regarding the sensitivities and adaptability of natural and social systems, the assessment of regional vulnerabilities is necessarily qualitative.

[b] The regions listed in Table 2 are graphically depicted in Figure TS-2 of the Technical Summary of IPCC 2001b.

[c] These words represent collective estimates of confidence by authors of IPCC 2001b, based on observational evidence, modeling results, and theory: very high (95% or greater), high (67–95%), medium (33–67%), low (5–33%), and very low (5% or less).

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get longer growing seasons and the poor tropical nations get more intense droughts and floods is clearly a situation ripe for increasing tensions in the world of the twenty-first century. Thus, not only is the climate-policy community faced with the need to estimate the impacts of a wide range of plausible climatic futures, but it must also estimate the relative adaptive capabilities of future societies so as to assess the equity implications of the consequences of slowing global warming. This in turn complicates the negotiations on solutions because many of the typically proposed mitigative activities could slow the economic growth rates of those very countries that need to build adaptive capabilities.[21] Yet, if these countries are allowed to emit unchecked amounts of greenhouse gases, the risks of severe impacts will increase. Therefore, the dilemma is to assess the range of possible outcomes as well as their costs and the distribution of those costs, and then to weigh those impacts versus the costs and benefits of a host of mitigation options carried out in various countries. All of this is played out against the historical background of large inequities in access to resources that make it difficult to achieve agreements that protect the global commons. It is our goal in this book to help you understand this complex interaction between political, economic, technological, and scientific issues as they relate to global climate change.

Is There Consensus on Global Warming?

The general public, especially in the United States, tends to think of global warming as a matter of intense and unsettled debate in the scientific community. A concerted effort by a handful of climate "contrarians" or "greenhouse skeptics"—scientists who do not share the views of most climate scientists—has kept the "debate" on global warming very much in public view.[22] The media, attempting to be fair to both sides has given the "contrarian" view publicity vastly disproportionate to its meager support in the community of climate scientists. Many policymakers also bring to their decisions a belief that prospects for global warming are murky, unsettled, and still very much a matter of debate—a belief reinforced by the dichotomous "debate" in the media between environmental activists proposing expensive sacrifices to avoid catastrophic climate change and those claiming that climate change would be beneficial, advocating that government stay out of all private matters, including their perceived "right" to dump wastes into the atmosphere without penalty.

Despite this ideologically-driven cacophony, there is a strong international consensus both on the basic science behind global climate change and on a broad range of future climate projections coming from modeling efforts. Why, then, is the public view—or at least the political debate in the U.S.—so out of step with mainstream science?

The Nature of Scientific Theories

Creationists attack Darwinian evolution because "it's just a theory." Critics still churn out counterproposals to Einstein's theory of relativity. And much of the public sees climate change in the same light: as just another scientific theory that might be right or might be wrong. The word *theory* is all too often an excuse to dismiss that with which one would like to disagree: "It's just a theory, so I don't have to accept it."

That attitude betrays a profound misunderstanding of the nature of scientific theories and scientific truth. A scientific theory is a coherent set of principles put forth to explain aspects of physical or biological or social reality. Decades of testing confirm a theory as providing the best available explanations for the phenomena at hand. It's always possible that an established theory may someday be proved wrong (or at least incomplete), but that possibility diminishes every time events in the real world live up the theory's predictions. Einstein's relativity, for example, is among the most solidly confirmed theories in science, tested not only in sophisticated astronomical observations and sensitive experiments but also in the workings of everyday devices from TV picture tubes to the Global Positioning Systems, neither of which would function correctly if relativity were wrong. Despite some gaps in the fossil record, Darwinian evolution remains the only consistent way science has found to understand the origin and demise of Earth's myriad species. Relativity and evolution may be "just theories," but they're so solidly confirmed that they've earned places in the canon of scientific truth. Likewise, gravity may be just a theory, but few would dare test it by jumping off the Empire State building.

The science at the basis of climate change has the same status. The essential idea—that Earth can maintain a constant temperature only if the rate at which energy reaches the planet equals the rate at which energy returns to outer space—is fundamental to the science of thermodynamics and was well established not only for Earth but for myriad other physical systems nearly two centuries ago. Measurements today confirm this idea of terrestrial energy balance to a high degree of precision. The role of greenhouse gases in that energy balance is also solidly established. We can measure the energy-absorbing properties of those gases in the laboratory, and field measurements provide accurate values for their atmospheric concentrations. The 33°C warming of Earth caused by natural greenhouse gases is well established and is further confirmed by our observations of the very different climates of Venus and Mars. The natural greenhouse effect is solidly established, and no reputable scientist would claim otherwise.

The public needs to recognize that established theories represent solidly confirmed bodies of scientific principles with broad explanatory powers and that, absent unlikely, radical new discoveries, such theories are the closest we can get to claiming we know the truth about physical reality. Many theories at the heart of modern science—including the thermodynamic basis of climate science and the theory of the greenhouse effect—fall into this category. They may be "just theories," but they're so solidly confirmed as to be universally accepted in the scientific community.

Does that mean there's no room for controversy about climate change? Of course not. It's one thing to accept a fundamental physical theory as rock-solid truth. It's quite another to affirm with high confidence the results of a complex computer model based on that theory but also depending on a host of other, more tenuous assumptions. Often our well-established theories are derived from very constrained and controllable situations, such as the fall of a particle in a gravitational field. But in the case of climate change, we are discussing a system of many interacting subcomponents. And, although we may be able to validate the behavior of many of the subcomponents via experiments and observations of the climate system, the interaction of all of them (that is, the behavior of the entire system) usually is not directly amenable to experimental confirmation. Furthermore, it is not possible even in principle to verify or to falsify a prediction for the year 2100—not before the fact, anyway. Thus, much of our confidence is based on the degree to which underlying principles are known for the major subcomponents of the system as a whole. This allows skeptics to cite out of context our poor understanding of a few subcomponents as proof that the whole system is poorly understood. Others do the opposite, singling out the best-verified components and neglecting the badly understood elements. That is why assessment teams of scientists from many disciplines and nations are summoned into activities such as the IPCC to try to provide a balanced perspective on the relative likelihood of various future events and their consequences. This is not "exact science" (itself an oxymoron) but the best representation of the state of the art. When the conclusions of such studies are juxtaposed against a few contrarian opinions in the name of "journalistic balance," the public and political process is muddied because few understand the very different relative credibility of these various claimants to state-of-the-art knowledge. Then it becomes incumbent on the citizen—whether in personal, corporate, or government capacity—to cut through this thicket of claims and counterclaims and use the literacy acquired in formal or lifelong learning activities to make sense of these controversies. Much of system science, of which climate change is a particularly important application, will always be murky. The fundamental principles are known and accepted, but the richness and complexity of nature coupled with imperfect knowledge of values, relationships, and processes make it impossible to predict accurately from first principles. Yet we can propose scenarios built on the best available science and provide meaningful estimates of our confidence in them.

Certainty and Uncertainty in Climate Science

Scientific "truth" is always a matter of probability. In the case of well-established theories such as evolution, relativity, thermodynamics, and the greenhouse effect, the probability that the theory is correct is so high as to constitute virtual certainty. But predictions and projections for complex systems may themselves be less certain. Again, the reasons are many and may include uncertainties in data that go into the calculations, uncertainties about the precise nature of physical processes, and uncertainties arising from approximations in the mathematical techniques used to solve complicated sets of equations. In climate science, examples of these uncertainties include, respectively, our imperfect knowledge of the global temperature record because of limited sampling sites and changes over time in instrumentation, urban growth, and other influences on temperature measurements; our limited understanding of physical processes in cloud formation and of the interaction of clouds with radiation; and the need for parameterization to handle mathematically processes (such as cloud formation) that occur on scales smaller than the numerical grids used in computer models.

However, the presence of uncertainty does not mean that such scientific results are speculative. Rather, it obligates the scientist to quantify just how uncertain a result may be, and it obligates any user of that result to take the stated uncertainty into account. In climate change studies, uncertainty manifests itself in the range of projected values for temperature, precipitation, and other climate variables. Uncertainty is further quantified by the confidence that the projected values will lie within the stated range.

A fundamental quantity in climate modeling is the sensitivity to a doubled atmospheric carbon dioxide concentration. The 1990, 1996, and 2001 IPCC reports all project a response to CO_2 doubling in the range 1.5–4.5°C. (Incidentally, the increased upper temperature range projected in the 2001 IPCC Working Group I report—6°C—results from an increased likelihood of higher greenhouse gas emissions, resulting in more than a doubling of preindustrial CO_2 levels by the end of the current century, combined with a decreased likelihood of offsetting aerosol cooling. The climate sensitivity estimates have not changed, but the CO_2 forcing has increased and the aerosol cooling decreased, hence the higher upper end of the projected temperature increase.) Where do these ranges in climate sensitivity come from?

The 2001 IPCC report lists 19 model runs, involving many different general circulation models, that show temperature increases (transient climate sensitivity) at the instant of doubled CO_2 ranging from 1.1°C to 3.1°C.[23] (These are transient simulations, which do not reflect the full amount of warming expected in a final equilibrium.) Expert opinion provides another measure of confidence in projections of global warming. A 1995 study by Morgan and Keith[24] elicited the subjective views of 16 leading climate scientists on the likely global response to doubled CO_2 concentration in equilibrium. All but one of the scientists gave their best estimates in the range 1.9–3.6°C. Each scientist (but one) also provided an interval in which he or she thought that the actual temperature change had a 90 percent chance of falling; the extent of these intervals ranged from 0.8°C to 8°C. None of this means we can say with absolute certainty that the twenty-first century will see a global temperature rise of several degrees. But when 15 different scientists and 19 distinct computer model runs suggest that a rise of this magnitude is likely, phrases such as "we're pretty sure" or "very likely" become appropriate ways of expressing confidence in projections of future climate. Chapter 2 explores further issues of uncertainty in relation to climate policy.

Scientific Consensus

What about that 1 scientist among the 16 experts whose estimate fell outside the 1.9–3.6°C range? That scientist suggested a best-estimate global temperature rise of only 0.3°C and was so confident as to be 90 percent certain that the actual rise would lie within a band only 0.7°C wide (see also the discussion in Chapter 2). Shouldn't his views be taken seriously? After all, scientific truth is not a matter of democratic vote. Might the 15 scientists be wrong and the single dissenter right? It's possible—but again, scientific truth is always a matter of probability, not absolute certainty. All 16 scientists in the Morgan and Keith survey share the same basic scientific knowledge, and it's the same Earth that they're all studying. Absent some overwhelmingly convincing reason to the contrary, it makes sense to weigh more strongly the views of the 15 scientists whose estimates are in general agreement.

Maybe the sample of scientists is biased. Had Morgan and Keith approached eight scientists who believe that we're due for significant global warming and eight who do not, their results would have been dramatically different. Would that have been a more balanced study? No, because that selection would not match the opinions of the scientific community in balanced proportion. Unfortunately, that is not what the public has always been led to believe. Instead, the public too often sees the debate over global warming as being between two factions with essentially equal scientific weight on both sides. That view is naïve both in its stark dichotomy and in its sense of equal weights. As we endeavor to inform the public about global climate change, it's crucial to set this point straight. First, climate scientists are not divided into two monolithic camps. The many scientists whose names appear as reviewers and contributors to the IPCC reports hold a range of views on the likely magnitude of future climate change, as the Morgan and Keith survey suggests. By 1995 these scientists were agreed that "the balance of evidence suggests a discernible human influence on global climate,"[25] and by 2001 they agreed that "most of the warming observed over the past 50 years is attributable to human activity."[26]

More importantly, there simply is no numerically substantial group of climate scientists whose views accord with the one dissenter in the Morgan and Keith survey—that is, who do not expect significant global warming in response to a doubling or greater increase of atmospheric carbon dioxide. What does exist is a small but vocal group that is visible out of all proportion to its numbers in the public debate over global warming. Often funded by the fossil fuel industry or by politically conservative think tanks, these scientists put forth the view that significant global warming is very unlikely or that limited warming will occur but will be beneficial. Unfortunately for scientific objectivity, they have been called in disproportionate numbers to testify at congressional hearings on climate change. They have also lent their names to slick, well-financed publications, Web sites, and video presentations that continue to leave the public with the impression of a balanced debate between equally tenable scientific positions. The amplified influence of these "greenhouse skeptics," and their close ties to the fossil-fuel industry, are well documented by journalist Ross Gelbspan in his book *The Heat Is On.*[27] More recent examples continue to crop up.[28]

So what should we teach the public about the nature of science, and climate science in particular? First, the basis of climate science—including the greenhouse effect—is firmly rooted in solidly proven scientific theories that are as close as we can get to scientific truth. Second, much of science is less certain than its fundamental theories, but that uncertainty can be quantified and may temper but not destroy our confidence in scientific projections. Third—and here science mixes with political reality—we need to convey the true nature of the scientific debate on the prospects for global climate change. That means exploring the idea of consensus in scientific communities and, in particular, revealing the substantial consensus that already exists in the climate science community.

Misconceptions

It's troubling enough that much of the public has only a vague understanding of climate science and of the nature of scientific debate and consensus on the subject. More troubling still are outright misconceptions that may be dangerous. In our efforts to educate the public and to implement sound policies toward climate change, we need to be aware of such widespread misconceptions and take explicit steps to eliminate them.

For much of the public—and even for a recent cabinet-level appointee in the U.S. with environmental responsibilities—ozone depletion is either synonymous or closely associated with global warming. This unfortunate confusion is confounded by the facts that both problems arise from anthropogenic gas emissions into the atmosphere and that both entered the public consciousness at about the same time. It doesn't help that one of the most visible environmental advocacy groups fighting for action against global warming was called Ozone Action. For the better informed, additional confusion arises because the two problems are related, albeit subtly: As we discussed earlier, ozone itself is a greenhouse gas, and the depletion of stratospheric ozone does affect Earth's energy balance.

But despite the public's confusion, ozone depletion and climate change contrast starkly not only in the scientific phenomena involved but also in light of attempts to solve each problem. Ozone depletion has been addressed by the most rapid and successful attack on an international environmental problem: the Montreal Protocol of 1987, which led to a worldwide ban on the most virulent ozone-depleting substances, the chlorinated fluorocarbons (CFCs). The solution to ozone depletion is being implemented (with full cooperation of most chemical manufacturers), and if the Montreal Protocol enjoys nearly full compliance, the problem of anthropogenic ozone depletion will be over in the roughly 50 years it will take for existing atmospheric CFCs to be removed naturally.

The status of international efforts to halt global climate change stands in dismal contrast (see Chapter 4). The most progressive international agreement on climate change, the Kyoto Protocol of 1997, takes some important steps but does not go nearly far enough to reduce anthropogenic global warming. And in the current political climate there appears to be no chance that the United States, the greatest single producer of greenhouse gases, will ratify the protocol.

Given that the problem of ozone depletion is essentially solved (albeit with a time delay), whereas there has been no effective progress on policies and measures to abate global climate change, public confusion of the two problems not only implies serious scientific misunderstanding but also carries the danger of public apathy toward urgently needed action on climate change.

To much of the public, carbon dioxide is just another of many pollutants produced by human activity, especially industry and transportation. Renewal of the Clean Air Act, tightening of automobile emission standards, inclusion of sport utility vehicles (SUVs) in automobile emission regulations, and lawsuits challenging older, dirtier power plants all sound like good news to a public that knows enough to recognize CO_2 as the main culprit in anthropogenic global climate change.

But this only highlights another misconception. In fact, CO_2 is not a pollutant, either in the legal sense or in the sense of an unwanted environmental contaminant produced inadvertently during combustion of fossil fuels. In fact, as the coal industry advertises, CO_2 is the raw material for photosynthesis, and the industry-supported Greening Earth Society advocates dumping more of it into the atmosphere as a "public service" to create a greener Earth. Unlike nitrogen oxides, carbon monoxide, sulfur oxides, ozone, and particulate matter, CO_2 is a necessary byproduct of fossil fuel combustion. Along with water vapor, it is what one wants to produce when burning fossil fuels. In that sense CO_2 is not a pollutant, and it is nonsensical to think of modifying the combustion process to eliminate CO_2 production. One might imagine sequestering combustion-produced CO_2 to keep it out of the atmosphere, but given some 20 pounds of CO_2 produced for every gallon of gasoline burned, that is a daunting and economically challenging prospect. But even that problem may succumb to technological solutions if hydrogen is extracted from fossil fuels, the carbon reinjected deep beneath Earth's surface, and the liberated hydrogen used in fuel cells to power cars and trucks. The key is at what cost this can be done and who pays, and the policy challenge is how to structure incentives to encourage our technological inventors to work on this problem.[29]

For a public that lumps CO_2 with "other" pollutants, there's a serious danger of complacency about CO_2 emissions in the face of tightening air quality regulations. Professional environmentalists have been heard to justify owning SUVs because they "meet California emission requirements." The vehicles in question may indeed be "clean" in that they emit few particulates or noxious gases, but a heavy SUV necessarily consumes more gasoline than a lighter car, and that gasoline produces CO_2 at the rate of some 20 pounds per gallon. No emission control technology can alter that figure. The gasoline-burning internal combustion engine is a Victorian industrial revolution technology, and to address the global warming issue more than superficially, we must reconsider the continued use—let alone expansion into the developing world—of this century-old technology. The only way to lower CO_2 emissions from cars and trucks is to burn less gasoline or to use another energy source altogether.

The confusion of CO_2 with other pollutants is a dangerous misconception because it leads to the complacent attitude that the CO_2 problem is coming under control. It isn't, and no amount of traditional pollution control will help (although building more fuel-efficient vehicles, power plants, and industrial boilers can reduce both traditional pollution and greenhouse gas emissions). Educating the public about climate change entails clearing up this glaring misconception.

An Informed Citizenry

This chapter began with the assertion that informed citizens and policymakers need a basic knowledge of climate science and climate policy to make intelligent policy decisions. So what's an informed citizen? First, it is one who understands the nature of science enough to appreciate that climate science is grounded in basic theories that are as close as we can get to scientific "truth" while recognizing that the projections of climate models are less certain but nevertheless carry a subjective but still expert-determined probability of being reasonably accurate. Second, an informed citizen is one who understands that the currently widespread view of a bipolar climate change debate between equally tenable scientific positions is simply incorrect and that most climate scientists are in a broad overall agreement that a significant global temperature increase is likely over the course of the twenty-first century. Third, an informed citizen understands the basic scientific ideas behind climate change projections, particularly energy balance, the greenhouse effect, and the nature and role of greenhouse gases. Finally, an informed citizen is aware of his or her own connection to the human processes that lead to climate change. Such a citizen is equipped to make intelligent value decisions about his or her own life choices as they influence climate and to participate in shaping the broader public response to the threat of climate change.

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