CHAPTER 5
CARBON EMISSIONS AND CLIMATE CHANGE

Human beings are now carrying out a large-scale geophysical experiment of a kind that could not have happened in the past nor be repeated in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in the sedimentary rocks over hundreds of millions of years... thus .... the need to observe vigilantly the consequences of man’s consumption of fossil fuels....

Revelle and Seuss (1957).1

Introduction

The idea that atmospheric carbon dioxide might somehow affect the earth’s climate is far from new. As early as 1824, the French mathematician Joseph Fourier suggested that the earth’s atmosphere caused the planet to be warmer than it otherwise would be.2 Not long after, in the 1850s, the Irish scientist John Tyndall, a noted alpinist who proposed that the cycles of glaciation in the Pleistocene, only recently discovered, were related to atmospheric CO₂, based on his ground-breaking studies of the absorption of infrared radiation by various gases, especially water vapor but including CO₂.3 This idea was put on a quantitative foundation by Arrhenius and Thomas Chamberlin at the end of the 19th century.4 Remarkably, it has

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1This report by Revelle and Seuss was provided to the oil industry as well, and is now seen as the “smoking gun” that provided the industry with information about which it subsequently pled innocence. Revelle and Seuss (1957).
2Fourier was anticipated by DeSaussure in the 1770s. See Hulme (2009).
3He showed that carbon dioxide and methane absorbed infrared, while oxygen does not. Tyndall (1861). He succeeded Michael Faraday at the Royal Institution in London. Joseph Black had discovered carbon dioxide a century earlier. Tyndall was the first to give a convincing explanation of why the sky is blue.
4Arrhenius (1896); Chamberlin (1899). In trying to explain the ice ages, Chamberlin remarked that one theory was that the earth has passed through a cold region of space!
been brought to light recently (2011) that the American scientist Eunice Foote published a paper 5 years before Tyndall, pointing out the role of carbon dioxide in trapping the sun's heat. The progress of science, as with other human endeavors, has much to answer for ignoring or suppressing the work of female scientific pioneers.

The modern quantitative study of the correlation between atmospheric CO$_2$ levels and temperature began in 1938 when Guy Stewart Callendar began publishing his studies, and in the early 1950s, Gilbert Plass further advanced the idea that increased atmospheric CO$_2$ concentrations would warm the planet, and argued that doubling CO$_2$ levels would raise the earth’s temperature by 3.6°C in a paper entitled “The carbon dioxide theory of climate change.” Although this was nearly seventy years ago, our current understanding is not drastically different. But when Revelle and Seuss wrote about CO$_2$ and its possible effects on climate in 1957 controversy still raged over whether most of it went into the oceans rather than the atmosphere, in which case climate effects might be small. Now we know that about half goes into the atmosphere, while a quarter is absorbed by the oceans, and an equal amount by terrestrial sinks, principally plants.

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5Foote (1856). See the article by Raymond Sorenson at go.nature.com/2xky63a

6An especially egregious case that comes to mind is that of Cecilia Payne (eventually Cecilia Payne-Gaposchkin.

7Callendar (1938).

8Plass (1956). His ideas appeared in Time magazine as early as May, 25, 1953. There is no better short summary of the history, through 2008, of the understanding of the role of carbon dioxide than an address by John Holdren President Obama’s Science Advisor, in 2015. The power point presentation is available at https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/jph-kavl-9-2010.pdf. Whether it will always be there is another question.

9Revelle and Seuss (1957). Climate activist and vice president Al Gore, was once a student of Revelle’s.

10Estimates for the fraction that goes into the atmosphere range from less than 45% to over 55%. 
The crucial event in our understanding of the role of CO$_2$ came in in 1958, when systematic measurements of atmospheric CO$_2$ began to be made from an observatory near the summit of Mauna Loa volcano in Hawaii by Charles Keeling. By 1963, over 50 years ago, we note, when a conference was held by the Conservation Foundation on the “Implications of rising carbon dioxide content of the atmosphere,” including Plass and Keeling, it was becoming clear what the consequences of unrestrained burning of fossil fuels could be.

The increasing concern about growing CO$_2$ emissions was reflected in a series of important papers in the late 1960s, highlighted by one in the *Journal of Atmospheric Sciences* by Syukuro Manabe and Richard Wetherald that has been voted the most influential climate paper in the modern era. But the nation had actually been put on official notice in 1965, when President Johnson’s Presidential Science Advisory Committee drew attention to “Carbon dioxide from fossil fuels—the invisible pollutant.” Many of the effects that the earth is now experiencing: global warming, sea level rise, were discussed.

This was, of course, at the height of the cold war, when attention was elsewhere. But crucial papers by Stephen Schneider appeared, and one by Charles Baes and co-authors in 1977 had the title “Carbon dioxide and climate: the uncontrolled experiment.” The modern era of the study of greenhouse gases and the climate was well underway. This heightened interest in the problem was in part due to the fact that detailed

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11 Manabe and Wetherald (1967).
13 Including important papers by Manabe and Wetherald (1975) and by Siegenthaler and Oeschger (1978), based on 3-D general circulation models.
information on atmospheric CO₂ concentrations were just becoming available. An early warning was given in 1975 by Wallace Broecker, in a paper entitled “Climatic change: Are we on the brink of a pronounced global warming?” noted that while the climate had not warmed in the previous 30 years (as the result of natural fluctuations), it was likely that the CO₂ effect would dominate in the coming years.¹⁴ He proved to be precisely correct.

Finally, a most critical event in the modern era of climate change awareness took place on June 24, 1988 when NASA scientist James Hansen, now the dean of climate scientists, warned the U.S. Congress that, with a 99% certainty, global warming was occurring and that man’s activities were the cause.¹⁵ Many have argued that this is when climate activism should have begun to push the political system in the direction of recognizing the problem, rather than 30 years later. Atmospheric CO₂ levels, which were then at about 350 ppm, have since increased by 17%, and global temperatures have risen 0.7⁰C (well over 1⁰F).¹⁶

**The Role of Carbon Dioxide; The “Greenhouse Effect”**

What does it mean to say that carbon dioxide is an important “greenhouse gas?” The analogy is to a conventional greenhouse, which can maintain comfortable winter temperatures while outdoors it is below freezing. This happens because the glass allows sunlight to pass freely, but absorbs the

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¹⁴ Broecker (1975).
¹⁵ A number of other scientists testified that day, including Manabe.
¹⁶ To be fair, in 1970 or even 1980, while there were those who had a clear vision of the future, there were still many uncertainties that drove a conservative response. In a 1970 article in Science titled “Man-made climate changes”, Helmut Landsberg raised concerns, about “energy added to the atmosphere by heat rejection and CO₂ absorption,” but observed that “the envisaged 2⁰C rise can hardly be called cataclysmic.” Landsberg (1970). Recall, as well, that global temperatures were essentially unchanged between 1945 and 1975.
heat and infrared energy radiated upward from the warm soil and plants. We have already noted that carbon dioxide is a natural and important component of the earth’s atmosphere that is essential to the process of plant photosynthesis, the main source of the oxygen we breath.\textsuperscript{17} This carbon cycle, in which CO\textsubscript{2} and solar radiation act together is a critical part of the global climate cycle, but despite its importance, carbon dioxide makes up only 0.04\% (400 parts per million, by volume; ppm or ppmv) of the atmosphere, 20 times less than argon, for example. Which begs the question: how large a problem can carbon, or specifically CO\textsubscript{2}, be, if it is both important to life itself, and at the same time is only a trace component of the atmosphere?\textsuperscript{18} The obvious answer is that if carbon dioxide is important enough to control plant growth and thus to generate the earth’s oxygen, and, by the way, making the earth a livable planet, then it can hardly be surprising that changes in the amount of it in the atmosphere might be important.\textsuperscript{19} An analogy sometimes used is that a small change in body temperature, from 99 to 101\textdegree, can make a huge difference in how one feels.\textsuperscript{20}

As a kind of shorthand we will be talking about atmospheric \textit{carbon}, although carbon by itself is not the issue; rather it is its combination with oxygen in the carbon dioxide molecule, CO\textsubscript{2}, and with hydrogen in methane, CH\textsubscript{4}, as well as in certain other organic molecules, that the difficulty arises. Chlorofluorocarbons (CFCs) also contribute. Carbon dioxide

\textsuperscript{17}Carbon dioxide, of course, consists of one carbon atom (\textsuperscript{12}C) and two oxygen atoms, and has a molecular weight of about 44.

\textsuperscript{18}Although the fraction of CO\textsubscript{2} in the atmosphere is small, its total mass is enormous, over 3 trillion metric tons (3x10\textsuperscript{12} tones.)

\textsuperscript{19}To get a feel for the massive amount of CO\textsubscript{2} in the atmosphere, note that above every square meter of the earth’s surface, to the top of the atmosphere, there are 6 kg (13 lbs) of carbon dioxide. Or, when your eye intercepts the light from the \(\frac{\pi}{2}\) deg diameter of the moon in the sky, it has passed through about 20 million kg of CO\textsubscript{2}! Moonlight is almost all in the visible part of the spectrum, so little is absorbed.

\textsuperscript{20}Which, by the way, is not a 2\% increase, but only 0.4\% in absolute terms.
levels have fluctuated over geological time scales, but in pre-industrial times the concentration was a little less than 0.03% (280 ppm) in an

![Graph showing atmospheric carbon dioxide concentrations for the past 800,000 years.](image)

**Figure 5.1.** Atmospheric carbon dioxide concentrations in parts per million for the past 800,000 years, based on EPICA (ice core) data, with the 2013 annual average concentration of 396.48 ppm (dashed line) appended. Current values are over 410 ppm. The peaks and valleys in carbon dioxide levels follow the advance of ice ages (lowest levels) and warmer inter-glacials (higher levels). NOAA Climate.gov, based on EPICA Dome C data (Lüthi, D., et al., 2008) provided by NOAA NCDC Paleoclimatology Program.

The atmosphere dominated by nitrogen (78%) and Oxygen (21%). The current elevated level of over 410 ppm is the highest in at least 800,000 years and 45% above 18th-century values (right hand edge of Figure 5.1).
The surface temperature of the sun is a very high 6000° K (degrees Kelvin; over 10,000 degrees F), which means that it emits short wavelength white or visible light containing all the familiar colors of the rainbow or visible spectrum from violet to red, and the earth’s atmosphere (and carbon dioxide in particular), absorbs very little of that incoming energy. And because that is true of oxygen, nitrogen and water vapor as well, the earth’s atmosphere is mostly transparent to sunlight, hence the clear blue skies of an October day with a blazing sun. The story is very different, however, when we consider the heat radiated back into space by the earth’s warm surface—the land masses and the oceans. If we take the average global temperature, for simplicity, to be “room temperature,” 68° F (20° C, or almost 300 K), then the thermal radiation from the earth will be in invisible infrared wavelengths, much longer than the red. And as shown in Figure 5.3, carbon dioxide molecules very efficiently absorb energy in the infrared, as the carbon and oxygen atoms vibrate against each other. The resulting CO₂ absorption spectrum, “discovered” by Tyndall (and Foote) 150 years ago, is fairly complicated, with “windows” where the atmosphere is transparent to infrared radiation, and others where it is opaque to it (Figure 5.3). But it is this absorption or trapping that gives rise to the greenhouse effect, in which, like a greenhouse, the atmosphere is transparent to the sun’s incoming energy, but blocks the return of heat back into space, raising its temperature and ultimately that of the earth’s surface, including the oceans.

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21 The Kelvin or absolute temperature scale. The “K” refers to temperature in kelvins, and this is the “absolute temperature.” It is measured from absolute zero and is obtained by adding 273° to the celcius temperature.
22 Holding a dark beer, or even a coke, up to the sun, shows that they absorb a lot of the sun’s energy. But if you hold a jar full of CO₂ up to the sun you will not notice any absorption.
23 To be a little more precise, a lower temperature of about 14° C, 57° F, or 287 K is a better representation of the global average.
The result is displayed in the figure below (Figure 5.2) which shows that only about 48% of the sun’s energy is absorbed by the earth, nearly 30% is reflected back into space, and another 23% is absorbed by the atmosphere. If you choose, you can simply accept that atmospheric CO₂ does trap heat from the earth’s surface and move on, but in what follows, we give the reader a hint of the physics behind this absorption. The physics, by the way, has been thoroughly established over the last 100 years and more.

**Figure 5.2. Global energy balance.** Averaging the total solar insulation (1366 W/m²) over a hemisphere yields about 340 W/m² (upper center). About 30% is reflected and about

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24 Total solar insolation is 1365 W/m²; averaged over the earth gives a ¼ factor or 340 W/m². About 30% is reflected, bringing the number down to 240 W/m². The 48% absorbed amounts to 160 W/m².
48% (160 W/m²) is absorbed by the surface.\textsuperscript{25} Robert Simmon.

\begin{center}
\textbf{Figure 5.3.} Atmospheric absorption of infrared radiation due to CO\textsubscript{2} and water vapor. The temperature 255 K is the temperature at the top of the earth’s atmosphere, or what the earth’s surface temperature would be without an atmosphere. Note that that neither water vapor, and especially CO\textsubscript{2}, absorb much incoming solar energy (far left part of the figures). (find better figure)
\end{center}

\textbf{Atmospheric Physics}

\textsuperscript{25} If the amount the earth actually receives, averaged over the whole planet, is about 240 W/m\textsuperscript{2}, the earth must radiate that much back into space, or it will warm. This energy imbalance is what drives global warming.
The intimidating figure above (Figure 5.3) shows the spectrum of incoming solar radiation (orange, left; 6000K) and that of the outgoing infrared radiation from the warm earth’s surface (red, right, 255K), as well as the absorption by atmospheric CO$_2$ and water vapor (black). The reason we use 255K (0°F), rather than 300K, is that this is the temperature at the top of the atmosphere, the “edge of space,” if you like, the earth’s effective temperature. It is what the temperature of the earth’s surface would be if it had no atmosphere. The strongest CO$_2$ absorption (near 15 μm)$^{26}$ is very close to the infrared region of the spectrum in which a hot object at that temperature radiates. Atmospheric carbon dioxide and other greenhouse gases (GHGs), including water vapor, trap energy being reflected or radiated upward from the earth’s warm surface, heating the atmosphere until equilibrium is reached at a higher temperature, with the same amount of energy being radiated back into space as is absorbed from the sun. Thus, rising greenhouse gas concentrations mean more trapped heat, a higher atmospheric temperature, more heat radiated outward, and a new equilibrium global temperature. This is “simple” physics.

Of course the greenhouse effect is by no means all bad, since we would not be here without it, because absent CO$_2$ and water vapor, the earth’s surface temperature would be about 0°F, well below the freezing point of water. So if it seems counterintuitive, or even impossible, that a “trace” molecule like CO$_2$ can play such a major role in changing the climate, consider that without it and also water vapor, the earth would be a frozen,

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$^{26}$μm stands for “micrometer” also known as the micron, a millionth of a meter, or a thousandth of a millimeter.
lifeless planet, somewhat like mars.\footnote{We cannot carry that analogy too far, however, since mars’ temperature is much lower than earth’s. It does appear, however, that there was liquid water on mars’ surface at one time.} And, of course, carbon dioxide is responsible through photosynthesis for the plant cover of the continents including the vast forests of the Amazon and elsewhere, without which we would not have oxygen.

It is an inescapable fact that carbon dioxide has a major impact on our planet, one that was until recently thoroughly beneficial. But its importance means that if we raise CO$_2$ levels in the atmosphere by nearly 50\%, as we have, climate equilibrium will be disturbed in a major way. Those who claim that more CO$_2$ in the atmosphere is a good thing—and some do—badly misunderstand what is happening or intentionally mislead.

Water vapor (H$_2$O), as we have noted, is also an important triatomic greenhouse gas (Figure 5.3), contributing as much as 60\% to the current greenhouse effect. But it is part of a natural transpiration cycle which is actually controlled by the temperature; we can’t affect the impact of water vapor without reducing the earth’s temperature. As the IPCC puts it, water vapor is a “feedback agent,” not a forcing agent, because of the important positive feedback cycle in which warming due to CO$_2$ and other greenhouse gases results in greater evaporation from the oceans, and the increased water vapor in the atmosphere reinforces the existing greenhouse effect. It is thought that this positive feedback mechanism comes close to doubling the warming effect of growing atmospheric CO$_2$.

Despite these arguments, it remains difficult to convince skeptics that CO$_2$ should be singled out as a dangerous GHG, when its concentration is only a little over 400 ppm in the earth’s
atmosphere. Our planetary neighbor Venus has a “runaway greenhouse effect,” causing its surface temperature to be higher by several hundred degrees, but its enormously dense atmosphere is 97% CO$_2$, so we ought not be surprised.\textsuperscript{28} In the case of the earth, with its relatively thin atmosphere, water vapor and carbon dioxide together had maintained an approximately stable equilibrium between solar energy absorbed and heat radiated back into space for at least tens or even hundreds of thousands of years, perturbed in the long term by orbital changes, and only slightly by bouts of volcanism and variations in solar output. This equilibrium was maintained by natural processes until the 18\textsuperscript{th} century, when with the onset of the Industrial Revolution, CO$_2$ emissions began increasing, first from burning coal and a century later, oil. Humans are now releasing nearly 40 billion metric tons (40 gigatons; Gt) of CO$_2$ into the environment annually, mostly by burning fossil fuels (Figure 4.2).\textsuperscript{29}

\textbf{The Direct Connection Between Atmospheric GHG Concentrations and Global Climate Change; Modelling}

The carbon cycle by which carbon (in the form of CO$_2$ and methane, mainly) is put into the atmosphere and exchanged with the oceans is a very complicated one.\textsuperscript{30} It determines, among other things, how long elevated levels of atmospheric CO$_2$ will persist even if CO$_2$ emissions are stopped immediately. One measure of that time period involves the “turn over” time-scale for the oceans, in which CO$_2$ in the upper layers is mixed with deeper layers. Individual CO$_2$ molecules have a residence time of only a few years in the atmosphere, a figure which has been

\textsuperscript{28}Being nearer the sun, Venus also receives about twice the solar energy input as the sun.
\textsuperscript{29}A metric ton is 1000 kg or about 2200 pounds.
\textsuperscript{30}See Graven (2016).
jumped on by global warming skeptics, but that has nothing to do with the long-term balance of CO\textsubscript{2} between the atmosphere and the oceans. As we will see, current elevated CO\textsubscript{2} levels will persist for centuries after fossil fuel emissions cease (Chapter 10), which means that our profligacy will have long-term consequences.

The earth’s oceans are among the real drivers of the climate (along with the sun, of course), and just the upper few feet of the oceans contain as much energy as the entire atmosphere. The combination of temperature and saline gradients, along with the earth’s rotation, determine the character of ocean currents, which are coupled to the atmosphere. As we have seen, and important fraction (about half) of the CO\textsubscript{2} emitted on land ends up being dissolved in the oceans, which gradually increases their acidity and endangers ocean ecosystems. Some of it is re-emitted as the oceans warm, a positive feedback mechanism.

Our claim in this chapter has been that a build-up of greenhouse gases, especially CO\textsubscript{2}, is the primary cause of global warming. Previously we could only show a correlation between GHG concentrations and climate change, but here we have shown from the physics, that increased atmospheric carbon leads to rising temperatures. Carbon dioxide (and methane) molecules in the upper atmosphere absorb energy radiated back into space from a warm earth. But we still need to convince ourselves that this well known physical process can actually produce the observed degree of warming. We could imagine that there is such a physical relationship, but that it doesn’t play a role in the climate cycle.

Empirical data such as we have given are always to be
preferred, but they can only show *correlations* among variables. So, in addition to these temperature records and their correlation with CO$_2$ levels, we also will have recourse to calculations of what the effect of the observed CO$_2$ levels *ought* to be, based on current science. This involves calculating the amount of infrared energy absorbed by the added CO$_2$, converting that into an increase in atmospheric temperature, taking into account the fact that some of the energy is in turn taken up by the oceans and land masses. The physics is straightforward but the calculations are not, involving a three-dimensional rotating planet, with oceans and continents, clouds, and aerosols, etc. Because of the complexity of the climate system, the climate models we use are very complex computer simulations that allow us to test the effects of increased CO$_2$ and other GHGs, making clear the *physical* relation between increasing atmospheric carbon and global warming. We will talk more about modeling in the next chapter, but it is worth noting here that skeptics are fond of saying that “the models disagree,” suggesting that that invalidates their results. In fact, each model has been constructed differently from the others, which is crucial, since if all models were the same, they would of course agree and we would only need one. The agreement would be meaningless. The models may disagree when it comes to fine details, but are almost always in general agreement on the global scale.

**Conclusion**

In this chapter we have explored the role of greenhouse gases as the cause of global warming, showing that the it is to the physics of the upper atmosphere that we must turn in order
to understand the way CO$_2$ and other GHGs trap infrared energy and keep it from escaping into space. It is clear that atmospheric carbon dioxide concentrations have been steadily increasing over the last two centuries as fossil fuel resources have been consumed. The correlation between emissions and atmospheric concentrations is beyond dispute (Figure 4.6), and as we saw in the previous chapter, it is actually possible to prove that these CO$_2$ concentrations have come from burning fossil fuels, should anyone still doubt this. And the correlation between rising CO$_2$ concentrations and a warming climate was also shown to be very strong. Finally, we have shown (Chapters 1 and 4) that there is only the very slightest chance that varying solar output is implicated in the current warming in any significant way.

None of this should come as a surprise to us, since it would be remarkable if such a major change in an important atmospheric component did not have serious consequences. But in the end, it comes down to the numbers: are we to believe that an increase from 280 to 410 ppm of atmospheric CO$_2$ can cause measurable and even disastrous climate change? Indeed, this is exactly what should be expected, based on atmospheric physics, and our final task will be to make use of climate modelling to project into the future. Our response to this crisis will be driven by what we expect the future to be like if we fail to act.

It is worth taking a quick look ahead to the consequences of this buildup of atmospheric greenhouse gases even though this is the subject of the next six or seven chapters, because some of the arguments have direct relevance here. Some
skeptics argue that the CO$_2$ effect may be saturating, meaning that additional CO$_2$ would not continue to warm the planet. This is a tacit admission of the cause of current warming, but in any case there is no evidence of saturation, models refute the idea, and we have already seen in Chapter 4 (Figure 4.11, for example) that saturation is not taking place. A related but equally false argument is that since water vapor absorbs infrared radiation already, CO$_2$ cannot add much to that absorption. This is also without foundation, the basic reason being that most of the infrared energy absorbed by carbon dioxide takes place in the upper atmosphere where the air is very dry, containing almost no water vapor. Moreover, CO$_2$ and water vapor absorb energy in different parts of the infrared spectrum (Figure 5.3), and any additional CO$_2$ adds to greenhouse warming. And, as we pointed out earlier, while water vapor makes the largest contribution to the greenhouse effect, it plays a natural role in the water cycle, and although that cycle is affected by global warming, water vapor is not in itself a cause of global warming.

Before we move on, we might look at what it would mean to stabilize atmospheric CO$_2$ at some specified level. Current targets vary from 350 to 450 ppm. Given the present level of over 400 ppm, the first goal seems a bit of a fantasy, since we would have to remove 400 Gt (gigatons, billions of tons) of CO$_2$ from the atmosphere to accomplish it, and the technology to do that does not exist. On the other hand, to cap at 450 ppm, we

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31 On sceptic vs. skeptic, the latter is common usage in American (and Canadian) English. Sceptic is preferred in most of the rest of the Anglophone world.
32 It is here that the temperature is in the neighborhood of 255K, just right for the radiation to be absorbed by CO$_2$. For the details and history of this issue, I recommend the discussion on the Real Climate website, dated June 16, 2007, or the Skeptical Science website. See also David Archer’s Global Warming: Understanding the Forecast.
33 But see Bill McKibben’s “350.org.”
can put an additional 400 Gt of CO$_2$ into the atmosphere, that is, emit about 800 Gt.\textsuperscript{34} But if all we do is cap CO$_2$ emissions at current levels to the end of the century, this would result in emissions of nearly 3000 Gt CO$_2$, four times the 450 ppm target!\textsuperscript{35} In other words, to stabilize at about 450 ppm, it will be necessary to reduce the average amount of greenhouse gas emissions per unit of energy by that same factor of four, which will require a reduction in use of fossil fuels by 75% or more.\textsuperscript{36} A tall order, but not impossible. We will consider such scenarios later.

In these initial chapters, we have shown that the planet is warming, and that the warming is due to increasing greenhouse gas concentrations in the atmosphere, resulting mostly from burning fossil fuels. Our next step is to try to forecast the future, depending how the use of fossil fuels is constrained. If we understand how the climate is likely to change, depending on how we act, we can—if we choose-- make enlightened and informed decisions that will mitigate the damage. There is only one way to do this, and it is through climate modelling, the subject of the next chapter.

\textsuperscript{34}Since about half are absorbed by the oceans and land masses. In the atmosphere, 1 ppm of CO$_2$ equals 7.81 Gt CO$_2$. This means that about 15 Gt of CO$_2$ emissions will add 1 ppm to the atmospheric concentration.

\textsuperscript{35}Raising atmospheric CO$_2$ concentrations to nearly 600 ppm, more than twice historical levels. A reminder, 3000 Gt CO$_2$ equals about 800 Gt carbon.

\textsuperscript{36}About 400 Gt of carbon have already been emitted since 1750. Miyama and Kawamiya (2009). Currently the atmosphere contains about 860 Gt of carbon or nearly 3200 Gt of CO$_2$.}