Central Coast Climate Science Education

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Lesson 7: Looking Forward by Looking Backward

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The full power of the system of satellites studying our Earth's climate, together with the explosion of knowledge gained by thousands of scientists studying the Earth's climate system is just now beginning to teach us about how this system works. But there is still an enormous amount yet to learn. We can expect an even greater advance in our knowledge in the coming decade compared to that from this past decade. Even so, observations of a few decades cannot sample anything like the variations in the Earth's climate that have occurred over the past thousands and millions of years.

That there have been large changes in the Earth's climate system in the past is known by most people. Indeed, the most frequent comment I encounter in discussing the current rapid warming of the last several decades is "But isn't this just part of a natural cycle?" At the risk of over-repetition it needs to be stated once again: Climate changes do not "just happen"--the laws of physics are always obeyed and there are causes for all changes even though the causes may be complex and imperfectly understood. But by first trying to reconstruct Earth's past climate, and then trying to understand the underlying causes for past climate changes, we may gain greater insight into the direction our climate may take in the future. In other words, we can "Look Forward by Looking Backward".

The sub-discipline of climate science studying the climates of the past is called "Paleo-climatology". It is convenient to divide these studies into three parts:

I) Reconstruction of world temperatures over the last 1500-2000 years

II) Study of the alternating series of ice ages and 'interglacial' periods over approximately the last 800,000 years

III) Study of the extreme ranges in the Earth's climate over much longer periods of time--tens and even hundreds of millions of years.

I) Temperature Reconstruction over the past 2000 Years

Although the first thermometers date back to the 1600's, no meaningful set of worldwide temperatures began to be assembled until about 1850. Thus, if one wishes to reconstruct temperatures over large areas of the globe dating back hundreds of years prior to this date, one needs to find other indicators of temperature. These indicators are called ***proxies***, though of course they do not have the precision of actual thermometers. Probably the best known of these proxies are tree rings. But corals show growth bands, and ocean and lake sediment layers are also used along with other techniques, and they all carry information about sea, land or air temperatures. Ice core in particular carry important information and we will discuss ice cores in more detail in Part II on the Ice Ages.

To use proxies two things must be done: i) An approximate ***date*** must be assigned to the particular layer or ring or band under study. ii) The interpretation of whatever data are extracted in terms of temperature must be ***calibrated*** by comparison with actual temperatures recorded in the last 100 to 150 years. In addition, care must be used to correct for the influence of factors other than temperature that influence the particular proxy. For example, the amount of precipitation will also influence tree ring patterns.

All the proxies have their strengths and weaknesses, so many of the current temperature reconstructions combine many proxies ("multi-proxy" studies). Finally, if one wants a picture of past ***global*** temperatures or of the ***northern*** or ***southern hemisphere*** temperatures, then the proxy records from various regions must be combined appropriately to give a global or hemispheric picture.

One of the first major attempts at temperature reconstruction of the past 1000 years was published over ten years ago and occasioned a major tempest in a moderate-sized teapot. This analysis concluded that, averaged over the Northern Hemisphere, the past few decades were warmer than at any time during the past 1000 years. This became the focus of much criticism and attention because it was perceived to be the strongest argument in favor of current global warming. (Essentially the same result was obtained for the ***globally*** averaged temperatures, but the results were weaker because data for the Southern Hemisphere were sparser). As discussed in Lesson 5, however, there are more direct arguments for the recent rise in global temperatures driven by fossil fuel combustion.

In any event, using larger data sets and a variety of improved statistical techniques, more recent analyses still produce the same basic result, an example of which is shown in Figure 1.

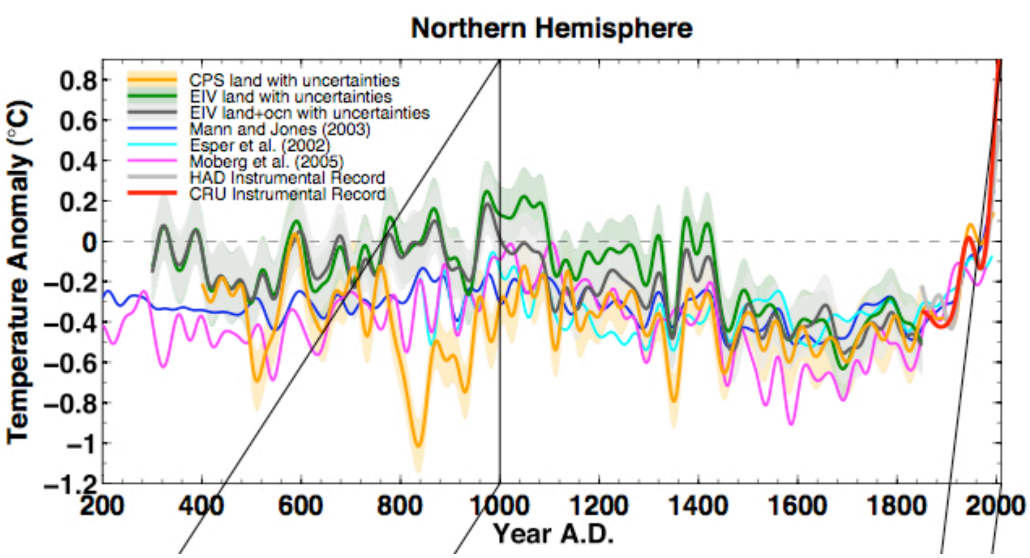

Figure 1. This figure is taken from a paper by Mann *et al*., published in the

Proceedings of the National Academy of Sciences in 2008 [1]. The diagonal and vertical black lines point to an expanded version of this same plot that is not shown here.

The graph shows the reconstruction of the temperature ***averaged over the Northern Hemisphere*** by several groups and using different techniques and proxies. “Temperature anomaly” as used in climate science means the difference in temperature between a given time and some arbitrarily chosen baseline period, rather than the more common usage of “anomaly” to mean something outside the ordinary. There are three important features to notice about this graph: 1) The heavy red line is the actual record of temperatures measured with thermometers and the steep increase over the last 40 years has resulted in the present temperature being well above any occurring over the last 1800 years, though the results become less certain at the earliest times. 2) There was an extended period peaking around 1050-1100 AD when temperatures were above the baseline period, though still well below the present northern hemisphere averaged temperature. This period is the so-called "Medieval Warm Period". 3) From about 1500 to 1800 AD, temperatures were lower than normal, averaged over the Northern Hemisphere, and this period is sometimes referred to as the "Little Ice Age", though it is not to be confused with, and was very much milder than, the vast ice ages we will discuss in part II.

It is unfortunate that the controversy accompanying the initial temperature reconstructions still tends to obscure a more interesting and still more recent result: With ever increasing proxy data being developed, it has become possible to reconstruct the past temperature history of individual regions, rather than just global or hemispheric averages. An important result is that there are very significant differences from one region of the globe to another during both the Medieval Warm Period and the Little Ice Age. This is in contrast to the present warming that has taken place over almost all of the entire planet. It appears that the ocean-atmosphere oscillations discussed in Lesson 4, for example the El Nino-Southern Oscillation (ENSO), favored one phase over another in a way that differs somewhat from the present.

Recall from Lesson 2 that the two main ***natural*** forcings which act over times short enough to cause significant climate changes over mere centuries are changes in solar energy and volcanism. Of course there were no satellites continually orbiting the Earth in those days, so we must rely on proxies for solar activity and volcanic activity, just as proxies are relied on for temperature. When computer simulations are run with these 'proxy forcings' included they can reproduce fairly well the temperatures ***averaged over the Northern Hemisphere***. This is shown in the following figure.

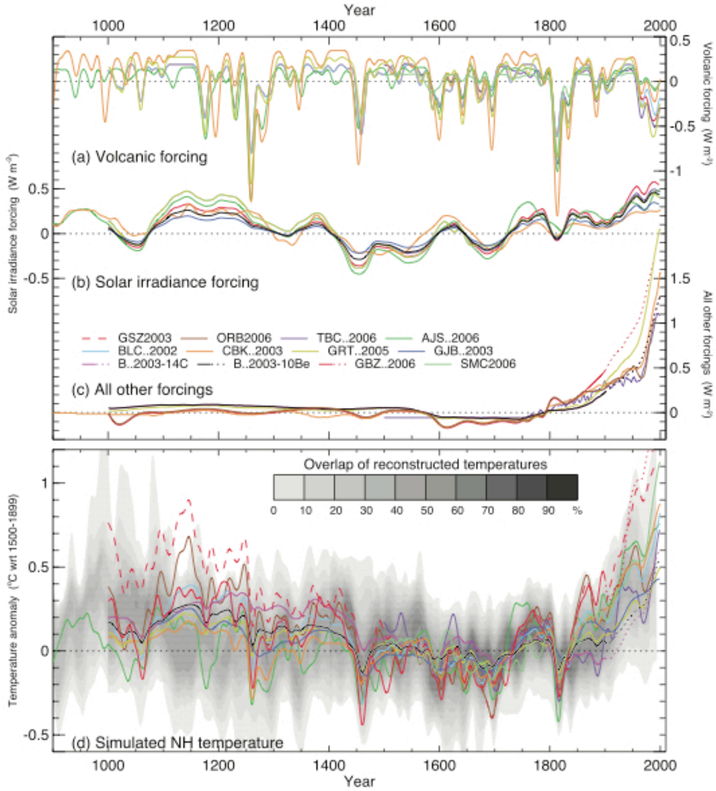

Figure 2. This is Figure 6.13 in IPCC AR4. The top panel shows estimated forcings from volcanic activity, solar energy variations and “other”, while the bottom panel shows the range of temperatures reproduced from computer models run with these forcings.

While these simulations were able to reproduce the moderate warming of the medieval warm period and the cooling of the “little ice age” such simulations in general are not able to account for many of the regional differences and the apparent shift in properties of the ocean oscillations. Some of the deficiencies in these simulations are known and some are not. But it may also be the case that some of the shift in the ENSO properties reflects extremely long term natural variability ('weather') of the type discussed in Lesson 4.

Since the human-induced forcing causing current warming probably exceeds the natural forcings experienced over the past 500-1500 years, and will almost certainly significantly exceed them before the end of this century, a crucial question yet to be answered is: Will these human-induced forcings bring about similar shifts in the relative frequency and intensity of the phases of the ENSO and other oscillations? If so, it will have major consequences for regional climate changes.

Almost everyone speaking about climate change has heard a comment something like the following: “Don’t you know that about a thousand years ago, people were farming and growing grapes in Greenland and it was warmer then than it is now! So how can you say that fossil fuel emissions have anything to do with current warming?” I have never been able to locate any credible evidence that in fact the Vikings grew grapes in Greenland, but there is evidence that the ice sheet had retreated inland leaving some coastal areas where some farming took place. The essential thing to note is that the medieval warm period was highly variable in both time and space—some areas warmed, while others did not or even got cooler, and the warmest times in some locations did not coincide with those in others. And, as illustrated above the temperature of today is significantly higher than the temperature during the medieval warm period when averaged over the northern hemisphere or entire globe.

II. THE ICE AGES

We now examine a longer interval in the more distant past, extending from about 10,000 years ago back at least 800,000 years. Not surprisingly, the further into the past one looks, the fewer the available proxies. However, this is partly compensated for by i) the much larger changes in climate that have occurred during this longer period of time, and ii) the relatively slow pace of change. Nevertheless, there are still important records of the Earth's climate from this period. Two of the most important are marine organisms deposited as ocean sediments and carrying information about the temperature at the time of their existence, and ice cores.

Scientists have drilled deep into the massive ice sheets of Greenland and Antarctica and retrieved cores from these ice sheets. Like tree rings, they have bands caused by seasonal variations in snowfall. An example is shown in Figure 2. (GISP is the "Greenland Ice Sheet Project", an international collaboration involving Denmark, Switzerland, and the U.S.)

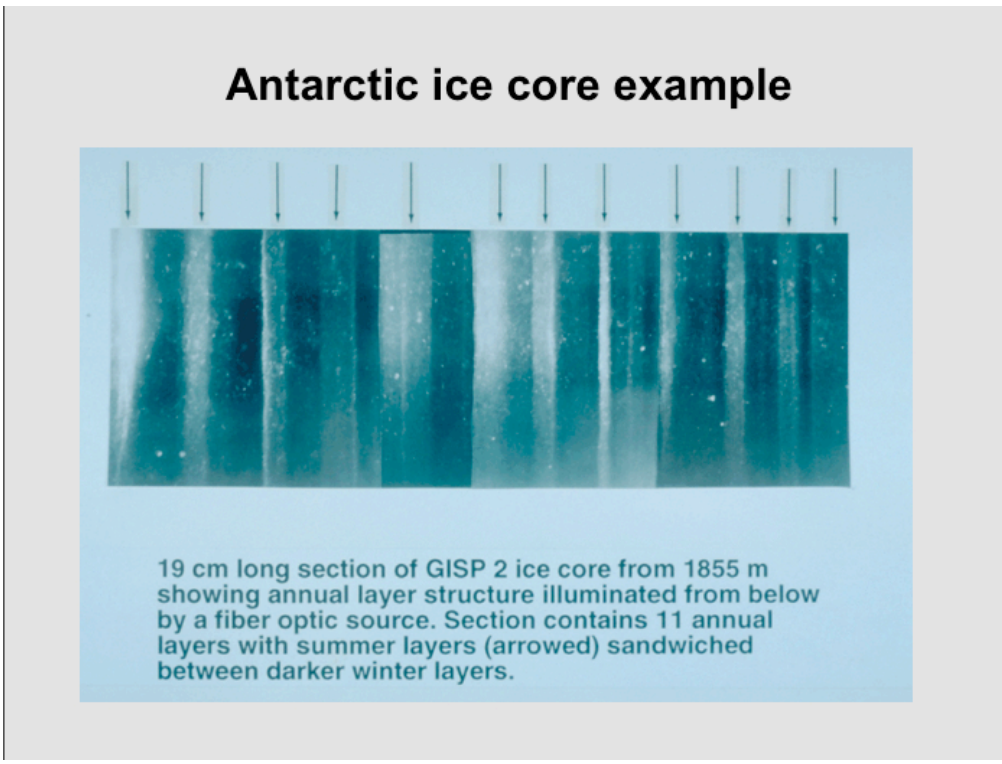

Figure 3: Seasonal bands in a Greenland ice core

Thus, counting the bands gives an approximate date for that particular band.

As the snow was compacted into ice, tiny air bubbles were trapped. Analysis of this air reveals the amount of carbon dioxide present at that time. As in the case of the carbon atom, the oxygen atom can exist as one of three different "isotopes". By far the most abundant is O^{16} with O^{18} comprising only about 0.2% and O^{17} much less still. Although chemically identical, the different weights of the isotopes affect the rate at which the water molecules they are a part of evaporate and precipitate, and these differences in rate in turn depend upon the temperature. Thus, the ice cores carry information about both the temperature and carbon dioxide abundance over hundreds of thousands of years.

Figure 4 is an often-reproduced figure showing the variation in temperature and carbon dioxide over the past 420 thousand years. It comes from ice cores drilled in the "Vostok" Antarctic research station. "Vostok" is located in one of the coldest parts of Antarctica on the vast Antarctic ice sheet. (Ice cores have been drilled in several places in both Greenland and Antarctica and now reach as far back as 800,000 years.)

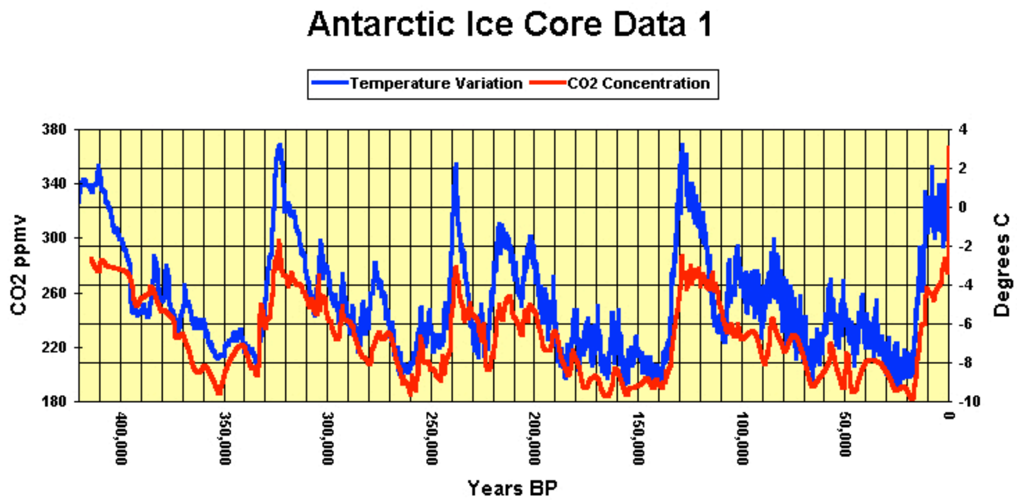

Figure 4: Temperature variations in blue (right scale) and CO_2 levels (red; left scale) from an Antarctic ice core. The present age is on the far right. "Years BP" stands for “years before the present”.

There are several important things to be learned from this graph:

1) The temperature (blue line) and the carbon dioxide (red line) follow the same pattern, though not exactly. When one goes up, so does the other, and conversely.

2) Over the last 450,000 years there have been five "interglacial" periods (including our current time) when the temperature was relatively warm. These have occurred at intervals of about 125,000 years. In between these periods, both the temperatures and the carbon dioxide levels were lower than during the interglacial periods. During the glacial periods, the ice sheets in Greenland were thicker and larger and huge ice sheets covered part of North America and part of Europe. As a consequence, sea levels were much lower. When the transition to interglacial periods occurred, sea levels rose, sometimes by several feet over a century or less.

3) Note how the carbon dioxide level shoots up at the extreme right edge of the diagram, so rapidly that it appears as just a thin vertical red line. This has happened in just the last century and is due to human consumption of fossil fuel. (See Lesson 6). This human-generated CO_2 spike-- (about 370 CO_2 molecules for every million molecules of air when this graph was made, but now already at about 395) --***is higher than at any time during at least the last million years. Under the 'business as usual scenario' where no global action is taken to curtail the accelerating use of fossil fuels, the amount of CO_2 in the atmosphere is projected to reach roughly 550 ppm by 2050***, ***double what it was at the***

start of the industrial revolution. As we will see in Part III this level has not been present on Earth ***for at least 20 million years.***

The rapidity of the recent rise in carbon dioxide can be better appreciated when the CO2 level is shown with an expanded time scale that only runs from the present back to the end of the last ice age, about 10,000 years ago. This is shown in the following graph:

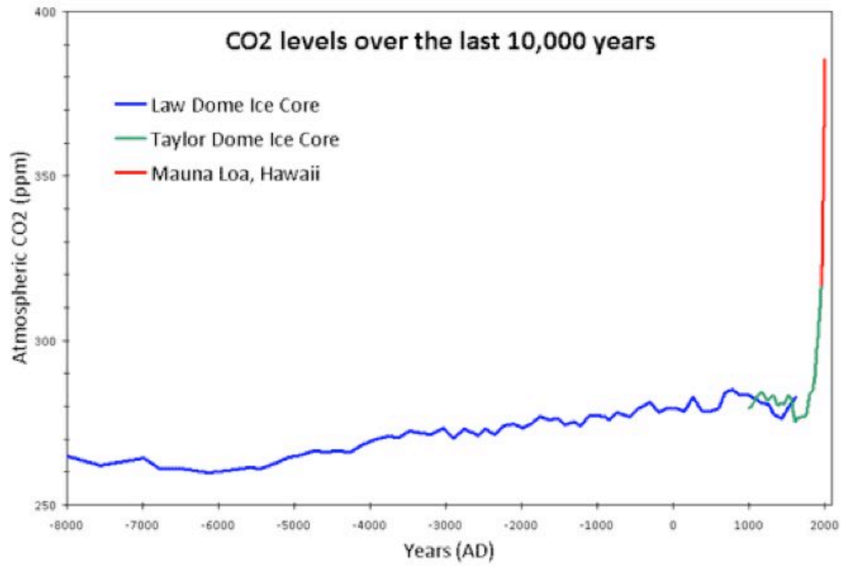

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Figure 5: Levels of carbon dioxide over the last 10,000 years. The red curve is from direct measures, while the blue and green curves are from ice cores.

Ice cores from Greenland show very similar behavior: these temperature and CO_2 swings were worldwide events, not confined to the Antarctic or even the southern hemisphere.

(Examination of both Figures 4 and 5 may suggest to some readers the following question: If carbon dioxide and global temperatures track each other so closely, why isn't the recent warming shown in Figure 1 quite as dramatic as the upturn in Figure 5? The short answer is that the huge heat capacity of the oceans gives a large amount of "thermal inertia" to the climate system, in the same way that it takes a long time for a ocean liner to make a full turn after the rudder is first turned. We will examine this lag in more detail in Lesson 8.)

The rough interval of 125,000 years between interglacial periods has led to the frequently heard comment that "climate change is just part of a natural cycle". At the scale of Figure 4, it is not apparent, but detailed analysis of the ice core data shows that typically the changes in the CO_2 lag behind the temperature changes by a few hundred years. (Though very recent research shows that this statement is not true over all parts of the globe as the changes in climate spread across the world.) This fact has often led to the additional claim that this lag "proves that human consumption of fossil fuel can't have caused the current rise in global temperatures."

Both of these claims are fallacious, as we now explain. What item (1) above tells us is simply that temperature changes and carbon dioxide levels are important components of powerful feedbacks. (See Lesson 2 for a discussion of feedbacks). It says nothing about causes.

So what has caused the alternating periods of interglacial and glacial climate? As readers of these Lessons are perhaps tired of being told, nothing just happens “by chance.”

Anyone who has been around four or five year old children for any length of time knows that one of their favorite words is "WHY"? If, for example, they ask "Why is it hotter in the summer than in the winter?" an inquisitive 4 or 5 year old child is not likely to be satisfied with the answer "Its just part of a natural cycle"--nor should she be! Assuming the adult *does* understand the causes of the seasons (!) then, showing the child how the tilt of the Earth's axis of rotation with respect to the plane of its path around the Sun results in more sunlight falling on, say, the northern hemisphere in July (our summer) than during January (our winter) should satisfy her. (If not, and she wants to know WHY the Earth's axis of rotation is tilted to the Earth’s path around the Sun, rather than being perpendicular to it, I suggest you punt and enroll her at Cal Tech).

Actually, the explanation for the interglacial/glacial climate changes is closely related to the causes of seasons, though the details are far more complex. An explanation for the ice ages was first proposed over 90 years ago by the Serbian scientist Milutin Milankovic who refined it over the next 20 years. While we think of the Earth's orbit and spin axis as unchanging in time, several important orbital properties change slowly over time. These changes are caused by the combined effects of the gravitational forces of the Sun, moon and other planets in our solar system, especially Jupiter.

Three of these slow changes have separate periods of about 23,000 years, 41,000 years and 100,000 years. Certain combinations of them gradually produce substantial changes in the amount of sunlight at the polar regions during summer time. The Earth's climate over the past several hundred thousand years seems especially sensitive to the changing amount of summer sunlight in the arctic regions. Recent research combining computer simulations with ice core and ocean sediment data confirm that these orbital changes are the 'triggering mechanisms' for the transitions between the interglacial and glacial periods, but they also show that other factors are involved. For example, the total volume of ice at the time of the beginning of 'deglaciation' seems to be important. Moreover, for some processes, the late spring and early summer enhanced 'solar insolation' in the arctic is more important than that in mid or late summer.

To 'climb out' of a deep glacial period once this triggering mechanism takes hold involves complex feedbacks involving: the 'albedo effect' wherein bright snow and ice are replaced by dark land and ocean surface; changes in vegetation; changes in ocean currents influenced by changes in the salinity and temperature of the oceans, and, decisively, ***release of carbon dioxide with warming ocean temperatures***.

This is a very active area of current research and the picture is not complete. but the following diagram, ***while a gross oversimplification***, gives the flavor of the chain of events:

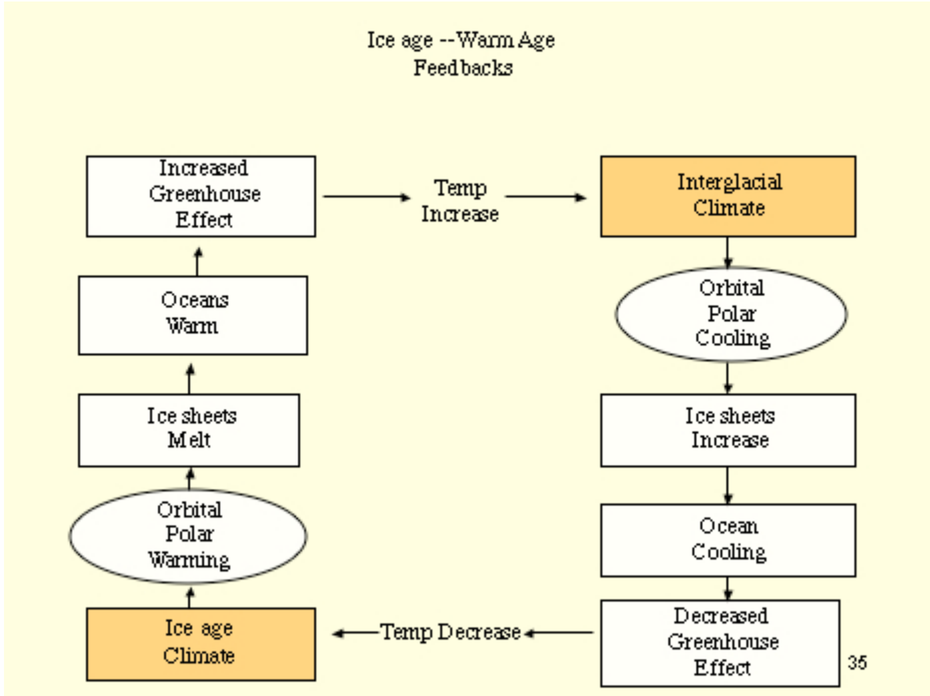

Figure 6: *A highly schematic and oversimplified diagram of the processes giving rise to ice age and interglacial periods.*

Examining this diagram makes it easier to understand why the initiation of some warming precedes the release of carbon dioxide. But without the greenhouse warming caused by this released carbon dioxide, the process from an ice age climate to an interglacial climate would not proceed to completion.

Some 'take away' points from the studies of the ice ages are these: The Earth's climate is not static but can 'flip' from one state to another, given the appropriate set of 'triggers'. The transitions can occur quite rapidly. During some of these transitions sea level changes of several feet have occurred in just a 100 years.

Examination of Figure 4 shows that the present interglacial period is already longer than the previous three, but studies of the changes in the Earth's orbital parameters that will occur in the future suggest that the interglacial period we are now in may last even much longer than previous ones--perhaps 50,000 years *in the absence of any human interference*. But these same studies suggest that, depending upon the total amount of fossil fuel consumed in the next century or two, any future return to ice age conditions *may be much further still into the future, perhaps by as much as several hundred thousand years*.

Looking back beyond the oldest ice cores, the 100,000-year periods weaken, are replaced by shorter periods and then gradually disappear. Looking further back in time reveals a climate *totally unlike that which has been experienced since the dawn of civilization* and this is the final topic of this Lesson.

III Earth's Ancient Climates

We now leave the "recent" past of the last 800,000 years and explore even further back in time. Ice core data are no longer available, but there are still proxies that can provide information on both carbon dioxide content and temperature. There is also indirect biological and geological evidence concerning sea levels and this in turn has implications for the size of the great ice sheets of the world (or their total absence). Not surprisingly, the uncertainties of these proxies are greater than the ice core data and the causes for the changes in climate harder to unravel.

Since this Lesson is already very long, we will only give the briefest of summaries:
a) There is paleo-climatological evidence that in the very distant past (several hundred millions of years ago and even earlier) much more massive glaciations were present on the Earth than existed even at the depths of the ice ages of the past few hundred thousand years. Such stages have been termed 'snowball Earth' (or at least 'slushball Earth'). Subsequent to these events, extreme climates in the opposite sense are found. The causes for these swings are not clearly understood, needless to say, but probably involved different configurations of land masses ('continental drift'), and/or perhaps different responses of biological systems to climate changes than exist today. Certainly extremely powerful feedback processes must have been involved, and it is crucial to take into account the changes in the Sun's brightness, since it was about 8% fainter a billion years ago than it is today.

b) In the much more "recent" past, more is being learned about the carbon dioxide content of the atmosphere and its connection to the Earth's climate. In one recent study [7] proxies for the carbon dioxide going back as far as 20 million years were checked by comparing them with the ice core data described in Part II, and then used to study intervals going back as far as 20 million years. **A key result is that the correlation between the global climate and the carbon dioxide levels in the atmosphere persist.**

A second key result is best illustrated by a direct quote from this study:

"During the Middle Miocene ... (10-14 million years ago) ... "temperatures were 3-6 C degrees warmer..." (5.4-10.8 F) ... "and sea levels were 25-40 meters" (80-130 feet) higher than present, and the ***carbon dioxide level was similar to modern levels"***. **"In fact, only during the period from about 14 to 16 million years ago was the carbon dioxide level higher than the 2009 level of 387". (**Italics mine; and now the current level as of November 2012 is 395…and rising.)

A second similar recent study [8] went back 60 million years, but paid special attention to an especially warm period around 50 million years ago, as well as to two remarkable very rapid (by geological time scales!) climate changes around 55 and 40 million years ago. The sweep of this study is best described by reproducing a figure from this paper:

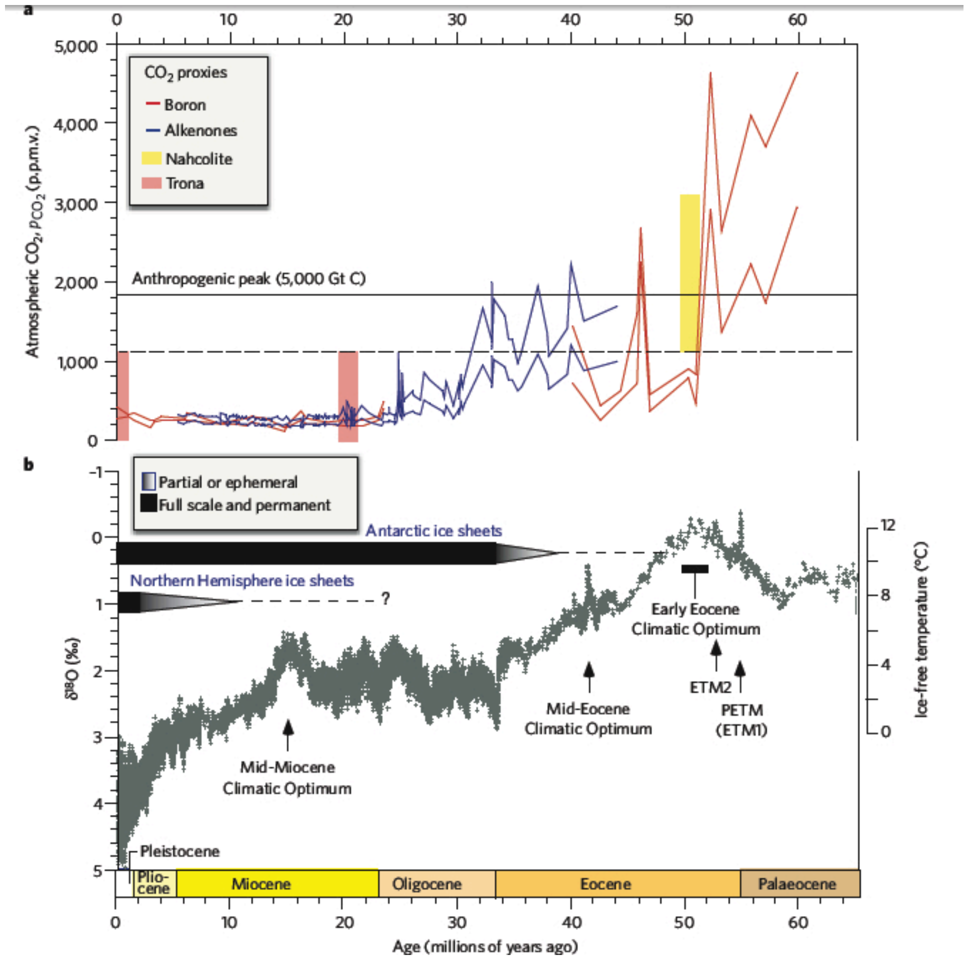

Figure 7 (From [8])

While this is a complicated figure, it carries some important information. You may want to scan a copy of this figure and print out a hard copy to make it easier to follow. First, note that the ***direction of time is opposite to that of Figures 4 and 5:*** In Figure 7, the present is on the far left. Also, Figure 7 covers a ***much larger slice of time*** than Figure 4--the right edge of Figure 7 corresponds to a time 65 million years ago. Next, notice that there are two sections to the figure: The top part of the figure shows rough estimates for the carbon dioxide level (the blue and red lines). The bottom section of the figure (the black line) is a proxy sensitive to the volume of ice, the ocean temperature, and to the overall state of the global climate. Roughly speaking, it corresponds to global temperatures.

The region of the graph marked “Mid Miocene Climatic Optimum” about 14-16 million years ago is the time noted in the quote from the previous study, when carbon dioxide levels were around 450 ppm. (We are almost certain to surpass that level within 25 years without a major reversal in international policies.)

Even further back in time, one sees that carbon dioxide levels were even higher during very warm phases of the climate (50 million years ago). At this time there were no large ice sheets, not even in Antarctica and palm trees grew in the arctic. With slowly falling carbon dioxide levels the climate cooled and large ice sheets were established. The two 'pencil-shaped' black bars mark the beginning of the Antarctic ice sheet (about 35 million years ago) and the northern hemisphere ice sheets (about 5-10 million years ago).

The sharp spikes in the bottom section of the figure, (e.g. the one marked "PETM" about 55 million years ago) seem to be driven by “sudden” injections of carbon dioxide or methane into the atmosphere--perhaps partially by release of the methane in the 'clathrates' described in Lesson 6. But “sudden” in this context still means ***very much more slowly*** than the rate at which we are now injecting carbon into the atmosphere by fossil fuel consumption.

The complex feedbacks that operate under the conditions associated with events such as the "PETM" is an area of intense research--and for good reason:

In Figure 7, the solid line in the carbon dioxide (upper) part of the figure labeled "Anthropogenic peak" is an estimate of the level of carbon dioxide that is estimated to result if our society tries to extract and burn the total estimated fossil fuel reserves, including the “unconventional” sources like those found in shale and tar sands. There is no absolute assurance that reaching this level of carbon dioxide (1800 ppm) would result in the drastically different climate of 50 million years ago--but absolutely no guarantee that it eventually will not, either!

A crucial point to be emphasized is that the ***rate*** at which human activity is injecting carbon dioxide into the atmosphere may be so fast that the slower “negative feedbacks” which offset some of the positive feedbacks and that ultimately brought about the climate we enjoy today may not have time to act before other powerful positive feedbacks--some known, some not, have time to act.

Before summarizing in my own words what I believe the “take home” message of Lesson 7 is, I will quote from an article [9] that I wish all readers of these Tutorial lessons could read in its entirety. It was published in 2004 but is still very relevant:

"Over the next 100 years, without substantial changes in energy technology or economic development, the atmospheric CO_2 concentration will rise to 800 to 1000 ppm. This rise represents a ***spectacular uncontrolled experiment that humans are performing on Earth.*** *The paleoclimate record may provide the best guess as to what may happen as a result..."*
"A final lesson from past climates is that climate changes are not always slow and steady, but can occur within decades or even years. The documentation of abrupt changes around the world during the last glacial period is a spectacular reminder of how quickly climate can change..."
"The climate system is very sensitive to small perturbations. The release of greenhouse gases through human activities represents a large perturbation, ***sending our atmosphere to a state unlike any seen for millions of years. It behooves us to remember the past as we anticipate the future."***

Here is my own assessment of what conclusions should be drawn from Lessons 1-7: Every line of evidence, together with all that is known about the laws of physics as applied to the climate system, strongly indicate that carbon dioxide plays a major role in how the climate changes: when CO_2 levels rise the climate will warm, ***regardless of whether very slow natural processes or current rapid human activities cause the CO_2 increase.*** Other changes in the climate system accompany this warming, and they will be considered in Lesson 9. What we have not discussed thus far is how much warming we can expect from the present and projected future human-caused CO_2 increases and how rapidly and for how long this warming will occur. This is the subject of Lesson 8.

SOURCE MATERIAL FOR LESSON 7

Part I: Most of this discussion is taken from the following sources:
[1] "Surface Reconstructions for the Last 2,000 Years". National Academies Press, 2006 ISBN-13: 978-0-309-10225-4
[2] M. Mann et al.: Proceedings of the National Academy of Sciences, Vol 105, p. 13252 (Sept. 9, 2008)
[3] M. Mann et al.: Science, Vol 326, p. 1256 (27 November 2009)
Figure 1 is taken from reference [2]

Part II: This discussion is taken from many sources, including:
[4] D. Paillard & F. Parrenin: Earth and Planetary Science Letters 227 (2004) p. 263– 271
[5] B. L. Otto-Bliesner et. al: Science Vol 311 p. 1751 24 March 2006
[6] J.T. Overpeck et al.: Science, Vol 311, p. 1747, 24 March 2006.
Figure 3 was supplied by Dr. C. Castro, Univ. Arizona.
Figure 4 has appeared in numerous places. It was based originally on work by J.R. Petit et al Nature Vol 399, p. 429 (3 June 1999) and has been updated and extended numerous times.
I am grateful to Dr. Matthew Huber, Purdue University, for supplying extensive references concerning the Ice Ages.

Part III: This discussion is base primarily upon the following references
[7] A.K. Tripati, C. D. Roberts & R.A. Eagle: Science**expres7**. 8 Oct. 2009
[8] J.C. Zachos, G. R. Dickens & R. E. Zeebe: Nature Vol 451, p. 279 (17 January 2008)
[9] The closing quotations are excerpted from: D.P. Schrag & R. B. Alley: Science Vol 306 p. 821 (29 Oct. 2004)
Figure 7 is taken from reference [8], with permission.