The Global Carbon Cycle

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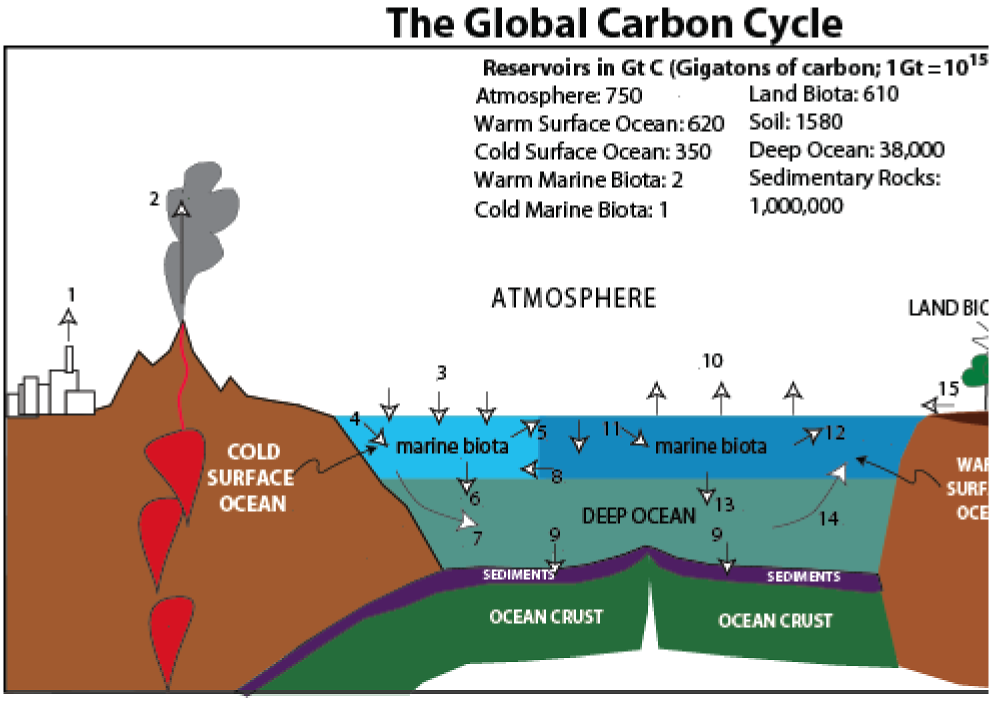
Introduction and History

Carbon is unquestionably one of the most important elements on Earth. It is the principal building block for the organic compounds that make up life. Carbon's electron structure gives it a plus 4 charge, which means that it can readily form bonds with itself, leading to a great diversity in the chemical compounds that can be formed around carbon; hence the diversity and complexity of life. Carbon occurs in many other forms and places on Earth; it is a major constituent of limestones, occurring as calcium carbonate; it is dissolved in ocean water and fresh water; and it is present in the atmosphere as carbon dioxide, the second most important greenhouse gas. The flow of carbon throughout the biosphere, atmosphere, hydrosphere, and geosphere is one of the most complex, interesting, and important of the global cycles. More than any other global cycle, the carbon cycle challenges us to draw together information from biology, chemistry, oceanography, and geology in order to understand how it works and what causes it to change. The major reservoirs for carbon and the processes that move carbon from reservoir to reservoir are shown in Figure 7.00 below. We will discuss these processes in more detail below and then we will construct and experiment with various renditions of the carbon cycle, but first, we will explore some of the history of carbon cycle studies.



The global carbon cycle, as best estimated, in 1994. Data slightly modified from Siegenthaler and Sarmient

Key to Flows:

1) Fossil Fuel Burning — 5 Gt C/yr
2) Volcanic Emissions — 0.6 Gt C/yr
3) Uptake of CO_2 by cold surface waters of the oceans — 90 GtC/yr
4) Photosynthesis of marine biota in cold surface waters — 18 GtC/yr
5) Respiration of living marine biota and rapid recycling of dead biota in cold surface waters — 14 GtC/yr
6) Sinking of dead marine biota (both organic and inorganic carbon) from cold water into deep water — 4 GtC/yr
7) Downwelling of cold surface water (mainly near the poles) — 96.2 GtC/yr
8) Advection (horizontal transfer) from warm to cold surface water — 10 Gt C/yr
9) Sedimentation on sea floor (both organic and inorganic carbon) stores carbon in sedimentary rocks — 0.6Gt C/yr
10) Release of CO_2 by warm surface waters of the oceans — 90 GtC/yr
11) Photosynthesis of marine biota in
12) Respiration of living marine biota warm surface waters — 26 GtC/yr
13) Sinking of dead marine biota (bot warm water into deep water — 6 Gt(
14) Upwelling of deep water (at equa 105.6 GtC/yr
15) River runoff transfers carbon frorr (2/3 to warm ocean, 1/3 cold)
16) Deforestation and land clearing r 1.5 Gt C/yr
17) Photosynthesis of land biota — 1
18) Respiration of land biota — 50 G
19) Litter fall and below-ground loss t the soil — 60 Gt C/yr
20) Respiration of micoorganisms in t atmosphere — 59.4 Gt C/yr

The global carbon cycle is currently the topic of great interest because of its importance in the global climate system and also because human activities are altering the carbon cycle to a significant degree. The potential effects of human activities on the carbon cycle, and the implications for climate change were first noticed and studied by the Swedish chemist, S. Arrhenius, in 1896. He realized that CO_2 in the atmosphere was an important greenhouse gas and that it was a by-product of burning fossil fuels (coal, gas, oil). He even calculated that a doubling of CO_2 in the atmosphere would lead to a temperature rise of 4-5°C -- amazingly close to the current estimates obtained with global, 3-D climate models that run on supercomputers. This early recognition of human perturbations to the carbon cycle and the climatic implications did not raise many eyebrows at the time, but the experiment was just beginning then.

About 60 years later, Roger Revelle, an American oceanographer, pointed out that we were effectively conducting a giant experiment with our climate system by emitting more and more CO_2 into the atmosphere. One of the problems, he realized, was that we were relatively ignorant about the possible results of this experiment and so he decided that it would be wise to begin monitoring atmospheric concentrations of CO_2. In the late 1950's, Revelle and a colleague, Charles Keeling, began monitoring atmospheric CO_2 at an observatory on Mauna Loa, on the big island of Hawaii. The record from Mauna Loa, shown in Figure 7.01 below, is a dramatic sign of global change that captured the attention of the whole world because it shows that this "experiment" we are conducting is apparently having a significant effect on the global carbon cycle. The climatological consequences of this change are potentially of great importance to the future of the global population.

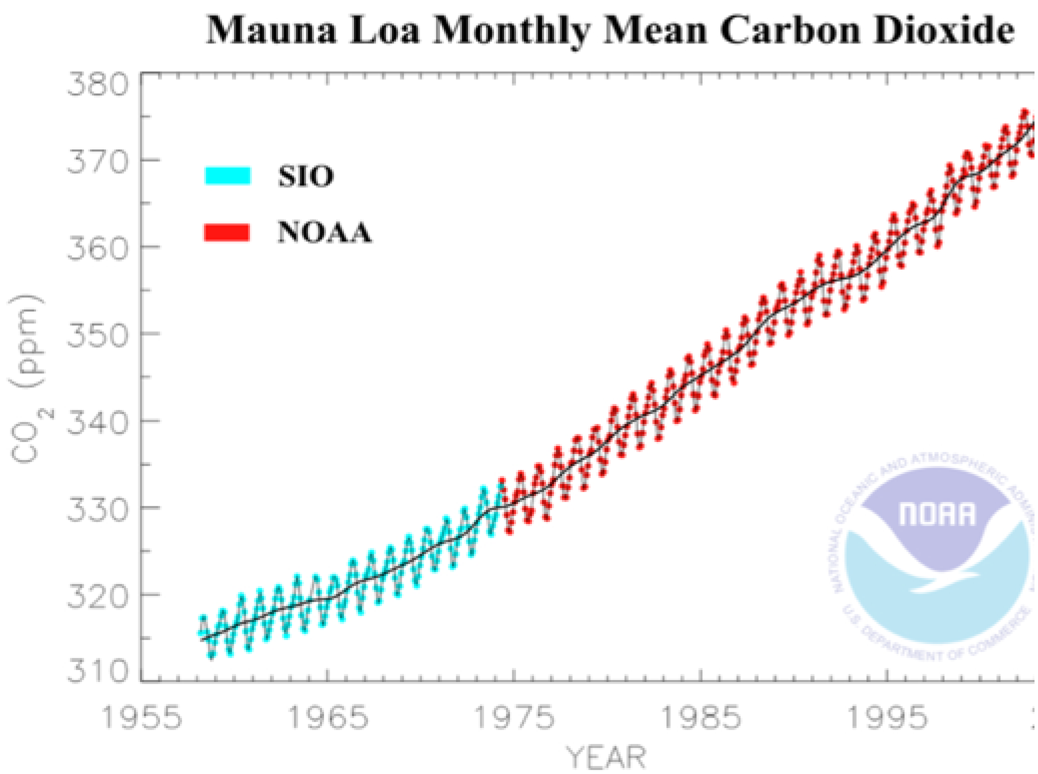


Figure 7.01 The record of CO2 measured at Mauna Loa, Hawaii shows seasonal cycles superimposed on a longer term rise. The seasonal cycles are related to seasonal variations in photosynthesis and soil respiration in the Northern Hemisphere where most of the land mass is located at present. The long term trend is related to the addition of CO2 to the atmosphere through the combustion of fossil fuels.

As the Mauna Loa record and others like it from around the world accumulated, a diverse group of scientists began to realize that we really did not know too much about the global carbon cycle that ultimately regulates how much of our emissions stay in the atmosphere. Consider, for instance, the present best estimate of what happens to all of the carbon dioxide emitted to the atmosphere through human activities, summarized in the table below.

Carbon Cycle Budget for Anthropogenic Effects

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<u>Sources</u>:

Fossil Fuel Burning & Cement Production 5.5±0.5 GtC/yr
Forest Burning & Soil Disruption 1.6±1.0 GtC/yr
Total Anthropogenic 7.1±1.1 GtC/yr

<u>Sinks</u>:

Storage in Atmosphere 3.3±0.2 GtC/yr
Oceanic Uptake 2.0±0.8 GtC/yr
Boreal Forest Regrowth 0.5±0.5 GtC/yr
Missing Sink 1.3±1.5 GtC/yr

GtC = Gigatons of carbon = 109tons data from IPCC, 1996

The primary problem in our understanding of the current state of the global carbon cycle is reflected by the "missing sink" -- we do not know where all of the anthropogenic CO_2 is going. We will explore this question of the missing sink in several of the modeling exercises in this chapter.

The importance of present-day changes in the carbon cycle, and the potential implications for climate change became much more apparent when people began to get results from studies of gas bubbles trapped in glacial ice. The bubbles are effectively samples of ancient atmospheres, and we can measure the concentration of CO_2 and other trace gases like methane in these bubbles, and then by counting the annual layers preserved in glacial ice, we can date these atmospheric samples, providing a record of how CO_2 changed over time in the past. The figure below shows the results of some of the ice core studies, relevant for the recent past -- back to the year 900 A.D.

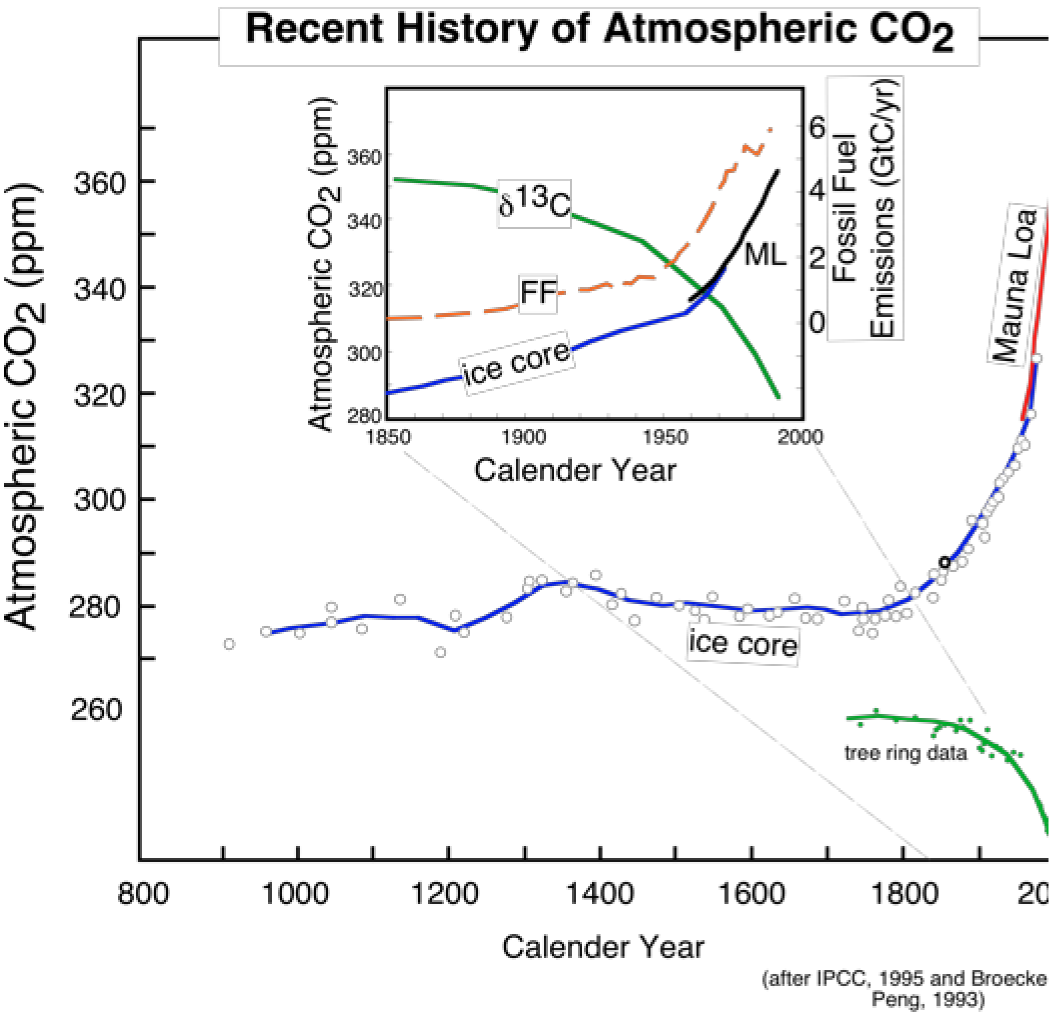

Figure 7.02. The recent history of atmospheric CO_2, derived from the Mauna Loa observations back to 1958 and ice core data back to 900 shows a dramatic increase beginning in the late 1800s, at the onset of the Industrial Revolution. At the same time, the carbon isotope composition ($d^{13}C$ is the ratio of ^{13}C to ^{12}C in atmospheric CO_2) of the atmosphere declines, as would be expected from the combustion of fossil fuels, which have low values of $d^{13}C$. The inset shows a more detailed look at the last 150 years, where we can see that the rise in CO_2 coincides with the rise in the burning of fossil fuels.

The striking feature of these data is that there is an exponential rise in atmospheric CO_2 (and methane, another greenhouse gas) that connects with the more recent Mauna Loa record to produce a rather frightening trend. Also shown in the above figure is the record of fossil fuel emissions from around the world, which show a very similar exponential trend. Notice that these two data sets shown an exponential rise that seems to begin at about the same time. What does this mean? Does it mean that there is a cause-and-effect relationship between emissions of CO_2 and atmospheric CO_2 levels? Although we should remember that science cannot prove things to be true beyond all doubt, it is highly likely that there is a cause-and-effect relationship -- it would be an extremely bizarre coincidence if the observed rise in atmospheric CO2 and the emissions of CO_2 were unrelated.

It is always worth considering if we can test a hypothesis. Here, the hypothesis is that human-related emissions of CO_2 are the cause of the rise in atmospheric CO_2. Can we test this? The answer is yes; there are in fact several ways of testing this hypothesis. One involves analyzing the ratios of carbon isotopes in CO_2 molecules found in the atmosphere. (A brief aside on carbon isotopes -- carbon atoms don't always have the same number of neutrons in them, so they occur with different atomic weights 14, 13, and 12, with ^{12}C making up around 98.9%, ^{13}C making up about 1.1%, radioactive ^{14}C, the radioactive one making up a tiny fraction. ^{12}C and ^{13}C are stable isotopes meaning they do not decay, while ^{14}C has a half-life of 5270 years and is continually being produced when ^{14}N in the atmosphere interacts with high-energy solar radiation.) The CO_2 produced by burning fossil fuels has a much lower ratio of ^{13}C /^{12}C than normal atmospheric CO_2. If we were adding new CO_2 that had the same ratio as the rest of the carbon in the atmosphere, the total amount of carbon will increase, but the ^{13}C /^{12}C ratio will stay the same; so by adding new with a much lower ratio of ^{13}C /^{12}C, we are diluting the atmospheric ratio of ^{13}C /^{12}C.

We therefore predict that if our hypothesis is correct, there should be a decline in the carbon isotope ratio in the atmosphere that should match the history of fossil fuel burning. But in order to test our hypothesis in a meaningful way, we would need to have some record of the carbon isotope ratio of the atmosphere far enough back to understand the significance of recent changes. We can get this information from bubbles of air trapped in glacial ice, and also from tree rings, which of course contain a lot of carbon and preserve a record of the atmosphere at the time they form. As shown in Figure 7.02 above, these data do show an exponential decrease beginning at about the same time as the onset of massive fossil fuel burning, so our hypothesis has passed the test, increasing our confidence in it.

Another test takes advantage of the fact that burning fossil fuels consumes an average of 15 oxygen molecules for every 10 molecules of CO_2; this means that we predict a decline in the overall concentration of oxygen in the atmosphere. This turns out to be a very difficult thing to measure, but Ralph Keeling (son of Charles mentioned above) has begun to make measurements and has already observed a decline in oxygen. Thus our hypothesis passes a second test, further increasing our confidence. A final test comes from the fact that the carbon released from burning fossil fuels is essentially devoid of ^{14}C, which has a short (5270 years) half-life; much of the fossil fuel we burn is on the order of 50 to 100 million years old, hence its depletion in ^{14}C. So, if our hypothesis is correct, then there should be a measurable decline in the concentration of ^{14}C in the atmosphere, beginning at about the time when we started to burn fossil fuels to fuel our industrial revolution. Indeed, this decline in atmospheric ^{14}C is observed, further strengthening our hypothesis that the rise in atmospheric CO_2 is caused by our burning of fossil fuels.

How serious is our modification of the natural carbon cycle? Here, we need a slightly longer perspective from which to view our recent changes, so we return to the records from ice cores and look deeper and further back in time than we did in Figure 7.02.

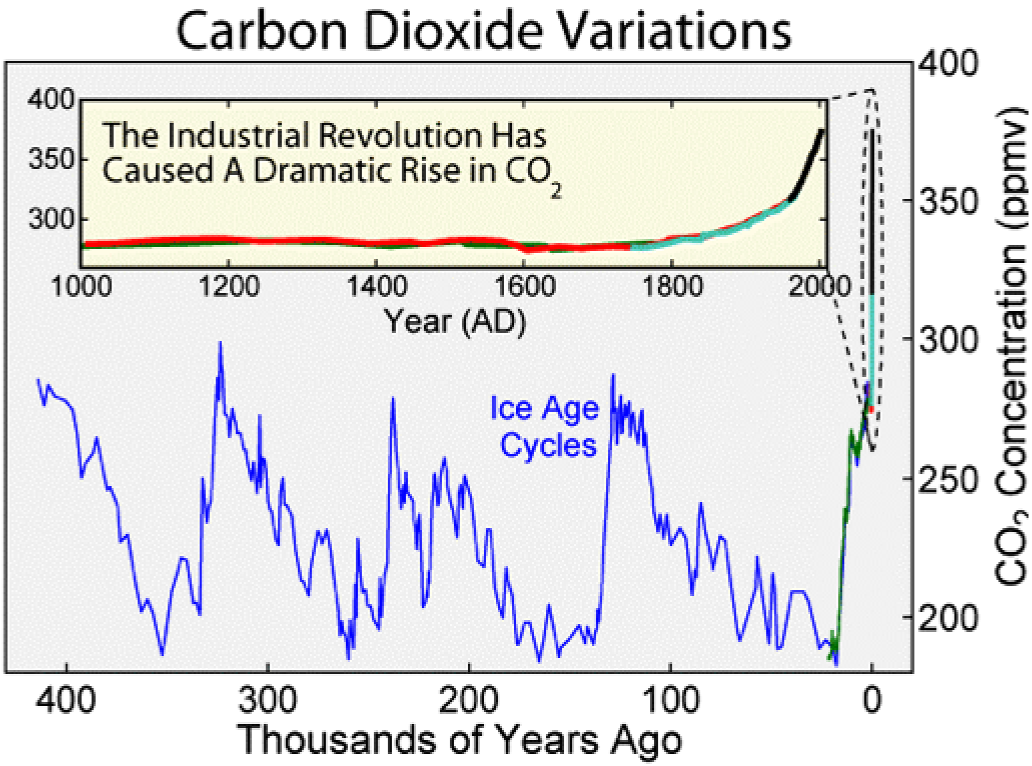

Figure 7.03. The record of atmospheric CO_2 over the last 400,000 years shows that the recent rise in CO_2 is unlike anything we've seen in the past 400 kyr both in terms of the rate of increase and the levels to which it is rising. Before this recent rise, CO_2 fluctuated by about 80 ppm in connection with the ice ages (which as you can see have a regularity to their timing); this pattern has clearly been interrupted by the recent trend. The data shown here come from a variety of ice cores (blue, green, red, and cyan) and the Mauna Loa observatory (black). Figure from Robert Rohde (http://www.globalwarmingart.com).

In addition to providing a record of the past concentration of CO_2 in the atmosphere, the ice cores also give us a temperature record. By studying the ratios of stable isotopes of oxygen that make up the glacial ice, we can estimate the temperature (in the region of the ice) at the time the snow fell (glacial ice is formed by the compression of snow as it gets buried to greater and greater depths). From these data, shown in Figure 7.03 below, we can see the natural variations in atmospheric CO_2 and temperature that have occurred over the past 160,000 years (160 kyr).

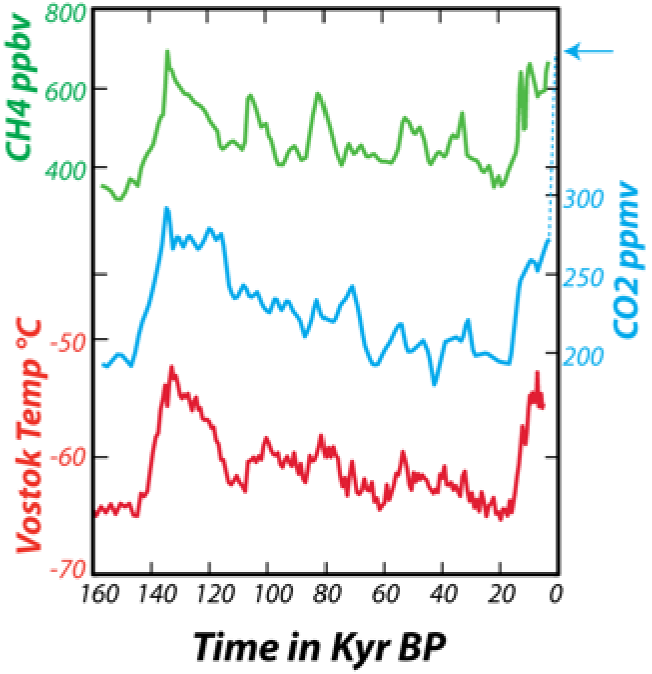

Figure 7.04 Data from the Vostok (Antarctica) ice core for the past 160 kyr show the relationship between variations in heat-trapping gases CO_2 (carbon dioxide) and CH_4 (methane) concentrations in parts per million (ppm) and parts per billion (ppb) and the temperature at Vostok. Note that each curve has its own scale for the vertical axis, but they all share the same time scale. The dashed blue line at the end shows the very recent rise in CO_2 to the present day value of about 390 ppm, indicated by the arrow. The gas concentrations come from tiny bubbles trapped in the ice as it forms near the surface, while the temperature variations come from studying isotopes of oxygen and hydrogen in the ice itself. The ice cores thus provide us with an exceptional picture of the natural variation of the important climate system variables.

Looking at this much longer span of time enables us to clearly see that the present CO_2 concentration of the atmosphere is unprecedented in the last several hundreds of thousands of years. As geoscientists, we are interested in more than just the last few hundred kiloyears, and so we look back into the past using sediment cores retrieved from the deep sea. Geochemists studying these sediments have been able to reconstruct the approximate concentration of CO_2 in the atmosphere and the sea surface temperature (SST).

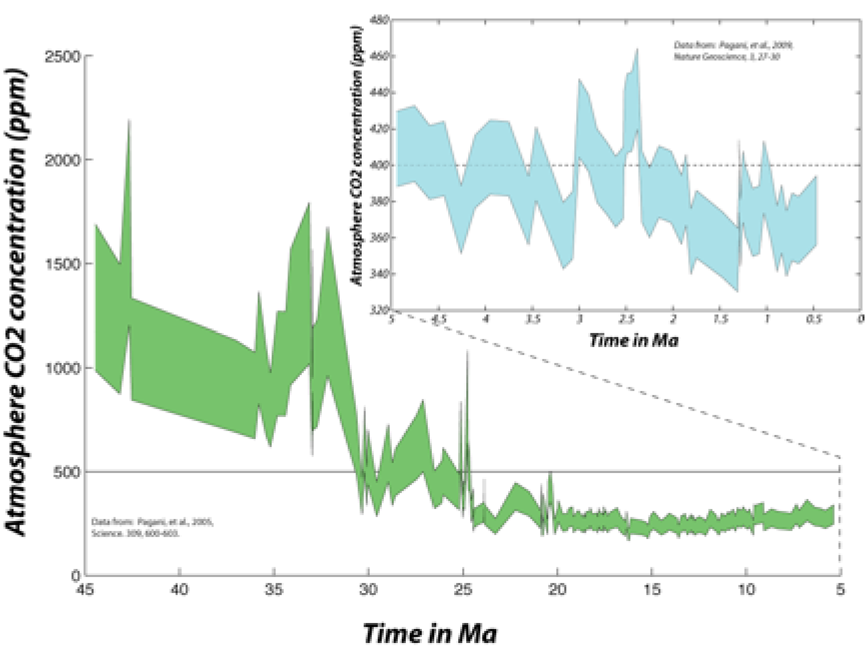

Figure 7.05. The longer history of atmospheric CO_2 as reconstructed from studies of deep sea sediments. In the upper right, the blue region represents the upper and lower estimates back through time — you can see that it is difficult to be too precise going back this far in time — and you can see that the last time the midpoint of these estimates rose above the current level was around 2.5 Myr ago. This was a time when there was far less ice on Earth; the Arctic was apparently 15 to 20°C warmer than it is today, and sea level was about 20 meters higher than the present. As we go further back in time, we see that the atmospheric CO_2 concentration rise to very high levels. The Earth was a very different place before about 30 Ma — sea level was perhaps 100 m higher and there was practically no ice on Earth.

To find atmospheric CO_2 levels equivalent to the present, we have to go back millions of years. This means that, to the extent that the state of the carbon cycle is closely linked to the condition of the global climate, we are pushing the system toward a climate that has not occurred anytime within the last several million years -- not something to be taken lightly.

The farther back in time we go, the more difficult it is to figure out how CO_2 concentrations have changed, but that has not stopped some from attempting:

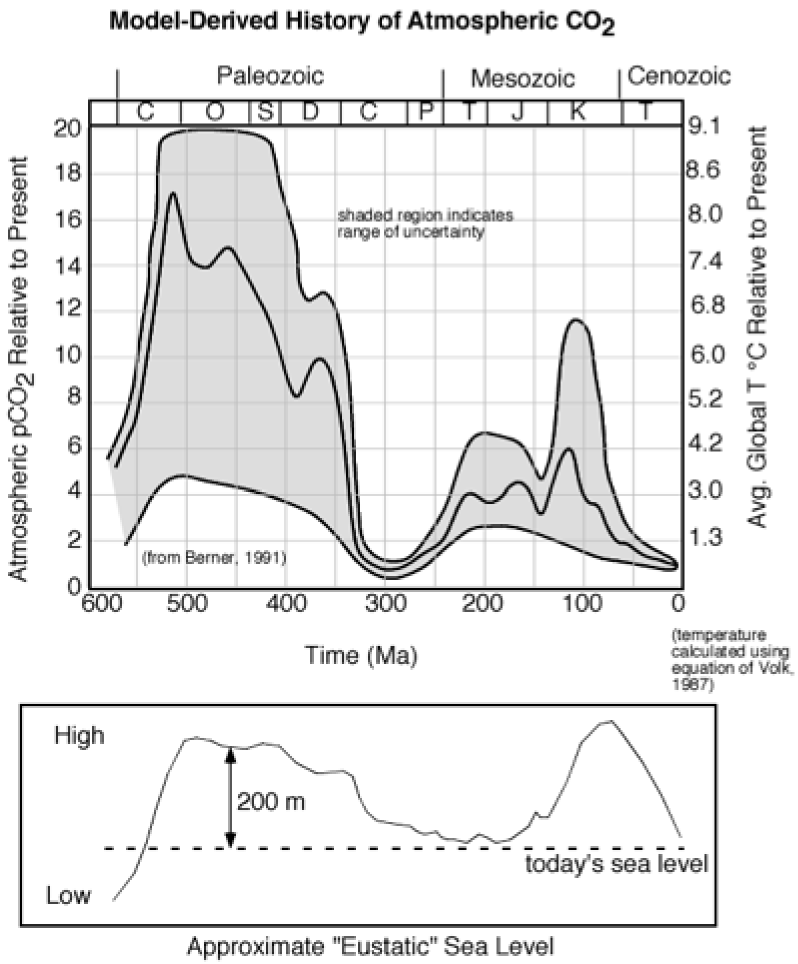

Figure 7.06. The history of atmospheric CO2 over the last 550 Ma, based on modeling, shows extremely high levels before 350 Ma. Note that there are huge uncertainties associated with these estimates, but the mid-range of the estimates suggests that CO2 levels were very high during this time period. Interestingly, these periods of high CO2 more of less coincide with periods of high sea level as can be seen in the lower panel.

From this brief look at the record of fossil fuel emissions and atmospheric CO_2 concentrations, it is clear that we have cause for concern about the effects of this global experiment. Because of this concern, there is a tremendous effort underway to better understand the global carbon cycle. In this section, we will explore the global carbon cycle by first examining the components and processes involved and then by constructing and experimenting with a variety of models. The first set of models will be relevant to the dynamics of the carbon cycle over a period of several hundred years -- these will enable us to explore a variety of questions about how the system will behave in our lifetimes. The second set of models will provide an introduction to modeling the changes in the isotopic ratios of carbon alluded to earlier. A third model will be relevant for much longer periods of time, allowing us to explore a different set of questions.

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