THIRD EDITION

ENERGY, ENVIRONMENT, AND CLIMATE

RICHARD WOLFSON

BIG ENERGY NUMBERS

Quantity	Watts	Quads/ year	Kilowatt-hours/ year	Joules/ year	Million barrels of oil equivalent/day
World energy consumption	18×10^{12} (18 TW)	540	1.6×10^{14}	5.7×10^{20} (570 EJ/year)	250
U.S. energy consumption	2.9×10^{12} (2.9 TW)	87	2.5×10^{13}	9.2×10^{19} (92 EJ/year)	41
Solar energy input to Earth system	1.73×10^{17} (173 PW)	5×10^{6}	1.5×10^{18}	5.5×10^{24} (5.5 million EJ/year)	2.6×10^{6}

ENERGY AND POWER UNITS

Energy unit*	Joule equivalent	Description
joule (J)	1 J	Official SI energy unit
kilowatt-hour (kWh)	3.6 MJ	Energy associated with 1 kW used for 1 hour
gigawatt-year	31.6 PJ	Energy produced by a typical large (1 GW) power plant operating full-time for 1 year
calorie (cal)	4.184 J	Energy needed to raise the temperature of 1 gram of water by 1°C
British thermal unit (Btu)	1,054 J	Energy needed to raise the temperature of 1 pound of water by 1°F, very roughly equal to 1 kJ
quad (Q)	1.054 EJ	Quad stands for quadrillion Btu, or 10^{15} Btu; 1 Q is roughly equal to 1 exajoule (10^{18} J)
tonne oil equivalent (toe)	41.9 GJ	Energy content of 1 metric ton (1,000 kg) of oil
barrel of oil equivalent (boe)	6.12 GJ	Energy content of one 42-gallon barrel of oil

Power unit	Watt equivalent	Description
watt (W)	1 W	Equivalent to 1 J/s
horsepower (hp)	746 W	Unit derived originally from power supplied by horses; now used primarily to describe engines and motors
Btu per hour (Btu/h, or Btuh)	0.293 W	Used primarily in the United States, usually to describe heating and cooling systems

*See Table 3.1 for more energy units.

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RICHARD WOLFSON
MIDDLEBURY COLLEGE

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PREFACE

Many behaviors distinguish the human species from our fellow inhabitants of Planet Earth. One of these behaviors—our use of energy in amounts far exceeding what our own bodies can produce—affects the environment in unprecedented ways. Centuries ago, pollution from coal burning was already a serious urban problem. Despite regulatory and technological progress in pollution control, diminished air and water quality continue to be major consequences of our ever-growing energy consumption. Further environmental degradation results as we scour the planet for fuels that contain the stored energy of which we demand an unending supply. Our energy-intensive society also enables other environmentally damaging developments such as sprawl, large-scale mechanized agriculture, and massive deforestation. At the same time, energy brings us higher standards of living and allows our planet to sustain a larger human population.

In recent decades, a new and truly global impact of humankind's energy consumption has overshadowed the long-standing and still significant consequences associated with traditional pollution, resource extraction, and energy-enabled development. That impact is global climate change, brought about largely by the emissions from fossil fuel combustion. Climate change is a problem that knows no national or even continental boundaries. It will affect us all—although not all equally. It won't have the civilization-ending impact of an all-out nuclear war or a major asteroid hit, but climate change will greatly stress an already overcrowded, divided, and combative world.

Achieving a healthier planet with a stable, supportive climate means either using less energy or using energy in ways that minimize adverse environmental impacts. Here we have choices: To use less energy, we can either deprive ourselves of energy's benefits or we can use energy more intelligently, getting the same benefits from less energy. To minimize environmental and especially climate impacts, we can shift from fossil fuels to energy sources that don't produce as much pollution or climate-changing emissions. Or we can learn how to capture the emissions from fossil fuels and sequester them away from Earth's surface environment.

Earth's energy resources are limited to a relatively few naturally occurring stores of energy—fuels—and energy flows such as running water, sunlight, wind, geothermal heat, and tides. A realistic grasp of our energy prospects demands that we understand these energy resources. We need to know, first and foremost, whether a given resource or combination of resources is sufficient to meet humankind's energy demand. For fuels, we need a good estimate of the remaining resource and a time frame over which we can expect supplies to last.

We need to understand the technologies that deliver useful energy from fuels and flows, to assess their environmental impacts, and to recognize that none is without adverse effects. And we need to be realistic about the near-term and long-term prospects for different energy sources in the economic context.

The oil shortages of the 1970s spawned a serious exploration of energy alternatives. Governments and industries sponsored research programs, while tax credits encouraged the installation of alternative energy systems. Vehicle mileage and other measures of energy efficiency increased significantly. At the same time, colleges and universities developed specialized courses in energy issues and the relationship between energy and environment. These courses emerged in traditional departments such as physics, chemistry, and engineering; in interdisciplinary programs dealing with technology and society; and in the burgeoning new programs in environmental studies and environmental science that sprang up with the emergence of a widespread environmental conscience in the last decades of the twentieth century. Textbooks written for such courses addressed the science and policy issues surrounding energy and the environment.

Energy, Environment, and Climate also focuses on energy and its impact on the environment. Unlike its predecessors, it's built from the ground up on the premise that climate change is the dominant energy-related environmental issue of the twenty-first century. More traditional concerns, such as pollution and energy resources, remain important, and they, too, are covered here. But a full five chapters—about one-third of the book—are devoted to climate and the energy–climate link.

Energy, Environment, and Climate begins with a survey of Earth's history and the origin of the planet's energy resources. A quantitative look at past and present patterns of human energy consumption follows, including a discussion of the link between energy, economic development, and human well-being. Chapters 3 and 4 provide an introduction to the science of energy, including the all-important role of the second law of thermodynamics. Chapters 5 through 10 describe specific energy sources and their resource bases, the role each plays in today's global energy system, their associated technologies and prospects for future technological development, and their environmental impacts. Chapter 11 rounds out the coverage of energy with discussions of electricity and hydrogen—both energy carriers, but emphatically not energy sources. The energy chapters are organized around fundamental resources, including fossil fuels, nuclear energy, geothermal and tidal energy, and direct and indirect solar energy. Because fossil fuels dominate today's energy supply, there are two chapters dealing, first, with the fossil resource and fossil fuel technologies, and second, with the environmental impacts of fossil fuels. Whereas other textbooks have separate chapters on such energy-related issues as transportation, *Energy, Environment, and Climate* includes these topics in the appropriate energy-source chapters. For example, hybrid vehicles and combined-cycle power plants appear in the fossil fuel chapters; fuel-cell and battery electric vehicles are discussed in the chapter that covers electricity and hydrogen as energy carriers; and wind turbines are included in the chapter on indirect solar energy.

Four chapters on climate follow the section on energy. Chapter 12 describes the scientific principles that determine planetary climates, including the natural greenhouse effect in the context of the planets Venus, Earth, and Mars. The chapter ends with a discussion of the nature of scientific theories and of certainty and uncertainty in science. Chapter 13 details the so-called forcings—both natural and anthropogenic—that can upset the energy balance that ultimately establishes Earth's climate. Chapter 14 documents observations showing that Earth is now undergoing unusually rapid climate change and explains why scientists are convinced that most of that change is attributable to human activities. Chapter 15, which outlines projections of future climates, includes a look at the workings of computer climate models and the role of climate feedbacks. The final chapter brings together the two main themes of the book—energy and climate—and explores how humankind might continue to enjoy the benefits of energy use while minimizing its climate-changing impacts.

Energy, Environment, and Climate is written primarily from a scientific perspective. However, questions of policy and economics are never far behind the science of energy and climate. The text therefore ventures occasionally into policy and economic considerations—although to a far lesser extent than a policy-oriented book would do. In particular, several chapters end with a section specifically dedicated to a policy-related issue that grows out of the science covered in the chapter.

Any serious study of energy and the environment has to be quantitative. We need to understand just how much energy we actually use and how much energy is available to us. It makes little sense to wax enthusiastic about your favorite renewable energy source if it can't make a quantitatively significant contribution to humankind's energy supply. Assessment of environmental impacts, too, requires quantitative analysis: *How much* pollution does this energy source emit? *At what rate* are we humans increasing the atmospheric CO_2 concentration? *What's the maximum* CO_2 concentration we can tolerate without incurring dangerous climate change? *How long* will nuclear waste remain dangerous? *How much* waste heat does this power plant dump into the river? *How much* CO_2 results from burning a gallon of gasoline? *What is exponential growth* and what are its consequences for future levels of energy consumption, pollution, or carbon emissions? In dealing with such questions, this book doesn't shy away from numbers. At the same time, it isn't a heavily mathematical text with equations on every page. Rather, the text attempts to build fluency with quantitative information—fluency that means being able to make quick order-of-magnitude estimates, work out quantitative answers to simple "how much" questions, and "read" numerical information from graphs. The book doesn't require higher mathematics—there's no calculus here—but it does demand your willingness to confront quantitative data and to work comfortably with simple equations. Anyone with a solid background in high-school algebra can handle the material here. As for a science background, the text assumes only that the reader has some familiarity with high-school-level chemistry and/or physics. Despite its scientific orientation, this book is written in a lively, conversational style that students have welcomed in my other textbooks.

Energy, Environment, and Climate helps reinforce qualitative and quantitative understandings of the text with its **Chapter Reviews**, which summarize the big ideas presented in each chapter, invite you to consider the meaning of new terms introduced in the chapter, and recap important quantitative information and equations. **Questions** probe the concepts behind energy sources, environmental impacts, and climate issues. **Exercises** provide practice in performing calculations based on the material introduced in each chapter. Answers to the odd-numbered Questions and Exercises are provided at the back of the book. **Research Problems** send you to sources of contemporary data—usually web-based—and allow for more detailed exploration of questions that may be related to energy and environmental issues in your home state or country. Given the discoveries quickly unfolding in this growing field, Research Problems may also ask you to update data presented in the book or to look more deeply into quantitative data on global energy use and its impacts. **Argue Your Case** questions ask you to formulate authoritative arguments for or against propositions relevant to each chapter's topics.

Energy, Environment, and Climate is illustrated with photos, line drawings, and graphs. Line drawings describe the workings of energy technologies, the flows of energy and materials throughout the Earth system, climate models and feedback effects, pollution-control and waste-storage systems, and a host of other content that's best seen to be understood. Most of the photos show actual energy systems, presented to give a sense of the technologies and their scales. Graphs quantitatively describe everything from the breakdown of our energy use by source or by economic sector to projections of future global temperatures. Every graph is traceable to an authoritative source, provided in the Credits and Data Sources at the end of the book.

Energy, Environment, and Climate deals with rapidly changing fields, and this third edition is as up to date as possible. Nearly every graph and item of numerical data has been updated through 2015 or later. Wind and solar energy have seen great advances since the 2008 first edition and the 2012 second edition, including much-expanded deployment of large-scale grid-connected systems, and these developments are reflected here. Relatedly, the chapter on direct solar energy has been reorganized to give greater emphasis to photovoltaic systems, and the indirect solar energy chapter includes new material on airborne wind energy systems. A new section on hydraulic fracturing highlights the revolutionary impact of fracking on oil and gas supplies, especially in North America. Another new section covers electric vehicles and compares the emerging technologies of battery and fuel-cell vehicles. Discussions of cogeneration and heat pumps have been expanded in light of these technologies' increasing use. The nuclear energy chapter includes new material on small modular reactors and alternative approaches to nuclear fusion, as well as incorporating the latest studies on the impacts of the Chernobyl and Fukushima accidents. Our understanding of climate change has advanced with the publication in 2013–2014 of the Intergovernmental Panel on Climate Change's Fifth Assessment Report, and the climate chapters have been appropriately updated with material from IPCC 5 or later. Material on energy and climate policy and legislation, both national and international, has been thoroughly updated; examples include an expanded discussion of renewable portfolio standards and a look at the Paris Climate Agreement that took effect in 2016. The text also describes new studies suggesting ways to meet the climate challenge, including those from the Carbon Mitigation Initiative and the Deep Decarbonization Pathways Project. Finally, there's a new section relating food, energy, and climate.

Other enhancements to the third edition include four new focus boxes on diverse topics: the Volkswagen emissions scandal, the policies of different U.S. states on photovoltaic solar energy, the difference between shale oil and oil shale, and ice-sheet instability. The third edition continues the second edition's trend toward more international emphasis. However, the book remains especially relevant to students in North America. For example, energy data are often presented for both the entire world and for the United States, while the new material on fracking for oil and gas emphasizes North America. And policy considerations focus on such matters as the United States' Clean Air Act or British Columbia's carbon tax. The Chapter Review Questions and Exercises have been revised in light of instructor and student suggestions, and the number of Exercises and Research Problems has increased.

Also complementing the main text are tables displaying important energy- and climate-related quantities; some of the most useful of these also appear inside the covers. An appendix tabulates relevant properties of materials, ranging from *R* values of building materials to half-lives of radioactive isotopes to global warming potentials of greenhouse gases. A Glossary defines all key terms that appear in the book and includes acronyms as well as symbols for physical units and mathematical quantities. A list of Suggested Readings, including authoritative web sites, is also provided. In addition, instructors teaching from *Energy, Environment, and Climate* will find supplementary resources at wwnorton.com/instructors, a password-protected web site that includes the figures and tables appearing throughout the text, as well as an instructor's manual with solutions.

Energy, Environment, and Climate is not a book of environmental advocacy or activism; it's much more objective than that. I have my own opinions, and I acknowledge that many—although not all—are in line with the views of the broader environmental movement. But I pride myself on independent thinking based on my own study of others' writings and research, and I'd like to encourage you to do the same. I'm also keenly aware that there's a much stronger scientific consensus on some issues, particularly climate change, than the popular media, the general public, and even some governments—including the current leadership of the United States—may acknowledge. I've been careful to base my scientific statements on the consensus of respected scientists and on peer-reviewed literature that's available to you and everyone else for direct examination. At the same time, I understand the uncertainties inherent in science, especially in an area as complex as the interconnected workings of the global environment. I openly state those uncertainties and quantify them whenever possible. That said, I would be pleased if the knowledge you gain from this book inspires you to work toward change in our collective patterns of energy consumption. I and the majority of my fellow scientists are convinced that such actions are essential in the coming decades if we're to avoid disruptively harmful environmental impacts.

ACKNOWLEDGMENTS

No individual can be an expert on all the topics covered in a book like this one, and during the writing process I've been fortunate to be able to call on specialists in many fields. They've contributed to making this book more authoritative and timely than I, working alone, could have done. With appreciation, I acknowledge the individuals who have given their expert opinion, read drafts of individual chapters, or otherwise contributed advice and encouragement to this project:

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scientific expertise that has enhanced the readability, teachability, and authority of this textbook. In addition to these formal reviews, I've benefited from ongoing correspondence with a number of instructors using the book, especially Daniel Prober (Yale University) and Mark Rosenberry (Siena College).

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I'm honored to be publishing this book with W. W. Norton, and I am indebted to former Norton editor Leo Wiegman for inviting me to write the first edition of this textbook. Inspired in part by this project, Leo left publishing to start his own environmental work; this third edition was in the able hands of editor Eric Svendsen and his assistants Rachel Goodman and Lindsey Osteen. Project editor Carla Talmadge and copyeditor Norma Sims Roche spearheaded an efficient and successful production process. I am grateful for all their efforts, and it has been a pleasure to work with all of them.

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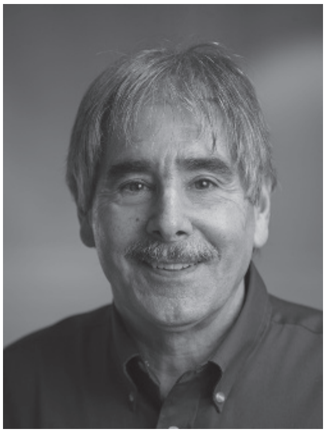


Richard Wolfson is Benjamin F. Wissler Professor of Physics at Middlebury College, where he also teaches environmental studies. He holds a B.A. in physics and philosophy from Swarthmore College, an M.S. in environmental studies from the University of Michigan, and a Ph.D. in physics from Dartmouth. His research involves solar astrophysics and terrestrial climate, and he has published nearly 100 papers in the scientific literature. Wolfson's other books include several introductory physics texts as well as *Nuclear Choices: A Citizen's Guide to Nuclear Technology* (1993) and *Simply Einstein: Relativity Demystified* (2003). He has produced five video courses for The Teaching Company's Great Courses series: *Einstein's Relativity and the Quantum Revolution: Modern Physics for Nonscientists* (1999); *Physics in Your Life* (2004); *Earth's Changing Climate* (2007); *Physics and Our Universe: How It All Works* (2011); and *Understanding Modern Electronics* (2014).

ENERGY, ENVIRONMENT, AND CLIMATE

Third Edition

Chapter 1

A CHANGING PLANET

Earth was born some 4.6 billion years ago, and our planet has been changing ever since. Earth's evolution is driven by an interplay between **matter**—the physical "stuff" that makes up the Universe—and **energy**, an equally important universal "stuff" associated with motion, heat, and the fundamental forces of nature. It's energy that makes everything happen; without energy, the Universe would be a static, unchanging, lifeless place. In Earth's case, agents of change are astrophysical, geological, chemical, and biological. Astrophysical events formed our planet and occasionally alter its history. Geological events build mountains and wear them down, move continents, shake the solid Earth, and spew gases into the atmosphere. Chemical reactions change the composition of rocks, soils, atmosphere, and oceans. Life appeared on Earth billions of years ago, and soon biological processes were radically altering the planet's atmosphere and chemistry. Hundreds of millions of years ago, life emerged from the oceans to colonize the land. Just a few million years ago, our human species evolved and began the process of **anthropogenic** (i.e., human-caused) environmental change. We've since become sufficiently plentiful and technologically advanced that we're now having a global impact on Planet Earth.

1.1 Earth's Beginnings

The time is some 4.6 billion years ago; the place, a vast cloud of interstellar gas and dust about two-thirds of the way out from the center of the Milky Way galaxy. Most of the material in the cloud is hydrogen and helium, the latter having formed in the first 30 minutes after the Universe began in a colossal explosion we call the Big Bang. But there are smaller amounts of oxygen, carbon, nitrogen, silicon, iron, uranium, and nearly all the other elements. These elements were formed by nuclear reactions in massive stars that exploded several billion years earlier and spewed their contents into the interstellar medium.

Gravitational attraction among the gas and dust particles that make up the cloud causes it to shrink, and—like ice skaters who approach, join hands, and spin—the shrinking cloud begins to rotate. As it rotates, it flattens into a disk, with all the matter in essentially the same plane. This collapse is remarkably rapid, taking only about 100,000 years.

A massive accumulation develops at the disk's center, and under the crushing pressure of gravitational attraction, its temperature rises. Eventually the central mass becomes so hot that hydrogen nuclei—protons—join, through a series of nuclear reactions, to produce helium. This process liberates vast amounts of energy, much of which escapes in the form of light. The Sun is born! The newborn Sun is about 30% fainter than it is today, but its energy output is still equivalent to some 300 trillion trillion 100-watt lightbulbs (that's 3×10^{26} watts). Nuclear "burning" in the Sun's core will sustain the star for 10 billion years, during which time it will slowly grow brighter.

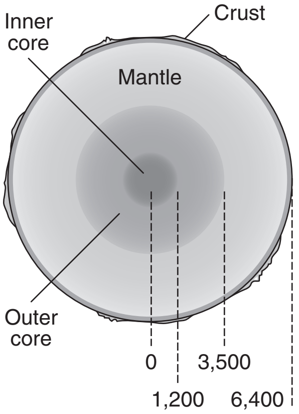
Farther out in the disk, dust particles occasionally collide and stick together. Mutual gravitation attracts more material, and small clumps form. These clumps, too, collide and grow; in a mere million years, the largest have reached kilometer sizes. The more massive clumps exert stronger gravitational forces, so they attract additional matter and grow still larger. After another 100 million years or so, the nascent Solar System contains planet-sized accumulations—protoplanets—including the newborn Earth. But large numbers of smaller chunks persist in the mix, and they bombard the protoplanets mercilessly, cratering their surfaces and heating them.

In the young Earth, heavier elements sink toward the center, forming Earth's core, and lighter elements float to the surface, eventually forming a solid crust. Gases escape from the interior to form a primitive atmosphere. Chunks of interplanetary matter continue their relentless bombardment, heating and reheating the planet. When Earth is a mere 50 million years old, a Mars-sized object plows into the young planet, leaving it molten and so hot that it glows for a thousand years like a faint star. Material ejected in the collision condenses to form Earth's Moon. But eventually Earth and its fellow planets sweep up much of the interplanetary material, and the bombardment tapers off, although occasional Earth-shaking impacts will occur throughout the planet's history. About a half billion years after Earth's formation, the planet cools, and water vapor condenses to form primeval oceans.

Earth's structure today reflects the basic processes from those early times. Its center is a solid inner core, mostly iron, at a temperature of many thousands of degrees Celsius. Surrounding this inner core is an outer core of liquid iron, whose motions generate the magnetic field that helps protect us surface dwellers from high-energy cosmic radiation. Covering the core is the mantle, a hot, thick layer that's solid on short timescales but fluid over millions of years. On top of the mantle sits the thin solid crust on which we live. Thermally driven motions in the mantle result in continental drift, rearranging the gross features of Earth's surface over hundreds of millions of years and giving rise to volcanic and seismic activity. **Figure 1.1** takes a cross-sectional look at our planet.

FIGURE 1.1

Structure of Earth's interior. The crust is not shown to scale; its thickness varies from about 5 to 70 km. The distances indicated are measured in kilometers from Earth's center.



1.2 Early Primitive Life

Sometime between 4.2 billion and 3.5 billion years ago, interactions among natural chemical substances, driven by available energy, led to the emergence of primitive life. The oldest evidence for life consists of fossil algae from

3.7 billion years ago. Some would argue that life arose within a few hundred million years of Earth's origin, perhaps as early as 4.2 billion years ago, but the violent bombardment and geological activity of Earth's first few hundred million years have obliterated any firm evidence of such early life. Nevertheless, even the 3.7-billion-year age of the earliest fossils shows that life has been a feature of Planet Earth for most of its history.

We don't know for sure how life developed. Today, some biogeologists regard the formation of life as a natural continuation of the processes by which Earth differentiated into its core, mantle, and crust. According to this view, the first life probably arose deep underground, and its formation was fueled by a chemical disequilibrium resulting from Earth's internal heat. Primitive bacterial life of this sort could be common in the Universe, occupying habitats ranging from Earth-like planets to the satellites of distant worlds. The more advanced forms of life we know on Earth, however, probably require specialized conditions, particularly a habitable planetary surface.

The earliest life-forms didn't change much over billions of years. In fact, some early fossil bacteria and algae are strikingly similar to their modern counterparts. There's a good reason for this: Such simple organisms are generalists, capable of surviving under a wide range of environmental conditions. In that sense they're highly successful, and there's little pressure on them to evolve. In contrast, most highly evolved organisms are specialists, surviving in narrow ecological niches and subject to continuing evolutionary pressures—or worse, extinction—as the environment changes.

PHOTOSYNTHESIS

The earliest organisms extracted energy from their chemical surroundings—energy that was ultimately **geothermal**, meaning that it came from Earth's internal heat. Some of those organisms, called chemotrophs, still thrive in deep-sea hydrothermal vents and at other subsurface locations. But at some point, organisms near the ocean's surface developed the ability to capture the energy of sunlight and store it in organic molecules built from carbon dioxide (CO_2) and water (H_2O) by the process of **photosynthesis**. The stored energy in these molecules is available to the photosynthesizing organisms themselves and to other organisms that prey on them. But there is—or rather was, at first—a downside to photosynthesis: The process released a new chemical compound, oxygen gas (O_2), into Earth's atmosphere. Oxygen is highly reactive and destructive of many chemical compounds, and was therefore toxic to the early life that had begun, inadvertently, to pollute its environment by creating this new substance.

Pinning down when photosynthesis first began is almost as hard as timing the origin of life itself. Geochemical evidence shows that photosynthetic bacteria were at work at least 2.7 billion years ago, but photosynthesis may have originated more than a billion years earlier.

1.3 Evolution of Earth's Atmosphere

The histories of life and of Earth's atmosphere are inextricably intertwined, so it's appropriate to pause here and focus on the atmosphere itself. The cloud from which the Solar System formed was composed primarily of hydrogen (H_2) and helium (He), and these gases constituted Earth's earliest atmosphere. But Earth's gravity wasn't sufficient to hold the light molecules H_2 and He, which soon escaped to space. Gases released from Earth's interior then gave the young planet an atmosphere that was largely carbon dioxide (CO_2) and nitrogen (N_2), with trace amounts of methane (CH_4), ammonia (NH_3), sulfur dioxide (SO_2), and hydrogen chloride (HCl). Water vapor (H_2O) was probably a significant atmospheric component early on, before most of it condensed to form the oceans.

Over Earth's first 2 billion years, the levels of methane, ammonia, and carbon dioxide declined slowly. The details of this early atmospheric history are sketchy, but it's believed that geochemical and biological removal processes accounted for the decline in atmospheric CO_2. In the geochemical process, CO_2 dissolves in atmospheric water droplets to form carbonic acid (H_2CO_3). Rain carries the acid-laden droplets to the planet's surface, where the carbonic acid reacts with exposed rocks in a process called **weathering**. The effect is to remove CO_2 from the atmosphere and sequester it—that is, to store and isolate it—in Earth's crust. In the biological process, early photosynthetic organisms at the ocean surface took up CO_2 from the atmosphere and, when they died and sank to the seafloor, sequestered the carbon in sediments that eventually became sedimentary rocks. The relative importance of geochemical versus biological CO_2 removal is not clear, and scientists are still debating the roles of these and other mechanisms. But it's clear that over billions of years, CO_2 went from being a major atmospheric component to a gas present in only trace amounts.

Atmospheric nitrogen in the form N_2 is largely nonreactive, so it has not been subjected to significant removal processes. As a result, Earth's atmosphere, since at least 3.5 billion years ago, has been largely nitrogen.

Even as atmospheric CO_2 declined, atmospheric oxygen was increasing as photosynthetic organisms released O_2 gas. At first the rise was slow because the highly reactive O_2 combined with iron and other substances in the oceans and in surface rocks by a process called oxidation. But by about 2.4 billion years ago, Earth's exposed surface had become almost fully oxidized, and atmospheric oxygen increased significantly—an occurrence known as the **great oxygenation event**. From then until about 500 million years ago, oxygen probably constituted about 1%–2% of the atmosphere, after which it rose to its current concentration of about 21%. Nearly all the rest of the atmosphere was, and still is, nitrogen.

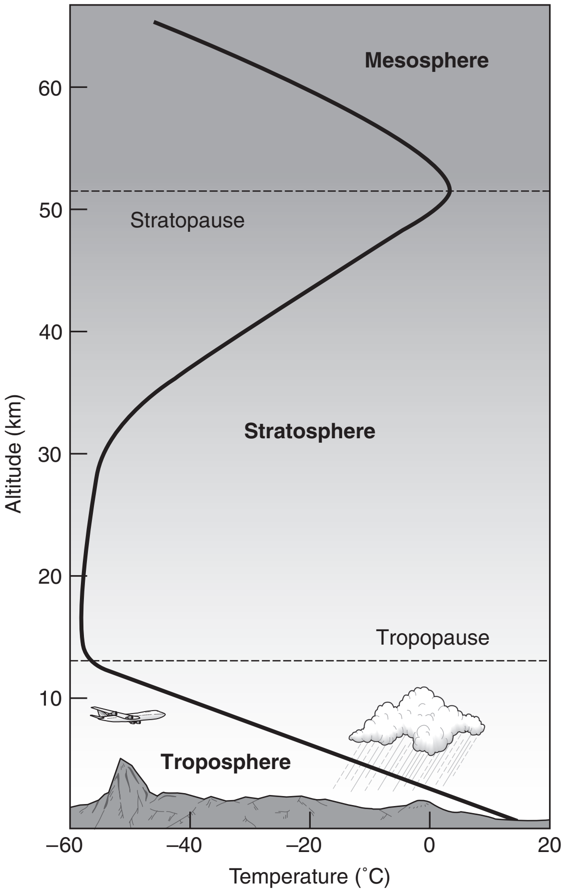
An atmosphere containing free oxygen is unusual. Of all the bodies in our Solar System, only Earth has an atmosphere containing significant oxygen. Because it's so reactive, oxygen in the form of O_2 soon disappears from the atmosphere unless it's somehow replenished. On Earth, that replenishment occurs through photosynthesis. Both the origin and the continued existence of our oxygen-rich atmosphere are the work of living organisms. Surely this global modification of Earth's atmosphere ranks as one of life's most profound effects on our planet. Incidentally, many astrobiologists believe that finding the signature of oxygen in a distant planet's atmosphere might strongly suggest the presence of life.

STRUCTURE OF THE ATMOSPHERE

Like the planet itself, Earth's atmosphere has several distinct layers. At the bottom, extending from Earth's surface to an altitude that varies between about 8 and 18 kilometers (km), is the **troposphere**. Some 80% of the atmosphere's total mass lies within the troposphere, and it's in the troposphere that most weather phenomena occur. The troposphere's temperature generally declines with increasing altitude, although particular meteorological conditions may alter this trend in the lower troposphere. A fairly sharp transition, the **tropopause**, marks the upper limit of the troposphere. Above this is the **stratosphere**, which extends upward to an altitude of about 50 km. The stratosphere is calmer and more stable than the troposphere; only the tops of the largest thunderstorms penetrate into its lowest reaches. The stratosphere contains the well-known **ozone layer** that protects us surface dwellers from harmful ultraviolet radiation. The formation of ozone (O_3) requires life-produced oxygen, so here's another way in which life has modified Earth's environment, in this case making the land surface a safe place to live. The absorption of solar ultraviolet radiation causes the temperature of the stratosphere to increase with altitude. Only the troposphere and stratosphere suffer significant effects from human activity, and these two layers also play the dominant roles in Earth's climate. Above the stratosphere lie the **mesosphere** and **thermosphere**, where the atmosphere thins gradually into the near vacuum of space. There is no abrupt endpoint at which the atmosphere stops and space begins. **Figure 1.2** shows the structure of Earth's atmosphere, including a typical temperature profile.

FIGURE 1.2

Structure of Earth's atmosphere, showing a typical temperature profile. Nearly all weather occurs in the troposphere, whereas the stratosphere is important in absorbing solar ultraviolet radiation. Tropopause altitude varies between about 8 and 18 km. Not shown is the thermosphere, a region of high temperature but low density that lies above the mesosphere.



1.4 Aerobic Life

Let's return to the discussion of life—because, again, the evolution of life and the atmosphere are inextricably linked. Although oxygen was toxic to the life-forms that originally produced it, evolution soon led to new life-forms that could use oxygen in their energy-releasing metabolic processes. In this new oxygen-based metabolism, the process of **aerobic respiration** combines organic molecules with oxygen, producing CO_2 and water and releasing energy. The result is a cycling of oxygen back and forth between life and atmosphere, alternating between the chemical forms CO_2 and O_2.

Because oxygen is so reactive, aerobic respiration releases energy at a greater rate than the **anaerobic respiration** that took place—and is still used by some organisms today—in the absence of oxygen. Aerobic respiration therefore helped facilitate the evolution of larger, more complex, and more mobile life-forms exhibiting new behaviors.

Another important behavior that emerged about a billion years ago was sexual reproduction: the organized intermingling of genetic information from two distinct individuals. This adaptation led immediately to much greater diversity of life and an acceleration of the evolutionary process. Soon thereafter, about 850 million years ago, the first multi-celled organisms appeared. The period from about 550 million to 490 million years ago then produced a tremendous diversification of multi-celled life-forms (**Fig. 1.3**). At this point, life was still a strictly marine phenomenon, but by about 400 million years ago, plants had begun to colonize the land, beginning another of life's major alterations to the planet. Animals, which soon followed, could take advantage of the food source represented by terrestrial plants. Amphibians, reptiles (including dinosaurs), birds, and mammals all appeared in the last 400 million years or so of Earth's 4.6-billion-year history. An important era in the context of this book is the **Carboniferous period**, some 360 million to 300 million years ago, when prolific growth of forests led to the burial of carbon that eventually became coal. Much more recently—about 2.8 million years ago—human ancestors of the genus *Homo* evolved, and we modern *Homo sapiens* have been around for only 200,000 years. **Figure 1.4** is a timeline of life's evolution on Earth.

FIGURE 1.3

The Cambrian period, from about 550 million to 490 million years ago, produced an enormous diversity of marine life-forms, shown here in an artist's conception.

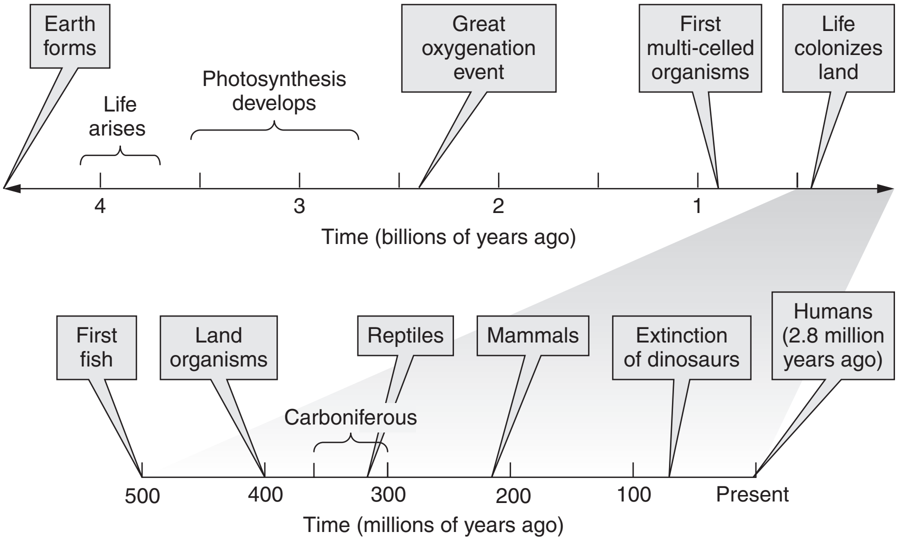


FIGURE 1.4

Some major events in the history of life on Earth. The origins of life and photosynthesis are uncertain, and the dates given for the last 500 million years represent the earliest definitive fossil evidence.

1.5 Earth's Changing Climate

Climate describes the average conditions that prevail in Earth's atmosphere—temperature, humidity, cloudiness, and so forth—and the resulting conditions at Earth's surface. Climate is distinct from weather, which describes immediate, local conditions. Weather varies substantially from day to day and even hour to hour, and it changes regularly with the seasons. Climate, being an expression of average weather, changes on longer timescales. But change it does, and natural climate change has been a regular occurrence throughout Earth's history.

We've already seen that life and atmosphere are linked through Earth's life-produced atmospheric oxygen and the aerobic organisms that evolved to take advantage of it. Climate, too, is obviously linked with life because the climate of a region determines the kind of life that can survive there. Many factors go into determining Earth's climate, but the two most important are light from the Sun and the composition of Earth's atmosphere. Sunlight provides the energy that warms our planet and drives the circulation of atmosphere and oceans.

Sunlight and atmosphere interact to establish Earth's climate; sparing the details for now, here's the big picture: (1) Sunlight brings energy to Earth, warming the planet. (2) Earth returns that energy to space, establishing an energy balance that maintains a fairly constant average temperature. (3) **Greenhouse gases** in the atmosphere act like a blanket, blocking the outgoing energy and making Earth's surface temperature higher than it would be otherwise. The most important of these gases are water vapor and CO_2. Change either the rate at which Earth receives solar energy or the concentration of atmospheric greenhouse gases, and you change Earth's climate.

We know from well-established theories of stellar evolution that the newborn Sun was some 30% fainter than it is today. We have a very rough record of the average temperature at Earth's surface over the past 3 billion years, and that record shows, remarkably, that the temperature hasn't tracked the gradual increase in the Sun's energy output. Take a look at this long-term temperature record shown in **Figure 1.5**: Despite a fainter young Sun, our planet, throughout much of its history, has been warmer than it is today.

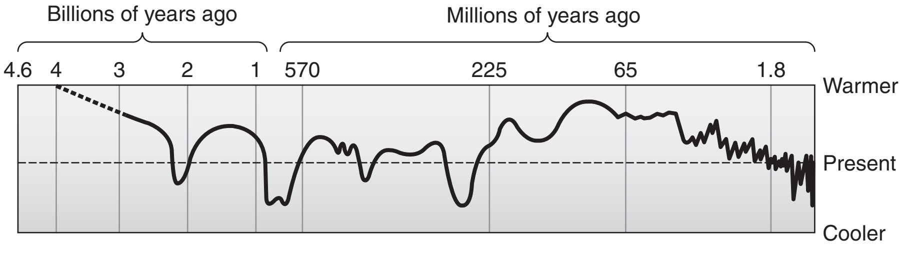


FIGURE 1.5

A rough estimate of Earth's temperature history over the past 3 billion years shows that much of the time it has been warmer than the present, despite the Sun's steadily increasing energy output. The temperature scale is only semiquantitative, with the overall variation shown being about 30°C—comparable to winter–summer differences in today's temperate climates. Note that the horizontal timescale is not uniform.

Many factors influence climate, and they act on timescales ranging from years to billions of years. But scientists believe that over the billions of years' time shown in Figure 1.5, geological processes regulate the concentration of atmospheric CO_2 and thus establish a relatively stable climate. The basic idea is simple: CO_2, as we discussed earlier, is removed from the atmosphere by weathering of rocks; it's replenished by CO_2 escaping from Earth's interior, especially through volcanoes. The chemical reactions that constitute weathering depend on temperature; the higher the temperature, the greater the weathering rate. And it's precipitation that brings CO_2 to Earth's surface in the form of the weathering agent carbonic acid. Precipitation, in turn, depends on how much water evaporates into the atmosphere—and that also increases with temperature. With increased temperature, then, both the rate of weathering and the amount of precipitation increase. Those increases promote greater weathering, and thus remove more CO_2 from the atmosphere. With less CO_2, the atmosphere acts less like an insulating blanket, and Earth's surface cools. This drop in temperature decreases the rate of weathering, and continuing CO_2 emission from volcanoes gradually increases the atmosphere's CO_2 concentration. These two conditions enhance the insulating blanket, and Earth's surface warms.

What I've just described is a process of **negative feedback**. Earth warms, and the Earth–atmosphere system responds in a way that counters the warming. Earth cools, and the system responds to counter the cooling. This is *feedback* because a system—in this case Earth and its atmosphere together—responds to changes in itself. It's *negative* feedback because the response opposes the initial effect. Scientists believe that the negative feedback process of CO_2 removal by rock weathering has acted over geological time much like a household thermostat, regulating Earth's temperature within a fairly narrow range, even as the Sun's energy output gradually increased (**Fig. 1.6**).

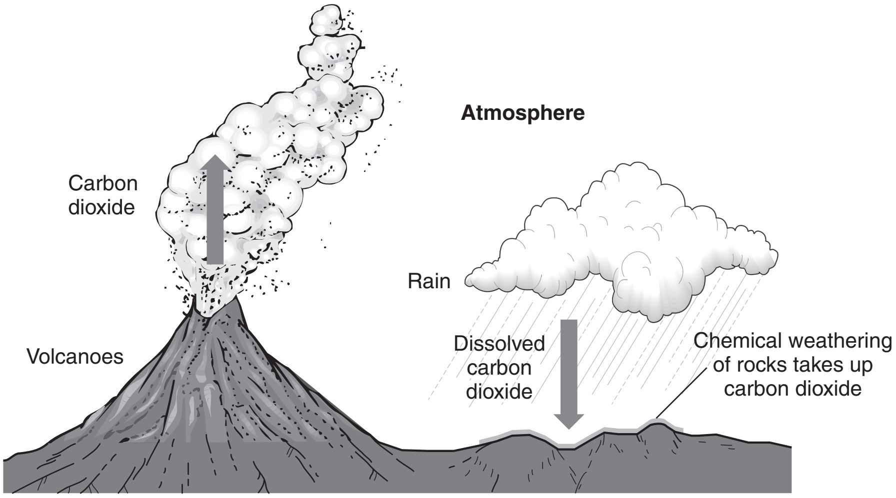


FIGURE 1.6

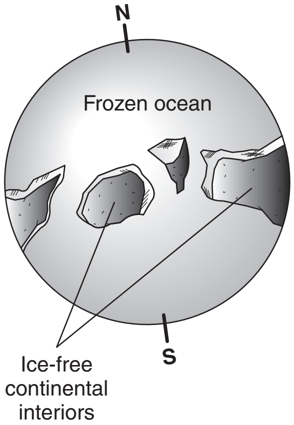
Over geological time, removal of CO_2 by precipitation and chemical weathering of rocks balances volcanic CO_2 emissions. Carbon dioxide removal increases with temperature, providing a negative feedback that regulates Earth's temperature.

SNOWBALL EARTH

Geological temperature regulation hasn't been perfect. Changes in volcanic activity, continental drift, variations in Earth's orbit, and other factors have led to excursions toward warmer or cooler conditions, as suggested in Figure 1.5. Scientists have found evidence of dramatic climate swings that plunged Earth into frozen "snowball" states that were followed by rapid warming. Perhaps as many as four such snowball episodes occurred between about 750 million and 580 million years ago. During that time, Earth's continents were probably clustered near the equator, and warm equatorial precipitation made for especially rapid removal of atmospheric CO_2 by rock weathering. The atmospheric CO_2 concentration plunged, and ice advanced across the landless Northern and Southern Hemispheres. The larger expanses of ice reflected more of the incoming solar energy back to space, cooling the planet further. The process overwhelmed the natural weathering thermostat, and soon the entire ocean was covered with ice. Starved of precipitation, land glaciers couldn't grow, and thus some of the land remained ice-free (**Fig. 1.7**).

FIGURE 1.7

Earth at the height of a snowball episode. The continents are clustered near the equator, and the entire ocean is frozen to a depth of about 1 km. The lack of precipitation arrests glaciers and leaves some land ice-free.



There's a problem here: Ice reflects most of the sunlight that's incident on it, so once Earth froze solid, it would seem impossible for it ever to warm up and thaw again. But remember those volcanoes, which continued to spew CO_2 from Earth's interior. Normally the atmospheric CO_2 concentration remains fairly constant, as CO_2 removal by weathering occurs at roughly the same rate as volcanic CO_2 emission. With the oceans frozen, however, there was no water to evaporate, precipitate, and cause rock weathering. But volcanism, driven by the planet's internal heat, continued, so atmospheric CO_2 increased rapidly—and with it the insulating effect of the atmosphere and Earth's surface temperature. Eventually equatorial ice melted, exposing dark ocean water to the strong tropical sunlight, and the warming rate increased. Both theory and geological evidence suggest that the climate swung from extremely cold to stiflingly hot and wet in just a few centuries. Eventually the weathering thermostat got things under control, and the climate returned to a more temperate state.

What happened to life during Earth's snowball episodes? Life, still entirely aquatic at this time, hunkered down beneath the kilometer-thick ice that covered the oceans, living off energy escaping from Earth's interior. Many single-celled organisms probably went extinct. Others, however, clustered around geothermal heat sources on the ocean floor, where they evolved in isolation and thus increased the overall diversity of living forms. In fact, some scientists credit snowball Earth episodes and their subsequent hot spells with engendering the huge proliferation of life during the Cambrian period about 500 million years ago (see Fig. 1.3).

1.6 Earth's Energy Endowment

The astrophysical, geological, and biological history I've just summarized has left Planet Earth with a number of natural sources of energy—sources that the planet taps to drive processes ranging from continental drift to photosynthesis.