



Fossil Fuels, Planetary Boundaries, and the Earth System

- 23.1 Introduction – 476
- 23.2 A Systems Approach – 477
- 23.3 Planetary Boundaries – 477
- 23.4 Climate Change – 480
- References – 486

23.1 Introduction

The decline in resource quality, measured in part by falling energy returns on investment, is a serious problem for our futures in and of itself. Access to fossil fuels has given many of us a far more comfortable life. Cellular phones are a ubiquitous possession, even among the world's poor. Fossil-derived energy has lifted the burden of heavy manual labor. Most Americans now work in offices and access electronic media at will. These feats would be impossible in the absence of electricity. Many people complain vociferously about how difficult commercial airline travel is these days with late flights, extra baggage charges, no food, and cramped seating. But imagine crossing the country in a Conestoga wagon. As an exercise, try thinking about the energy that is embodied in your day-to-day consumption patterns. Not surprisingly, people are reluctant to do without the goods they have acquired and become used to. When environmental educator Ray Bowdish, speaking at a recent symposium, asked his students what they could simply not give up, a frequent answer was “my truck!”

Fossil fuels have a direct effect on the economy, as we have seen in prior chapters. Gross domestic product has increased exponentially with a similar increase in fossil fuel use (► Fig. 4.1). Since the peak of domestic conventional oil production in 1970, every spike in oil prices has been followed by a recession in the US economy. Murphy and Hall [1] enunciated the growth paradox. Maintaining business-as-usual economic growth requires new sources of oil or other very high quality energy. Since the only remaining sources require higher prices to bring them forth, this helps reduce the potential for economic growth. As a result, the economy exhibits a high degree of volatility. Petroleum geologist Colin Campbell called this an undulating plateau. As we saw in the last chapter, declining energy returns on investment in the long term are a factor in long-term slow growth or secular stagnation, as well as in cyclical variations.

This portends a future in which we should not assume automatically that our children and grandchildren will be better off than are we. But if this were our only problem, we could manage, for a while, by turning to coal that is still abundant and possesses a high energy return on

investment relative to many alternative fuels. Perhaps we will be able to use the remaining fossil fuels to power the transition to a solar economy that provides nearly the same amount of energy as we have access to now. Or maybe we can't do this. It is a distinct possibility that petroleum and coal are one-time gifts of nature that simply have no substitutes, much to the ignorance and eventual chagrin of mainstream economists. Maybe we will have to give up our trucks, as difficult as that may be.

Unfortunately, this is *not the only problem* we face regarding our energy future. Growth of the human economy and its social systems, driven by fossil fuel consumption, is overwhelming the proper functioning of the Earth systems. We are reaching the limits of what Herman Daly called the full world, as we have reached at least three of our planetary boundaries and are hurtling precipitously toward others. In many ways the human economy appears already too big for its supporting biophysical systems, and a system in overshoot cannot grow its way into sustainability [2].

This represents a challenge for our economy or at least as it presently exists. We have, clearly, a capitalist economic system. As we showed in ► Chap. 5, capitalism must grow. Periods when the economy does not grow are called stagnation, recession, and even depression and come complete with rising unemployment, shuttered businesses, poverty, and declining opportunities. Is this a “new normal” we must learn to live with? Everyone from the smallest entrepreneur to the chair of the largest multinational corporation will tell you about the growth imperative. Companies that do not meet their growth projections see their stock values decline. People who work for them see their salaries stagnate or see one another at the unemployment office and often seek some kind of a resurrection from extremists who promise, without evidence, a return to “the good old days.” Yet if we are in overshoot already, then we must shrink in order to live within nature's change limits. Degrowth means getting smaller, and a steady-state economy means staying smaller permanently. A question we must ask is “how can biophysical economics provide the insights to help us, and generations to come, cope with or adapt to nature's new normal?”

23.2 A Systems Approach

Let us return momentarily to the biophysical economics model presented in ► Chap. 3 (■ Fig. 3.3) that showed the economic process from the acquisition of solar energy to extraction, production, and consumption. At the very bottom, right-hand corner was a pile of fetid waste. This is the part of the system we must now consider. In addition, Herman Daly's model of the embedded economy (■ Fig. 3.2) showed the sun's energy creating sources of economic potential by means of photosynthesis, as well as showing human access to the ancient products of photosynthesis known as fossil fuels. On the right-hand side of the embedded economy model were the planet's sinks. The sinks, including the land, the oceans, and the atmosphere, are where the wastes of the human enterprise accumulate. If the growth of the open economic system confined within a finite and nongrowing ecosystem continues, we use more resources and create more effluents. If we put more waste into our sinks than they are able to assimilate, we suffer from myriad environmental problems, from litter to pollution to a climate change. But how do we know how much is too much? These are questions that can be answered by biophysical science. Only on the basis of solid science can we develop an economic policy to cope with our new system-level constraints.

Evidence continues to pile up regarding the overuse of our sinks. Landfills, which are basically holes in the ground, eventually fill up and close. Stories of garbage barges traveling the world looking for a place to dump their trash and frequently being rejected are the stuff of newspaper headlines. In the Finger Lakes area of New York, home to both the State University of New York College of Environmental Science and Forestry and Wells College, acrimonious local politics heat up periodically as to whether to keep the local landfill, affectionately known as Seneca Meadows, open to the trash of New York City for the revenues or to close it for issues of health, traffic congestion, and water quality. *The Washington Post* recently reported that one-third of plastics escape collection systems. In 2015 over eight million metric tons, or five full garbage bags per foot of coastline, ended up in the world's oceans. *The Post* cited a

World Economic Forum study that predicted the mass of plastic would outweigh that of fish by 2050 [3]. Much of this plastic is concentrated into ocean vortexes known as gyres. The plastic floating in the North Pacific Gyre, to the northeast of Hawaii, is twice the size of Texas. The plastics break down into tiny parts where they contain large quantities of PCBs and DDT. As larger fish dine on the smaller ones who have ingested the plastic, the toxins bioaccumulate in the process made famous by Rachel Carson in *Silent Spring* [4]. In addition, the North Pacific garbage patch is but one of five. The first mate of a research vessel put it bluntly, saying that it was “just a reminder that there's nowhere that isn't affected by humanity” [5].

23.3 Planetary Boundaries

In 2009 a team headed by Johan Rockström of the Stockholm Resilience Centre [6] published a paper in the prestigious journal *Nature*, entitled “A Safe Operating Space for Humanity.” The team, which included Nobel Prize-winning atmospheric chemist Paul Crutzen and climatologist James Hansen, identified nine “planetary boundaries” that are necessary to remain within, to assure the proper functioning of the Earth's biophysical systems. The list includes climate change, ocean acidification, biodiversity loss, stratospheric ozone depletion, and disruption of nitrogen and phosphorous cycles, among others (Table 23.1).

Rockström and his team calculated meticulously the preindustrial, or pre-fossil fuel era, baselines and proposed thresholds where the kinds of tipping points could occur that would lead to irreversible changes that could affect the entire Earth system. Before the age when coal was used to propel machinery by means of the steam engine in the late 1700s, the atmospheric concentration of carbon dioxide was 280 parts per million volume. Their proposed threshold to avoid a tipping point was 350 parts per million. Current concentrations exceed 400 parts per million. Regarding the climate, the team also measured radiative forcing. If you recall, the planet receives about 1400 Watts per every square meter that is in the sun, although about 30% bounces off the atmosphere. If you have ever seen the picture of “Earthrise” taken by the Apollo 11 astronauts,

Table 23.1 Planetary boundaries, preindustrial baselines, and current levels

Earth system process	Parameters	Proposed boundary	Current status	Preindustrial value
Climate change	1. Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	2. Change in radiative forcing (watts per meter squared)	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1–1
Nitrogen cycle (part of a boundary with the phosphorus cycle)	Amount of N ₂ removed from the atmosphere for human use (million of tonnes per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quality of P flowing into the oceans (million of tonnes per year)	11	8.5–9.5	–1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km ³ per year)	4000	2600	415
Change in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis	To be determined		
Chemical pollution	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals, and nuclear waste in, the global environment or the effects on the ecosystem and functioning of Earth system thereof	To be determined		

what you saw was the light bouncing off the atmosphere. This is also known as albedo. The Earth's atmosphere is sensitive to very small changes. A slight human-induced change in the amount of radiation that the Earth receives can have a large effect on the planet's ability to trap heat. In pre-fossil fuel times, there was no human-induced radiative forcing. The proposed boundary is 1 Watts per square meter. The current threshold is 1.5. They measured biodiversity loss by the rate of extinction. The baseline figure was the loss of between 0.1 and 1 species per every million. The boundary is 10, while the current rate exceeds 100 species per 1 million. In other

words, we are currently seeing the greatest mass extinction since the end of the age of the dinosaurs, also known as the Cretaceous-Tertiary boundary.

Human, fossil fuel-based activity is also disrupting our biogeochemical cycles. Liebig's law of the minimum states that growth of a system is limited, not by total resources, but by the most limited resource. For centuries, the resource limiting agricultural yields was nitrogen and phosphorous fertilizer. A shortage of manure led the British to scour the battlefields of the Napoleonic Wars to obtain the phosphorous-leaching bones of the fallen soldiers. In the 1900s the quest for nitrogen

turned to the shores of South America for phosphorous-rich bird guano. But the removal of the ancient supplies outstripped the new droppings and the resource peaked. In the early twentieth century, German chemist Fritz Haber and chemical engineer Karl Bosch figured out how to make “bread from air” in the process described in ► Chap. 15. Since then the runoff from nitrogen and phosphorous fertilizers has been accumulating in hypoxic “dead zones” at the mouths of our major rivers, including the Mississippi. The extra nutrients cause algal blooms which consume all available oxygen upon their death, leaving the water body unable to support other forms of life. Before the invention of the Haber-Bosch process, people removed almost no nitrogen for human use from the atmosphere. The proposed safe threshold is 35 million metric tons per year. We currently remove 121 million metric tons per year. This creates a dilemma. Agricultural scientist Tim Wise of the Global Development and Environment Institute put the matter bluntly. “Ask any third-world farmer what sustainable agriculture is and they will tell you, more fertilizer.” Yet the current level of nitrogen removal exceeds the proposed safe, or sustainable, level of by a factor of 3 and one-half times.

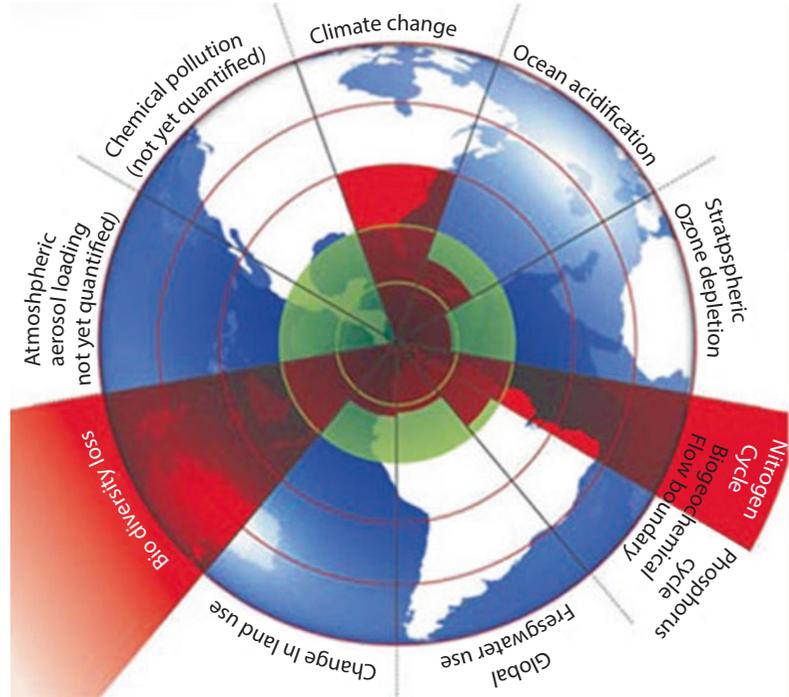
Human use of carbon, other species, and nitrogen has gone beyond the safe operating space of the planetary boundary already. Other categories are close to the edge. In preindustrial times, more phosphorous was returned to the ocean than taken out in fish harvests. The Rockström team calculates that a safe threshold would be 11 million metric tons of phosphorous flowing into the ocean. The current level is between 8.5 and 9.5 tonnes. The ocean is becoming more acidic as the carbon released into the atmosphere by the burning of fossil fuels is eventually sequestered in the ocean. Before the age of fossil fuel enabled industrial agriculture and suburban housing, humanity drew about 415 cubic kilometers of water from our aquifers. The Stockholm team estimates the safe level to be 4000 km³, while we currently extract about 2600. Changes in the conversion of wild lands into cropland were miniscule in the days before industrialization. We now convert a little less than 12%. The proposed boundary is 15%, so we are about 80% of the way to exceeding the safe levels of land use. The impact of deforestation to feed the needs for food production, potential medicines, and forest products and beef for the developed world is continually pressuring

the world’s remaining tropical forests, and the debt-ridden governments of the often-poor nations in which the forests are located have a difficult time resisting the conversion of forest to land to resettle a burgeoning urban population and the need for foreign exchange.

The team has yet to calculate thresholds for chemical pollution and atmospheric aerosols. Aerosols are difficult to calculate, yet are an important component of climate science. Black aerosols, such as those produced by diesel engines, absorb sunlight and heat the planet. White aerosols, including sulfur dioxide that are emitted by coal-burning power plants, especially in areas of the world that lack stringent pollution-control laws, and volcanic eruptions, as well as nitrogen oxides from automobile tailpipes, reflect electromagnetic radiation and cool the planet. When Mount Pinatubo erupted in 1991, the oceans cooled for several subsequent years. If we underestimate the amount of reflective aerosols actually in the atmosphere, they may be masking the actual degree of climate forcing. Getting the estimate correct will take time and effort, but the effort will be well worth it for the scientific understanding, if not for the fate of humanity (► Fig. 23.1).

Perhaps the most interesting case is that of stratospheric ozone depletion, for it shows humans are capable of taking collective action to reverse environmental damage. The upper atmosphere contains a relatively small amount of three molecules of oxygen bonded together called ozone (O₃). Ozone is very rare, with only three molecules of ozone for every ten million molecules of oxygen, and it is measured in Dobson units, with one DU equaling only 0.01 mm in thickness. Ozone is created by a complex interaction with ultraviolet radiation and absorbs the shortest, and most harmful, wavelengths of ultraviolet light, UV-B and UV-C. These are the most powerful component of sunlight that can cause skin cancers and reductions in crop yields. In 1971 Dutch atmospheric chemist Paul Crutzen made the connection between nitrogen oxides and ozone depletion. In the same year, British scientist James Lovelock found molecules of chlorinated fluorocarbons (CFCs) ubiquitously mixed into the entire atmosphere. Sherwood Rowland and his postdoctoral fellow, Mario Molina, found that the stable CFC molecules interacted with stratospheric ozone, splitting the ozone molecule into oxygen (O₂) and chlorine monoxide (ClO). The ozone layer was thinning, especially in

Fig. 23.1 The Green represents a safe operating space, while the distance that the red segment is from the origin represents the proportion of that category relative to the proposed maximum that the Earth can sustain



the southern latitudes, bringing with it the capacity for more UV light to reach the Earth's surface, and cause considerable environmental harm, such as damage to the retinas of vertebrate eyes. For their efforts Crutzen, Rowland, and Molina won the 1995 Nobel Prize in Chemistry.

But where did all the CFCs come from? It is a classic story of the unintended consequences of industrial production. It would be difficult to argue that human life has not been improved by refrigeration. Modern humans in electrified societies are far less likely to sicken or die from food-borne pathogens. Early refrigerators used toxic materials such as ammonia, methyl chloride, and even liquid sodium (which explodes on contact with oxygen) as refrigerants, and the use of them was limited. But, during the 1920s, the number of US homes served by electricity increased from 25% to 80%, and the possibility for mass marketing of a safe refrigerator was on the verge of possibility. General Motors, owners of Frigidaire, commissioned chemist Thomas Midgley to create a safe refrigerant. His invention of a chlorinated fluorocarbon, with the trade name of Freon, seemed like the answer. It was odorless, tasteless, nontoxic, long lasting, and cheap. CFCs found their way into myriad propellants, from whipped cream to deodorants to hairspray. In the 1950s

some 20,000 tons per year found their way into the stratosphere. By 1970 the figure stood at 750,000 tons [7]. But the unintended consequences of the miracle invention were being mixed into the upper atmosphere and participating in the ozone-reducing reactions that were now threatening life on the planet. Could humanity respond?

In 1985 the nations of the world met in Montreal and ratified the Montreal Protocol on ozone-depleting substances. We found that we could live without spray deodorant and without Freon without too much sacrifice. Moreover, complying with the treaty was made easier by the simple technological change of adding hydrogen to the chlorine and fluorine. A chlorinated hydrofluorocarbon does not have the ozone-depleting potential of a CFC. Unfortunately, unintended consequences still remain, as these CFHCs are powerful greenhouse gases.

23.4 Climate Change

Scientists have known about the connection between atmospheric composition and temperature for a long time. In the 1820s Jean Baptiste Fourier hypothesized that the thickness of the atmosphere and the conditions of the planet's surface deter-

mined the Earth's average temperature. In 1859 John Tyndall concluded that the atmosphere and its trace gases (primarily carbon dioxide), along with water vapor, were transparent to visible light but “opaque” to the less energetic wavelengths of infrared radiation. In other words, carbon dioxide allowed high-energy photons to pass through the atmosphere but trapped some of the resultant heat from escaping into space, much like the glass in a greenhouse. Heat-trapping gases such as carbon dioxide, methane, sulfur hexafluoride, and CFHCs are today known as “greenhouse gases.” Swedish chemist Svante Arrhenius confirmed Tyndall's hypothesis and expressed concern that we are warming the planet by “emptying our coal mines into the sky” [8].

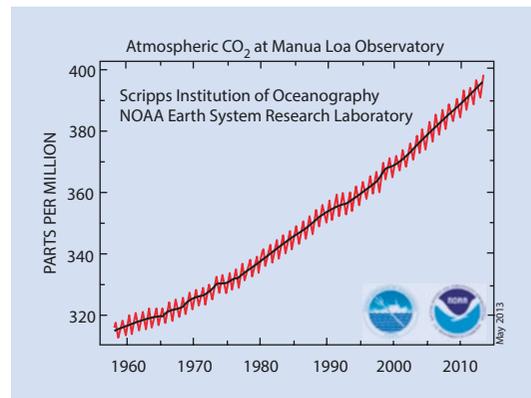
Today there is a broad scientific consensus that the observed increases in the temperature of the Earth are linked to the level of carbon dioxide and other heat-trapping gases, although no respectable climate scientist dismisses other causes or thinks that atmospheric dynamics are simple and straightforward. For example, increases in temperature usually precede increases in carbon dioxide. Moreover, the most powerful greenhouse gas is not CO₂ but water vapor. The “debates” or outright denial of the connection between carbon and climate are generally found among politicians, business executives, and workers with jobs to lose instead of scientists. Climate change is a difficult issue to conceptualize, even for many atmospheric scientists. There are many variables and the theory is often far ahead of the data. To begin with weather is not climate. Weather is what is happening here, today. Climate is long-term averages. There is a big difference. Today in Massachusetts, USA, the temperature increased by 20 °F over the course of the day. It was cool and rainy in the morning and hot and muggy in the afternoon. But average temperature across the world is different. Climate scientists John Anderson and Alice Bows conclude that we must keep the increase in average temperature to less than 2 °C (3.6 °F). For Anderson and Bows, 2° is not the threshold between safe and dangerous; it is the threshold between dangerous and extremely dangerous. In the developed world, a positive feedback loop has developed. As the temperature warms, more people purchase and use air conditioning. This uses more electricity and puts more carbon into the atmosphere. The planet warms. People use more air conditioning. The planet warms. The ubiquitous use of air conditioning is a fairly recent phenomenon. When one of

your authors (Klitgaard) grew up in the hot and arid Southwest, nobody he knew had an air conditioner. Now they are part of the “middle class life” in most parts of the country. And carbon dioxide emissions continue to increase.

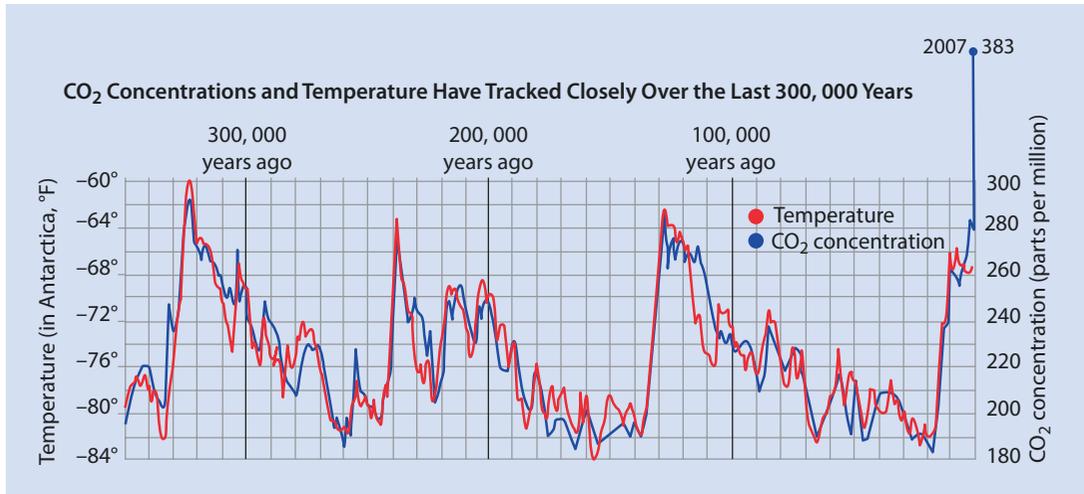
In 1992 the United Nations held its Framework Convention on Climate Change. Since that time diplomats have been meeting in regular Conferences of Parties (COPs) to try to reach agreement on limiting the emission of greenhouse gases, with little to show for the effort. Poor nations saw the industrialized part of the world grow rich on the power provided by coal and other fossil fuels and ask why they are now precluded from doing the same. Rich nations do not want to lose their competitive advantage to newly industrializing nations like China and India, with low per capita incomes but high total emissions. But finally, in 2016, the nations of the world signed the Paris Accord, committing themselves to enact policies to stay within the 2° threshold. Whether the agreement will be successful is now questionable, as new US President Donald Trump has vowed to pull the United States out of the Accord because it gives too much competitive advantage to China. Business aside, what are the scientific concerns, and what is the evidence?

In 1957 Roger Revelle and Charles Keeling began to measure carbon dioxide concentrations in the Northern Hemisphere at an observatory on Mauna Loa in Hawaii, and the taking of atmospheric samples continues to this day. In 1957, they measured concentrations of 315 parts per million volume (ppmv). The latest readings are nearly 409 ppmv. Look at the graph in ■ Fig. 23.2.

You should notice two crucial details, a sawtooth pattern and a trend. The sawtooth pattern is



■ Fig. 23.2 Keeling curve (Courtesy NOAA)



■ Fig. 23.3 Vostok ice core data

the Earth breathing [11]. In the Northern Hemisphere, leaves of deciduous trees fall in the autumn. Oxygen production ceases as photosynthesis stops and carbon dioxide concentrations increase. In the spring new leaves form, oxygen production begins again, and carbon dioxide concentrations fall as new leaves are formed. But the disturbing feature is the trend of growth. Can this be attributed to humans and their burning of fossil fuels, or is it just a natural variation? Atmospheric scientists have collected data back to more than 350,000 years ago by taking ice core sample in Antarctica, where ice rarely melts. Since dirt accumulates in thin layers between winter snowfall, a clear year-by-year record can be found by drilling deep into the ice. Ice contains air bubbles, and one can, using sophisticated machinery, test for the composition of ancient air. A main sampling station is at Vostok Station in Antarctica. ■ Figure 23.3 displays the Vostok ice core data. As one can see, temperature and carbon dioxide concentrations are correlated closely. As CO₂ concentrations rise, after a lag period, temperature follows. When carbon dioxide falls, so does temperature, and certain patterns repeat through history. Temperature rises rapidly and cools more slowly. But look at the very right hand of the graph, and you will see something unusual: climate stability. The epoch in which humans evolved, known as the Holocene, is

marked by unusual climate stability and warmth, which is critical to humans—at least until recently. The study of the ancient climate is known as paleoclimatology. Will it continue as carbon dioxide levels increase to a level greater than anything observed in the past 350,000 years? Will we, as a species, be able to adapt? What are the problems we might anticipate?

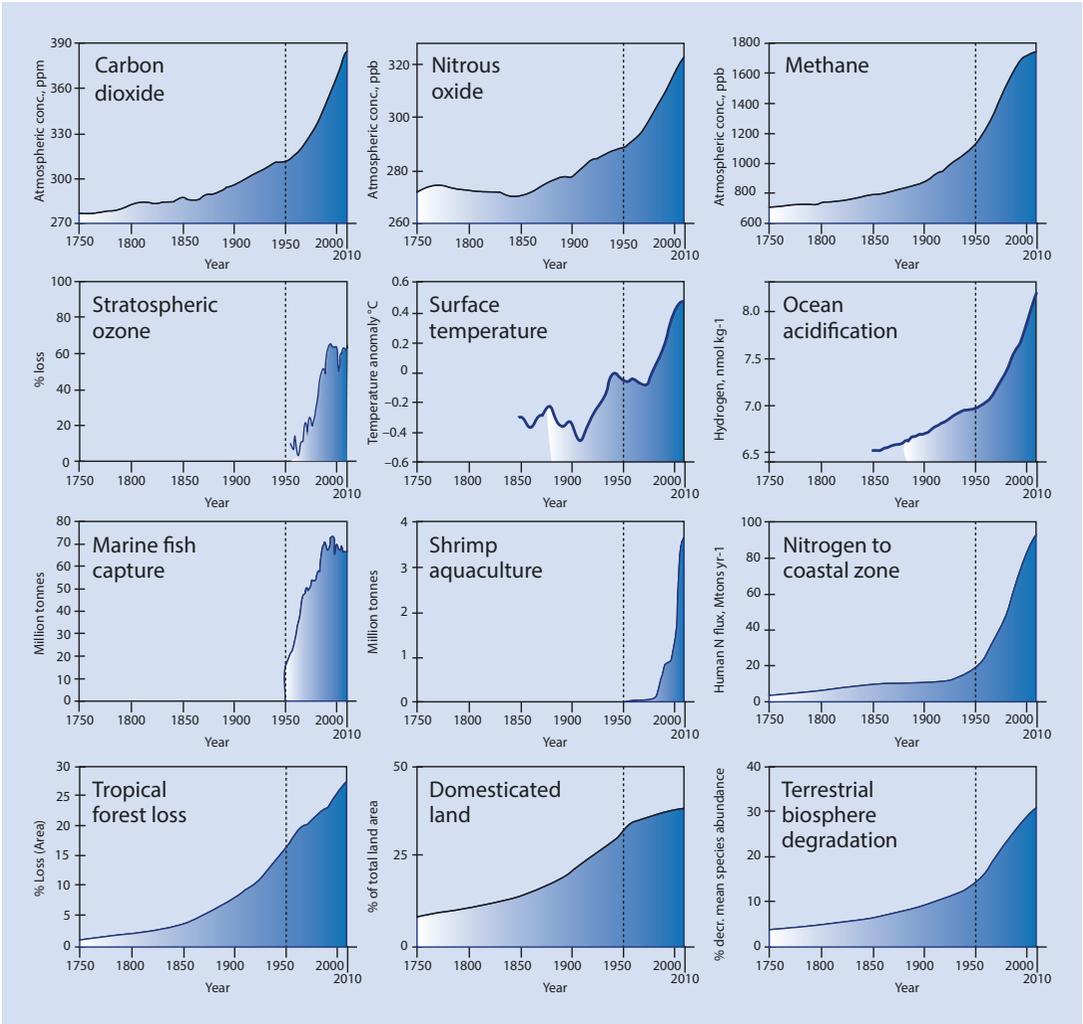
One problem is increased volatility of the weather. Computer simulations predict more frequent and stronger storms, as tropical cyclones feed on warmer water, and more severe thunderstorms and tornadoes are born from the clash of dry and humid air masses. Evapotranspiration increases exponentially with temperature. As the temperature warms and crosses the arid West, the air becomes desiccated and seeks out all available moisture from the ground. As the same warming air masses cross the humid Gulf of Mexico, they pick up more moisture. The part of the country where the cool dry air masses flowing eastward from the Rocky Mountains meet the warm humid air of the Gulf is known as tornado alley. Increased storm damage is now a fact of life in states such as Oklahoma, Texas, and Arkansas. Those on the coast fear storm surge from more powerful oceanic storms. The National Oceanic and Atmospheric Administration has now taken to naming winter storms as they name hurricanes.

Another environmental change attributable to global warming is sea level rise. Water expands as it gets warmer, so part of sea level rise comes from thermal expansion. Part of the rise comes from a positive feedback mechanism called the albedo effect. *Albedo* measures reflectivity, and a reduction in reflectivity can lead to the absorption of more of the sun's radiation. Newly fallen snow reflects about 99% of the radiation that hits it, and blacktop absorbs and reradiates as heat nearly all of the radiation that strikes it. Physicists call an object that absorbs and reradiates 100% of the radiation that strikes it a “perfect black body.” As the planet warms, the ice shelves, which act as “speed bumps,” which inhibit the flow of the glaciers towards the oceans to keep the ice sheets in place, begin to melt. This exposes additional dark ocean water which absorbs more solar radiation. This raises the temperature and melts more ice. The process continues as long as the ocean continues to warm. If the ocean would become warm enough to melt the ice surrounding frozen methane in the Arctic tundra and in the oceans, a 6 °C warming could be a distinct possibility. The sea levels will also rise because the ice shelves have melted and the moving ice sheets add their mass to the ocean. If you recall from ► Chap. 6, humans were likely to have migrated from Asia to the Americas during an ice age. Enough ocean water was taken up in ice to lower the sea levels and create a “land bridge” upon which our ancestors could walk. If carbon dioxide concentrations continue to rise, the opposite will occur. Nearly the entire state of Florida, along with nations such as Bangladesh, is likely to be flooded, along with many coastal cities. Moreover, the drinking water source of billions of Asians can be found in a handful of Himalayan glaciers which are the headwaters of the Ganges, Brahmaputra, Mekong, Irawati, and Yangtze Rivers. The combination of sea level rise and reduced water supply could create a climate refugee problem of epoch proportions. It is likely that these events will occur in the same time frame as running short of petroleum. Will the people of the developed world, deprived of their sources of comfort and convenience and perhaps facing economic dislocation or even collapse, open their arms and welcome billions of climate refugees?

Climate change also has biological effects. According to climatologist James Hansen, more than a thousand studies have shown an average migration rate for various species toward the poles of about four miles per decade. However, the lines of equal temperature called isotherms have been moving poleward at a rate of 35 miles per decade. If carbon emissions continue at the present rate, the isotherm movement will double to 70 miles per decade by the end of the century [9]. Polar and Alpine flora and fauna are simply being pushed off the planet.

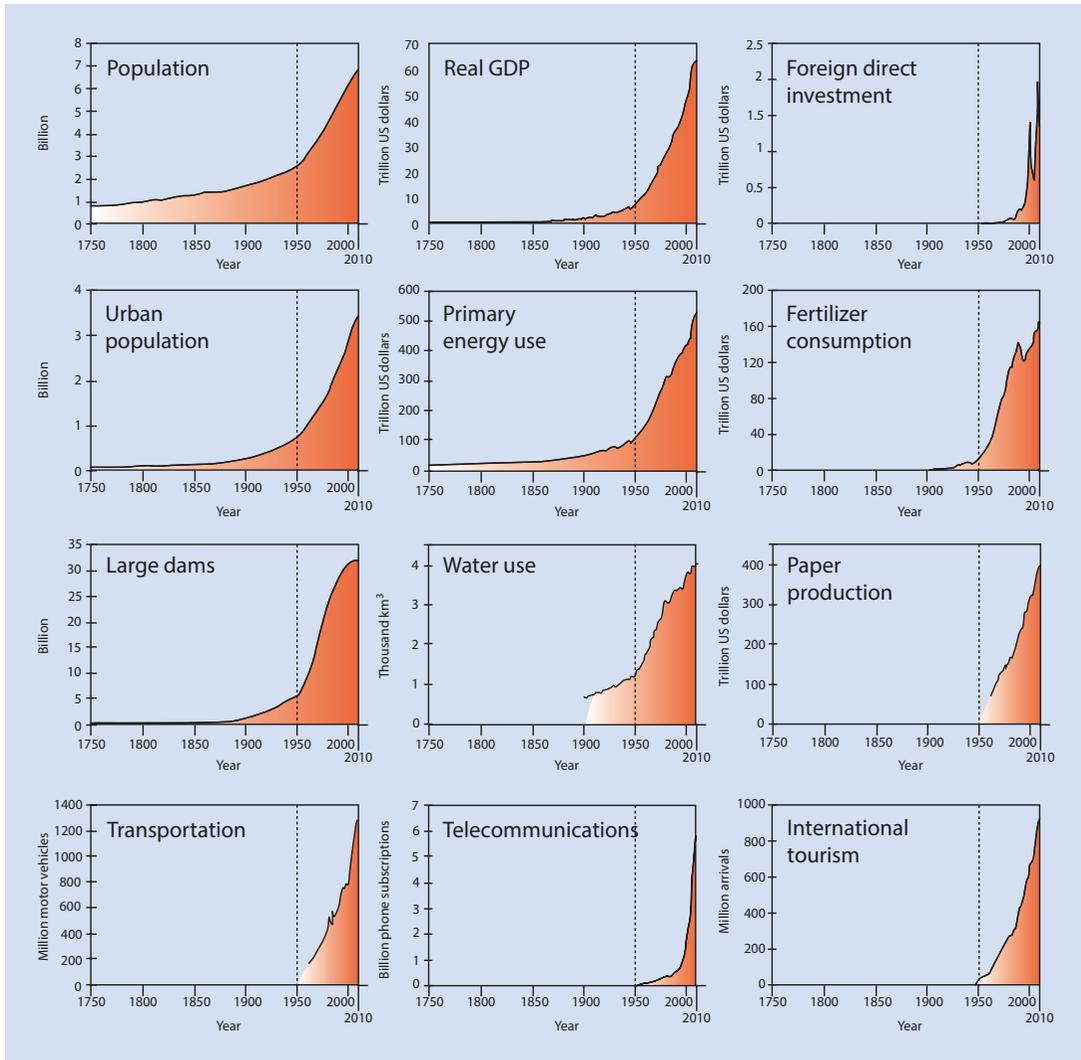
Will we remain in the Holocene, or are we entering a new geological epoch dominated by human action called the Anthropocene? Geologists are still debating the issue. A proponent of the idea that we are now in a new geological epoch is Will Steffan, director of the International Geosphere-Biosphere Program (IGBP). Steffan and colleagues published their analyses in the 2004 *Global Change and the Earth System* [10]. In it they recorded the trajectory of the human enterprise from 1750, the humble beginnings of the fossil fuel age, to 2000. They presented a series of 24 graphs, including both the Earth system and the socioeconomic system. The results were shocking. Nearly every series they looked at was escalating exponentially, with a sharp increase around 1950. They dubbed the period “The Great Acceleration.” On the Earth systems side, carbon dioxide emissions, tropical forest loss, ocean acidification, and coastal nitrogen pollution, among others, were all rising exponentially. In the socioeconomic realm world and urban populations, real gross domestic product, primary energy use, and foreign direct investment showed similar exponential patterns. The series are presented in ■ Figs. 23.4 and 23.5.

People should ask themselves at least two questions. Can the exponential growth of both Earth systems and socioeconomic trends be compatible with the Holocene stability with which our species evolved and thrived, or will the acceleration of carbon dioxide emissions that have not been seen for at least 400,000 years push us into a period of instability or chaos? How will humans adapt and react? We will take up these and other pressing questions in our final chapter (■ Fig. 23.6).



■ Fig. 23.4 Earth system trends

23.4 · Climate Change



■ Fig. 23.5 Socioeconomic trends



■ Fig. 23.6 Carbon emissions in historical perspective

References

1. Murphy, D., and C.A.S. Hall. 2011. Energy return on investment, peak oil, and the end of economic growth. In *Ecological economic reviews*, Annals of the New York Academy of Sciences 1219, ed. R. Costanza, K. Limburg, and I. Kubiszewski, 52–72. Boston: Blackwell Publishing on behalf of the New York Academy of Sciences.
2. Klitgaard, K. 2013. Heterodox political economy and the degrowth perspective. *Sustainability*. 5: 276–297.
3. Kaplan, S. 2016. By 2050 there will be more plastic than fish in the world's oceans. *Washington Post*. January 20.
4. Carson, R. 1962. *Silent spring*. Boston: Houghton-Mifflin.
5. Hoshaw, L. 2009. Afloat in the oceans, expanding islands of trash. *New York Times*. November 9.
6. Rockström, J., W. Steffan, K. Noone, A. Persson, S. Chapin III, E. Lambin, T.M. Lentin, M. Scheffer, C. Folke, H. Joachim, H.J. Schellnhuber, B. Nykvist, C.A. De Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, V.J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J.A. Foley. 2009. *Nature* 461 (24): 472–475.
7. Angus, A. 2016. *Facing the anthropocene*. New York: Monthly Review Press.
8. Foster, J.B., B. Clark, and R. York. 2012. *The ecological rift*. New York: Monthly Review Press.
9. Hansen, J. 2009. *Storms of my grandchildren*. New York: Bloomsbury.
10. Steffan, W., A. Anderson, P.D. Tyson, J. Jäger, P.A. Matson, B. Moore III, F. Oldfield, K. Richardson, H.J. Schellnhuber, R.L. Turner II, and R.J. Wasson. 2004. *Global change and the earth system*. Berlin: Springer.
11. Hall, C.A.S., C. Ekdahl, and D. Wartenberg. 1975. A fifteen-year record of biotic metabolism in the Northern hemisphere. *Nature* 255: 136–138.