Chapter Three – Climate models and carbon budgets (6556 words)
7 Figures, 3 Tables, 1 Box, 2-4 Color plates

In the first two chapters, we looked at the many components of the climate system and how human activity has driven out the Earth's energy balance with its surroundings in space. Our purpose now is to tie this information together by understanding how this remarkable system functions as a larger whole. To do this we must learn something about **climate models**, which are computer simulations that illuminate how processes in the atmosphere, oceans, cryosphere, land and biosphere are coupled with each other. We know that climate models are reliable because they are able to replicate both climates of Earth's deep past and the contemporary changes driven by human activity.

1. A cornucopia of fossil fuels

Earth possesses an abundance of fossil fuels, which are nothing more than the compressed and transformed remains of living organisms from bygone eras.[1] We will gain a good perspective from a brief tour of these resources, looking at how they originated, where they are found, how much of each type we've already excavated and burned, and how much we think remains (Tables 1).
Coal, oil (petroleum) and natural gas differ most obviously in their material phases: solid, liquid and gas, respectively. Although they are all hydrocarbons and burn with oxygen according to the same basic reaction,[2] they differ in their *energy contents*. Burning one ton of coal produces only about 75% of the energy obtainable from the same amount of natural gas, with oil intermediate between the two. The coal hydrocarbon also has a much higher ratio of carbon to hydrogen atoms as compared with natural gas. Because of this, coal burning emits much more carbon dioxide per unit of energy production compared with natural gas, with oil again intermediate (Table 1).[3]

Coal was formed at various times in Earth's past, but most of it was created from abundantly thick plants present during the hot and moist Carboniferous period (between 359 million and 299 million years ago.) The plants broke down to form a complex polymer, **lignin**, which persisted in the soils because of its resistance to bacterial attacks. As the lignin became buried and compressed, it was slowly converted to peat and then ultimately to coal.[4] Fossil fuels have been colorfully described as *buried sunlight*, since the Sun enabled life to develop in the first place.

In contrast, both oil and gas originated from the oceans, including in shallow inland seas that, nowadays, form dry land. Hydrocarbons produced via photosynthesis by marine microorganisms, called **phytoplankton**, settle to the sediment at the bottom, where (as in coal generation) some again resist bacterial attack. As these compounds become deeply buried below the seafloor, they encounter higher temperatures and pressures, and undergo reactions that produce both natural gas and oil. The gas accumulates in pockets underneath impermeable rock, while oil is trapped in nearby porous rock layers.[5] Contrary to modern myth, oil did not form from the remains of dinosaurs. However, the origins of fossil fuels in other living organisms proves that burning them has produced the steep increases in atmospheric carbon dioxide levels (Box 1).

Fossil fuels are still by far the major energy source driving the global economy, creating powerful, entrenched interests that resist changes to the system that has made them so wealthy. Dislodging the hold of fossil fuels and replacing them with carbon-free energy sources is the most important technical and political challenge of the 21st century.

Fossil fuels are not renewable, of course, so they will eventually be depleted if we continue to mine them. For some time, the idea that the globe was actually ~~really~~ running low on these fuels, especially oil, was taken seriously and many books on "peak oil" were written.[6] Some even dared to think that, while an imminent scarcity of oil resources and consequent price increases would produce a global economic shock, it could also force a rapid transition to renewable energy in the first half of the 21st century.

Reserves and resources

The US fracking boom clearly shows that new technology can allow mining of resources that were, in the past, inaccessible or too costly to develop with less efficient methods.[7] Fossil fuel companies are also salivating over the opening of more public lands for energy development and the potential that sea ice melting offers for accessing new oil in the Arctic.[8] Globally, consumption of all fossil fuels together has nearly doubled in the past 40 years, with sustained growth through the first two decades of the 21st century.[9]

The total amounts of coal, oil and gas that have already been burned are well known (Table 1), but estimating how much of each remains (the total *resource*) is difficult for at least three reasons. First, while some parts of Earth's subsurface are thoroughly mapped, other potential areas, like the Arctic, remain relatively unexplored. Second, the extents of some oil and gas deposits are unclear because they are trapped in geologic formations from which extraction is difficult. The US oil shale is an example of a formerly trapped large resource that was liberated by the new technology of fracking. Finally, some resources are known to exist in large quantities, but are poorly described because current prices make them uneconomical to investigate. For example, **methane hydrates** are available in enormous quantities on seafloors, but mining them would not yield a profit at current prices.[10]

While the total coal, oil and gas resources available on Earth are difficult to estimate, the amounts in the *proven reserves* are reasonably well-determined. Proven reserves are the subset of total resources that exist in known locations and are economical to develop given current prices. In the energy industry, the amounts of fossil fuels remaining are indicated by a number called the *reserves-to-production ratio*, or R/P. This ratio is a single number that indicates how many years of production are left, given two pieces of data: the present estimate of proven reserves, and the amount that was used in the most recent year. For example, the R/P for the world supply of oil was 50 years at the end of 2018. This means that if no new proven reserves are found, and if in each successive year we continue to burn the same amount as in 2018, the world's oil would *run out* in the year 2068. Similarly, the 2018 world R/P ratios for natural gas and coal are 50 years and 132 years, respectively (Table 1).[11]

A key fact about these R/P ratios is that *they have changed little in the past 10-30 years*.[12] In other words, as fossil fuels are burned and R/P starts to decrease, some previously unknown or uneconomical *resources* come on-line and are transferred to the proven reserves. For example, when fracking the oil shale in the U.S became technically possible and economical in 2009, *proven reserves* increased and the R/P for oil rose. U.S energy companies with financial stakes in oil shale happily watched R/P go up, envisioning many more years of oil burning made possible by the fracking revolution. Indeed, the entire history of fossil fuel development is a steady story of expansion into areas that were once technologically or economically off limits.[13] Despite the access to new oil and gas resources, however, values of R/P for the U.S reserves today are nonetheless quite low - at least as reported in the widely used compilation by the British energy company BP (Table 1).[14]

The key question now is: how much of the proven reserves of coal, oil and gas can still be burned while keeping Earth's climate in a recognizable state? Table 1 shows that the proven reserves of all fossil fuels still substantially exceed the total amounts burned since 1900, and this is not even considering all the additional and still uneconomical resources. We will develop the argument in more detail in the next section, but given the substantial climate change we've experienced just from the amounts burned so far, this data clearly indicates that most of these profitable reserves are going to have to be left in the ground. Notwithstanding the hopes of some "peak oil" advocates in the 2000s, we are not going to be saved from climate change because of fossil fuels running out.

2. Climate models and carbon budgets

A central purpose of climate models is to project what is likely to happen to the Earth's system in response to anthropogenic forcings. This will allow us to see how our choices in the next few decades will determine the climate for the rest of the 21st century and beyond. Given the dominant role of fossil fuel burning, a key way to look at human activities in the upcoming decades is in terms of **carbon budgets**. These are estimates of how much coal, oil and gas we can still afford to burn while staying within habitable temperature limits.

The budgets unambiguously tell us that rapid transition to a carbon-free economy, over the next three decades, is necessary to limit warming to a relatively manageable 1.5 - 2.0ºC.

Swift reduction in carbon dioxide emissions is the main goal driving ambitious policies to mitigate climate change. Of course, the atmospheric carbon dioxide level can only be stabilized over a transition period, in which fossil fuels are phased out and replaced by carbon-free energy sources. At the end of this period, carbon dioxide emissions from human activities must be reduced to near zero. This is because of the long residence time of carbon dioxide in the atmosphere, which means that a good deal of what we're emitting now will remain in the atmosphere over timeframes extending through centuries and millennia.[15]

As we will see, humanity is already on a path to create a fossil fuel-free economy, a process called **decarbonization**. We will get there eventually, but the severity of climate change depends on how much carbon dioxide and other greenhouse gases are emitted in the meantime. As advocates, our job is to build urgency for a very fast transition, leaving as much fossil fuel in the ground as possible. We will be more effective if we have a solid understanding of what the best climate science says about this.

Nothing in climate diplomacy directly specifies how long the energy transition should take. However,
according to an international treaty from 1992, the **United Nations Framework Convention on Climate Change**, global warming must be kept within limits that *minimize dangerous anthropogenic interference with the climate system*.[16] In the following decade, a consensus reached among climate scientists and policymakers established that, to accomplish this, warming should not exceed 2°C above the preindustrial temperature.[17] In another international treaty, the **Paris Accords** of 2015, it was further agreed that all efforts should be made to keep warming below the more ambitious target of 1.5°C.[18] As we will see, all major climate change impacts on the natural and human worlds become more severe if temperatures are allowed to reach 2°C of warming as compared with 1.5°C.[19]

The question of how fast we must accomplish the energy transition largely comes down to how much coal, oil and gas can still be burned, while staying below the 1.5°C or 2°C targets. Climate scientists discuss this key issue in terms of a **carbon budget**. Like a financial statement, the carbon budget lays out how much we have to "spend"; that is, how much more carbon dioxide we can afford to still emit.[20] Blowing the budget would invite potentially catastrophic climate change, so it is important to develop new policies with the upper carbon limit clearly in view.

Calculating a carbon budget is not a simple matter. It is not appropriate to simply double the known emissions that have led to the 1°C warming so far, and call that good for the 2°C budget. This is because the climate system does not respond linearly when perturbed. One way to see the nonlinearity is to think about the ice albedo positive feedback loop that we discussed in the last chapter. It has a runaway quality to it: the melting of white snow exposes dark ocean, which absorbs more heat, leading to more melting. That is certainly not a linear trend. Heat transfer into the deep ocean is also nonlinear because it depends on large-scale ocean circulation and ocean-atmosphere interactions, which makes themselves subject to multiple feedbacks. The complex effects of clouds on Earth's radiation balance, and the strong year-by-year variability of carbon uptake by the land, also defy attempts at simplification.[21]

Basics of climate modeling

Climate models work by defining a starting point; for example, the Earth in the preindustrial year 1800. In the computer simulation, the climate system is then allowed to change over time, within constraints imposed by known scientific laws and the way these laws apply to the components of the climate system. Then it is possible to test the effect of changes that humans are imposing. For example, the atmospheric concentration of methane could be increased by a specified amount over time, and the effects on the climate system then calculated. The results of this methane-change simulation would be compared with an identical simulation in which the methane concentration is held constant.[22]

Climate scientists address the complexity of the climate system, including carbon budgets, through **climate models**.[23] A fully developed climate model, known as a **general circulation model**, is a computer simulation that incorporates interactions among the five physical parts of the climate system (Figure 1).[24] All such simulations feature two key components. First, they include equations from physics and chemistry that embody the basic laws about how mass and energy are conserved and moved around the climate system. Second, they incorporate experimental measurements, such as the composition of the atmosphere, the topography of the Earth's land surface, and maps of the ocean floor. We will gain a better appreciation of carbon budgets if we understand something about the models that make them possible.

Let's get one very basic, but super important distinction out of the way, we are talking about climate, not *weather*. Climate points to the weather averaged over long spans of time (30 years is a typical period), while weather describes the conditions outside today, perhaps extending into the next two to three weeks, but no longer.[25] Climate models *project* what average temperatures will be like, say, 30 years from now, and run many times with different assumptions about what humans will do between now and then to curtail greenhouse gas emissions. Weather forecasts, on the other hand, *predict* what conditions will be like at the beach next weekend. This distinction may seem very straightforward, but it is easy to misuse the terms.[26] Climate change denialists conflate weather and climate when they claim that cold weather at particular times and places is evidence that the climate is not warming. This occurred on the U.S Senate floor in February of 2015, when

Senator James Inhofe, Republican of Oklahoma, displayed a snowball and proclaimed that global warming was obviously not a problem.[27]

The upper limit of a few weeks for weather predictions comes from the fact that even small, local disturbances to the atmosphere propagate to yield unpredictable consequences elsewhere. There is an intrinsic variability, sometimes called **chaos**, in the system.[28] This inherent and physical limit means that it will *never* be possible to forecast the weather at the beach, say, at the end of next month. How, then, can climate projections decades ahead be of any value? The answer is that climate models only seek to use our understanding of the Earth system to project general future trends, not the details of what will happen at specific times and places.

Climate simulation "experiments," such as this, are necessary because the actual climate system is so complex that it is not possible to hold everything constant while varying the factor to be tested, which can be done in many other areas of science. Certainly, limited experiments are useful; for example, the results of studying how the temperature of a gas mixture affects its ability to hold water are very relevant and are incorporated into climate models. Also, there are some "natural" experiments that can be looked at, like the 1992 Mount Pinatubo eruption that caused global cooling. But of course, there's no "control Earth" that would allow us to examine what would have happened had that eruption not occurred.[29] The only way to get insight into that is with a simulation.

Climate models: simple, yet complex

To get a better feel for climate models, let's revisit the bare rock model of the Earth from chapter 1. The model is so simple that it includes only a few equations that describe how the Sun's radiation affects the temperature of the Earth. Unsurprisingly, it gives a very poor result, predicting that Earth's average surface temperature should be -15°C. Taking off on this, a second model was made by adding an idealized atmosphere to the bare Earth. The new model performed better, predicting a warmer temperature much closer to what we actually measure.[30]

Of course, that second model is also still very crude. For example, the only way energy can move around is by radiation, even though on Earth, much of the heat is transferred by the evaporation of water near the surface (releasing heat), rising of the water vapor up into the atmosphere, and then condensation back into liquid (absorbing heat). Circulation of the atmosphere and oceans also transports heat from the equator to the poles. The major atmospheric and ocean circulation patterns are well known and incorporated into today's climate models. The way that these circulations are coupled to each other is also included (Figure 2).

To further account for the complexity of the Earth system, climate models also incorporate the many feedback loops that are operating. The ice albedo positive feedback gets a lot of attention because it is causing the melting of Alaska,[31] but a different positive loop called the **water vapor feedback** has even larger effects on overall warming. The atmosphere heats up as greenhouse gases accumulate and warmer air is able to hold more water vapor than cooler air. Water vapor is a powerful greenhouse gas, so the warmer the atmosphere gets, the more heat-trapping water vapor can be held within it.

There are also **negative feedback loops** that have dampening effects, keeping the Earth system from spinning out of control. One of these is the **blackbody radiation feedback**: as the Earth's surface warms, it radiates out more Earthlight, some of which is not reabsorbed by greenhouse gases, so it escapes the planet. This isn't enough to stop the warming, but provides just enough counteracting force that it allows there to be less warming than would otherwise occur. Many more feedbacks, both positive and negative, are also part of the climate system (Table 2).[32]

Climate models are able to make reliable projections because they include representations of these and many other processes. The built-in complexity of the models then allows estimation of other important quantities besides overall surface temperature, such as temperature and pressure variations across Earth's surface and at different altitudes, changes in wind speeds and the large-scale pattern of atmosphere circulation, how ocean and atmosphere circulations influence each other, and alterations to the carbon and nitrogen cycles.[33]

To do all of this, comprehensive climate models include the cryosphere, land surface and biosphere in addition to the atmosphere and ocean (Figure 1). This is where carbon budgets come in. By including equations that describe the way carbon moves around the climate system, it is possible to run simulations in which specific amounts of fossil fuels are excavated and carbon dioxide emitted to the atmosphere. That is what climate scientists do to examine how much coal, oil and gas must be burned to add a given amount of carbon to the atmosphere, which will then give rise to a projected amount of additional warming. This kind of modeling is the basis for the carbon budgets presented below.

The amount of warming that occurs in response to the addition of a given amount of carbon dioxide to the atmosphere is known as the **climate sensitivity**; it measures how susceptible the Earth system is to human influence. This is most often expressed as the amount of warming associated with doubling the pre-industrial carbon dioxide level, and given the symbol ΔT_{2x}. Because of the challenges associated with incorporating all the relevant feedbacks, past climate models returned broad estimates of ΔT_{2x}, in the range of 1.5 – 4.5°C. However, a comprehensive study incorporating decades of advances in modeling has now narrowed this range to 2.6 – 3.9°C.[34] This is the temperature increase we can expect if Earth comes back into energy balance when carbon dioxide levels near 560 ppm. With carbon dioxide levels today nearing 420 ppm, we are about halfway there already.[35]

Reliability of climate models

Before we look at what climate models tell us about the carbon budget, it is important to learn something about how well they work. You will probably not be surprised to learn that attacks on the reliability of climate models are a mainstay of climate change denialists. One line of attack is simply to suggest that climate policies should be grounded in hard experimental data, not, as claimed, on speculative models full of *fudge factors*.[36] Another denialist strategy is to play up the uncertainties inevitably present when modeling something so complex. With that seed planted, the arguments then easily slide into implications that the predictions are so bad as to not be worth paying attention to or even if there is some merit to a few predictions. *Surely* there is not enough confidence to drive policies that would restructure the entire global economy, and would cost a lot to boot.

The first line of attack comes from the failure to understand why experimental measurements are not enough to project the future climate. The reason they are not is because no matter how comprehensive the data sets are, they cannot incorporate the positive and negative feedback loops that have major influence on the climate system. Feedback loops simply can't be measured directly; they can only be understood at a whole systems level. There is no way to accurately project future climate without incorporating the feedbacks, and there is no way to incorporate feedbacks except through models.[37]

Of course, all the measurements are still important because they provide reality checks to test the models. Computer simulation outputs are compared to the efforts of scientific teams fanned out across the entire planet, where they are recording data on ice thickness in the Arctic, humidity in the Western US, wind speeds of Pacific cyclones, sea level rise along the US Atlantic and Gulf coasts, and a thousand other sets of observations. The models then also provide a way to integrate and make sense of all these measurements.[38]

One way to convince doubters about the reliability of climate models is to point out that they are not just needed to predict the far future, but also to make sense of what is happening now. Anyone who relies at all on a *weather* forecast is actually depending on a *climate* model. The same equations, data and computer networks used to simulate the climate in 2050 are also used to predict the weather tomorrow.

Virtually everybody relies on weather forecasts. Importantly, users of weather forecasts know that they are based on probabilities, and certainly don't expect perfection even if they grumble about things that they don't get quite right. And the forecasts are much better than they used to be. It was remarkable to watch the predicted track of category 5 Hurricane Dorian in September 2019, for example. The storm headed straight to Florida, but did not come on land there, and instead headed north while remaining offshore- exactly as predicted. How did the forecasters know enough to confidently predict that Dorian would not turn south instead of north, or would not come on land in Florida? That is the power of the *climate* models.[39]

Another reason to place confidence in climate models is that it is possible to carefully calibrate them to match the complexity of the Earth's climate system. This takes advantage of the fact that the past is a known quantity. Figure 3 shows simulations together, measured with data on the average global surface temperature, from 1880 to 2020.[40] The experimental data are shown in black and are exactly the same in all three panels, while the yellow, red and orange hatched traces show the results from a general circulation climate model that started with the Earth system as it was in 1880, and then was run for 140 years. The thicknesses of these traces provide a measure of the uncertainties in the computer simulations, which are obtained by running them many times.

Panel (a) of Figure 3 is a simulation with human influence left out - it simulates the Earth's climate without including input from fossil fuel burning or other human activities. In contrast, panel (b) excludes the natural forcings – variations in solar intensity and volcanoes, while keeping fossil fuel consumption. Panel (c) includes both natural and anthropogenic contributions. Note that the sharp known temperature increase beginning in 1960 is reproduced only when human contributions are included, and that natural drivers yield no warming at all. Including natural forcings in the model (panel (c)) yields only slightly improved fits compared to anthropogenic influences alone (panel (b). Panel (b) also shows that the effects of ozone, land use and aerosols have offset some of the warming from greenhouse gases.[41]

These simulations, and many more like them, demonstrate that the attribution of recent temperature rise to human activity is reliable. This gives confidence that the use of that model to predict a particular future scenario – say, one in which fossil fuel burning accelerates, would also yield reliable insights. Model results have also been compared to paleoclimatology data from Earth's past, when the distribution of sunlight around the planet was different than it is today. They are also tested against contemporary shocks to the system, like the Mount Pinatubo explosion that caused global cooling. In each case, the models performed well, building additional confidence in their predictive abilities.[42]

But are the models full of "fudge factors," as critics claim? There are, of course, some significant sources of error. Climate model outputs of temperature, wind speed and other variables are calculated on a three-dimensional grid, but the resolution, or spacing between grid points, is limited by computer power. Typical high-resolution simulations report data on grid points spaced about 60 miles apart on the Earth's surface, and at perhaps 20-30 altitude layers in the atmosphere (though models on regional scales can be much finer). This means that smaller features that could be important to climate, such as clouds or small islands, are often missed.

To handle this, models calculate average cloud covers at grid points based on factors such as temperature and humidity. Small features on land, such as local variations in elevation and tree cover, also are estimated and averaged based on observational data. These approximate procedures, necessary because of the complexity of the system, are what denialists deride as “fudge factors.” However, what the critics leave out is that the models are run many times, varying the tuning parameters to optimize the fits to experimental data. Ambiguities are reduced as the structure of the models is fine-tuned, computer power increases, and more experimental data are gathered.

All uncertainties in climate models are fully acknowledged by the climate science community. Perhaps the best expressions of this are in the IPCC reports, where syntheses of the state-of-the-art in climate science are accompanied by qualitative statements, which indicate the level of confidence held by the expert consensus on each point.[43] Because IPCC reports also require approval by governments, they are very circumspect about overstating conclusions. In fact, there are numerous examples showing that, if anything, climate scientists are underestimating the climate response.[44] There is little or no concern that findings are overstated.

Worldwide, the climate science community continues to make extraordinary efforts to improve the reliability of the models, and there are good reasons to think that this effort is working.[45] It is also important to recognize that it is impossible to eliminate all uncertainty, because there is simply too much inherent natural variation. This produces noise, above which the signal of human activity must be discerned. But at this point, a very large number of simulations all lead to the reality of climate change and its anthropogenic cause, and an overwhelming consensus exists in the climate science community on both points.[46] Models don’t need to be perfect in order to be correct about the big picture. And we will see soon that the impacts of climate change, already well in view, are more than enough to drive home the urgency of the situation.

Carbon budget estimates

Let’s now look at what climate models say about the carbon budget. The main component of any carbon budget is carbon dioxide emissions from fossil fuel burning. Usually, the effects of other greenhouse gases are incorporated as well, through their carbon dioxide equivalents (CO_2(e); chapter 2). The most comprehensive budgets also include changes to land use that affect carbon uptake and its return to the atmosphere. Land use change contributed a great deal to emissions in the early to mid-20th century, and its contribution is crucial for estimating the total amount of carbon dioxide equivalent emitted so far.[47]

Figure 4 shows the cumulative human influence on the Earth’s carbon budget from 1850-2018. It includes carbon dioxide emissions from fossil fuel burning, industry operations, and cement manufacturing, as well as net emissions from land use change, mostly deforestation.[48] The total amount of carbon dioxide emitted from fossil fuels and industry operations is 440 GtC, with an additional 205 GtC from land use change.[49] Thus, the total anthropogenic carbon load to date has been 645 GtC (2253 $GtCO_2$), with an estimated uncertainty of 12%, mostly from difficulties in estimating the land use factor.[50]

Figure 4 also shows what has happened to these carbon dioxide emissions over time. A little over half the carbon dioxide has been incorporated into the land and ocean, in roughly equal amounts. The other half, though, is still in the atmosphere and continues to warm the planet. This illustrates the longevity in the atmosphere of a major portion of carbon dioxide emissions.[51] We should also recognize that the ability of the land and ocean sinks to continue to sequester carbon will likely change as warming continues. For example, when the ocean surface is warmer, there is a smaller temperature difference with respect to deeper waters, making it more difficult for winds to stir up the water column and promote the sinking of rich carbon-dioxide surface water. However, the ocean circulation varies significantly over decade time periods, and sometimes this increases carbon dioxide uptake despite the warmer temperatures. Thus, future trends are uncertain.[52]

How much more carbon can be emitted while staying within 1.5°C or 2.0°C worlds? Carbon budgets were first reported in 2013 for the fifth IPCC report, and a number of other groups have approached the problem since then. Here we will use the carbon budget estimates from a special 2018 IPCC report that assessed the comparative impacts of global warming at 1.5°C and 2°C above preindustrial temperatures (Table 3).[53]

The IPCC's carbon budget is expressed in probabilities to account for uncertainties in the modeling calculations. For example, Table 3 indicates that humans can only emit an additional 570 gigatons of carbon dioxide to secure a two-thirds probability of staying within a 1.5-degree world. Emitting 770 gigatons would decrease the odds to only 50%. For context, estimated global emissions of carbon dioxide in 2019 were 37 gigatons (Figure 5).[54] If we continue to emit at this level, then the 67% budget for a 1.5°C world would be fully depleted by 2033, and the 50% budget in 2039.[55] These estimates account for the cooling influence of aerosols from fossil fuel burning, which will be eliminated as fossil fuels are phased out.[56] The calculations assume that emissions of the other greenhouse gases will decrease in tandem with carbon dioxide.

The IPCC budget shown in Table 3 does not fully account for the additional heat that will come out of the oceans, as the Earth system slowly comes back into equilibrium after fossil fuel burning is stopped. Full equilibration would lead to about 0.3°C of additional warming after fossil fuel burning is halted, but there is a considerable amount of uncertainty in this estimate because it is unclear how much atmospheric carbon dioxide might also outgas from the oceans when this occurs.[57] The estimates also don't consider carbon cycle feedbacks, such as melting of the Arctic permafrost. This could release significant amounts of both carbon dioxide and methane, although the temperature threshold that might trigger this is unknown.[58]

Comparing the data in Tables 1 and 3 allows a rough estimate of how much of the remaining proven fossil fuel reserves are "burnable" without blowing the carbon budgets. The strictest carbon budget shown in Table 3, required for a two-thirds chance of staying within a 1.5°C world, would allow us to burn just 16% of the proven reserves.[59] Even a low stringency budget, such as that required to achieve 50% odds of staying within 2.0°C, would still leave slightly over half the proven reserves in the ground. There is no escaping it: preserving the stability of Earth's climate requires that much of the known, economically extractable fossil fuel resource be left in the ground, forever.[60]

We will close this section with a warning from Earth's past. There is good geological evidence that about 55 million years ago, a large natural release of about 2500 to 7000 billion tons of carbon occurred. Earth's surface warmed by 5°C at the equator and 9°C at the poles, and the high temperatures persisted for about 200,000 years.[61] This episode is called the **Paleocene Eocene Thermal Maximum** (PETM). The size of this natural release is on the order of ten times more than the 440 billion tons humans are so far responsible for - but our *rate* of emissions is much higher. There is no known historical analog to today's emissions rate; we are in uncharted territory there.[62] And the proven fossil fuel reserves, together with some of the much larger resource, may well be enough for us to create our very own replica of the PETM, should we be foolish enough to want to do that.

3. Pathways for decarbonization

Carbon budgets are important because they frame the possibilities for how we might act. For example, if emissions were to be maintained at the pre-covid 2019 level, the IPCC climate models predict that 1.5°C of warming would be reached by 2040.[63] This would spend the entire budget: the 2019 emissions of 37 $GtCO_2$ (Figure 5) multiplied by 20 years gives 740 $GtCO_2$, putting us at the 50% confidence level for a 1.5°C world (Table 3).[64] At that point, it would probably no longer be possible to stay even within a 2.0°C world. But if we begin emission reductions right away, then the fixed budget can be spent over a longer period, enabling a less disruptive transition to a carbon-free energy economy.

In addition to calculating carbon budgets, climate models are also used to project what will happen to the Earth system in a variety of hypothetical futures where emissions are curtailed rapidly, slowly, or not at all. In the more favorable futures, less greenhouse gas is emitted, leading to overall smaller radiative forcings and milder temperature increases. In contrast, much greater warming is projected when emissions continue to rise over the next few decades. These different scenarios are called **representative concentration pathways** (RCPs).[65] They are used to estimate the impacts of emissions on global temperatures, ice melting, extreme storms, and other characteristics of the natural and human worlds.[66] Acquiring some feel for the RCPs is helpful for appreciating the range of possible 21st century climates that we will look at in the next chapter.

In 2013, the IPCC developed four distinct RCPs RCP2.6, RCP4.5, RCP6.0 and RCP8.5 (Figure 6). The numerical parts of these designations represent approximate radiative forcings in units of watts per square meter (W/m^2) that correspond to each pathway.[67] The original best-case scenario, RCP2.6, peaks at 3 W/m^2 and then declines to 2.6 W/m^2 by 2100. This corresponds roughly with a 2.0°C world. Later, a new RCP1.9 pathway was developed with even lower emissions, consistent with a 1.5°C world.[68] The RCP1.9 and RCP2.6 pathways yield the carbon budget estimates for 1.5°C and 2.0°C worlds, respectively, that are presented in Table 3.

RCP4.5 and RCP6.0 are intermediate pathways, in which carbon emissions peak and decline before 2100.[69] These scenarios are closest to what our future may be like if we continue with *business as usual* - steady but slow and uneven progress toward decarbonization. Finally, in the most extreme RCP8.5 projection, carbon dioxide concentrations rise sharply for the entire 21st century, before finally plateauing at well over 1000 ppm sometime after 2100. The rise in global temperature here is about 5°C, a truly catastrophic future, and fortunately not one that we are presently on track for.[70]

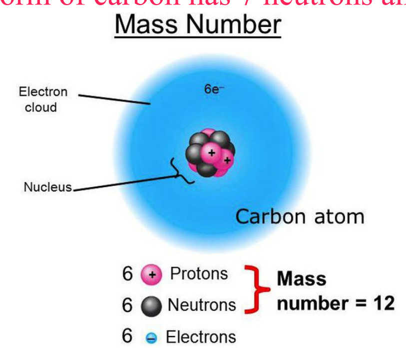
What do the RCP1.9 and RCP2.6 pathways tell us about how fast we must act to preserve 1.5°C or 2.0°C worlds? For a 1.5°C world, annual global carbon dioxide emissions must sharply decrease from the present 37 $GtCO_2$ to between 13-20 $GtCO_2$ by 2030, and must then decrease to zero by 2050 (Figure 7). The 2.0°C target allows for more time and a shallower decrease: 23-30 $GtCO_2$ by 2030, and zero emissions by 2075.[71] Comparable decreases in the other greenhouse gases are also required to meet either temperature target.

Figure 7 also shows that even in the modeled scenario with the sharpest emissions reduction (scenario P1), a small fraction of the emissions is difficult to eliminate. This is shown by the "fossil fuel and industry" section of the plot, which does not reach zero until after 2050. To compensate, natural land management methods to improve carbon sequestration in forests and agriculture (AFOLU) are invoked. The AFOLU portion of the plot starts out positive in 2020, contributing some emissions, but becomes negative by 2050, which means that carbon is sequestered on the land. However, longer delays in bringing about sharp reductions require increasing amounts of industrial carbon sequestration, designated BECCS in Figure 8, to meet the temperature target. BECCS, which stands for **bioenergy with carbon capture and storage**, is only one of the large-scale industrial methods that could potentially remove carbon from the atmosphere. These approaches will be needed if emissions are not reduced quickly because the natural sequestration capacity of the land is limited.[72]

Many new initiatives will be needed to accomplish the rapid emissions reductions mandated by these strict carbon budgets. These include economywide policies for electricity generation, energy efficiency, transportation, urban development, agriculture and forestry. Fortunately, very detailed roadmaps have been developed that describe plausible pathways for the U.S renewable energy transition over the next few decades. They include descriptions of what needs to happen in all areas of the economy and set priorities for which sectors should take the lead. The roadmaps outlined in the Interlude, along with specific policy approaches to accomplish the goals, are taken up in the second half of the book.

Box 1. Isotopes and atmospheric carbon dioxide

Isotopes of an atom have the same number of protons and electrons, but a different number of neutrons. The vast majority of carbon atoms have six neutrons, which when added to the six protons, and then gives 12 particles in the nucleus. These carbons are designated ^{12}C. A rare form of carbon has 7 neutrons and is designated ^{13}C.



Here's the punch line: all the fixed carbon in living cells has more of the lighter ^{12}C isotope, as compared to carbon embedded in minerals, like limestone, or dissolved in the oceans, each of which have relatively more ^{13}C. The reason being that the proteins that fix carbon dioxide during photosynthesis work poorly with ^{13}C and exclude most of the carbon dioxide molecules with that isotope. So ^{12}C gets concentrated in photosynthetic cells, and then is distributed around when animals eat the plants. Chemical analysis of atmospheric carbon dioxide shows that its ^{12}C abundance is increasing, consistent with its origin from living material – the plants and marine microorganisms that were the source of the fossil fuels. This proves that the accumulating atmospheric carbon dioxide comes from fossil fuels, and not from volcanoes or from ocean outgassing.[73]

Figure source: https://www.forbes.com/sites/startswithabang/2016/08/03/where-does-the-mass-of-a-proton-come-from/#169e5822e1d7
Can be redrawn and we can make it work without color as long as it is possible to distinguish the protons and neutrons

A common question about global warming is: where are the new atmospheric carbon dioxide is coming from? Climate scientists say that the driver is human fossil fuel burning, but how do they know for sure? Volcanoes and hot springs do deliver some carbon dioxide directly from the deep underground – couldn't that be the explanation? Or what if the physicists measuring sunlight are getting it wrong, and the extra heat from the Sun is causing more carbon dioxide to outgas from the oceans?

The proof comes from the chemistry of carbon **isotopes**. All atoms are made the same way: they have a nucleus made of positively charged protons and other particles called neutrons, surrounded by a cloud of electrons. The identity of an atom depends on how many protons are in the nucleus. For carbon, that number is 6 (if it were 7 or 8, then the atom would be nitrogen or oxygen, respectively). When atoms form bonds with each other, like the bonds between the carbon and the oxygens of carbon dioxide, the carbon and oxygen electron clouds overlap and become shared (see the Figure).

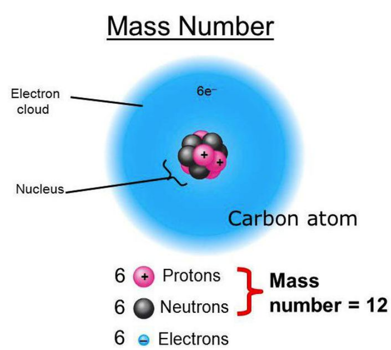


Table 1. Fossil fuel reserves

Fossil fuel	C/H ratio [a]	CO_2 per unit of energy[b]	Burned so far[c]	Proven reserves[d]	R/P (world)	R/P (US)
Coal	1.4	1.67	171394 Mtoe[e]	738348	132 yrs	390 yrs
Oil	0.44	1.33	206928 Mtoe	242195	50 yrs	11 yrs
Natural gas	0.25	1	103007 Mtoe	171394	50 yrs	14 yrs

[a]Ratios for typical constituents: anthracene (coal), octane (oil) and methane (natural gas). Structures are depicted in Figure 3 of Chapter 1.
[b]Natural gas is arbitrarily assigned a value of 1, for comparison with oil and coal.[74]
[c]Estimates for the years 1900-2018. Data compiled from various sources.[75]
[d]Data for proven reserves and R/P from the BP Statistical Review of World Energy, 2020.[76]
[e]Mtoe means *million tons of oil equivalent*, the amount of energy derived from burning one million tons of oil. It can be easily converted to more familiar energy units, like calories or kilowatt-hours (Box 1, Chapter 2). Mtoe values can also be converted to *tons of coal*, *barrels of oil*, and *cubic feet of gas*; www.unitjuggler.com

Table 2. Some climate feedbacks

Feedback	Type	Characteristics
Ice albedo	Positive	Warming causes bright, reflective ice to melt to dark nonreflecting
Water vapor	Positive	Warming atmosphere holds more water vapor; water is a potent greenhouse gas, leading to more warming
Methane release	Positive	Warming causes methane release from Arctic permafrost thaw, wetlands, and shallow hydrates; increased atmospheric methane traps more Earthlight, leading to
Sea level rise	Positive	Warming causes ice melt and sea level rise; continued sea level rise decreases ice shelf stability, leading to more ice
Blackbody radiation	Negative	Warming increases surface temperature; hotter Earth radiates more Earthlight into space, leading to cooling
CO_2 fertilization	Negative	Warming from higher CO_2 levels increases the efficiency of photosynthetic carbon fixation, leading to cooling
Weathering	Negative	Higher CO_2 levels increase the rate of mineralization, leading to cooling (over long timeframes)
Ocean solubility pump	Negative	Higher CO_2 levels increase the rate of carbon penetration into the deep ocean via marine photosynthesis and mixing, leading to cooling (also depends on ocean circulation)

Table 3. Estimated remaining carbon budget[a]

Approximate warming (°C)[b]	Remaining carbon budget ($GtCO_2$ starting Jan 1, 2018)		
	33%[c]	*50%*	*67%*
1.5	1080	770	570
2.0	2270	1690	1320

[a]Data are from IPCC, 2018.
[b]Warming is compared to the average of Earth's surface temperature in the years 1850-1900.
[c]Probabilities of remaining below 1.5°C or 2.0°C

[1] An alternative (but mostly rejected) idea is the "abiotic" theory of fossil fuel formation, which holds that some oil is not of biological origin, but rather was formed from inorganic carbon and hydrogen-containing materials deep under the Earth's surface. See https://enviroliteracy.org/energy/fossil-fuels/abiotic-theory/

[2] The combustion reaction is described and compared to the respiration component of the photosynthesis cycle, in chapter 1.

[3] Spiro 2003, p. 25-29.

[4] The Carboniferous Period. https://ucmp.berkeley.edu/carboniferous/carboniferous.php

[5] Spiro 2003, p. 21-24, and J.M. Hunt et al., *Early developments in petroleum geochemistry*, Organic Geochemistry 33, 1025-1052 (2002).

[6] For example, see Goodstein, 2004 and Simmons, 2005.

[7] See chapter 6 for a description of fracking technology.

[8] The Rainforest Action Network has published an exhaustive analysis on fossil fuel expansion and how it might be financed. See https://www.ran.org/wpcontent/uploads/2019/03/Banking_on_Climate_Change_2019_vFINAL1.pdf

[9] Among the three fossil fuels, coal contributed 32% of total consumption in 2017, while oil contributed 40% and natural gas 28%. Ritchie and Roser, *Fossil Fuels*, Our World in Data, https://ourworldindata.org/fossil-fuels This resource is part of the highly regarded *Our World in Data* compilation, which measures and reports on a wide range of global problems and trends. See also the Global Change Data Lab, https://global-change-data-lab.org.

[10] US Department of Energy, *Gas Hydrates*, https://www.energy.gov/fe/science-innovation/oil-gas-research/methane-hydrate

[11] Exhaustive statistics on global fossil fuel use, prices, production, and reserves are available free from the BP Statistical Review of World Energy, 69th edition, 2020, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

---

[12] BP Statistical Review of World Energy, 69th edition, 2020, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf R/P for both oil and gas have remained nearly constant at about 50 years since at least 1988 (the earliest data included in BP's analysis). BP reports that the R/P for coal decreased from about 230 years to 130 years between 1998 and 2007, which is presumably due to large overestimates of proven reserves in 1998 and earlier. Since 2007 R/P for coal has remained nearly constant at 130 years.

[13] For a definitive history of fossil fuel development, see Yergin, 2008.

[14] BP Statistical Review of World Energy, 69th edition, 2020, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

[15] See the discussion of carbon cycle timeframes in chapter 1.

[16] The UNFCCC is an international environmental treaty among 197 member countries, which are known as Parties to the Convention. It went into force in 1994. For a summary of its key elements and links to further information, see https://unfccc.int/process-and-meetings/the-convention/what-is-the-united-nations-framework-convention-on-climate-change. For the statement on dangerous anthropogenic interference, see United Nations Framework Convention on Climate Change, Article 2. United Nations, New York, 1992. https://unfccc.int/resource/docs/convkp/conveng.pdf

[17] Samuel Randalls, *History of the 2°C climate target*. WIREs Climate Change, 20 July 2010. https://onlinelibrary.wiley.com/doi/abs/10.1002/wcc.62

[18] Each year since 1994, the Parties to the UNFCCC (the member countries) hold a conference. The Paris Agreement of 2015 was reached at the 21st Conference of the Parties (COP21). See United Nations Climate Change. *The Paris Agreement*. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[19] Climate impacts are discussed in detail in chapter 4.

[20] Some basic information about the carbon budget is given by Our World in Data, at https://ourworldindata.org/how-long-before-we-run-out-of-fossil-fuels A useful summary in the form of an infographic is available from the World Resources Institute: https://www.wri.org/resources/data-visualizations/infographic-global-carbon-budget This infographic shows the IPCC-based carbon budget from the 5th Assessment Report, which includes data through 2011. See the text for more recent analysis.

[21] See Kerry A. Emanuel, *Climate Science and Climate Risk: A Primer*. ftp://texmex.mit.edu/pub/emanuel/PAPERS/Climate_Primer.pdf
Pages 8-12 provide a good introduction to the complexity of the climate system and development of climate models.

[22] Houghton 2015, p. 90-94.

[23] A readable and nicely detailed explanation of climate modeling is provided by CarbonBrief, at https://www.carbonbrief.org/qa-how-do-climate-models-work CarbonBrief is an excellent journalism website based in the United Kingdom, covering a wide range of topics on climate change and energy.

[24] As discussed in chapter 1, these are the atmosphere, ocean, cryosphere, land and biosphere. For more about general circulation models (GCMs), see https://www.ipcc-data.org/guidelines/pages/gcm_guide.html

[25] Houghton 2015, p. 95-99. Also see Paul Voosen, *How far out can we forecast the weather? Scientists have a new answer*. Science, Feb. 14, 2019, doi:10.1126/science.aax0032. https://www.sciencemag.org/news/2019/02/how-far-out-can-we-forecast-weather-scientists-have-new-answer

[26] An informative video explaining the distinction between climate and weather, by climate scientist Katherine Hayhoe, is available at https://www.skepticalscience.com/weather-forecasts-vs-climate-models-predictions-intermediate.htm

[27] Senator Inhofe's performance can be viewed at http://time.com/3725994/inhofe-snowball-climate/

[28] Houghton, 2015, p. 99.

[29] Edwards 2010, p. 139-140.

[30] Archer 2012, p. 23-26. In the improved model, the temperature at the ground comes out to be 19% warmer than the temperature high in the atmosphere, actually not a bad reproduction of reality.

[31] The ice albedo feedback loop is discussed in the section on carbon dioxide and temperature, in chapter 2.

[32] Brief explanations of 15 distinct climate feedback loops, both positive and negative, are available at https://earthhow.com/climate-feedback-loops/

[33] See Edwards, 2010, p 143-149, for a very readable description of how climate scientists improved models over time, adding successively more complex features.

[34] S. Sherwood et al., *An assessment of Earth's climate sensitivity using multiple lines of evidence*, Reviews of Geophysics, 22 July 2020, https://doi.org/10.1029/2019RG000678

[35] Paul Voosen, *Earth's climate destiny finally seen more clearly*, Science 369, 354-355, 24 July 2020.

[36] *Skeptical Science*, *How reliable are climate models?* https://www.skepticalscience.com/climate-models.htm

[37] See http://ossfoundation.us/projects/environment/global-warming/models-v.-observations

[38] For a full development of these ideas, see Edwards, 2010, especially the Introduction and Chapters 6 and 7 on weather and climate models.

[39] For details on how general circulation models are used differently to model weather *versus* climate, see Edwards, 2010, p 148-149.

[40] Hayhoe, 2018, Figure 2.1.

[41] The effects of climate change drivers to produce heating or cooling are discussed in chapter 2.

[42] Houghton, 2015, p. 116-120.

[43] The uncertainty analysis in the IPCC reports is described in Stocker, 2013.

[44] For a general discussion of the tendency toward conservative projections, see N. Oreskes, M. Oppenheimer & D. Jamieson, *Scientists have been underestimating the pace of climate change*, August 19, 2019, https://blogs.scientificamerican.com/observations/scientists-have-been-underestimating-the-pace-of-climate-change/

[45] Flato, 2013, p. 743-745.

[46] Over 97% of peer-reviewed climate science papers find support for anthropogenic warming. See http://theconsensusproject.com

[47] See the discussion on land use change in chapter 2.

[48] Friedlingstein, P. et al., *Global Carbon Budget 2019*, Earth System Science Data, 11, 1783-1838, 2019, DOI: 10.5194/essd-11-1783-2019 (2019), https://essd.copernicus.org/articles/11/1783/2019/essd-11-1783-2019.pdf

[49] See Box 3 in Chapter 1 for how to interpret the gigaton units.

[50] Friedlingstein, P. et al., *Global Carbon Budget 2019*, Earth System Science Data, 11, 1783-1838, 2019, DOI: 10.5194/essd-11-1783-2019 (2019), at p. 1813, https://essd.copernicus.org/articles/11/1783/2019/essd-11-1783-2019.pdf

[51] See the discussion of the carbon cycle in chapter 1.

[52] T. DeVries et al., *Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning*. Nature 542, 215-218 (2017).

[53] See https://www.ipcc.ch/sr15/faq/faq-chapter-1/ Also see Rogelj, 2018, section 2.2.2.2 and Table 2.2.

[54] Global Carbon Project, Carbon Budget 2019, https://www.globalcarbonproject.org/carbonbudget/index.htm

[55] The International Energy Agency (IEA) has calculated a carbon budget for a 2.0°C world that is similar to that provided in the IPCC1.5 report, see https://www.carbontracker.org/carbon-budgets-explained/

[56] Rogelj, 2018, section 2.2.2.2 and Table 2.2.

[57] T. Mauritsen and Robert Pincus, *Committed warming inferred from observations*, Nature Climate Change 7, 652 (September 2017).

[58] A large release of methane and carbon dioxide from the Arctic permafrost represents a potential climate change tipping point. See chapter 4 for discussion.

[59] Author's estimate based on the amount of fossil fuel burned so far (Table 1), and the amount of carbon emitted from fossil fuel burning from 1850-2017, ignoring differences in carbon emissions among the three fossil fuels. Le Quere, C. et al., *Global Carbon Budget 2018*. Earth Syst. Sci. Data 10, 2141-2194 (2018), https://www.earth-syst-sci-data.net/10/2141/2018/ Similar estimates of the fraction of burnable reserves have been made; see, for example, Ritchie, H. and Roser, M. *Fossil Fuels*. Our World in Data, https://ourworldindata.org/fossil-fuels (estimating that 63% of proven reserved must be stranded for a carbon budget that produces a 2.0°C world).

[60] We will look at the economic and political implications of stranding fossil fuel assets in chapter 6.

[61] Ruddiman 2014, p.134-135.

[62] R.E. Zeebe et al., *Anthropogenic carbon release rate unprecedented during the past 66 million years*, Nature Geoscience 9, 325 (2016).

[63] See https://www.ipcc.ch/sr15/faq/faq-chapter-1/ FAQ1.2, Figure 1.

[64] See Friedlingstein, P. et al., *Global Carbon Budget 2019*, Earth System Science Data, 11, 1783-1838, 2019, DOI: 10.5194/essd-11-1783-2019 (2019), https://essd.copernicus.org/articles/11/1783/2019/essd-11-1783-2019.pdf

[65] Houghton 2015, p. 134-137.

[66] We will take up the subject of climate change impacts in chapter 4.

[67] In 2011, the total anthropogenic forcing was estimated as 1.13 – 3.33 W/m^2. See Figure 1 in chapter 2 and the related discussion on radiative forcing.

[68] Hausfather, Z. *New scenarios show how the world could limit warming to 1.5C in 2100*, CarbonBrief, May 3, 2018, https://www.carbonbrief.org/new-scenarios-world-limit-warming-one-point-five-celsius-2100

[69] GP Wayne, *The Beginners Guide to Representative Concentration Pathways*, p. 14-18, Skeptical Science, https://skepticalscience.com/docs/RCP_Guide.pdf Information in this review is drawn in part from DP van Vuuren et al., *The representative concentration pathways: an overview*. Climatic Change 109, 5-31 (2011).

[70] See the Interlude.

[71] IPCC, 2018.

[72] See chapter 10 for discussion of natural land managament and industrial carbon sequestration.

[73] See https://blogs.nicholas.duke.edu/citizenscientist/volcanic-carbon-dioxide/ For a more detailed discussion, see World Meterorological Organization, WMO Greenhouse Gas Bulletin, No. 15, 25 November 2019, https://library.wmo.int/doc_num.php?explnum_id=10100

[74] Spiro, 2003, p. 25.

[75] Author's calculation based on data assembled by Ritchie and Roser, *Fossil Fuels*, Our World in Data, https://ourworldindata.org/fossil-fuels, BP Statistical Review of World Energy, 68th edition, 2019, and Smil, 2017. For more information on how estimates of remaining fossil fuel resources are made, see Hannah Ritchie, *How long before we run out of fossil fuels?* Our World in Data, https://ourworldindata.org/how-long-before-we-run-out-of-fossil-fuels.

[76] See https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf