CLIMATE CHANGE
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4 November 2015
REVISED 15 November 2017
REVISED 2 April 2022

"... *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.

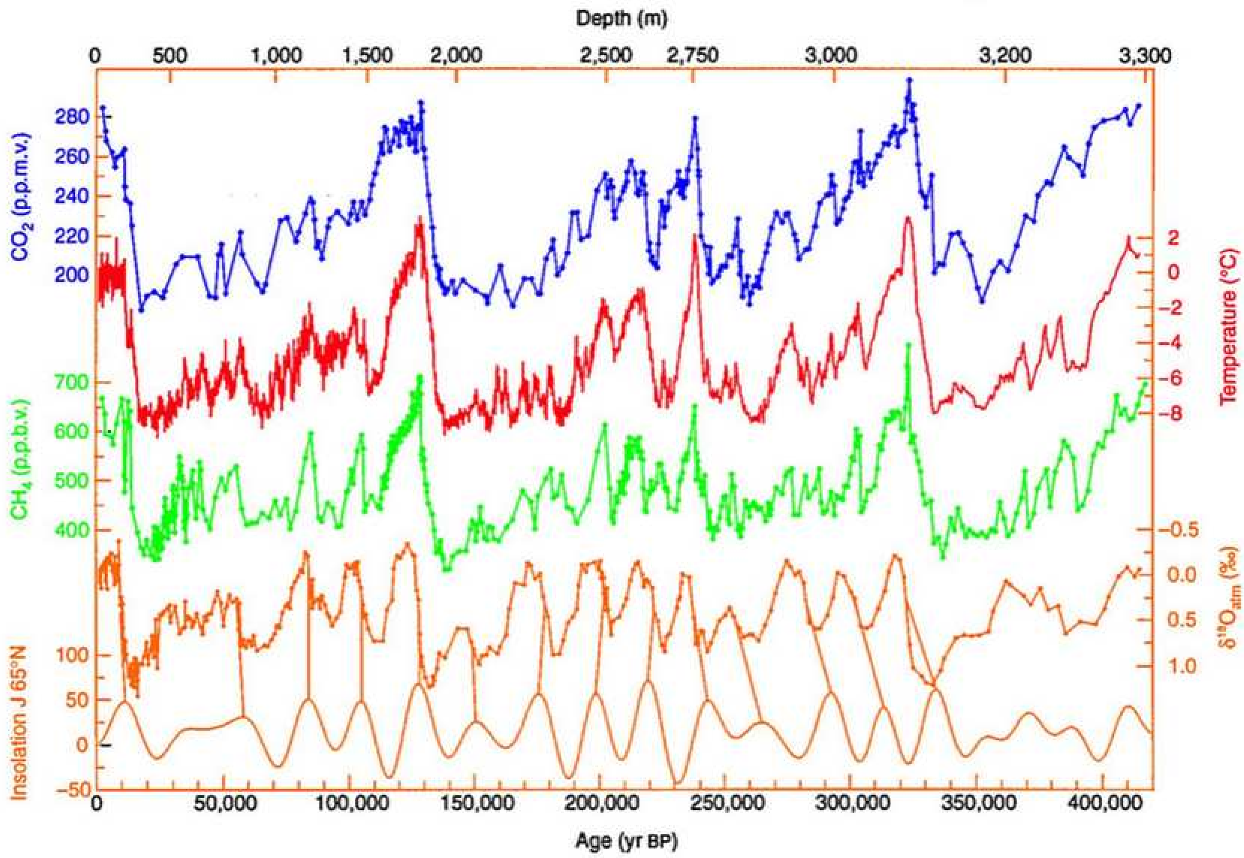
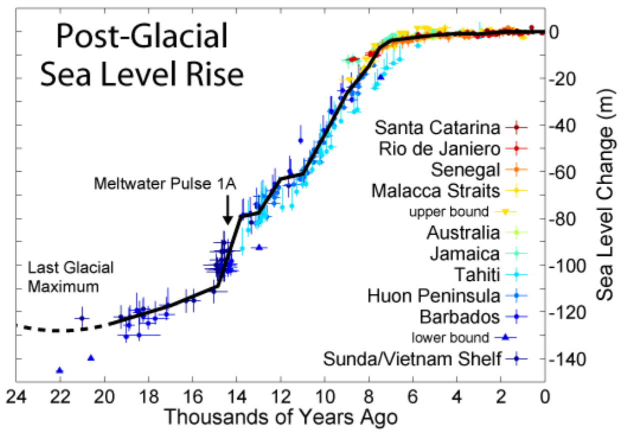


Figure 1. Global temperature change over the past 420 thousand years, as shown by an ice core from Vostok Station in Antarctica. from Petit, J. R. *et al.* Nature, **399**, 429 (1999).

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.



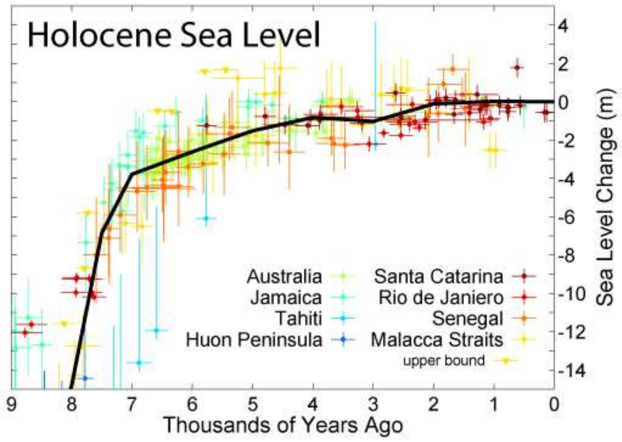


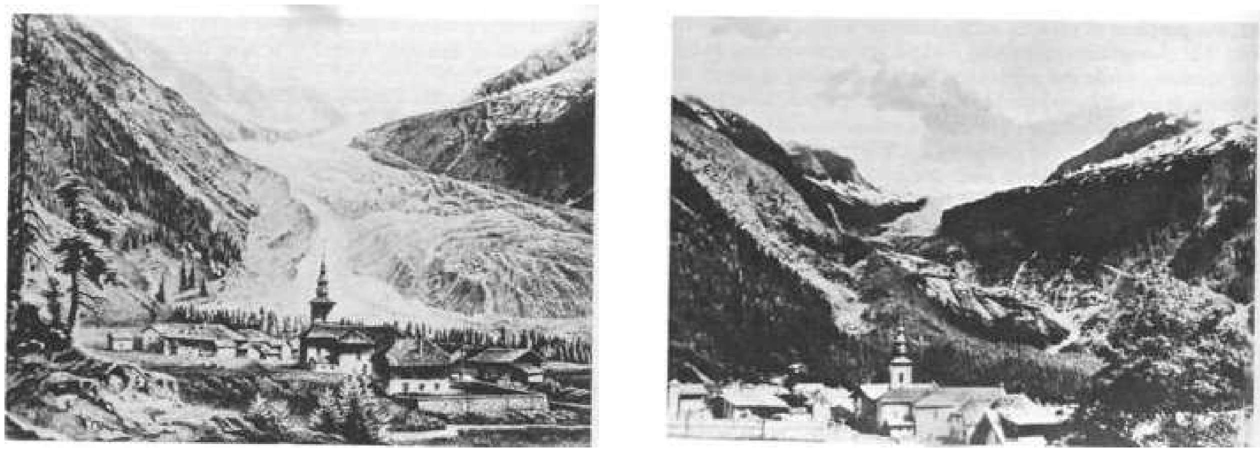
Figure 2 and Figure 3. from Flemming, K. *et al.* Earth and Planetary Science Letters **163**, 327 (1998)

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.

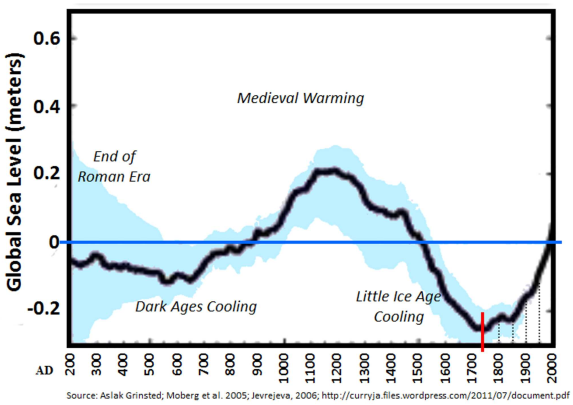
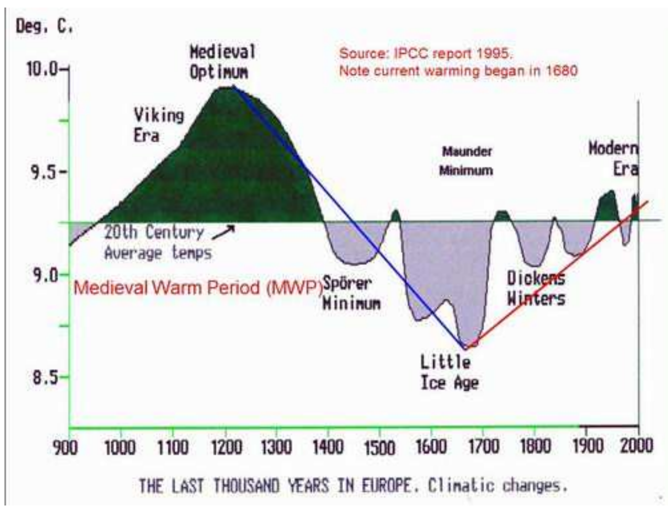


Figure 4. after Grinsted, A., J. C. Moore, and S. Jevrejeva (2009), Reconstructing sea level from paleo and projected temperatures 200 to 2100AD, Clim. Dyn., doi:10.1007/s00382-008-0507-2.



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.

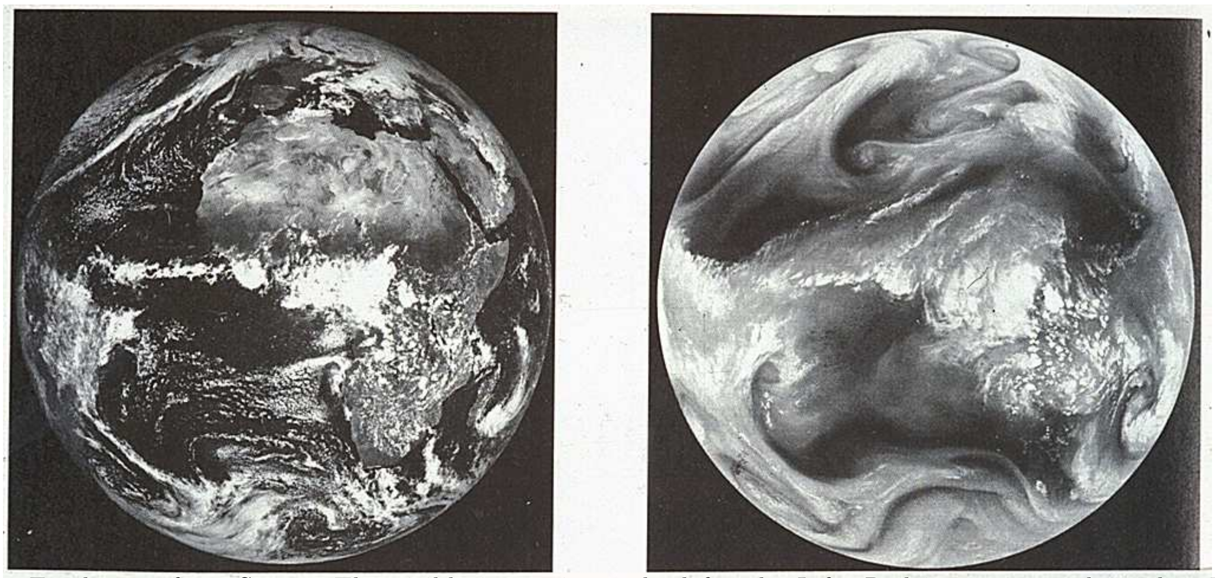
What are the effects expected from the current high carbon dioxide levels?

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.

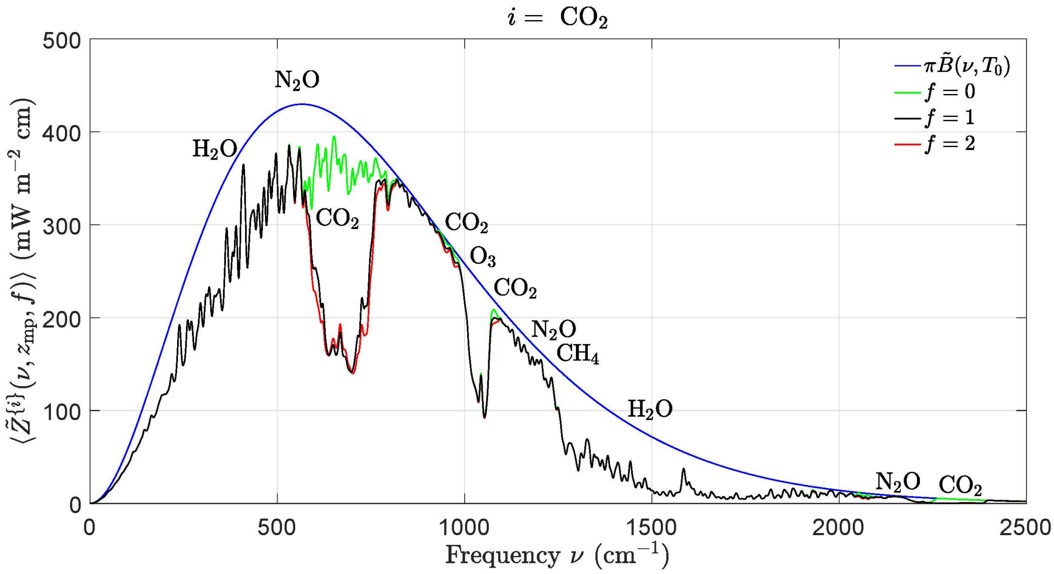


The Earth seen from Space. The visible image is on the left. the Infra-Red image is on the right. The surface is completely obscured by molecular absorption in the Infra-Red image, where only the cloud tops can be seen.

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 total power radiated once again balances the total power absorbed from the Sun. The relation between temperature and radiated power is $P = \sigma T^4$, where σ is the Stefan-Boltzmann constant. Assuming that the Earth absorbs and radiates like a black body, we have visible and infrared albedos, $\alpha = 0$, $a = 1 - \alpha$, $a_V = a_{IR} = 1$, and radiative forcing of $f = 0$. Here, $S = 1360$ W/m^2 is the solar constant.

$$a_V S\pi r^2 + f 4\pi r^2 = a_{IR} 4\pi r^2 \sigma T^4 \quad T = \left(\frac{S}{4\sigma}\right)^{1/4} = 278.3^\circ K = 5.1^\circ C$$

The actual temperature of the Earth is about $15^\circ C$, so atmospheric greenhouse gasses raise the temperature about $10^\circ C$.



The effects of changing concentrations of CO_2. The smooth blue line is the spectral flux from a surface with $T = 288.7^\circ K$ and no greenhouse gasses. The green line is with standard greenhouse gas concentrations, but with CO_2 removed. The black line is with all greenhouse gases at standard concentrations. The red line is with with standard greenhouse gas concentrations, but with the CO_2 concentration doubled from 400ppm to 800ppm. From van Wijngaarden and Happer (2020)

The calculation of the amount of blockage caused by greenhouse gasses in the atmosphere is complex. van Wijngaarden and Happer (2020) used the strengths and transition frequencies of hundreds of thousands of individual rot-vibrational spectral lines to perform line by line calculations in order to estimate the effects of doubling H_2O, CO_2, O_3, N_2O, and CH_4 concentrations from current levels. They used a standard atmosphere temperature profile divided into 500 altitude segments taking into account radiative and convective heat transport as well as the latent heat of water vapour. Collisions significantly broaden absorption lines in the troposphere and stratosphere. The result is given in terms of radiative forcing, which requires compensation through an increase in the Earth's temperature. For the current greenhouse gas concentrations, they calculate a forcing of $f = 117\text{W/m}^2$ which produces:

$$T = \left(\frac{S + 4f}{4\sigma}\right)^{1/4} = 299.6^\circ K = 26.5^\circ C.$$

This is about 10.9° hotter than expected. With visible and infrared albedos of $\alpha_V = 0.30$, and $\alpha_{IR} = 0.099$ we have:

$$T = \left(\frac{a_V S + 4f}{a_{IR} 4\sigma}\right)^{1/4} = 288.7^\circ K = 15.6^\circ C,$$

The visible albedo of 0.30 was determined from Earthshine. Here, the infrared albedo of 0.099 was adjusted to provide the correct average temperature of the Earth. According to van Wijngaarden and Happer (2020), doubling the concentration of CO_2 from 400ppm to 800ppm produces an additional forcing of $\delta f_{CO_2} = 3.0\ \text{W/m}^2$ which results in:

$$T = \left(\frac{a_V S + 4(f + \delta f_{CO_2})}{a_{IR} 4\sigma}\right)^{1/4} = 289.3^\circ K \qquad \delta T = 0.61^\circ C.$$

Reducing the the concentration of CO_2 from 400ppm to 200ppm would produce reduced forcing of $\delta f_{CO_2} = -3.0\ \text{W/m}^2$, and a $\delta T = -0.6^\circ C$.

Assuming that the Earth radiates as a black body, the Stefan-Boltzmann law, $P = \sigma T^4$, can be used to estimate the warming produced by radiative forcing. Differentiating $dP = 4\sigma T^3\, dT$, and inserting $\sigma = P/T^4$, we obtain

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

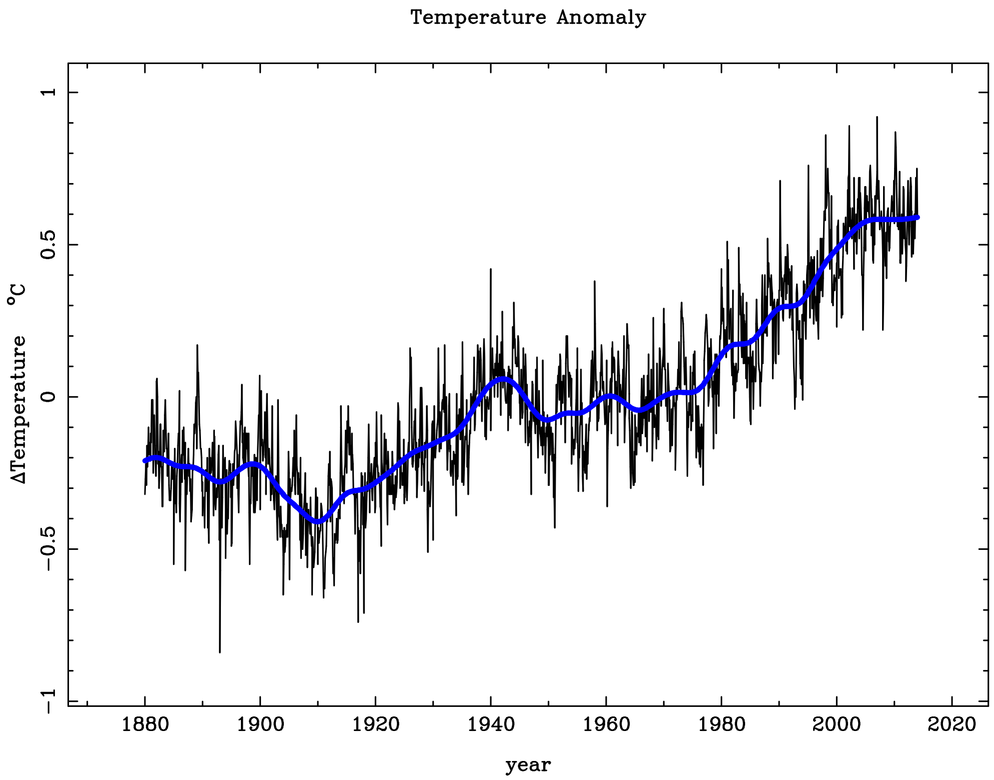
The present global temperature is $T = 15°\mathrm{C} = 273.15 + 15 = 288°\mathrm{K}$. The mean solar constant is 1360 W/m^2 collected over πr^2 and radiated over $4\pi r^2$. Thus the radiated power is $P = 1360/4 = 340$ W/m^2 . Substituting values for T and P yields

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

Thus, a radiative forcing of 4.7 W/m^2 is needed to produce a temperature change of 1°C.

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. With $dP = 2.2 \pm 1.0$ W/m^2 we expect $dT = 0.41 \pm 0.21°\mathrm{C}$.

According to van Wijngaarden and Happer (2020), halving the concentration of CO_2 from 400ppm to 200ppm produces a reduced forcing of $\delta f_{CO_2} = -3.0$ W/m^2, a reduction of CO_2 concentration from 400ppm to preindustrial 300ppm produces a reduced forcing of $\delta f_{CO_2} =$ 1.5 W/m^2. With $dP = 1.5$ W/m^2 we expect $dT = 0.32°\mathrm{C}$ as the effect of increasing the concentration of CO_2 from 300ppm to 400ppm.



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

The observed increase in global temperature is greater than 1°C, while the anthropogenic warming is less than half this amount. Doubling the concentration of CO_2 from 400ppm to 800ppm would produce and additional 0.6°C of warming.

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 favoured 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 neutralise 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.

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