Additional reading

The Working Group I report of the IPCC's Fifth Assessment describes, at varying levels of detail, the evidence attributing the recent warming to humans. For the most detail, see Chapter 10 of the report. For a less detailed overview, see Section TS.3 of the Technical Summary. And, for a short, high-level discussion, see Section D.3 of the IPCC's Summary for Policymakers (you can download all of these at www.ipcc.ch/report/ar5/wg1/).

SkepticalScience.com has several useful write-ups that summarize the evidence that humans are responsible for most of the recent warming (www.skepticalscience.com/its-not-us-basic.htm, www.skepticalscience.com/empirical-evidence-for-global-warming.htm).

See www.andrewdessler.com/chapter7 for additional resources for this chapter.

Problems

1. a) List all of the physical processes that can alter the climate.
   b) For all processes in part (a) except greenhouse gases, explain why they are unlikely to be the cause of the warming over the past few decades.
   c) List the evidence that greenhouse gases are responsible for the recent warming.
2. What did the IPCC say in its 2013 report about whether humans are causing climate change? What are the three caveats in the statement?
3. Why are feedbacks (e.g., increases in water vapor) not discussed as potential causes of climate change?
4. Explain the physical mechanism for the occurrence of ice ages. Make sure you explain the role of carbon dioxide and its timing with respect to the temperature change.
5. Critique this statement: "It is clear that it was warmer around 1000 AD, during the Medieval Warm Period, than it is today. Therefore, humans cannot be causing today's warming." Assume that the claim that the Medieval Warm Period was warmer than today is correct (it may have been, but it is debatable). Is this argument correct? Why or why not?
6. What are the three ways that the Earth's orbit varies? How does each variation affect the climate?
7. Explain how the Paleocene-Eocene Thermal Maximum provides support for the claim that today's warming is caused by humans.
8. How does continental drift affect our climate?

8 Predictions of future climate change

In Chapter 6, we discussed the concept of radiative forcing, which is an imposed change in planetary energy balance. In response, the planet's temperature adjusts so as to restore energy balance. Thus, if we can predict how radiative forcing will evolve in the future, we can then estimate how much climate change we will experience.

Predicting future radiative forcing basically comes down to predicting how much greenhouse gas and aerosols will be emitted into the atmosphere each year from human activities. Such projections, known as *emissions scenarios,* therefore form the backbone of our predictions of climate change. In this chapter, I describe how they are constructed and what they tell us about our future climate.

8.1 The factors that control emissions

At its simplest, the amount of greenhouse gas released by a society is determined by the total amount of goods and services consumed by that society. This is true because the production of any good or service – be it a car, an iPhone, a university lecture, a cheeseburger, or an hour of tax consulting – requires energy. And energy is mostly derived from the combustion of fossil fuels, which leads to the release of carbon dioxide to our atmosphere. The emissions of other greenhouse gases and aerosols also generally scale with the amount of consumption, although the causal linkages may not be as direct.

The total value of goods and services produced by an economy is known as the *gross domestic product,* abbreviated GDP. Thus, total emissions by a society are basically set by that society's GDP. If the GDP doubles, then we expect emissions to double, as long as everything else remains the same. This strong link between GDP and emissions can be seen during recessions. For example, during the severe economic downturn of the late 2000s, global carbon emissions posted their biggest drop in more than forty years as the global recession froze economic activity and slashed energy use around the world.

Rather than consider GDP as a whole, it is useful to break it into the product of two factors: population and affluence. It should be obvious that GDP scales with population. Every person in a society consumes goods and services, so if the population doubles (and everything else remains the same), then total GDP will also double. Emissions will therefore also scale with population – so emissions double if the population doubles.

In addition to the number of people, how rich each person is also matters because, as people get richer, they consume more. To illustrate the affect of affluence on GDP and emissions, consider the following three families. The first is a family of four who live as subsistence farmers in sub-Saharan Africa. This family lives in a small one-room house without electricity or running water. They do not own a car and are too poor to buy anything but the bare necessities of life. They farm by hand or with a draft animal. Because the members of this family are so poor and consume so little, they are responsible for little greenhouse-gas emissions.

Now consider a family of four near the bottom of the economic spectrum in the United States. They live in an apartment and they own one car. Their apartment is not air-conditioned; they own a television and one or two heavy-duty electrical appliances, such as an oven. Compared with the subsistence farming family in Africa, this family is far richer and consumes far more and is therefore responsible for more greenhouse-gas emissions.

Finally, consider an upper-class family of four in the United States. This family lives in a 4,000-ft^2 single-family house and owns three cars (for the husband, wife, and a teenage child). The house has televisions in almost every room, several computers, VCRs, game consoles, and a rich assortment of electrical appliances. The family flies to several vacation locations every year. Because of the significant consumption allowed by their affluence, this family is responsible for more emissions than the poorer U.S. family and many, many times the emissions of the subsistence farming family.

This wealth effect leads to enormous disparities in emissions per person. In the United States, emissions are about 5 tons of carbon per person. Emissions in China are 1.7 tons per person – about one-third of U.S. per capita emissions. However, China's population is so large that they nevertheless lead the world in total carbon emissions. Emissions in Nigeria are 0.1 tons per person – about one-fiftieth of the United States – reflecting the country's poverty.

We need a third factor to convert a level of total consumption, expressed in dollars, to greenhouse-gas emissions. This last factor relates how much greenhouse gas is emitted for every dollar of consumption; it is known as the *greenhouse-gas intensity*. Putting these all together, we can now relate emissions to the factors that control it in a simple equation:

$$I = P \times A \times T \tag{8.1}$$

Here I represents the total emissions of greenhouse gases into the atmosphere (these emissions then cause climate impacts, which is why emissions are represented by the letter I); P is the population, A stands for affluence, and T stands for greenhouse-gas intensity. Affluence A is GDP per person – the average amount of goods and services each person consumes – so the product of P and A is the GDP. The decomposition of emissions into these factors is often referred to as the *IPAT relation* or the Kaya Identity.

The greenhouse-gas-intensity term T can be usefully broken down as the product of two terms:

$$T = \text{EI} \times \text{CI} \tag{8.2}$$

EI stands for *energy intensity* – the number of joules of energy it takes to generate one dollar of goods and services. The EI of an economy is primarily determined by two factors. First is the mix of economic activities that make up the economy. For example,

it takes much more energy for a steel mill to produce one dollar's worth of steel than for a university to produce one dollar's worth of teaching. The steel mill must run blast furnaces and other heavy equipment, whereas the university only requires lighting, air-conditioning, computers, and the like. More generally, industrial manufacturing has a higher energy intensity than white-collar service-oriented activities. The more industrial manufacturing an economy has, the higher its energy intensity.

The second factor in determining the energy intensity of an economy is the efficiency with which the economy uses energy. For any economic activity, there are usually several technologies to accomplish it. For lighting, for example, there is the standard incandescent light bulb (the kind with the filament) or the compact fluorescent light bulb. As described in Chapter 3, incandescent light bulbs are dreadfully inefficient, requiring 60 W of power to produce the same light as a compact fluorescent light bulb drawing 14 W. Both light-bulb technologies can light a room, but they consume vastly different amounts of energy doing it. The trade-off is that better technology is often more expensive. As a result, it takes a certain level of wealth in order to adopt the most energy-efficient technology, and the efficiency with which different countries utilize energy can vary greatly.

CI in Equation 8.2 stands for *carbon intensity* – the amount of greenhouse gas emitted per joule of energy generated – which reflects the mix of technologies used to generate energy. Put another way, it is determined by whether the economy uses coal, oil, gas, nuclear, wind, solar, etc. to generate energy. Among fossil fuels, combustion of natural gas (methane or CH_4) produces the least carbon dioxide per joule of energy generated. Thus, it has the lowest carbon intensity, which is one of the reasons it is often considered to be the "greenest" of the fossil fuels. Oil produces more carbon dioxide per joule than methane, so it has a higher carbon intensity. The most carbon-intensive fossil fuel is coal – it produces roughly twice the carbon dioxide per joule as methane – which explains why many people who are concerned with our climate are opposed to the construction of new coal-fired power plants. Energy sources also exist that produce no carbon dioxide, such as hydroelectric, nuclear, wind, and solar energy sources.

For a country such as France, which generates most of its electricity from nuclear energy, the carbon intensity will be smaller than for a country such as China or the United States, which both rely heavily on coal for electricity.

An aside: Check the units!

One of the most powerful ways to check your work is to make sure that the units in a problem work out. We do this now to close the loop on our understanding of the factors that regulate carbon emissions.

Population is obviously the number of people. Affluence is dollars of GDP per person. The product of population and affluence is therefore GDP, which has units of dollars:

$$\#\text{ of people} \times \frac{\$\text{GDP}}{\text{person}} = \$\text{GDP}$$

Energy intensity has units of joules per dollar, and carbon intensity has units of carbon dioxide emitted per joule. Greenhouse-gas intensity is the product of energy

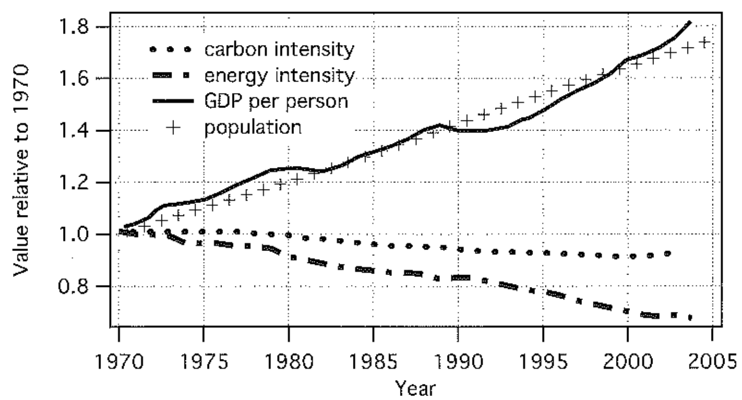

Figure 8.1 Population, affluence, carbon intensity, and energy intensity for the entire world, relative to values in 1970 (adapted from IPCC, 2007b, figure 2).

intensity and carbon intensity, and therefore it has units of carbon dioxide emitted per dollar:

$$\frac{J}{\$GDP} \times \frac{CO_2}{J} = \frac{CO_2}{\$GDP}$$

Finally, the product of population, affluence, and technology has units of carbon dioxide emitted:

$$\#\text{ of people} \times \frac{\$GDP}{\text{person}} \times \frac{CO_2}{\$GDP} = CO_2$$

8.2 How these factors have changed in the recent past and how will they change in the future

In the last section, emissions of carbon dioxide were deconstructed into the controlling terms: population, affluence, energy intensity, and carbon intensity. Let us look at how these terms have changed over the past few decades and how they might change in the future.

8.2.1 Population

Population has been rapidly increasing for the past few centuries. It took all of human history up to 1804 for the global population to reach 1 billion. The 2-billion-people mark was reached 123 years later, in 1927, and the 3-billion-people marker was reached 33 years later, in 1960. Since then, world population has been increasing by 1 billion people every twelve to thirteen years, reaching 6 billion in 1999 and 7 billion in 2011. Figure 8.1 shows that the population has increased by 80 percent over the past few decades. Today, world population is increasing by roughly 200,000

people per day, a population growth rate of approximately 1 percent/year. Most of this growth is occurring in the developing world, where fertility rates remain high.

In estimating future population change, some of the controlling factors are well known. Affluence, for example, strongly determines how many kids a woman has, with the poorest countries having the highest fertility rates. In extremely poor societies, children can be put to work at a young age and are therefore a source of income. This is generally not the case in rich countries, where children are a net drain on family resources for many years (trust me on that). In addition, high rates of childhood death in poor countries mean that parents must have many children to ensure that some of them survive into adulthood. Improvements in health care that occur as a society gets richer, however, mean that rich parents can reasonably expect their children to survive into adulthood. The amount of education that women receive is also a factor, with fertility rates declining as women become better educated and good-paying jobs become available to them as an alternative to child rearing. Our understanding of these factors gives us some ability to predict future population.

However, some events that affect population are impossible to predict. It is impossible to predict, for example, societal changes, such as a future Pope suddenly embracing birth control, causing a fertility decline among the roughly one billion Catholics. Or the occurrence of chance events, like a nuclear war or the emergence of new diseases like AIDS, which kill millions of people.

The lowest population scenarios predict population will peak at around 9 billion in the middle of the twenty-first century, decreasing thereafter and reaching 7 billion by 2100. Higher population scenarios predict population increasing, more or less continuously, reaching 16 billion by 2100. Our best estimate is that world population will stabilize during the twenty-first century around 10 or 11 billion.

8.2.2 Affluence

Figure 8.1 shows that affluence, measured as GDP per person, increased by 80 percent over the past few decades of the twentieth century. My personal experience backs this up. When I was a college student in the early 1980s, I did not own a cell phone or a laptop or tablet computer, my car had handcranked windows, did not have air conditioning or antilock brakes or an airbag, and only had an AM radio. I did not own a TV or videogame console. I had, in other words, a far lower standard of living than most of today's college students.

We can also see discrete political events in the affluence data, such as the 1989 collapse of the Soviet Union and the associated political upheaval in Eastern Europe, as well as various recessions. Moreover, in the past decade, the remarkable economic growth of China (with affluence growing at 10 percent/year or so) and other large developing countries has played a key role in driving global growth of consumption.

In the future, factors such as the level of education in the population, rule of law, free trade, and access to technology will be key in determining how fast affluence grows. In general, economic growth rates are highest for countries making a transition out of poverty and into the group of rich countries of the world. For example, economic growth was fastest in the United States in the late nineteenth century, in Japan after World War II, and in China today. Growth rates are lower for large, advanced societies. Based on these factors, expert predictions are that affluence will increase over the twenty-first century at 2 to 3 percent/year for developing countries and 1 to 2 percent/year for industrialized countries.

8.2.3 Technology

The first part of the technology term, the energy intensity term, has decreased over the past century as our society has developed more efficient ways to use energy (Figure 8.1). Some of this increasing efficiency has been driven by market forces: Because energy costs money, a more energy-efficient piece of equipment or process will reduce costs, which consumers want. As a result, just about everything you buy today is more energy efficient than the comparable version of a few decades ago. Much of this increase in efficiency is incremental, meaning that each new generation of a particular piece of equipment uses slightly less energy than the previous version. Sometimes, however, there is a revolution in technology that greatly reduces energy consumption. A good example is the revolution in lighting technology we are now experiencing. As the world switches from incandescent bulbs to compact fluorescent bulbs and LED bulbs, the amount of energy being consumed by lighting will experience a substantial one-time drop.

Changes in the mix of goods and services produced by the world's economy has also led to decreases in energy intensity. Over the past century, the fraction of the world economy based on energy-intensive heavy industry and manufacturing has declined, while the fraction based on services has increased.

Overall, energy intensity has at times decreased as fast as 2 percent/year, but the periods of fastest decreases occurred during periods of rapid economic shifts or as responses to energy price shocks. More typical values for the twentieth century were decreases of 1 percent/year. It is likely that this rate of decrease can be sustained over the coming century.

Figure 8.1 also shows that carbon intensity, the amount of carbon dioxide released per joule of energy generated, has decreased slightly over the past few decades as the world shifts from coal to cleaner natural gas. Nevertheless, coal plants continue to be built, particularly in developing countries such as China, and this prevents more rapid decarbonisation of our economy.

Continued reductions in carbon intensity can be expected given the flood of cheap natural gas that has arisen from the development and application of new drilling techniques, in particular hydraulic fracturing (more commonly known as fracking). Increases in renewables (e.g., wind and solar) are also expected to reduce carbon intensity. Depending on government policies, however, adoption of renewables could be slow or rapid, leading to minimal or large reductions in carbon intensity. These trends are expected to continue the long-term decline in coal usage, although coal consumption is still increasing in certain places, such as China.

Overall, increases in population (P) and affluence (A) have increased faster than greenhouse-gas intensity (T) has declined, leading to an increase in emissions of 75 percent between 1970 and 2005. Whether this happens in the future depends in large part on how the world's economy evolves and what the world decides to do about climate change, as we discuss in the next section.

8.3 Emissions scenarios

"It's hard to make predictions – especially about the future?"[1]

Although we have a good idea of the factors that control greenhouse-gas emissions, making accurate predictions of these factors is difficult. For example, predicting future population trends requires predictions of factors such as the rate of poverty, evolution of religious and social views on birth control, the rate of education of women in high-fertility regions, available healthcare in these regions, and so on.

Because of this difficulty, it is impractical to make a single prediction of future emissions. Instead, the community of experts has developed a set of alternative *emissions scenarios*. Each scenario is an internally consistent vision of one way the world might evolve in the future, and the full set of emissions scenarios is designed to span a plausible range of alternative futures.

The scenarios most recently used by the IPCC in its predictions of future climate change are known as the *Representative Concentration Pathways*, frequently abbreviated RCP. The individual RCP scenarios are named RCPx, where x is the radiative forcing in 2100. Thus, the RCP8.5 scenario has radiative forcing of 8.5 W/m^2 in 2100, while the RCP2.6 scenario has radiative forcing of 2.6 W/m^2 in 2100.

Each RCP scenario is associated with an internally consistent set of assumptions for population, affluence, and technology. For example, because people have fewer children as they get richer, the scenarios in which the world's poor become richer feature slower population growth than the scenarios in which poverty is rampant. And the development and adoption of new technology requires high economic growth to support it – so the higher the economic growth scenarios also have more rapid adoption of new and cleaner technologies.

Given an emissions scenario, the atmospheric concentrations of carbon dioxide can be calculated by feeding those emissions into a carbon-cycle model. The carbon-cycle model calculates how much of the carbon dioxide emitted to the atmosphere is absorbed by the ocean and land reservoirs. The remainder stays in the atmosphere and increases atmospheric carbon dioxide.

Figure 8.2 shows yearly carbon dioxide emissions during the twenty-first century. The RCP8.5 scenario is the most pessimistic – it assumes that humans make essentially no effort to reduce emissions. As a result, emissions increase throughout the twenty-first century, reaching 30 GtC/year by 2100 – about triple today's emissions. Emissions level off and decrease after 2150, reaching near-zero emissions by 2250.

Figure 8.3 shows that atmospheric carbon dioxide abundances increase rapidly in response to RCP8.5's huge emissions, with mixing ratios exceeding 1,800 ppm in 2200 – this is more than six times the preindustrial abundance of 280 ppm.

The RCP6 and RCP4.5 scenarios assume that the world makes some effort to reduce emissions; as a result, they have emissions peaking in the middle of the twenty-first century. This leads to atmospheric carbon dioxide stabilizing early in the

[1] This statement has been attributed to various people, including Niels Bohr and Yogi Berra.

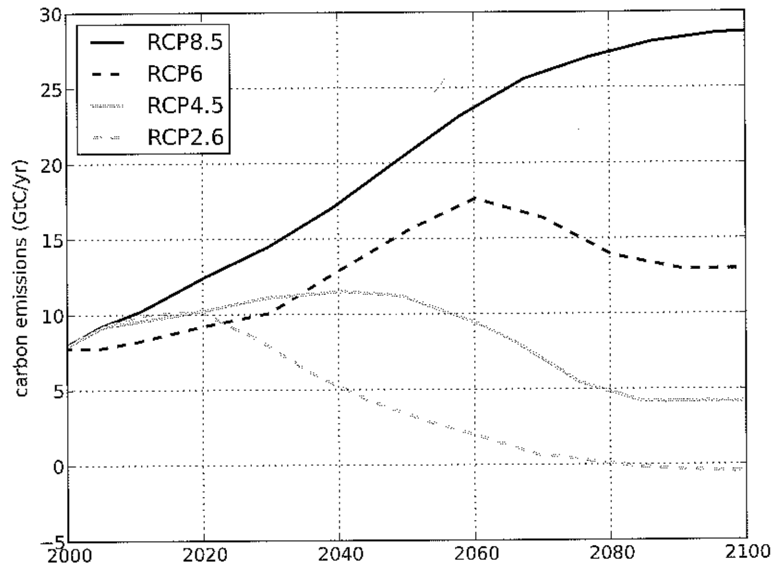

Figure 8.2 Emissions of carbon dioxide for the four emissions scenarios. The emissions are in GtC per year (adapted from figure 6 of van Vuuren et al., 2011).

next century at 750 ppmv and 540 ppm, respectively – corresponding to about three times and twice preindustrial carbon dioxide abundance.

The RCP2.6 scenario is the most optimistic scenario, with emissions peaking around 2020 and then decreasing throughout the rest of the century. After 2080, emissions actually become net negative, meaning that carbon removal from the

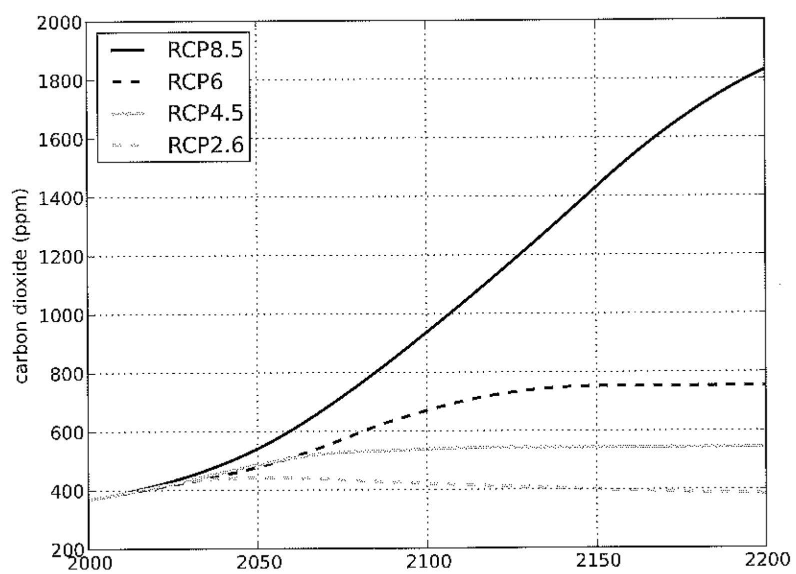

Figure 8.3 Atmospheric abundances of equivalent carbon dioxide (in ppm) for the four emissions scenarios. Equivalent CO_2 is the amount of CO_2 that gives the same radiative forcing as the full suite of radiative forcers in the atmosphere in any year (data downloaded from the RCP database: www.iiasa.ac.at/web-apps/tnt/RcpDb).

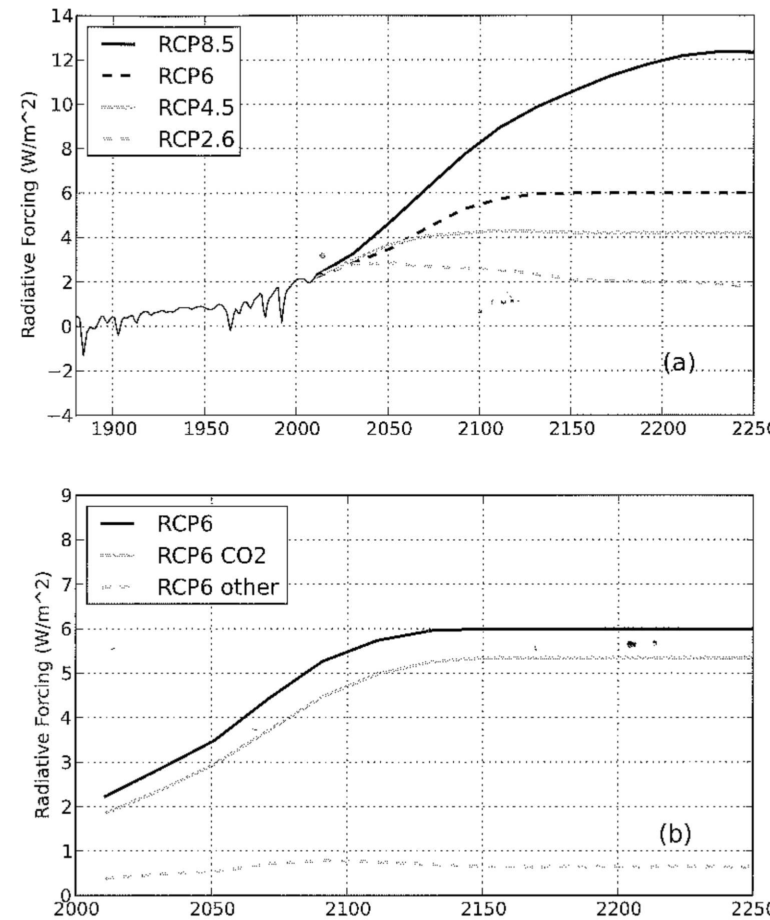

Figure 8.4 (a) Radiative forcing for the emissions scenarios (historical radiative forcing is plotted before 2010). (b) Radiative forcing for the RCP6 scenario, along with the radiative forcing in that scenario just from carbon dioxide and from everything other than carbon dioxide (data downloaded from the RCP database: www.iiasa.ac.at/web-apps/tnt/RcpDb).

atmosphere (by, for example, growing plants and then burying the carbon) exceeds carbon released to the atmosphere. This leads to atmospheric carbon dioxide peaking in 2050 at 440 ppm and decreasing thereafter. By 2150 it is below present day values of 400 ppm, and by 2500, it is 327 ppm – almost back to preindustrial carbon dioxide. Achieving anything close to the RCP2.6 trajectory would require truly heroic efforts.

8.4 Predictions of future radiative forcing

Given the atmospheric abundances of carbon dioxide in Figure 8.3, along with abundances of other greenhouse gases and aerosols, the radiative forcing can be calculated. Figure 8.4a shows the radiative forcing predicted for each scenario over the next

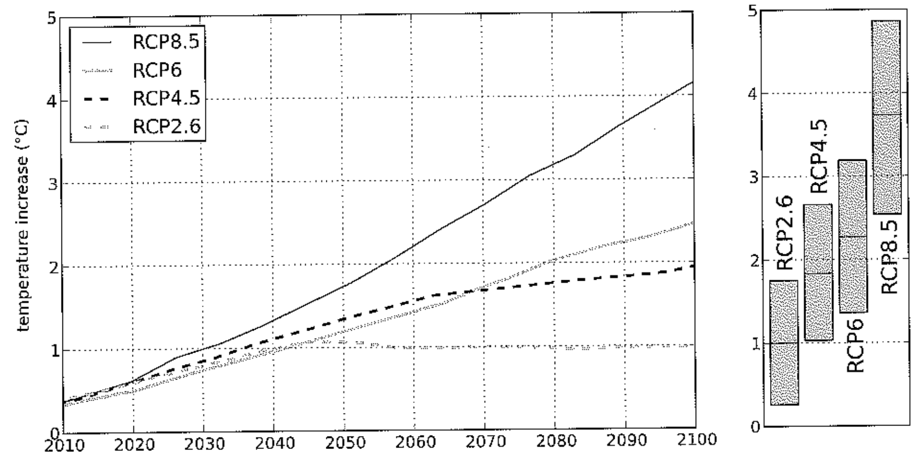

Figure 8.5 (left) Model estimates of global annual average surface temperature for the four emissions scenarios (relative to the 1986–2005 average). The bars at right are the likely temperature difference between the 1986–2005 period and the 2081–2100 period. Adapted from figure SPM.7 of IPCC [2013].

250 years. Forcing in the RCP8.5 scenario increases until about 2200, when it reaches more than 12 W/m^2. Forcing in the RCP6 and RCP4.5 scenarios stabilizes around 2100 at 6 and 4.5 W/m^2, respectively. Radiative forcing from the optimistic RCP2.6 scenario declines continuously from its peak around 2020. By 2150 in this scenario, radiative forcing has declined below present day values.

Figure 8.4b shows radiative forcing from the RCP6 scenario, along with the radative forcing broken down into the contribution from carbon dioxide and from everything else. The plot shows that, as we go into the future, carbon dioxide is responsible for virtually all of the increase in radiative forcing – the non-carbon dioxide component does not change much. The reason for this is carbon dioxide's long lifetime in the atmosphere (discussed in Chapter 5) – once emitted, carbon dioxide stays in the atmosphere for centuries. So carbon dioxide accumulates in the atmosphere like water in a stopped up sink, and the radiative forcing from it accumulates too. Other greenhouse gases, like methane, have a much shorter lifetime (methane's is about ten years), so it does not accumulate in the same way that carbon dioxide does. This explains why there is such a strong focus on carbon dioxide in policy debates over climate change.

8.5 Predictions of future climate

8.5.1 Over the next century

The estimates of atmospheric radiative forcing shown in Figure 8.4 are then input to climate models, which calculate a future climate for each scenario. These are plotted in Figure 8.5 and they show that the set of emissions trajectories translates into a wide range of future climates. The large emissions associated with the RCP8.5 scenario

lead to temperature increases of 4°C over the twenty-first century, while the low emissions associated with the RCP2.6 scenario lead to temperature increases of only 1°C, mostly during the first half of the century. If you want to relate the warming to preindustrial temperatures, add about 0.8°C to each of these numbers.

Given the present political environment, the RCP2.6 scenario, which has emissions peaking around 2020, appears hopelessly optimistic. This RCP4.5 scenario, with emissions peaking around 2040 and atmospheric carbon dioxide stabilizing around 540 ppm, seems (to me, at least) the best we can hope for. That scenario yields warming of 1.8°C over the twenty-first century. Of course, we might do worse than this, and even the RCP8.5 scenario is not out of the question. Given this, a reasonable estimate of temperature increases over the twenty-first century might be 1.8–4.2°C.

It is worth noting that, despite huge differences in emissions, the scenarios predict relatively similar warming until they begin to diverge around 2040–2050. This occurs for two main reasons. First, emissions reductions require us to fundamentally rebuild our energy infrastructure. Doing this at any kind of reasonable cost means that it will take place over several decades. Thus, even the most stringent efforts to cut emissions will have only modest near-term impact (this can also be seen in emissions estimates in Figure 8.2). Second, the high heat capacity of the ocean means that any difference in radiative forcing needs to act for several decades before significant differences in surface temperatures are evident.

The upshot is that the temperature trajectory over the next few decades has already been determined largely by greenhouse-gas emissions that have already occurred, investments in energy infrastructure that we have already made, and the slow response of the climate system due to thermal inertia from the ocean.

But Figure 8.5 also clearly shows that we do have significant control over the amount of warming experienced by the end of the twenty-first century. This is one of the many aspects of climate change that make it difficult to solve. Addressing climate change will require us make investments now and in the next few decades in renewable energy and other energy efficiency technologies. But these investments will really only pay off in the second half of the century. In other words, addressing climate change requires people today to take actions that mainly benefit future generations.

The right-hand panel in Figure 8.5 shows the likely range of temperatures at the end of the twenty-first century predicted for all four RCP scenarios. This range is generated by taking the same emissions scenarios and running them through a large number of different climate models. Because each climate model handles the details of the physics of the climate system differently, the models produce slightly different results. Thus, predictions of climate at the end of the twenty-first century are uncertain because of uncertainty in which emissions pathway the world will follow and also because of uncertainties in the physics of the climate models.

An aside: Will the evolution of the climate over the twenty-first century look like the trajectories plotted in Figure 8.5?

Not really. If you look at Figure 2.2a, you will see that, over the past 130 years, the climate has generally warmed, but it also shows significant year-to-year variability, which is caused by things such as El Niño cycles and volcanic eruptions. Such variability means that temperatures can decline for a few years, even as the climate is experiencing a long-term warming (this was shown in Figure 2.5). Individual model simulations also show this year-to-year variability. The model lines plotted in Figure 8.5, however, are not the result of individual model runs. Instead, each line is the average of many model runs. In the individual model runs going into the average, the highs and lows caused by the short-term variability do not occur at the same time, so when you average many model runs together, the short-term ups and downs tend to cancel out and you get a smooth increase in temperature throughout the century. In reality, short-term variability is going to be important and we can expect the same kinds of ups and downs seen in the past 130 years to continue to occur in the future.

8.5.2 Climate change beyond 2100

Even though Figure 8.5 stops in Year 2100, climate change does not stop at that date. Exactly how long emissions can continue is a fiercely debated point. Fossil fuels must eventually run out, and emissions from their combustion will then cease. The range of total possible emissions until that occurs extends from lower values of 1,500 GtC to more worrying estimates of 5,000 GtC. These estimates are all well above the 370 GtC that humans have already emitted into the atmosphere over the past few centuries, and even the lowest estimates of carbon reserves would, if we burned it all, lead to a manyfold increase in atmospheric carbon. It seems likely to me that greenhouse-gas emissions will eventually cease because of concern about climate change or because technological developments make fossil fuels obsolete. But, given the deadlock in the public climate change debate, it is difficult to predict when that will occur.

In Chapter 5, we talked about the long lifetime of carbon dioxide in our atmosphere: Of carbon dioxide emitted into the atmosphere today, about 25 percent will still be in the atmosphere in several centuries, and it will take hundreds of thousands of years to remove all of the added carbon from the atmosphere (Figure 5.9). The impact of the long residence time of carbon dioxide in our atmosphere is shown in Figure 8.6a, which shows atmospheric carbon dioxide over the next 1,000 years for emissions scenarios in which atmospheric carbon dioxide increases until it reaches 550, 850, and 1,200 ppm, at which point emissions from human activity decline instantly to zero.

Even by the year 3000, eight to nine centuries after carbon dioxide emissions ceased, atmospheric carbon dioxide in all scenarios remains well above preindustrial values (280 ppm). This is simply a reflection of how long it takes for an addition to atmospheric carbon dioxide to be removed.

The long-term evolution of temperatures associated with these carbon dioxide time series are shown in Figure 8.6b. Even after emissions cease, the temperatures do not significantly decline over the next 1,000 years. This is a consequence of three factors. First, carbon dioxide remains elevated throughout the millennium, so it continues to trap heat for a very long time after emissions stop. Second, the ocean's large heat capacity means that the planet cools off very slowly because of its large heat capacity. This is the flip side of the situation in which the warming lags the carbon dioxide

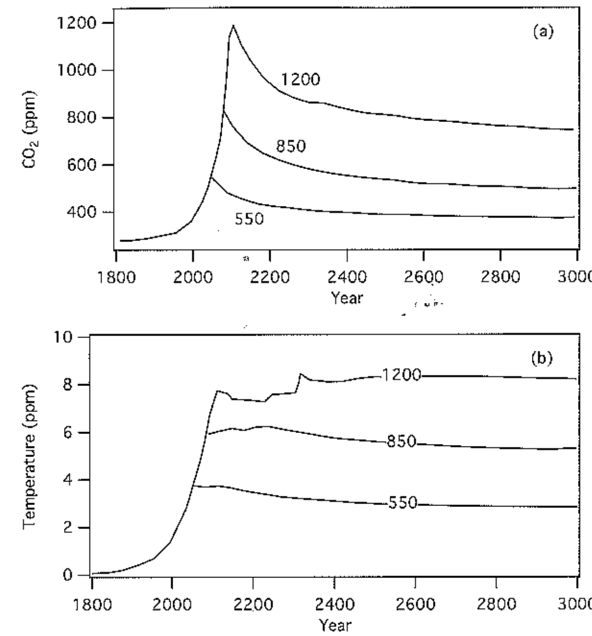

Figure 8.6 (a) Amount of carbon dioxide in the atmosphere as a function of time, for the next 1,000 years. Carbon dioxide emissions rise at 2 percent/year until it hits a peak abundance (550,850, and 1,200 ppm); then emissions are decreased instantly to zero. (b) The temperature time series corresponding to each carbon dioxide time series (adapted from Solomon et al., 2009, figure 1).

increase – the cooling will lag any decrease in atmospheric carbon dioxide abundance. Third, slow feedbacks, such as the very slow destruction of the planet's big ice sheets, will act to oppose any cooling.

The important point here is that emitting large amounts of carbon dioxide to the atmosphere this century commits the planet to elevated temperatures for thousands of years. Once the temperatures rise, reducing emissions will not bring the temperature back down quickly. We can therefore think of climate change as being irreversible over any time period that we conceivably care about. This also means that actions we take today (or do not take) to curb emissions over this century will essentially determine the climate for thousands of years. It is sobering indeed to realize that people of the year 3000 or 4000 will be so affected by actions we take today.

The irreversibility of carbon dioxide emissions can be usefully contrasted with the second most important greenhouse gas, methane. Methane has an atmospheric lifetime of ten years, meaning that a few decades after emission, just about all of the methane is gone from the atmosphere. Thus, if humans ever stop emitting methane, we would be back down to its preindustrial value in a few decades.

8.6 Is the climate predictable?

One criticism of climate predictions goes something like this: "We cannot predict the weather next week, so why does anyone believe predictions of the climate in a hundred years?" This may sound reasonable, because it is based on the correct observation that weather predictions are only accurate a week or so into the future. However, the argument is built on a fatal flaw – it makes the mistake of equating weather predictions with climate predictions. In fact, it *is* possible to predict the climate in 100 years even if weather is only predictable for a few days.

The root cause of this conundrum is that predicting the weather and predicting the climate are fundamentally different problems. A weather forecast is a prediction of the exact state of the atmosphere at an exact time: "At 8 AM tomorrow, the temperature in Washington, DC, will be 3°C, and it will be raining." If you get the time of an event wrong – for example, you predict rain for 8 AM but it does not rain until 6 PM – then you have blown the forecast. If you predict rain for the Washington, DC, area but the rain falls 50 km to the west in Northern Virginia, then you have blown the forecast. And if your temperature is off by a few degrees and snow falls instead of rain, and it completely snarls traffic on Interstate 495, then you have *really* blown the forecast.

A climate prediction, in contrast, does not require predicting the exact state of the atmosphere at any particular time; instead, it requires predicting the *statistics* of the weather over time periods of years. Thus, a climate prediction for the month of March for the years between 2080 and 2090 for a particular location might be as follows: average monthly temperature of 12°C, with an average high of 16°C and an average low of 5°C; monthly average precipitation of 6.0 cm; and so on.

Being unable to make a prediction of the exact state of a complex system (e.g., the weather) does not preclude the ability to predict the statistics of the system (e.g., the climate). As an analogy, consider that it is virtually impossible to predict the outcome of a single flip of a coin. However, the statistics of coin flips are trivial: If you flip a coin 100 times, I can tell you that you will get approximately fifty heads and fifty tails. In other words, the inability to accurately predict any single coin flip does not preclude the ability to predict the long-term statistics of the coin.

To make this point more concretely, answer the following question: "Is it going to be hotter in Texas next January or next August?" If you know Texas weather, you can predict with 100 percent certainty that August is the hotter month, and you can make this prediction months, years, or decades in advance. Think about that for a minute: You just made a climate prediction that is valid years in advance – far beyond the ability to predict weather.

More technically, weather forecasts belong to a class of problems known as initial value problems. This means that, to make a good prediction of the future state of the system, you must know the state of the system now. If you have a marble rolling down a slope, and you want to predict where it will be in one second, you need to know where it is now to make that prediction. Similarly, to make a good weather forecast for tomorrow, you have to accurately know the state of the atmosphere today. The state of today's atmosphere is then put into a forecast model, which turns out a prediction of tomorrow's atmosphere. However, small errors in our knowledge of today's atmosphere grow exponentially, so that a forecast more than a few days in the future is dominated by the errors in our knowledge of today's atmosphere. That is why weather forecasts break down after a few days.

Climate forecasts are a class of problems known as boundary value problems. This type of problem does not require knowledge of today's atmospheric state but rather requires a knowledge of the radiative forcing of the climate. This is why, for example, we can predict with 100 percent certainty that August in Texas will be on average hotter than January in Texas. We know this because we know that more sunlight falls on Texas and the rest of the northern hemisphere during summer, leading to higher temperatures.

Increases in greenhouse gases also increase the heating of the surface, although by infrared radiation rather than visible. Thus, we can have confidence that, if we add greenhouse gas to the atmosphere, the increase in surface heating will warm the planet – just as we can predict that summer will be hotter than winter.

One should not take this to mean that predicting the climate is an easier problem than predicting the weather, only that they are different problems. Some aspects of the climate problem are, in fact, harder than the weather problem. For example, because weather forecasts cover only a few days, weather models can assume that the world's oceans and ice fields do not change. Climate models, however, cannot make this assumption, because both the world's oceans and its ice fields can significantly change over a century. Climate models must therefore predict changes in these and other factors in order to accurately predict the evolution of the climate system over a century.

8.7 Chapter summary

- Prediction of future climate requires predictions of future emissions of greenhouse gases from human activities. Such predictions are known as emissions scenarios.
- The factors that control emissions are population (P), affluence (A), and greenhouse-gas intensity (T). This is expressed by what is known as the IPAT relation: $I = P \times A \times T$, where I is carbon dioxide emissions.
- Greenhouse-gas intensity is the product of energy intensity and carbon intensity. Energy intensity reflects the efficiency with which the society uses energy as well as the mix of economic activities in the society, with units of Joules of energy consumed per dollar of economic output. The carbon intensity reflects the technologies the society uses to generate energy, and it has units of carbon dioxide emitted per Joule of energy produced.
- Because predictions of the future are so uncertain, scientists have constructed a set of plausible, alternative scenarios of how the world might evolve. Taken as a group, these Representative Concentration Pathways span the likely range of future emissions trajectories.
- Putting these emissions scenarios into a climate model yields predictions of warming over the twenty-first century of 1.8 to 4.2°C. This is much larger than the warming of 0.8°C that the Earth experienced over the course of the twentieth century.
- Climate change does not stop in Year 2100. Carbon dioxide stays in the atmosphere for centuries after it is emitted, so large emissions of carbon dioxide this century will cause the Earth's temperatures to remain elevated for thousands of years.

- Even though weather is not predictable beyond a few days, we can nevertheless make climate predictions decades in advance. A climate prediction is a prediction of the statistics of the system. For many complex systems, predicting the statistics is easier than predicting the specific state of the system.

Additional reading

Chapter 11 (Kirtman et al., 2013) and chapter 12 (Collins et al., 2013) of the IPCC's 2013 report detail, respectively, short-term and long-term predictions of climate change.

Section 12.3 of Collins et al. (2013) describes the RCP scenarios. For a more readable description, see SkepticalScience: www.skepticalscience.com/rcp.php

D. Archer, *The Long Thaw: How Humans Are Changing the Next 100,000 Years of Earth's Climate* (Princeton, NJ: Princeton University Press, 2010). Among the many things covered in this book is the very long-term evolution of climate change.

See www.andrewdessler.com/chapter8 for additional resources for this chapter.

Terms

Carbon intensity
Emissions scenario
Energy intensity
Greenhouse-gas intensity
Gross domestic product (GDP)
IPAT relation
Representative Concentration Pathways

Problems

1. a) Someone asks you about how much the climate will warm over the next 100 years if we do nothing to address climate change. How do you answer?
   b) If the amount of carbon dioxide and other greenhouse gases stopped increasing today and were held constant into the future, how do you think the climate would change over the next century?
2. a) Define each term in the IPAT identity.
   b) What are the units of each term? Show how the units cancel so that the *I* term has units of emissions of greenhouse gases.
3. a) The *T* term can be broken into two terms. What are these two terms, and what are their units?

   b) If we switch from fossil fuels to solar energy, which of the terms changes, and does this term increase or decrease?
   c) If we convert from traditional incandescent lighting to LED lights, which of the terms changes, and does this term increase or decrease?
   d) If we switch from natural gas to coal, which of the terms changes, and does this term increase or decrease?
4. Consider this argument: "We cannot predict the weather in a week, so there is no way we can believe a climate forecast in 100 years." Is this argument right or wrong? Explain your answer.
5. If we emit significant amounts of carbon dioxide this century, how long will the planet remain warm?
6. Assume population grows at 2 percent/year and affluence grows at 3 percent/year.
   a) How fast does the technology term have to decrease so that total emissions do not change?
   b) How fast does the technology term have to decrease to reduce emissions by 20 percent in twenty years?
7. Explain how your level of wealth impacts how much emission of carbon dioxide you are responsible for.
8. In 2002, the Bush Administration set a goal of reducing greenhouse gas intensity by 18 percent by Year 2012. How ambitious is this goal? What does this goal tell us about changes in emissions?