CHAPTER 4

IMPLICATING GREENHOUSE GASES

Introduction. The cause of climate change

The reader will agree, I hope, that we showed in the previous chapter that we are already experiencing global warming, and that it has become a fact of everyday life. We further showed that the warming has been growing for at least a century, reaching temperatures not seen in the last 2000 years, and probably the last several hundred thousand years. We also learned that it is all but certain that the warming has some specific or definite cause, rather than being the result of natural random climate fluctuations.

The planet cannot spontaneously warm (it would violate energy conservation), and natural internal cycles simply redistribute energy around the globe and among oceans, land, and atmosphere. The radiative forcing due to the Milankovitch orbital and spin cycles we spoke of in the first chapter act on a time scale of 100 or more centuries, so the only promising explanation for this warming other than human intervention is an increase in solar energy output. Volcanism does play a role, but it has not been an important factor in the past century, as global warming has accelerated.\(^1\) Although complex non-linear systems\(^2\) like the earth’s climate can show internal fluctuations, mostly driven by the oceans--the ENSO (El Niño-Southern Oscillation) is an example--these natural climate variations will

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1 In general, the sun provides about 99.998% of the energy input to the climate system, with geothermal providing the rest.

2 All real complex systems are non-linear to some degree, which means that the relation between input and output can be very complicated and even unpredictable.
not undergo long-term changes without some external cause. Our firm conclusion in the first chapter was that it is extremely unlikely that a variable sun can have played a significant role in recent warming. If one accepts that conclusion, the remaining alternative is that human activities are the cause. And in this chapter we will consider the plausibility that greenhouse gases, primarily CO$_2$, are the culprit. Note, as we mentioned earlier, that these conclusions do not depend in any way on modelling; they are what the data show. Modelling, we will see in Chapter 6, can let us extrapolate from the present and peer into the future.

Our strategy will be as follows: First we will look at the correlation between carbon dioxide emissions and atmospheric concentrations, establishing that CO$_2$ levels are due to human activity, mainly the burning of fossil fuels. That is the easy part. Second, we will look at the correlation between these atmospheric CO$_2$ (equivalent) levels and the global temperature anomaly, which is the difference between the actual temperature and the 20$^{\text{th}}$ century average (or some similar benchmark). This correlation will not, ipso facto, prove that increased levels of greenhouse gases are the cause of the warming, but it will go a long way toward making our case, all the while keeping in mind that, as is popular (and quite proper) to say, “correlation is not causation.” But correlations must have a cause, and what is the cause, if not the activities of man? To be absolutely certain, we will revisit the possible effects of increased solar energy output by reconstructing past solar activity over time, in order to conclusively establish that the sun cannot bear the main responsibility. In the end we will be left with only human intervention as the possible cause of global warming. Finally,
rather than settling for a *correlation* between increasing atmospheric CO$_2$ concentrations and global warming, in the next chapter we will go on to explain the physics of increased greenhouse gas levels and how they are responsible for the warming of the planet.

**CO$_2$ Emissions and Atmospheric Concentrations**

Historically, atmospheric CO$_2$ levels have fluctuated greatly in the last 420,000 years,\(^3\) from below 200 ppm, up to nearly 300 ppm (Figures 4.1 and 5.1), though they were much higher in the very

![Graph showing CO$_2$ emissions and global temperatures](image)

**Figure 4.1.** Global temperatures (blue) and CO$_2$ concentrations (yellow dots) at the end of the last ice age. The Holocene began about 12,000 years ago. Antarctic temperatures are in red. (Shakun, et al, 2012).

**Atmospheric Carbon Dioxide**

\(^{3}\) Such data, going back 420,000 years, come largely from Antarctic ice cores, which, incidentally, show that CO$_2$ levels are both the result and cause of climate changes (Berger and Loutre, 1996; Petit, et al, 1999.).
distant past. Figure 4.2 shows the rate at which carbon has been emitted at the surface since 1900, increasing nearly 20-fold in that period. The emission growth rate in the post-war era (since 1945) has been about 3% per year, doubling about every 20 years, and since precise measurements of atmospheric levels began in the late 1950s, global emissions have quadrupled. Atmospheric CO$_2$ concentrations have increased steadily in response, rising in the same period by about 30% (Figures 4.3 and 4.6), more slowly because of the huge amount of CO$_2$ already residing in the atmosphere. Atmospheric CO$_2$ concentrations peaked on May 15, 2019 at nearly 416 ppm.

![Figure 4.2 Annual Global Carbon Emissions Over Time Since 1900. Emissions are now at about 10 Gt per year. To get metric tons of CO$_2$ multiply by 3.7. Note the trajectory change following WWII. Cumulative emissions since 1900 amount to about 400 Gt of carbon.](image)

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4When I say “huge,” it is because the atmosphere contains over 3000 gigatons of CO$_2$. 
The most important data on these atmospheric CO$_2$ concentrations come from measurements taken near the summit of the Mauna Loa volcano on the island of Hawaii since 1958, shown in Figure 4.3. Note the seasonal fluctuations by 3-9 ppm, which give a measure of the precision of the data. Figures 4.4 and 4.5 show in detail the variations in CO$_2$ levels during the past decade. Even if we decide at this point to suspend judgment on the effects of these increasing levels of atmospheric CO$_2$, we can certainly see the correlation between the growth in emissions and atmospheric concentrations (Figure 4.6). The impact, we leave to the next several chapters.

Figure 4.3 Atmospheric CO$_2$ concentration over the last 60 years. The growth rate has averaged has about 0.4% per year.
Figure 4.4 Details of the growth of atmospheric CO$_2$ concentrations since 2011. Note the seasonal changes as plants green up in the spring and summer (see also the figure below).

Figure 4.5. Carbon Dioxide levels on Mauna Loa during 2016-17.
Figure 4.6 Growth of CO₂ emissions and atmospheric concentrations over the last 40 years. Emissions more than doubled in this period and atmospheric concentrations grew by 20% or 60 ppm.

While pre-industrial levels of CO₂ never exceeded 280 ppm, current levels measured on the slopes of the Mauna Loa volcano are now more than 410 ppm, representing an increase of 48%, mostly in the last century. The figure above shows how CO₂ emissions and atmospheric concentrations have tracked each other over the last four decades, inexorably growing together. Emissions have grown at an average of about 1.5% per year (and as high as 2.6%), while atmospheric CO₂

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5 415 ppm in May, 2019, having reached 400 ppm in March 2013. The observatory is located at an elevation of 11,141 ft, well above local human influences. CO₂ levels are adjusted for outgassing by the volcano. The relationship between CO₂ and climate is not simple. In the Paleozoic CO₂ levels were 10 times higher than they are today. In short, CO₂ is by no means the only driver of climate. Solar energy output was some 4% less than current levels in that era.
concentrations have increased at a slower 0.4% pace, again, because of the CO$_2$ already in the atmosphere. For the same reason, atmospheric CO$_2$ concentrations in Figure 4.6 lack the fluctuations shown in the emissions. When a standard statistical test is applied to the data in the figure, the growth in emissions and atmospheric levels correlate at the level of 99.7%, showing what is apparent to the eye, that emissions and CO$_2$ concentrations are very strongly correlated. An important fact for our future discussions is that at least 50% of CO$_2$ emissions end up in the atmosphere, with the rest being absorbed by the oceans and land masses.$^6$

Of course while CO$_2$ is the most important greenhouse gas, it is not the only one, and other emissions, methane especially, have increased in "lock-step" with CO$_2$, again, because of human intervention. Figure 4.7 shows reconstructed CO$_2$ and methane concentrations over the last millennium as deduced from ice core data, and Figure 4.8 shows how methane concentrations alone have increased over just the last quarter century, in data also taken at Mauna Loa. Notice that both greenhouse gas levels were essentially constant until just before 1800, as the Industrial Revolution was getting underway.

$^6$ Currently, human activities generate about 10 Gt of carbon yearly, of which 2 Gt each go into the land biosphere and the oceans and 4+ Gt go into the atmosphere. Five gigatons of carbon, which translates to 18 Gt of CO$_2$, at the rate of 7.8 Gt CO$_2$ per ppm, represent a yearly increase of about 2 ppm CO$_2$, which is what is observed.
Figure 4.7. Derived atmospheric CO$_2$ and methane concentrations from ice core data, for the last 1000 years, with direct Mauna Loa measurements superimposed.
Figure 4.8. Increase of methane concentrations since the 1980s, as measured at Mauna Loa.

That atmospheric CO$_2$ levels are due to the emission of carbon dioxide in human activities, principally burning fossil fuels, is quite clear. But we have even more definitive proof that increasing atmospheric CO$_2$ concentrations are due to human activity, and that comes from the measured levels of the cosmogenic isotope $^{14}$C in the atmosphere over time, obtained from ice core measurements.$^7$ In Figure 4.9, which we showed in Chapter 1 for an entirely different reason, the minima (the Maunder minimum, for example) represent periods of low solar activity, which is when $^{14}$C production is high. The “modern [climate] maximum” of the last century or so, at the right edge of the diagram, represents a decrease in atmospheric $^{14}$C, as the ice core samples on which these data are based are being

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$^7$ Consisting of one carbon atom and two oxygen atoms. Any quantity of CO$_2$ contains a small number of $^{14}$C atoms, which are radioactive. Since the half-life is short, the $^{14}$C concentration has to be replenished or will continually decline.
augmented by very old carbon, extracted from the earth’s crust in the form of coal, petroleum, and natural gas, and then emitted by burning these fossil fuels. The $^{14}$C in these ancient sources is depleted because its half-life is only 5700 years and most of it has decayed. This dilution of the $^{14}$C by ancient carbon has been called the “Seuss effect,” and it establishes beyond doubt that current CO$_2$ levels result from the burning of carbon sequestered in fossil fuel reserves long ago.

![Solar Activity Events in $^{14}$C](image)

**Figure 4.9.** Important excursions in solar activity over the last millennium, as determined from $^{14}$C levels in ice cores.

**The Correlation Between CO$_2$ Concentrations and Global Warming**

The figure below shows how global temperatures have climbed since about 1910, having increased in the Northern Hemisphere by a full 1°C. But of much greater interest is the correlation between these rising temperatures and CO$_2$ concentrations, shown in Figure 4.11. The correlation is very strong, amounting to about 96%. That would seem to clinch the case for *man-caused* global warming, though one could still ask

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8 The gradual increase in $\delta^{14}$C between 1000 and 1700 AD reflects a slow decline in solar activity. Note the peaks in solar activity at about 200 year intervals.
which is the cause and which is the effect? Could rising temperatures cause CO₂ levels to increase, as some skeptics would like to argue? The answer is a qualified “yes,” but what then caused the rising temperatures? There is no explanation. And what we know of atmospheric physics, coupled with climate modelling (see Chapter 6) which incorporates this physics, tells us that global temperatures ought to rise just as they have, in response to these rising CO₂ concentrations. Our final step, which we have already taken in Chapter 1, but will revisit, is to eliminate any other possible cause for the current warming. Remember that we have already shown that it must have a specific cause (or causes), and cannot be a natural fluctuation.

![Annual Temperature Anomalies (1880–2012)](image)

*Source: J.E. Hansen, R. Ruedy, M. Sato, and K. Lo
NASA Goddard Institute for Space Studies*

**Figure 4.10** Global temperature anomaly since 1880.
Figure 4.11. Atmospheric CO$_2$ concentrations and temperature trend over the past century.

One way to look at this is to ask, having established that current atmospheric greenhouse gas concentrations are due to human activity, and that the planet is warming (Chapter 3), is it even conceivable that this warming is NOT due to these greenhouse gases, principally CO$_2$? The answer is YES; it is possible, though it would be an extraordinary coincidence, that while temperature and CO$_2$ levels are strongly correlated and further, that CO$_2$ concentrations have been shown to be due to human activity (Figure 4.11), the warming is actually due to some other cause, namely an increase in solar output (total solar irradiance, TSI). In that case, increased levels of CO$_2$, though real, would be making a negligible contribution to the warming.\(^9\)

\(^9\) For example, there is a fairly strong correlation between the length of the sunspot cycle and global temperatures since about 1890, though not between the intensity of the cycle and temperatures. What possible mechanism could be involved? Most likely none. Damon and Laut (2004) have shown that the most famous papers on the subject are flawed.
This is the only argument remaining that the skeptic can offer as an alternative to anthropogenic warming. So we must be sure that there is no other possible source of the warming, so that it doesn’t just correlate with rising CO$_2$ levels, but is caused by them.

**Revisiting the Sun**

Here we briefly remind the reader of the exhaustive arguments from Chapter 1, in which we looked at the role of the sun in driving the climate. Although we have accurate direct measurements of solar output for only the last 40 years, the figure below (Figure 4.12), covering those 40 years of satellite data, shows no evidence of changes in total solar irradiance other than short-term fluctuations due to the sunspot cycle, which amount to about 1 W/m$^2$ or about 1/10%. And during this period of constant solar output, the average global temperature increased by well over 0.6°C (1°F), and as much as 0.8°C in the northern hemisphere (Figures 4.10 and 4.11). Crucially, in Figure 4.13, in which the data on solar activity are averaged over the 11-year length of the sunspot cycle, we see that in the last half-century, during a period of rapid warming, solar activity and temperature have been moving in opposite directions! 

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10. Even though reconstructions of solar irradiance have been obtained for the last 400 years and longer (Figure 1.11).

11. This is consistent with a response to doubling CO$_2$ (ECS) of 2°C.

12. Furthermore, during the deep sunspot minimum post 2005-2010, there was a net positive global energy imbalance due to anthropogenic effects. (Hansen, et al., 2011).
Figure 4.12. Total solar irradiance (NOAA) since measurements began in 1978.

Figure 4.13 Solar activity (irradiance) and global temperatures over the past 130 years, showing the recent (half-century) divergence of solar activity and temperature. The earlier data on solar activity are from the SATIRE model of Krivova, et al (2010). From the Skeptical Science website.

The sun is not without influence, of course, but it appears to be at the level of a few tenths of a percent, as shown in
Figures 1.10, 1.11, and 4.13. Climate models show that these modulations of solar output could cause a temporary $0.5^0$ C change in temperature, and, for example, could have brought on the Little Ice Age, although a period of intense volcanic activity between about 1275 and 1300 may also have contributed. It is probable that the total solar irradiance has increased by a very modest 0.1% or so since the Maunder Minimum 350 years ago (e.g.,Figure 1.11), and the IPCC concludes that since 1745 the forcing due to changes in TSI—that is, the sun--amount to $0.05 \pm 0.05 \text{ W/m}^2$, which is consistent with zero. Any important role for the sun in the 20th century warming is effectively ruled out. To clinch the case, climate models show that the present climate can only be reproduced if current levels of atmospheric CO$_2$ are included.

The final argument against an increase in solar energy output being responsible for the 20th-century warming comes from the fact that this warming is precisely what we would expect from atmospheric physics, which is why early scientific figures dating back to the 18th century predicted that warming would occur in response to CO$_2$ emissions long before it was observed. The predictive power of a theory is a powerful and important factor in its favor. In the last few decades this has been confirmed by sophisticated global climate modelling, and global warming in response to increased CO$_2$ levels is what all models predict. There is, of course, always the matter of degree: is the amount of warming consistent with the physics and chemistry of the atmosphere? We address these questions in

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14 See, for example, Lean (2000).
15 IPCC AR5, p. 705.
Chapter 6, but we don’t need modelling to tell us that the planet is warming or that man is the cause.

**Climate Sensitivity to CO₂ Concentrations**

During the century following 1910, as shown in Figure 4.10, global temperatures rose nearly 1°C in response to an increase in CO₂ concentrations of about 100 ppm or 35%. Before 1940, CO₂ levels were growing at about 0.1% per year, about 1 ppm every 3 years, but since 1950 they have been growing four times that fast, and post-1970 the growth rate has reached nearly 2 ppm/yr. As we have seen (Figure 4.11), global temperatures have directly followed CO₂ concentrations. We note also that there is not a hint of the mythical saturation of the CO₂ effect that skeptics often retreat to. If there were, we would see CO₂ concentrations continuing to rise, while the global temperature would not. There is very little room for the

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17 Including emissions from the cement industry which approach 5% of global carbon input to the atmosphere. Deforestation also contributes, and of course methane and other trace GHGs add to the effective amount of carbon in the atmosphere. Skeptics have tried to make the case that in the distant past, CO₂ levels have followed temperature increases. This argument confuses the causes of the warming, which was mostly the Milankovitch cycles, not CO₂. More on this in Chapter 13. It should be noted that in Figure 4.6 the scales were chosen to make the curves lie on top of each other, which can be misleading. That said, they have the same shape and both show inexorable increases, although the temperature record is much “noisier.” The temperature has risen in the last 95 years (1910-2005) at about 0.01°C per ppm of CO₂ concentration, or about 1.0°C for a CO₂ increase of 100 ppm (meaning an ECS of about 3°C). Whether this relationship might continue indefinitely is difficult to say, but there is nothing to suggest saturation or flattening out at any modest value of global temperature increase (anomaly). Indeed, the contrary is observed. The CO₂ growth rate was 0.5%/yr between 1955 and 2005, about 1.5 ppm/yr, while the temperature rose at the rate of about 1.3°C per century. The rise has been even steeper in the last 30 years (about 2°C per century) with the 20% increase in CO₂ levels in that period representing a doubling time of 125 years or about 0.6% per year, assuming the growth to be exponential. CO₂ concentrations grew at about 2 ppm/yr in that period. In fact, CO₂ concentrations increased by 3 ppm in 2015, and nearly the same in 1998: both were El Niño years. Climate models indicate that the equilibrium climate sensitivity, or the temperature response to a doubling of atmospheric CO₂ levels is in the range of 2.4-4.5°C, with a probable value of nearly 3°C. On the other hand, for the 30 years 1975-2005, the correlation between CO₂ levels and temperature rise suggests a climate sensitivity of about 2.3°C. The longer time series 1920-2005, gives a lower climate sensitivity of about 2.1°C. So the ECS may be closer to 2°C than 3, which would be a good thing. More on this in future chapters.

18 There is a caveat here that need not bother most readers.
most seasoned skeptic to argue against mankind’s crucial role in global warming.

If we are honest about it, we are left with only one avenue of escape from serious greenhouse-gas induced global warming, and it is the not the reality of anthropogenic global warming, but the degree of it. How sensitive is the climate to changes in greenhouse gas concentrations? To be sure, the climate is warming, but perhaps it will not be so bad… In that case we can do nothing, or move slowly.

So, what is the expected warming that would result from a specified increase in atmospheric CO$_2$ (CO$_2$-eq)? A shorthand way of presenting this is to look at the global temperature increase that would result from a doubling of atmospheric CO$_2$ levels, known as the equilibrium climate sensitivity (ECS), often associated with Jule Charney’s name because of a 1979 report from the National Academy of Sciences.$^{19}$ This will force us to get a little bit into the weeds, here.

The ECS can be estimated without using elaborate climate models, and attempts to do so go all the way back to 1896, when the Swedish scientist Svante Arrhenius projected an increase of 6°C from doubling CO$_2$. The first serious attempt to derive a realistic ECS using modern computational resources came in the 1950s, when Gilbert Plass obtained a value of 3.6°C.$^{20}$ Although the sophistication of such calculations has improved enormously in the ensuing half-century and the simulations are orders of magnitude more robust, the result has not changed very much, and the spread of possible values of the climate

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$^{19}$ The modelling community uses other measures of climate sensitivity such as “transient climate response” and “effective climate sensitivity.” To explain the reasons for these would take us too far afield.

$^{20}$ Plass (1956).
sensitivity has not been reduced significantly, which is a measure of how complex the climate system is. Thus the ECS still has a large degree of uncertainty, usually stated between 1.5 and 4.5°C (3 and 8°F).\(^{21}\) This is where the greatest uncertainty lies. Although we understand the role of CO\(_2\) and other greenhouse gases, much of the uncertainty has to do with feedback mechanisms that are hard to model. They can amplify or reduce the effects of the GHGs.

If the ECS is as low as 3 degrees Fahrenheit (1.5°C), the problem is much more manageable, and there is more time to decide how to address it. But if it is just in the middle of this range, about 3°C, as now seems likely, it is an entirely different story. A slow response to rising global temperatures could allow us to reach CO\(_2\) concentrations twice their pre-industrial values (560 ppm) late in this century, resulting in a much hotter planet (by 5°F or more). See Chapter 7 for further details. Another attempt to determine the response of the climate system to forcing by GHGs results in an “earth system sensitivity,” which takes into account numerous feedbacks. The ESS could be as high as 6°C, but the response time of the climate system may be very long (over a millennium).\(^{22}\)

The takeaway message here must be that yes, global warming is occurring, that it is caused by human emissions of CO\(_2\) and other greenhouse gases mostly as the result of burning fossil fuels, but that we cannot yet be sure how rapidly the global temperature will rise with increasing emissions. That is the only uncertainty, but it is an important one, although, as we will soon see, there is close to a consensus that the ECS is

\(^{21}\) Another way to express the ECS is to say that it is 3/4°C for 4 W/m\(^2\) of forcing. Too technical, probably.
around $3^0$ C. And there is much that we can do in narrowing the range of estimates of ECS, especially by looking at what has happened since 1910, or even since 1965. As we proceed we will try to reduce this uncertainty, but also the make the point that the climate has already warmed significantly and will continue to warm, worst-case scenario or not. The consequences of that warming, we leave to future chapters.

**Trends in CO$_2$ Emissions**

![Graph showing CO$_2$ emissions by sector](image)

*Figure 4.14. Global CO$_2$ emissions by sector.*

Carbon dioxide is the most important GHG because of the volume of CO$_2$ being generated by the burning of fossil fuels. In 2013, the U.S., until recently the world’s greatest emitter, generated 5.5 billion metric tons (5.5 Gt) of this greenhouse
gas, divided between transportation, electricity generation; industry; and commercial, residential, and agricultural uses (Figure 4.14). Almost all of these emissions can be eliminated by replacing fossil fuels with carbon-neutral energy sources, given time to scale up wind and solar, and if the political will to make more use of nuclear power is there. The most difficult sector to bring to zero CO\textsubscript{2} emissions is air transportation, which makes up 3-4\% of all GHG emissions, but the large agriculture sector poses challenges as well. It goes without saying that greatest advantage of the electric vehicle is that the electricity can come from any source, solar, wind, nuclear, etc. At the moment, unfortunately, most of the energy being used in electric vehicles comes from burning fossil fuels, something that will have to change dramatically in the future.

Only recently has China passed the U.S. as the largest source of CO\textsubscript{2} emissions, but one can glean from Figure 4.15 that India, which is expected to become the world’s most populous nation in a little over a decade, is also becoming a major source. U.S. CO\textsubscript{2} emissions have been in decline for a decade (with fluctuations), and are projected to fall further (Figures 4.15, 4.16), despite the discouraging fact that U.S. emissions surged by 3.4\% in 2018! At the same time, it should be remembered that U.S. cumulative emissions are by far the largest of all the countries of the world—on the order of 25\% of all greenhouse gas emissions. And we will see in Chapter 7 that every ton of CO\textsubscript{2} emitted, over time, counts more or less equally.

\textsuperscript{23}China is now responsible for twice the fossil fuel emissions of the U.S., and over ¼ of the world’s total of GHGs (22.7\%). On the other hand, the U.S. emits more than twice as much CO\textsubscript{2} per capita as China and nearly 10 times as much as India. China and the U.S. together are responsible for about 40\% of global emissions. While U.S. citizens are responsible for about 16 metric tons (Mt) per capita of CO\textsubscript{2} emissions per year, for Japan and the EU it is 5-10. China, at nearly 8 Mt/yr is comparable to the EU, while India is at less than 2 MT/yr, but growing rapidly, having tripled since 1985. This should give one pause.

\textsuperscript{24}But dropped again in 2019.
There have been recent indications that China’s emissions are close to stabilizing, although a look at the figure below (red line) might make one wonder. If this were to happen soon, the progress will have been enormous and will bode well for the future. On the other hand, global emissions continue to rise, driven by China and India. While the post war growth rate of 3% (Figure 4.2) is unlikely to be sustained, just a 1% rate of increase would mean that on the order of 1200 Gt of carbon would be emitted to the end of the century (800 Gt at the current rate), far beyond the amount that would keep temperatures in check, as we shall soon see.  

Figure 4.15  Global carbon emissions over time for several countries.  Note that U.S. emissions seem to have peaked.

25 Global carbon emissions grew in 2019, but only by 0.6%.
although they increased by 3.4% in 2018. Recent data show that Chinese emissions are slowing. cdiac.ornl.gov.

Figure 4.16. The 13% decline in U.S. CO$_2$ emissions since 2005. Only energy-related emissions are included. Will the trend continue?

Other Carbon Sources

Although CO$_2$ is the most important greenhouse gas, amounting to about 80% of GHG emissions, it is by no means the only one.\footnote{To reiterate, water vapor, although the most important greenhouse gas, is not counted in GHG emissions. Rather it is part of the natural transpiration cycle.} Other atmospheric constituents that can contribute to a greenhouse effect include, especially methane, but also nitrogen oxides (principally nitrous oxide, N$_2$O), ozone (O$_3$), and chlorinated fluorocarbons (CFCs). When greenhouse gases are ranked according to their “global warming potential” (GWP), which for CO$_2$, by convention, is unity, we find that the GWP of methane is at least 30 times that of carbon dioxide,
and for nitrous oxide the value is nearly 300, for the same quantity of gas by weight. Methane is a very strong GHG, but emissions are much lower than for CO$_2$ and its residence time in the atmosphere is short, resulting in concentrations of only one or two ppm (1800 ppb); current levels are about twice those of pre-industrial times. By comparison, the residence time for CO$_2$ in the atmosphere is 5-200 years and even longer. Nonetheless, and despite having only about ½% of the atmospheric concentration of CO$_2$, methane’s contribution to global warming is about 19%, just about one fourth that of CO$_2$.\textsuperscript{27} No serious attempt to control GHG emissions can ignore methane. Sadly, in the U.S., restrictions on methane emissions are currently being weakened.

\textsuperscript{27} Methane emissions are about ¼ that of CO$_2$, but its contribution to global warming is about 19% of all GHGs.
Major sources of methane are the production and use of natural gas and petroleum, agriculture, and landfills, but also natural sources such as wetlands, plants, and bacteria. Methane clathrates in the sea bed and melting permafrost\textsuperscript{28} are real or potential sources that would not have existed on a cooler planet and represent a positive feedback mechanism. There is additional growing concern over the possibility of an abrupt release of methane from sea bed permafrost. Methane’s contribution will continue to grow as the world shifts more of its emission to natural sources.

\textsuperscript{28}In which methane is incorporated into the crystal structure of water ice.
energy generation to natural gas, which is primarily methane, and as a warmer climate leads to melting of arctic permafrost.

Nitrous oxide emissions have been nearly constant during the past quarter-century but still make a 5% contribution to GHG emissions. Some of this comes from combustion in a nitrogen rich atmosphere, including the transportation sector and the burning of forest cover, but there are many other human sources, including agriculture, livestock, and sewage. And there is an important natural nitrogen cycle in which the oceans play an important role. Although the N$_2$O contribution is relatively small, it may be difficult to meet any mid-century goal for control of greenhouse gases without addressing it as well.

As we have noted, CO$_2$ is the most important of the GHGs because of its relatively high concentration in the atmosphere and the continuing huge emissions from fossil fuels, but methane emissions by 2100 could again double. Because of the complexity of the situation raised by methane and other GHGs, some of which have GWP values in the thousands, we can use carbon dioxide as a proxy for the larger issue, so that we can speak of “CO$_2$-equivalent” levels of GHGs, converting the effects of methane, nitrous oxide (N$_2$O), ozone, and even CFCs to equivalent levels of CO$_2$ in ppm.\(^{29}\)

It may come as a surprise that the cement industry is responsible for on the order of 5% of all global CO$_2$ emissions. Some of this is from the carbon dioxide evolved in the calcination process, that is, in heating the raw material, usually limestone (mostly calcium carbonate, CaCO$_3$), but the rest is

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\(^{29}\)Generally, as we proceed, we will be using these CO$_2$-equivalent levels (CO$_2$-eq), even when we do not explicitly say so.
due to direct release of CO$_2$ into the environment by burning fossil fuel in the heating process. There are important opportunities to reduce emissions from calcination by using something other than fossil fuels, finding an alternative to CaCO$_3$, sequestering some of the carbon, and so on. But it seems unlikely that concrete will be replaced as a building or road paving material in the future.

**Deforestation**

Up to this point we have only considered CO$_2$ and other GHG emissions from fossil fuels and other sources. But in fact up to 15% of equivalent CO$_2$ emissions are the result of deforestation, primarily in tropical rainforests. Deforestation removes a sink for CO$_2$, thus effectively increasing emissions. This process continues virtually unchecked, with governments unable or unwilling to bring it to a halt. Fully one-fourth of the surviving forest cover is in the Amazon basin, where clearing is rampant. These tropical forests are currently worth more dead than alive, either because of the value of the forest products themselves, or to open up land for marginal agriculture. Burning forest areas or felling trees and letting them decay in place releases the CO$_2$ that has been stored in them over decades, and an important sink for CO$_2$ has been lost.$^{30}$ The world’s forests (and other plant material) are estimated to absorb over 2 Gt of carbon yearly, nearly a quarter of global emissions, more or less equal to absorption by the oceans. However, only the most naive optimist could expect that the Amazonian forest will survive in anything like its present size.$^{31}$ To compound the problem, it also appears that the role of forests

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$^{30}$It is estimated that one broadleaf tree, over a 100-year lifetime, will absorb about one ton of CO$_2$.

$^{31}$Considering especially what is going on in Brazil as I write this.
in producing rainfall has been underestimated and that the loss of forest cover will result in decreased rainfall and disruptions of rain patterns such as the monsoon.\textsuperscript{32}

One can understand why many in a tropical country such as Brazil are resistant to placing a major part of their sovereign territory off limits to development, especially when they look at what northern hemisphere nations have done to their own forests, but this ignores rights of indigenous people who live in these forests, and the impact on the whole planet. Perhaps some sort of sustainable use of these rain forests can be achieved, but the prospects are slim. Although boreal forests receive less press, they contribute about 40\% to the global forest cover and are less threatened, mainly because many northern countries are becoming increasingly urbanized. Reforestation can mitigate the climate problem, but not solve it.

Conclusion

In this chapter we have tried to establish beyond any reasonable doubt the \textit{causal} relationship between greenhouse gas emissions and global temperature rise by looking at direct measurements of the climate variables over the last 130 years.\textsuperscript{33} If unconvinced, the reader should go back over the arguments given above or consult the massive, half-million word 2007 IPCC report or the even larger fifth assessment of 2013.\textsuperscript{34} The strong correlation between CO\textsubscript{2} emissions and atmospheric concentrations and the similar correlation between the latter and global temperature rise documented in all of these reports

\footnote{Sheil (2014).}

\footnote{As the IPCC put it in its Fifth Assessment in 2013, “It is \textit{extremely likely} that human influence has been the dominant cause of the observed warming since the mid-20\textsuperscript{th} century.” This is a very conservative statement.}

\footnote{The next such report, AR6, is due in 2022.}
essentially clinches the case. And remember that these conclusions are not based on “models,” but rather on actual data. Models, as we will see in the next chapter, allow us to look into the future, and they can confirm, on physical grounds, what the actual data show, but as scientists we are subject to the “tyranny of the data.” Most recently, the IPCC has released a “Special Report on Global Warming of 1.5°C,” the goal of which is to show how the target of no greater rise than 1.5°C can be reached, and the U.S. administration has published its Fourth National Climate Assessment (NCA4), including the very detailed volume I, “Climate Science Special Report,” which is especially relevant to this chapter.

In future chapters we look at how the worst effects of climate change can be prevented or mitigated by various strategies, which basically involve stopping the burning of fossil fuels as quickly as possible. We will also examine the social, economic, and environmental costs that might follow on the heels of continued warming. We will find that the outcome will depend dramatically on how quickly and how deeply these cuts are made. There is naturally disagreement over whether our goal should be 350, 400, or 450 ppm of CO₂ (or its equivalent), though it is not obvious, considering politics and demographics, that any of these targets can be met. But it is our grandchildren who will pay the price of inaction.

35 Even so, we have to keep in mind, for the future, the role of solar variability, and as an unpredictable radiative forcing, it cannot easily be incorporated into climate modeling. The IPCC’s judgment (2013) is also that while there is “very low confidence concerning future solar forcing estimates...,” there is “high confidence that the TSI RF [total solar irradiance radiative forcing] variations will be much smaller than the projected increased forcing due to GHG during the forthcoming decades.” If we are to be honest, we have to settle for these qualified statements.

36 SR15, in October, 2018.
37 Issued November 23, 2018.
If you have read this far, digesting the science, and are not convinced of the crisis that the earth faces, I urge you to look back over this chapter and the previous one. We scientists are not used to making categorical statements without some “wiggle room,” but this is a close to a dead cinch that any of us will encounter. Despite all the skeptics, deniers, and contrarians, there is no longer any room for debate.