CLIMATE CHANGE
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"*... change is built into the nature of things, nothing is inherently fixed ...*"
Siddhartha Gautama of the Sakyas (The Buddha) 563BC-483BC

In order to understand the changing climate of today, we must start by looking at the climate of the past.

Ice drill cores from Antarctica and Greenland, and sediment drill cores from the oceans, show that the Earth has undergone a series of ice ages and inter-glacial warm periods during the past 420 thousand years.

The semi-periodic inter-glacial warm periods are understood in terms of variations in the Earth's orbit, which causes variations in the amount of sunlight that falls at high latitudes. When the high latitudes do not get enough sunlight, the winter snow does not entirely melt during summer, and increases year after year forming an ice sheet. Eventually the sunlight does increase enough to melt the accumulated ice and produces an inter-glacial warm period.

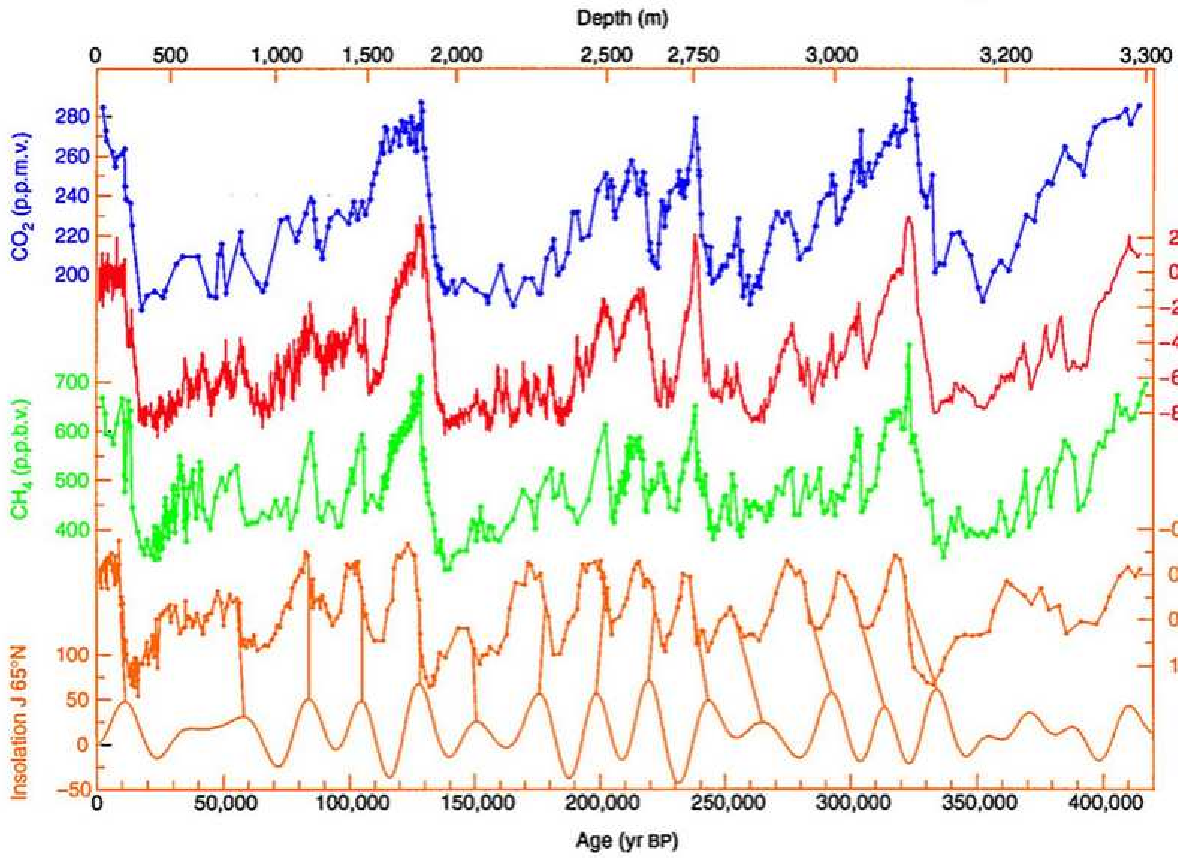


Figure 1. Global temperature change over the past 420 thousand years, as shown by an ice core from Vostok Station in Antarctica. from Petit, J. R. *et al.* Nature, **399**, 429 (1999).

In every inter-glacial warm period, along with the rise in temperature, there is a rise in sea level, and an increase in atmospheric carbon dioxide (CO_2) and atmospheric methane (CH_4). The rise in sea level is due to the melting of the ice sheets, and the rise in atmospheric CO_2 and CH_4 is due to the out-gassing of the oceans, because the solubility of a gas in a liquid decreases as the temperature rises. The oceans contain 50 times more CO_2 than the atmosphere, and 4.4% is transferred to the atmosphere for every 1° rise in temperature. The rise in atmospheric CO_2 from 180ppm to 280pp at the end of a glacial period corresponds the release of CO_2 by a 7.4° rise in ocean temperature.

Is the present inter-glacial warm period any different from the previous ones occurring during the last 420 thousand years?

The previous inter-glacial warm period occurred 130 thousand years ago and was some 4° warmer than the present. The present inter-glacial warming began 20 thousand years ago. As the ice sheets melted, sea level rose 120 meters to the present level.

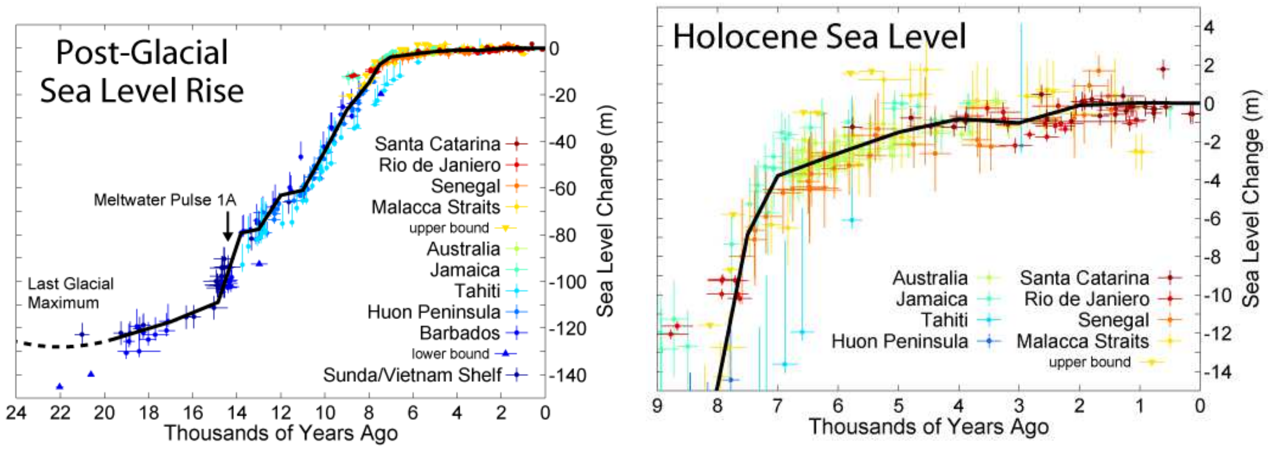
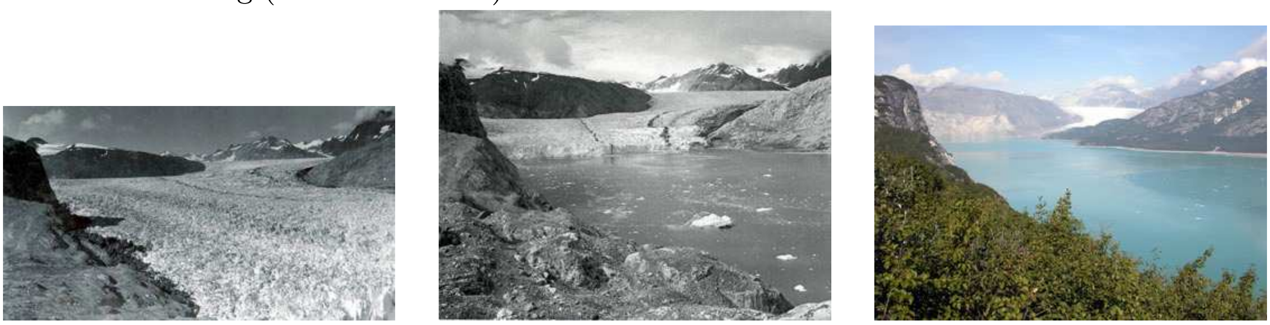


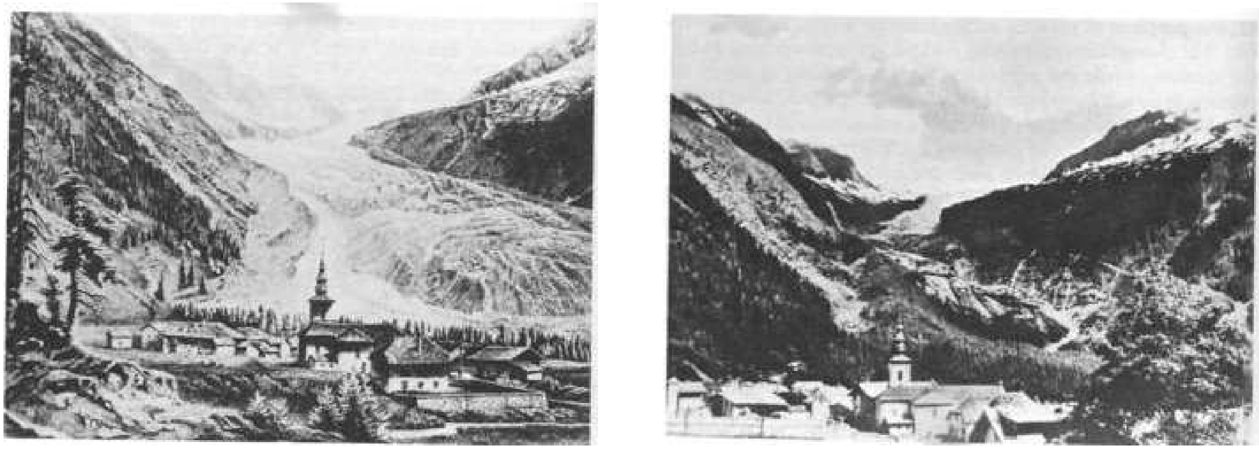
Figure 2 and Figure 3. from Flemming, K. *et al.* Earth and Planetary Science Letters **163**, 327 (1998)

An increase in Antarctic snow began 10,000 years ago as the Earth warmed and emerged from the last ice age. However, satellite data demonstrate that the increase in the Antarctic ice sheet is slowing from 112 Gt of ice per year from 1992 to 2001 to only 82 Gt tons per year from 2003 to 2008. Ice losses in the Antarctic Peninsula and West Antarctica are increasing, and are expected to exceed the snowfall gains within 20-30 years.

Currently, the mountain glaciers and the Antarctic ice on the Antarctic Peninsula and in West Antarctica are melting. The ice is just uncovering areas that were ice free during the Medieval Warming. Still rooted tree stumps dated to the Medieval Warming have been uncovered by retreating glaciers in the Alps, along with an irrigation system that historical records date as having been closed in 1385 by the advancing ice of the Little Ice Age (Grove *et al.* 1994). Ice retreat in the Antarctic Peninsula has exposed an area where moss was growing during the Medieval Warming (Hall *et al.* 2010)



Muir Glacier: 1941, 1950, 2004



Argintiere Glacier: 1860 etching, 1966 photograph. Fig.46 Imbre and Imbre 1979

The ice cores do not have the time resolution to record the climate changes that took place in historical times. We know that Roman Times were a relatively warm period followed by a cooler period during the Dark Ages. The Medieval Period was warmer than the present, but was followed by the Little Ice Age, which was colder than the present. Over the past 2 thousand years, sea level as oscillated ±25 cm around the present sea level. Sea level was high during Roman Times, low during the Dark Ages, 20 cm higher than the present during the Medieval Warming, and 25 cm lower than the present in the 1700's during the Little Ice Age.

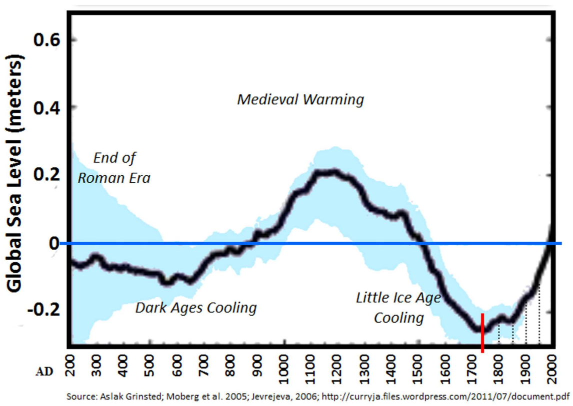
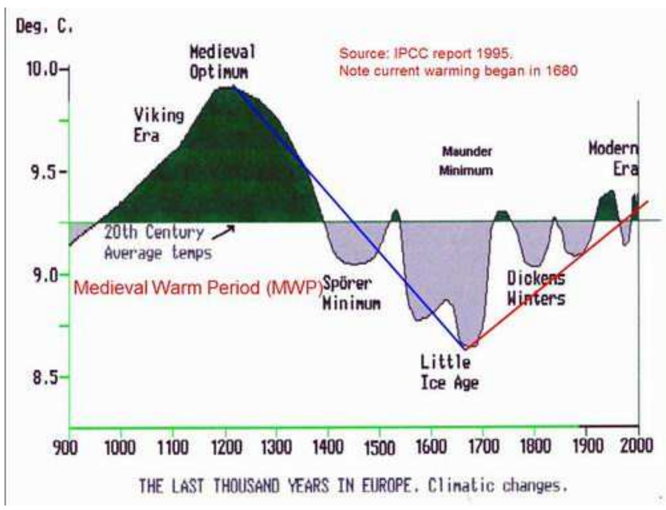


Figure 4. after Grinsted, A., J. C. Moore, and S. Jevrejeva (2009), Reconstructing sea level from paleo and projected temperatures 200 to 2100AD, Clim. Dyn., doi:10.1007/s00382-008-0507-2.



The warming and cooling of the climate over the past 2000 years is not well understood. Efforts have been made to link such climate changes to solar sunspot cycles, but no compelling mechanisms have been found.

An examination of climate history shows that the present climate is currently within natural climate variability, **except** that the atmospheric CO_2 levels are 35% higher than during any of the four previous inter-glacial periods, and during any of the last 2000 years.

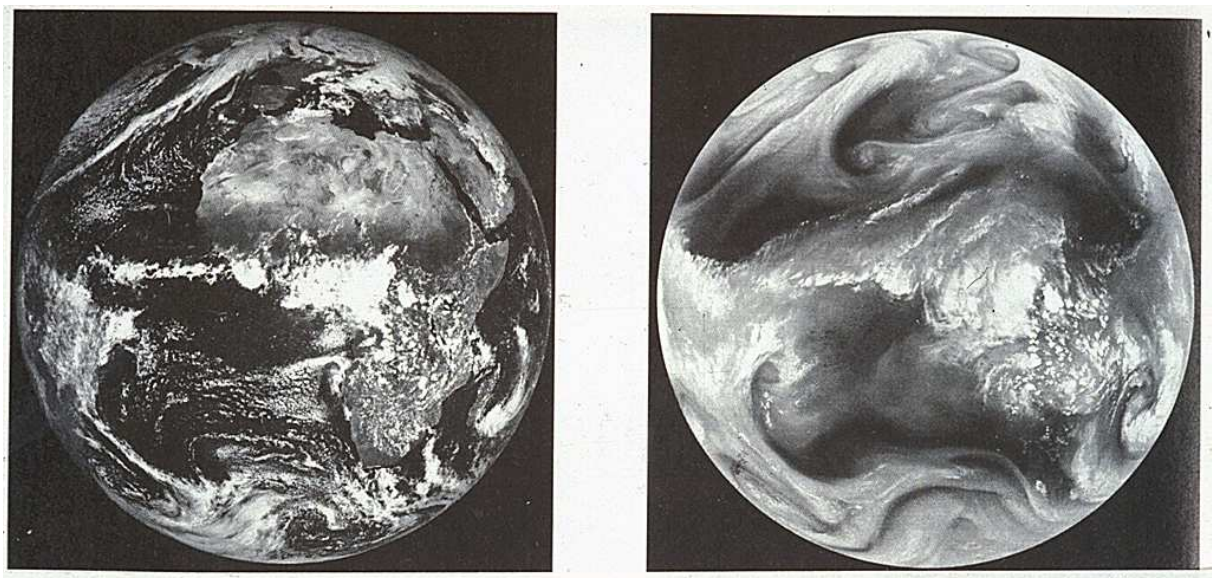
What are the effects expected from the current high carbon dioxide levels?

The present inter-glacial warm period differs from previous ones in that the atmospheric CO_2 level is now 400 ppm (parts per million by volume), whereas the atmospheric CO_2 level in all prior inter-glacial warm periods never exceeded the pre-industrial atmospheric CO_2 level of 290 ppm. Thus, the present atmospheric CO_2 level is 35% greater than in any of the past 420 thousand years.

This additional 100 ppm in the present inter-glacial warm period comes from the burning of fossil fuels. Carbon has three isotopes – ^{12}C, ^{13}C, and ^{14}C. The lighter isotopes, ^{12}C and ^{13}C, are primordial to the Earth and stable. The heaver isotope, ^{14}C, is radioactive with a half life of 5,700 years, and is the result of cosmic ray bombardment of the atmosphere. The lightest carbon isotope, ^{12}C, is more reactive, and is preferentially incorporated in biological carbon compounds. The burning of coal and oil is increasing the $^{12}C/^{13}C$ ratio in the atmospheric CO_2 as well as increasing the overall level of atmospheric CO_2.

INCREASE IN TEMPERATURE

The Earth warms by absorbing Solar radiation over the area of πr^2 which faces the sun, and cools by radiating into space over its entire surface area of $4\pi r^2$. The temperature of the Earth adjusts so that the radiation absorbed equals that radiated back into space. The radiation from the Sun has a wavelength distribution that peaks in the visible wavelengths where the Earth's atmosphere is transparent, while the radiation from the Earth peaks in the infra-red wavelengths where CO_2, H_2O, CH_4 and other molecules have absorption bands.



The Earth seen from Space. The visible image is on the left. the Infra-Red image is on the right. The surface is completely obscured by molecular absorption in the Infra-Red image, where only the cloud tops can be seen.

The effect of increasing the CO_2 in the atmosphere is to block the Earth's Infra-Red radiation, causing the temperature of the Earth to increase, until the energy radiated once again balances the energy absorbed from the Sun.

The calculation of the amount of blockage caused by increased CO_2 in the atmosphere is complex. The result is given in terms of radiative forcing, which requires compensation through an increase in the Earth's temperature.

The 5th IPCC report (Figure TS.6, p54) gives the total anthropogenic radiative forcing as $dP = 2.2 \pm 1.0$ W/m^2 between 1750 and 2011. Using the Stefan-Boltzman law $P = \sigma T^4$, differentiating $dP = 4\sigma T^3\, dT$, inserting $\sigma = P/T^4$, we obtain

$$dT = \frac{1}{4}\frac{T}{P}dP. \tag{1}$$

The present global temperature is $T = 15°\text{C} = 273.15 + 15 = 288°\text{K}$. The mean solar constant is 1360 W/m^2 collected over πr^2 and radiated over $4\pi r^2$. Thus the radiated power is $P = 1360/4 = 340$ W/m^2 . Substituting T and P in the equation (1) yields

$$dT = \frac{1}{4.7}dP. \tag{2}$$

Thus, a radiative forcing of 4.7 W/m^2 is needed to produce a temperature change of 1°C., and the total anthropogenic radiative forcing of $dP = 2.2 \pm 1.0$ W/m^2 produces $dT = 0.41 \pm 0.21°$C.

The above calculation assumes that the Earth radiates as a black body, whereas line blanketing changes the spectral distribution of the absorbed and re-emmitted radiation. This has been simulated using an albedo of $a = 0.367$ for the Earth, and a Plank function

$$P_\lambda = \frac{2\pi hc^2\lambda^{-5}}{e^{hc/k\lambda T} - 1} \tag{3}$$

that is blanked out from 10 to 18 microns. With an albedo of $a = 0.367$ for the Earth, the black body temperature of the Earth would be 252°K, and the radiated power would be 228.64 W/m^2, the amount required to balance the absorbed power. The radiated power of a black body with the current temperature of the Earth, 288°K, is 390.05 W/m^2, but with radiation from $10 - 18.11155$ microns set to zero, this becomes the required 228.64 W/m^2. Now suppose anthropogenic activity blocks and additional 2 W/m^2 reducing the re-radiated power to 226.64 W/m^2. This is simulated by increasing the wavelengh range that is being blocked from $10 - 18.11155$ to $10 - 18.2668$ microns with the temperature held at 288°K. Increasing the temperature to 288.616°K restores the radiated power to the 228.64 W/m^2 required to balance the absorbed power. Here we have $dT/dP = 0.616/2$ or

$$dT = \frac{1}{3.247}dP \tag{4}$$

and the total anthropogenic radiative forcing of $dP = 2.2 \pm 1.0$ W/m^2 produces $dT = 0.68 \pm 0.31°$C.

With $dT = 0.68 \pm 0.31°$C., the observed 1° increase in global temperature since 1910 might be entirely attributed to anthropogenic causes.

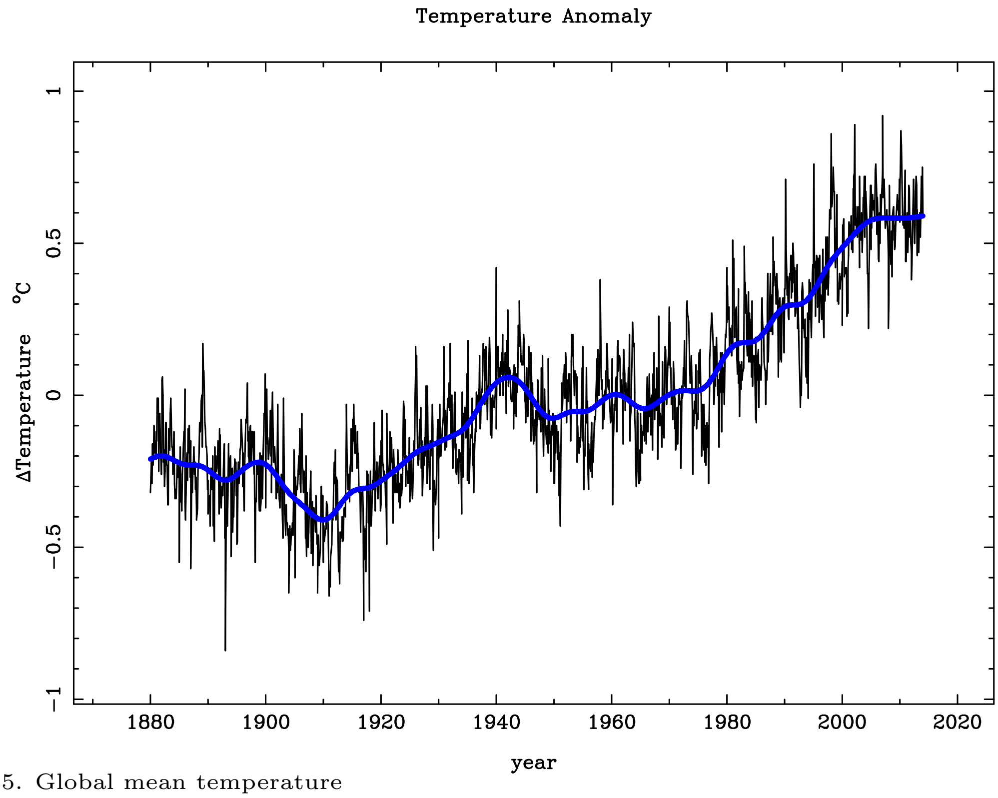


Figure 5. Global mean temperature
from http://data.giss.nasa.gov/gistemp/tabledata_v3/GLB.Ts+dSST.txt

OCEAN ACIDIFICATION

Carbon dioxide in the ocean takes several forms in addition to that of a simple dissolved gas. The CO_2, in effect, disassociates water forming $[H^+,HCO_3^-]$, and $[2H^+,CO_3^{--}]$. Increasing CO_2, increases H^+, reduces the pH of the ocean, and reduces CO_3^{--}, because the formation of $[H^+,HCO_3^-]$ is then favored over the formation of $[2H^+,CO_3^{--}]$. This reduces the stability of calcium carbonate, $CaCO_3$, the mineral used by marine organisms to build shells and skeletons. The effects of acidification on the calcifying organisms at the base of the oceanic food webs could potentially destroy fisheries.

Furthermore, the influx of Ca^{++} from rivers, as a result of weathering, buries $CaCO_3$ in ocean sediments, but this influx is less than 1% of the quantity required to neutralize the CO_2 being produced by fossil fuel burning at the present rate.

The ocean pH has not been below 8.1 during the past 2 million years, and has varied by less than 0.04 over the previous 10,000 years. From 1700 to 2000 the oceans have absorbed about 1/3 of the anthropogenic CO_2, with result that the surface ocean pH has reduced from 8.2 to 8.1. During the last inter-glacial warming, the pH changed at the rate of 0.0015 units per century, whereas the current rate is 0.14 units per century, a change 5 times larger and 70 time faster.

One has to go back 55 million years to find the atmospheric CO_2 at present levels. This was caused by volcanism and took place over thousands years. On a time scale of hundreds of years, the natural reservoirs that exchange carbon (atmosphere 200 Pg, biosphere 500 Pg, soils 1,500 Pg, surface ocean 1,000 Pg – 1 Pg = 10^{15}g) hold less than 4,000 Pg and would be overwhelmed by fossil fuel reserves (5,000 Pg) released over a few hundred years.

REFERENCES

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Grove, J.M. and Switsur, R. 1994. "Glacial geological evidence for the medieval warm period." *Climatic Change*,**26**,143-169.