Central Coast Climate Science Education

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Lesson 6: The Carbon Cycle

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In Lesson 1, Energy Balance: A Fundamental Law of Nature, we discussed one of the most fundamental laws in physics: energy is neither created nor destroyed, but can flow from one place to another and can change from one form to another. In Lesson 5, Is Earth Currently in Energy Balance, we saw the implications of this for the current changes in the Earth's climate system: The Earth's climate system is out of energy balance and is accumulating energy. In this Lesson we will deal with another quantity that is neither created nor destroyed, can move from location to another and changes from one form to another. This is carbon, the atomic element that is the basis for all life.

Carbon is found in the atmosphere, in the form of carbon dioxide (CO_2), and we have previously discussed its role in reducing the amount of heat in the form of infrared radiation that escapes into space. A large fraction of the carbon dioxide emitted into the atmosphere, whether naturally or by human activity, ends up being absorbed into the ocean. Upon reacting with water it forms a weak acid, carbonic acid. Were it not for the ocean's ability to absorb carbon dioxide from the atmosphere, the increase of CO_2 in the atmosphere caused by human activity would be much greater than it has been.

Both on land and in the ocean, every form of life contains carbon, and vast quantities of carbon are stored in the forests and soil. Trees and other vegetation use CO_2 in the atmosphere, along with water and the energy derived from sunlight, to convert the carbon into more complex forms and in the process release oxygen. This process involves ***photosynthesis***. Animals and humans consume some of these complex products, combine them with the oxygen we breathe from the air and recover some of the energy originally derived from sunlight. In the process, carbon dioxide is released back into the atmosphere. In addition, some of the carbon stored in trees is also released back into the atmosphere from fires, whether started naturally or by humans. Some marine organisms build shells incorporating carbon in them, and ultimately this carbon is incorporated into limestone.

There are also vast amounts of carbon stored as methane in what are known as "clathrates" in which the methane (CH_4) is surrounded by a "cage" of frozen water molecules. Clathrates are found in regions of permafrost and in the oceans on the outer continental shelves. Clathrates may have played a crucial role in profound climate changes in the past and could conceivably do so in the future. This will be discussed in Lesson 7, Looking Forward By Looking Backward. In the addendum to Lesson 2, it was pointed out that melting permafrost may give rise to another potent feedback as the warming temperatures release methane that, also being a greenhouse gas, adds to the warming.

As vast as is the amount of carbon stored in all the forms above--in the atmosphere, the ocean, soil, and the "biomass"--that amount of carbon is dwarfed by the amount stored in various forms deep in the Earth. The most obvious examples, and the focus of most of the attempts to control climate change are, of course, coal, oil and natural gas deposits. These are formed when organic matter is subjected to extreme pressure deep underground. In retrieving and burning these 'fossil fuels' we are simply recovering some of the solar energy stored in this organic material tens or hundreds of millions of years ago. An even larger store of carbon occurs in many carbon-containing minerals in the Earth's crust, typically also containing the elements calcium, magnesium, iron and oxygen.

If we were to follow the history of a given carbon atom over enough time it would likely pass through all these forms, but the total number of carbon atoms does not change. The migration of carbon atoms through these various storage areas comprises the 'carbon cycle'. However, the time spent in a given form varies drastically, and it is convenient to divide the processes into those that proceed very slowly, and those that take place over intermediate or short periods of time.

The following two figures show, first, the "slow cycle" and then the intermediate and short period cycle. Do not be intimidated by the apparent complexity of these two figures, since we do not need to go into great detail; the essential features will be explained!

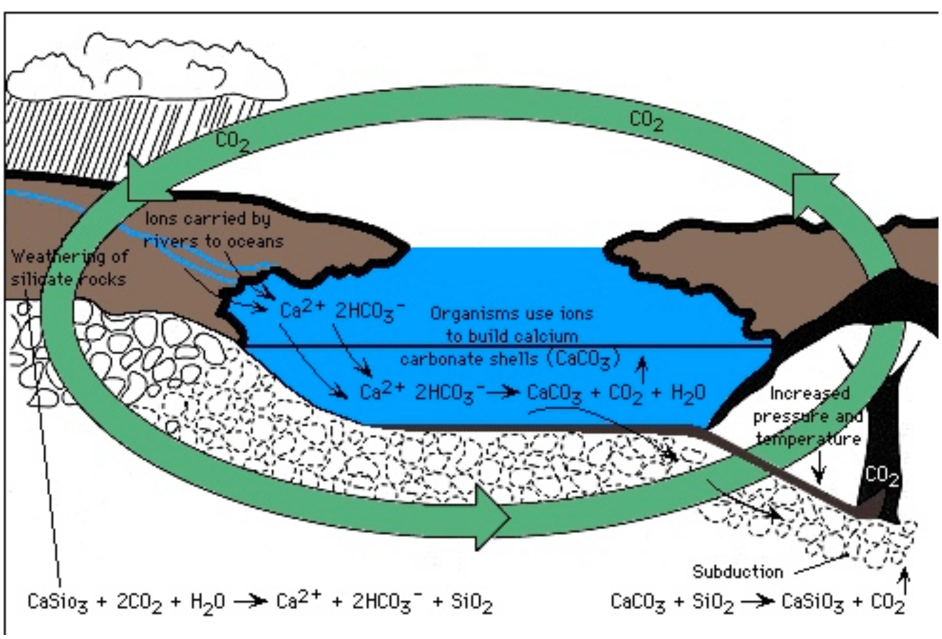


Figure 1: The long term carbon cycle

Figure 1 shows the essential features of the 'long term' carbon cycle. Starting in the upper left portion of the diagram, carbon dioxide from the atmosphere and water molecules (shown in this case as rain), react chemically with various minerals to ***extract*** carbon dioxide from the atmosphere. The products of this reaction, including carbon-containing molecules, are eventually washed into the ocean, where marine organisms store up the carbon in the form of shells, composed of calcium carbonate. Some carbon dioxide is also produced, which is absorbed by the ocean.

In addition, however, a large amount of carbon stored as carbon-containing minerals is carried deep into the Earth as portions of the Earth's crust slide beneath other portions of the Earth's crust in a process called 'subduction'. Under these circumstances the minerals are subjected to very high temperatures and pressures. These extreme conditions produce molten material as well as carbon dioxide and other gases. The 'subduction zones' are therefore areas where volcanoes are numerous, as well as being the sites of frequent earthquakes. When the carbon dioxide reaches the surface it is released into the atmosphere. This long term cycle typically takes hundreds of thousands to millions of years. This means that if we are only interested in shorter term changes in the carbon storage areas -- decades to a few thousand years or so -- we can ignore this long-term cycle. But if we wish to understand the behavior of the Earth's climate over millions of years, it is crucial.

The intermediate to short term carbon cycle is shown in Figure 2.

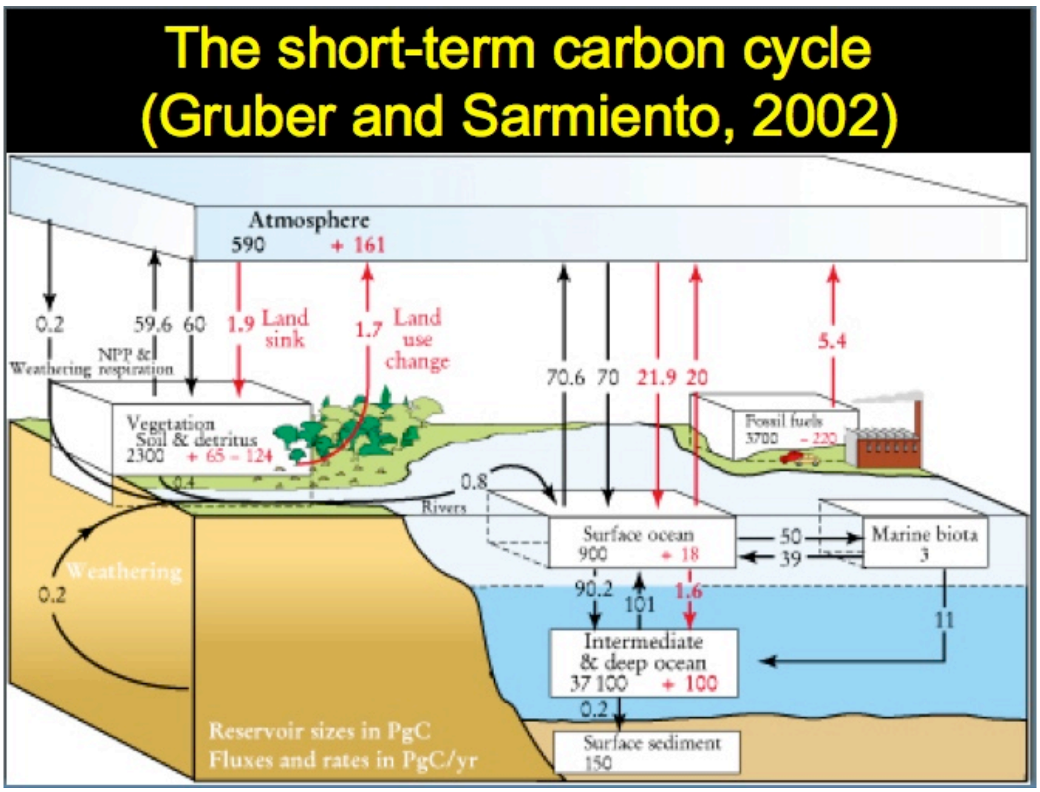


Figure 2. The short-term carbon cycle

As in Figure 1, we need not worry about all the details. The basic components in the diagram involve boxes and arrows. The numbers in the ***boxes*** represent the amount of carbon in the various places where carbon is stored. ***Black*** numbers refer to the situation ***before*** human consumption of fossil fuels and significant changes in land use occurred. ***Red*** numbers show the effect of human activity. (The units are PgC, which stands for "petagrams of carbon". This is equivalent to one billion tonnes of carbon and "tonnes" refers to a 'metric ton' which is about 10% more than our ordinary 'ton'). ***Arrows*** show the ***rate*** (in PgC per year) at which carbon is either entering or leaving a box, and, as in the case of the boxes, the ***black*** arrows show the situation prior to humans altering the carbon cycle while the ***red*** arrows show how we have altered it.

Consider the top box labeled 'atmosphere' and consider only the black numbers: If you add up the numbers associated with the 'up' arrows and subtract the numbers associated with the 'down' arrows, you will get 0.0. Here are the details:
Up arrow from the vegetation box = 59.6; ***up*** arrow from the surface ocean box= 70.6, yielding 130.2 PgC per year into the atmosphere, prior to disruption of the cycle by human activity. Down arrows from the atmosphere are: 0.2 from weathering, as discussed above (this is a slow process which is why it occurs at a small rate, though it has been included in this diagram); 60.0 back into the vegetation box (photosynthesis) and 70.0 back into the ocean, for a total of 130.2 PgC per year.

That is, prior to the onset of the industrial revolution and the accompanying very rapid increase in human population, the amount of carbon in the atmosphere (mostly in the form of carbon dioxide) was in balance. Of course these numbers are not known with this precision, but are estimated with the constraint that the amount of CO_2 in the atmosphere has changed very little over the last few thousand years—since the last great ice age came to an end. This has been verified to be very nearly the case as will be discussed in Lesson 7, Looking Forward By Looking Backward.

On the other hand, if we consider the ***alteration*** in the carbon flow into and out of the atmosphere represented by the ***red*** arrows. Now if you add both the red ***and*** black arrows going into and out of the atmosphere box, you will find that the carbon balance has been upset and every year the atmosphere gains about 3.3 PgC of carbon due to human activity. ***The primary source of this imbalance is the red 5.4 PgC per year going into the atmosphere due to the combustion of fossil fuels.***

As can be seen from Figure 2, the increasing amount of CO_2 in the atmosphere has caused a modification of the exchange of carbon between both the ocean and land carbon storage and the atmosphere. As the Earth's climate system "tries" to keep up with the imbalance in the carbon cycle caused by human activity, it is currently managing to absorb about half of the amount injected into the atmosphere by the combustion of fossil fuels. (As is evident from Figure 2, this paper dates to 2002 and the numbers have been somewhat revised since but the basic picture remains the same.) Over several decades this has been the case, though the rate at which carbon dioxide has been accumulating in the atmosphere is rapidly increasing as the consumption of fossil fuels themselves rapidly increase. Moreover, there is no assurance that the "Earth will do its part" and continue to absorb about half of the injection of carbon into the atmosphere caused by deforestation and fossil fuel consumption. Indeed, as mentioned in the Addendum to Lesson 2, a recent study of melting permafrost concluded that in a few decades the land masses in the far north, instead of absorbing more carbon than they give off, will start to give off more than they absorb (i.e. this land becomes a source rather than a sink of carbon.) This may also be the case in other components of the climate system. Needless to say, if fossil fuel emissions continue to accelerate this will only make the accumulation rate in the atmosphere more severe as the “sinks” of carbon turn into “sources”.

Here is a simple “cartoon” illustrating the current imbalance between the sources and sinks of carbon dioxide. But note that the “bathtub” is the atmosphere, not the ocean:

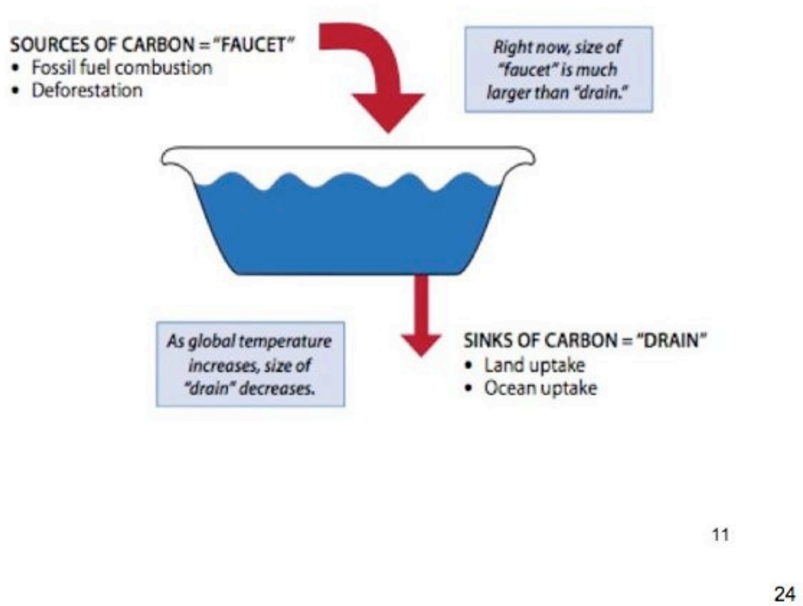
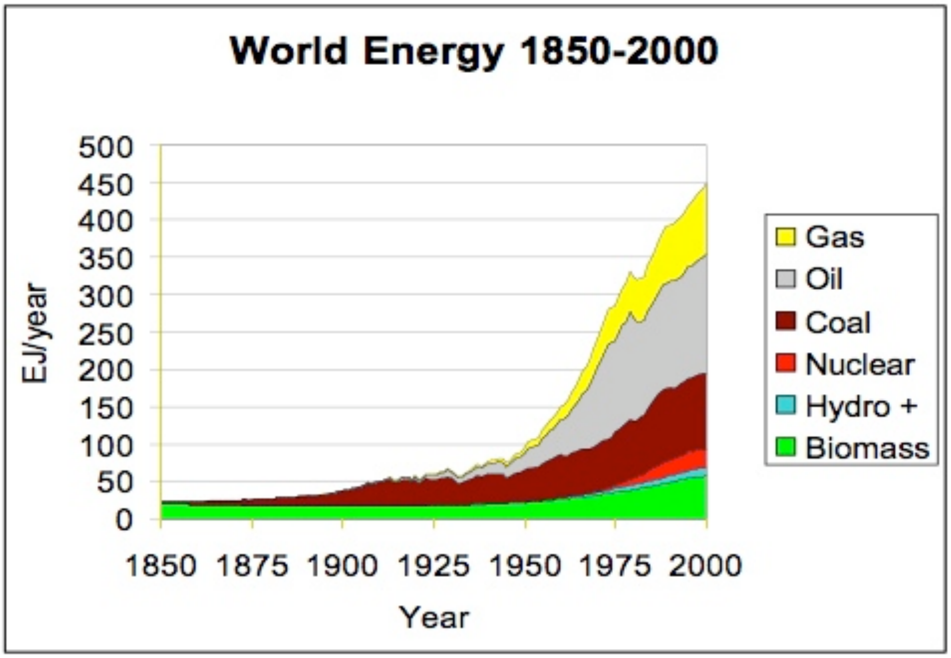


Figure 3

The estimate of the amount of carbon injected by fossil fuel combustion comes from records of the amount of energy consumed and since the amount of carbon dioxide produced by the combustion of various forms of fossil fuel is known, this leads to estimates of the amount of carbon dioxide injected into the atmosphere.
 (There is sometimes confusion between the tonnage of carbon dioxide and carbon itself: The weight of each carbon dioxide molecule is very nearly 44/12 or about 3.7 times the weight of the carbon in the carbon dioxide molecule itself, owing to the two oxygen atoms.)

A history of overall energy usage is shown in Figure 4.



Fossil fuels drove most of the growth & were almost 80% of supply in 2000.

Figure 4

It is no accident, of course, that this figure is similar to the measured increase in carbon dioxide as directly measured since approximately 1960. This is Figure 4, the “Keeling Curve” that we already saw in Lesson 3.

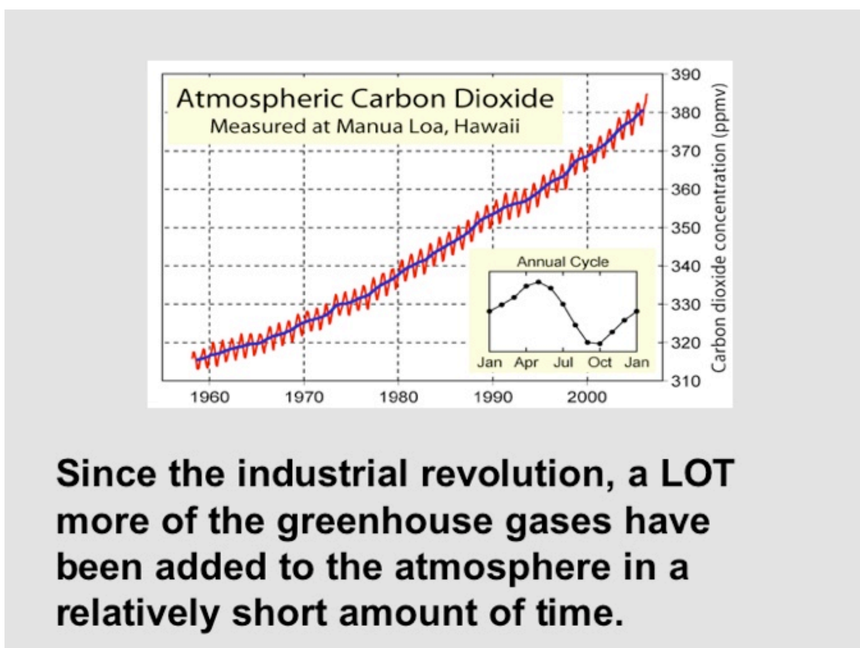


Figure 5: The "Keeling Curve"

The rate of energy consumption has steadily increased since 2000, to a large extent driven by the desire of developing nations, especially China, to achieve the standard of living enjoyed by the developed countries, and cheap abundant energy has been a key to this.

Readers who have digested the material in Lesson 1, Energy Balance: A Fundamental Law of Nature, and Lesson 5, Is Earth Currently in Energy Balance, will notice the similarity between energy balance and carbon balance: In both cases the Earth's climate system was pretty closely in balance over the few thousand years prior to the industrial revolution in both energy and carbon. In both cases, however, the amount by which the system is out of balance is relatively small, percentage-wise: In the case of the energy imbalance, it is very roughly only 0.3%, whereas in the case of the carbon imbalance it is very roughly 2.5%.

In both cases, there is extremely strong evidence that these imbalances are primarily due to human activity. Nevertheless, it is important to obtain a more detailed understanding of the workings of the carbon cycle since this is important in projecting how the amount of carbon dioxide will increase with time, given how the use of fossil fuels develops in the future. The ocean currently is probably the larger of the two carbon dioxide sinks but the soil and biomass on land is also important and still imperfectly understood. There were high hopes that a NASA satellite, the Orbiting Carbon Observatory, would significantly add to our understanding of the sources and sinks of carbon. Unfortunately, during the launch on February 24, 2009, from Vandenberg Air Force Base, the launch vehicle suffered a malfunction and the satellite was lost. A second version of this instrument is scheduled to be launched in July 2014. Let's hope it goes well.

The Longevity of CO_2 in the Atmosphere

The longevity of CO_2 in the atmosphere is a critical issue when assessing the impacts of continued use of fossil fuel. This concept is often misunderstood so it is worth explaining in a little detail. Suppose we were to follow a single carbon dioxide molecule as it travels on its journey around the carbon cycle, and suppose we start following it shortly after it has entered the atmosphere. It is quickly carried to and fro both vertically and horizontally by air currents with the result that the distribution of carbon dioxide almost uniform with height and over the surface of the Earth (Thus, carbon dioxide is referred to as a "well-mixed" greenhouse gas.

As you can see in Figure 2 by the rates at which CO_2 leaves the atmosphere, it is most likely to be absorbed by the ocean but with an almost equal probability of ending up being absorbed by vegetation. It is then the "luck of the draw" whether it quickly leaves the atmosphere again or lingers for a while. We can get a ***very rough*** estimate of the **average** time a CO_2 molecule spends in the atmosphere by simply taking the total amount of CO_2 in the atmosphere and dividing by the rate at which it is leaving the atmosphere. Using the pre-industrial values (the values in black—adding the red numbers doesn't change things a great deal), we get: 590/130, which is about 4 ½ years.

Does this mean, therefore, that if suddenly the world were to stop producing CO_2 by burning fossil fuel that the level of CO_2 in the atmosphere (currently at 395 ppm as of November 2012) would return to its pre-industrial value of about 280 ppm in about 4 or 5 years, thus quickly restoring our climate system to a state of energy balance? Unfortunately, no! The reason is that the upward arrows ***into*** the atmosphere do not magically turn off—there would be continued natural flows of CO_2 into the atmosphere as well.

Detailed estimates of the amount of CO_2 that will eventually accumulate in the atmosphere depend on when, and whether, the nations of the world curtail the use of fossil fuel. There is enough carbon available in the form of fossil fuels to reach levels as high as 1200 ppm. If at that time the input were suddenly stopped here is a calculation of how the return towards the preindustrial value would proceed:

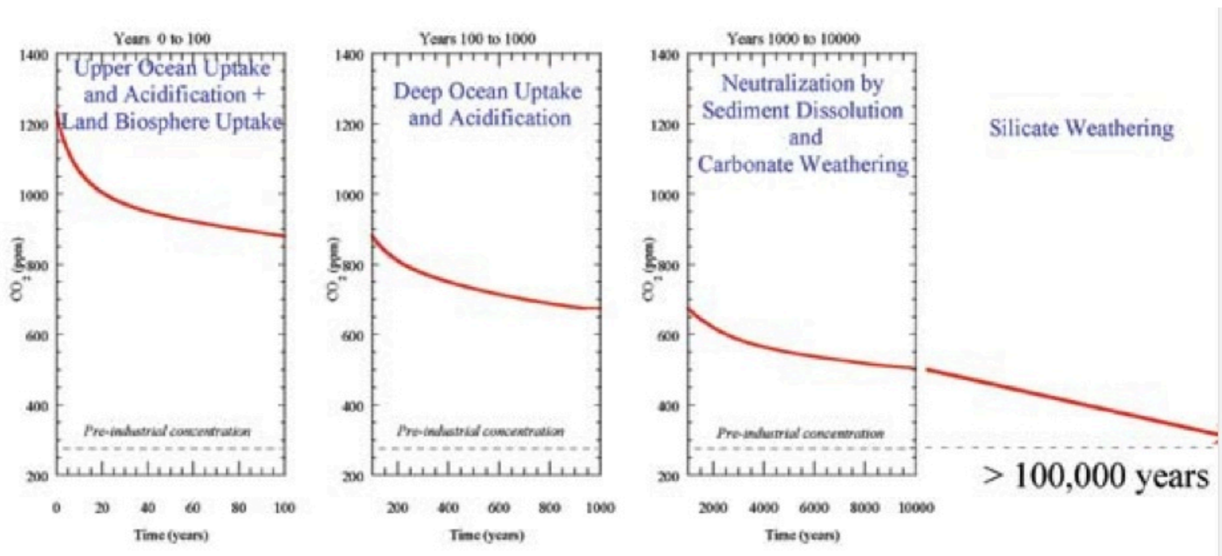


Figure 6

Note that each panel has a very different scale of years associated with it. The sobering and crucial point of this figure is this: the excess amount of CO_2 we are putting into the world lingers for a ***very long time*** during which, for all this time, the Earth will be getting warmer and warmer. We will return to this figure and its implications in Lesson 8.