What Geology Has To Say About Global Warming

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Last month I gave a public lecture entitled, *When Maine was California*[1], to an audience in a small town in Maine. It drew parallels between California, today, and Maine, four hundred million years ago, when similar geologic processes were occurring. Afterward, a member of the audience asked me what geology had to say about global warming. The following is an expanded version of my answer. Note that I use the word *geology* to mean any element of the earth sciences that is focused on earth history, and do not distinguish the many sub-disciplines about which a specialist would be familiar.

Geologists think of the last 50 million years as the *recent* past, both because they represents only about one percent of the age of the earth, and because plate tectonics, the geologic process that controls conditions within the solid part of the earth, has operated without major change during that time period. This is the time period that is most relevant to gaining insights about earth's climate that can be applied to the present-day global warming debate.

The geological record of ancient climate is excellent. Ancient temperatures can be determined very precisely, because the composition of the shells of corals and other marine organisms varies measurably with it. Furthermore, the plants and animals that lived during a given time and are now preserved as fossils indicate whether the climate was wet or dry. The overall climatic trend has been cooling, from an unusually warm period, called the Eocene Optimum, 55-45 million years ago, to an unusually cool period, colloquially called the Ice Age, which ended just twenty thousand years ago. The overall range in temperature was enormous, about 35°F. The earth was so warm during the Eocene Optimum that Antarctica was ice-free; ice caps did not start to form there until about 35 million years ago. Palm trees grew at high latitudes and that cold-blooded animals, such as crocodiles, lived in the Arctic.

Lesson 1. The earth's climate (including its average temperature) is highly variable.

Notwithstanding very divergent conditions, life flourished both during the Eocene Optimum and the Ice Age, though in both cases life was more abundant in some parts of the world than in others. The fossil record indicates that forests were common during the Eocence Optimum, yet some areas were sparsely vegetated steppes and deserts. While the great glaciers of the Ice Age were lifeless, extremely large mammals such as Woolly Mammoth and Giant Ground Sloth inhabited lower latitudes. The changing climate produced both winners and losers. Some species adapted; others went extinct.

Lesson 2. Life flourished during both warm and cold periods; changes in climate produced both winners and losers.

An important issue is whether climate variability is due to processes occurring on the earth, or to changes in the intensity of sunlight – for it it's the sun that keeps our planet warm. The geological evidence, though subtle, strongly supports earthly, and not solar, causes. This evidence is drawn from the study of the many shorter period climate fluctuations, some which last millions of years and other just thousands, which are superimposed on the long-term cooling trend.

Climate during the Ice Age (the last four million years) has been particularly unstable, with many swings of more than 10°F. These fluctuations are recorded in the annual layers of snow preserved in glaciers and in marine sediments, whose properties track the temperature at which they were formed. The timing of these swings closely follows regular fluctuations in the tilt of the earth's axis and the shape of its orbit around the sun. Called Milankovitch cycles, they are due to the gravitational influence of the moon and planets. Their magnitude can be reliably calculated, since they are due to fluctuations of the position and orientation of the earth relative to the sun, and not to any change in the sun's brightness. Surprisingly, they are too small to account for the large swings in temperature, unless the earth's climate system is acting to amplify them. Here's the subtle part of the argument: this mismatch between the feeble amplitude of the Milankovitch cycles and the large swings in climate is strong evidence that internal processes can cause strong climate variability.

Lesson 3. Variations in climate are mainly due to processes occurring on the earth, as contrasted to in the sun.

Ice Age carbon dioxide levels are well known, because bubbles of Ice Age air are preserved within the Antarctic and Greenland glaciers. More ancient carbon dioxide levels are difficult to measure, since no samples of older air have been preserved. Several indirect methods are in use, one based on the effect of ocean carbon dioxide levels on the composition of marine sediments, and another on its effect on now-fossil plant leaves. These measurements show fairly convincingly that the long term cooling trend over the last fifty 50 million years is associated with a gradual decrease in carbon dioxide levels, from 2000-3000 parts per million during the Eocene Optimum to 200 p.p.m. during the Ice Age. The cause of this decrease is not fully understood, but seems to indicate that the total amount of carbon that can influence climate (carbon in the atmosphere, biosphere and ocean) is slowly decreasing, possibly because an increasing amount of carbon is being tied up in sedimentary rocks such as limestone.

Lesson 4. Atmospheric carbon dioxide levels are highly variable, with the highest levels being associated with warm periods and the lowest levels associated with cold periods.

The correlation of atmospheric temperature with carbon dioxide reflects the latter's role as a greenhouse gas. By absorbing heat radiated from the earth's surface and re-radiating it back downward, it causes the earth's surface to be warmer than it otherwise would be. The earth would be uninhabitable without the greenhouse effect, as can be seen by comparing the earth's average temperature of about 60°F to the minus 100°F average temperature of the moon, which receives exactly the same amount of sunlight. An important question is whether the high carbon dioxide level at the time of the Eocene Optimum was the cause of the high temperatures that occurred during that time period.

Ascribing causes to fluctuation in climate is a tricky business, because atmospheric carbon dioxide level is only one factor among several that determine earth's climate. Other important factors include: the amount of water vapor (another green house gas) in the atmosphere; the percentage of the sky covered by clouds, which reflect sunlight back into space; the percent of land covered with ice and snow, which are also very reflective; and the percentage covered by oceans and and forests, which are very absorbing. All factors act together to maintain a given temperature; yet they feed back upon one another in complicated ways. Thus, for instance, had the Antarctic been glaciated during the Eocene Optimum (and the geological evidence is that it was ice free), the world would have been somewhat cooler due to the high reflectivity of the ice. On the other hand, glaciers were absent precisely because the world was so warm. Geologic evidence alone cannot prove that the high levels of atmospheric carbon dioxide during the Eocene Optimum *caused* the high temperatures then, since the contribution of other factors, such as clouds and water vapor are unknown. Nevertheless, global climate models seem to indicate that such a high temperature only can be maintained in a world with high carbon dioxide; no other combination of factors can explain it.

Changing global temperatures induce changes in patterns of rainfall, winds, ocean currents, all of which can have a profound effect on the ecosystem of a given region. A large decrease in rainfall will, of course, turn rainforest into a desert. However, geology has few specific s to offer on the subject of how any particular region will be affected. The factors that cause climate change at a given geographical location are too varied to allow convincing geological analogues. However, geology shows that variability is the norm. Some of today's deserts were forested a few million years ago, and some of today's forests were formerly deserts. From the human perspective, climate change has the potential of causing some areas to become less agriculturally-productive (and therefore less inhabitable), and other to become more so.

Lesson 5. Local climates are very variable, changing dramatically over times periods of thousands to millions of years.

Changing global temperature can cause rise or fall in sea level due to the accumulation or melting of glacial ice. This effect is global in extent and one that can have an extremely deleterious effect on us human beings, since so many of us live near the coast. The geological evidence is very strong that sea level was higher by about 200 feet at times, such as the Eocene Optimum, when Antarctica was ice-free and was about 400 feet lower during the height of the Ice Age. The range is enormous; the world's coastlines are radically altered by such changes. The continental shelves were substantially exposed during the low stands, and many low-lying coastal areas were underwater during the high stands. Woolly Mammoths roamed hundreds of miles offshore Virginia during the Ice Age. Beach sand deposits in inland North Carolina indicate that the shoreline was far inland during the Eocene Optimum.

Lesson 6. Sea level has fluctuated as the world's glaciers grow or recede, and was about 200 feet higher at times when Antarctica was ice-free.

Carbon dioxide levels have risen since the end of the ice age, first to a natural level of about 280 p.p.m. just before the start of the Industrial Era and then to 400 p.p.m. as people burned coal and petroleum in large quantities. Carbon dioxide is currently increasing at a rate of about 2.6 p.p.m. per year.

A critical question is the level of atmospheric carbon dioxide 35 million years ago, when glaciers began to form in Antarctica, for it serves as a rough estimate of the concentration needed to melt present-day

Antarctica. It's a rough estimate only, for geological conditions were not exactly the same now and then. In particular, strong ocean currents that today keep warmer waters away from Antarctica were not present 35 million years ago, owing to the somewhat different configuration of tectonic plates. Unfortunately, the best currently-available estimates of atmospheric carbon dioxide during this critical time period have large uncertainties. Carbon dioxide decreased from 600-1400 pp. at the start of the glaciations to 400-700 several million years later. These measurements are consistent with modeling results, which give a threshold of about 780 p.p.m. for the formation of a continental-scale ice cap on Antarctica. This value will be reached by the year 2150 at the present growth rate of atmospheric carbon dioxide – or sooner if emission rates continue to soar - suggesting that Antarctica will be at risk of melting at that time.

Antarctic ice will not melt overnight even should the threshold be reached. The deglaciation at the end of the Ice Age provides a useful example. The rate of sea level rise was initially low, just one tenth an inch per year. It then gradually increased, peaking at about three inches per year about fourteen thousand years ago, which was about five thousand years after the start of the deglaciation. This rate persisted for 1,600 years, during which time sea level rose a total of 60 feet. The average rate of sea level rise was slower, about a half inch per year.

Lesson 7. Sea level rise as fast as a few inches per year can persist over thousands of years.

The most extreme scenario for future carbon dioxide levels considered by the Intergovernmental Panel on Climate Change (IPCC) predicts about 0.4 inches per year of sea level rise over the next century[2]. This rate is less than, but similar in magnitude, to the average rate during the Ice Age deglaciation, but considerably smaller than its peak. Because of its focus on the current century, a reader of the IPCC report might be left with the sense that sea level rise will be over by 2100. Precisely the opposite is true! Geology demonstrates that melting accelerates with time and can last for several thousand years.

The most important lessons drawn from geology are that the earth's climate *can* change radically and that the pace of change can be rapid. Geology also supports the theory that past periods of especially warm temperature were caused by high atmospheric carbon dioxide level. Of the many effects of global warming, geology is currently most relevant to sea level rise caused by melting glaciers. The precision of the measurement is currently too poor to give an exact answer to a critical question, *At what carbon dioxide level are we in danger of melting Antarctica?* However, while crude, these estimates suggest that this threshold will be reached in 150-300 years, if carbon dioxide levels continue to rise at the current rate.

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[1]www.ldeo.columbia.edu/users/menke/talks/downeast/Menke_Downeast_Lakes_Land_Trust.pdf

[2]www.climatechange2013.org/images/report/WG1AR5_SPM_FINAL.pdf