Calculating the Anthropogenic Part of CO$_2$ in the Atmosphere

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The anthropogenic CO$_2$ emissions are considered responsible for the observed increase in global temperature, in particular because of fossil fuel burn, but also from agriculture and other processes. As the presence of CO$_2$ in the atmosphere is also a consequence of natural processes, it is of interest to determine the amount of the anthropogenic part accurately. This is important for being able to assess any potential dangers that may arise as a consequence of those emissions, as well as to establish a suitable policy to regulate those emissions, if necessary.

We examine the findings presented in the scientific reports of the UN Intergovernmental Panel for Climate Change (IPCC). We then compare the measurements of CO$_2$ concentrations with the known anthropogenic emissions, and show that there is a notable mismatch in their trends.

We then show a simple but accurate calculation of the anthropogenic part of the atmospheric CO$_2$ concentration via the convolution integral, taking into account the decay of 14C concentration in nature following the 1963 Treaty to ban the nuclear explosions in atmosphere. The results obtained considerably reduce the severity of the predicted climate changes that might be caused by anthropogenic emissions. The majority of the observed CO$_2$ concentration increase after 1850 can be attributed to natural causes.

Introduction

Since its formal constitution in 1988, the IPCC has been issuing warnings about the increasing emissions of CO$_2$, which in their view is the dominant cause for the global temperature increase.

Measurements of CO$_2$ concentration using chemical methods have been performed sporadically from the end of the 19th century, but for a number of reasons the results of those measurements are not considered reliable. From 1958, continuous monitoring is performed at the Mauna Loa Observatory, Hawaii, where Charles David Keeling established the first permanent measuring station using IR absorption, and from 1970 onward in many other parts of the world by other methods (manometry), as well as spectral analysis from satellites. Over time, the measurements have exposed strong seasonal variations superimposed on a steadily increasing trend, referred to as the Keeling curve, Fig.4.

The history of temperature measurements is much longer. Already in ancient times it has been known that certain materials expand when heated. Many inventors have contributed to the development of the thermometer, but the first to use mercury with a fixed scale as indicator was the Dutch scientist Daniel Gabriel Fahrenheit in 1714. Andres Celsius proposed a different scale in 1742, based on the boiling and freezing point of water. Measurements of air temperature, as a way of following and predicting weather variations, became a common practice from about 1750,

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but only after 1850 can we speak of a worldwide standard adopted by the International Meteorological Association. Whilst locally accurate, temperature measurements must be processed and interpolated for relatively large areas between stations, which considerably compromises the accuracy of estimating the global temperature. More so because of the uneven network density worldwide. From 1978, satellites with microwave sensors offered the most reliable form of measuring global temperatures, because in this way the whole surface of Earth can be covered uniformly and by the same sensors, even if the absolute precision of satellite sensors is somewhat lower than of conventional thermometers. Besides, satellites allow the measurements of temperatures in the high troposphere (at altitudes between 6 and 10 km), where the highest sensitivity to changes is theoretically expected and easily detectable. Global temperature records are published today by several institutions using different source data, and they all compare well to each other, differences between various methods used are small, and data set uncertainty is within ±0.25°C. There are nevertheless some notable differences in long term trends.

CO_2 concentration in the atmosphere started to increase rapidly after 1945 (Fig.4) coinciding with the industrial development, increase in traffic, and food production after the war (Fig.2). This prompted some to conclude that anthropogenic activity must be the sole cause. On the other hand, the global temperature did not always follow the increase of CO_2. At first, the temperature was decreasing until about 1975, which at the time has been attributed to aerosol emissions, and many meteorologists have expressed their concern about the possible new ice age coming. But after 1975, the global temperature began rising, which was interpreted as a consequence of increased CO_2 concentration. The simultaneous increase of global temperature and CO_2 concentration correlated well until about 1998. This triggered all sorts of predictions in the scientific literature and the media, from mild and slow warming to serious climate threats with catastrophic consequences if the human race would not change its behavior, mostly regarding the use of energy. This resulted in demands for political actions and economic measures to enable the transition to less polluting production processes and active environment conservation in order to mitigate the consequences of the predicted climate changes.

However, the temperature trend leveled off after 1998, in spite of continuing CO_2 concentration increase. Nevertheless, the climate alarmism continued and intensified, forcing governments to implement many of the proposed measures to limit the emissions. The cost of the transition is already showing up as higher energy prices and greater tax burdens on all goods, for both industry and agriculture. Suffering mostly is the population of underdeveloped countries because of their development slowdown and a steep increase of food prices.

It is therefore important to assess the true influence of human activity on CO_2 concentration and consequently on climate, to ponder all negative and positive effects, and in accordance with the results set the appropriate amount and the dynamics of implementing any long term changes in the society.

The influence of human activity on climate can be divided into a number of distinct categories, such as industrial emissions of various waste compounds into the environment, waste deposition

of used and worn industrial products, land use change, deforestation and food production on large monoculture farming areas, transport and traffic influences, etc. We are going to focus our attention here on CO_2 emission, mainly because of its alleged influence on climate via its greenhouse properties.

CO_2 is produced by almost all burning processes, as well as slower oxidation processes of bio-material decay, and as a collateral waste of many chemical processes, say, production of cement, and others. However, CO_2 can hardly be regarded as a pollutant, since it is an essential ingredient of plant growth and the oxygen production cycle via photosynthesis [1].

Besides those obviously positive effects, the influence of higher CO_2 concentration on climate is thought to be dangerous. CO_2 absorbs radiation from the Earth surface in the far IR band (dominantly within the 14-16μm wavelength) and reduces the rate of cooling of the planet towards space, thus effectively increasing the surface temperature. Some describe this as the greenhouse effect, but physically this is not correct: in a conventional greenhouse, the glass walls trap the heat by preventing the warm air to rise and expand. The heat trapping 'mechanism' is different in open atmosphere, and it would take another article of this size to describe it properly; here it will be sufficient to say that some warming does result from increased atmospheric CO_2. The effective climate forcing for a doubling of CO_2 amounts to a reduced power flow of about 1.1 W/m^2, as has been measured in laboratory experiments, so it is not questionable. What is often disputed in literature is the positive feedback via water vapor, which according to the IPCC reports amplifies the CO_2 forcing by about 2.5× to 3×. However, other researchers claim that the feedback from water vapor is not positive, but slightly negative, partially because of the evaporation cooling of the surface, and partially by the shading of the surface by stratospheric clouds. The total effect of water vapor therefore reduces the CO_2 forcing by 1/2 or more.

To evaluate the thermal effect of CO_2 on climate we would have to establish at least the following:

1) What is the climate sensitivity to increasing atmospheric CO_2 concentration (how much will the temperature increase if the CO_2 content is doubled);
2) What is the thermal effect of CO_2 compared to other gases, in particular to water vapor (in which part of the thermal radiative spectrum is the effect greatest, by what amount do the different spectra of different gases at different concentrations overlap, etc.);
3) Which natural processes increase and which ones reduce the resulting radiative forcing;
4) What is the difference between the surface thermal radiation and the radiation from the upper atmosphere towards outer space (at which altitude there is a thermal radiation equilibrium);
5) What is the radiative thermal balance of the planet in relation to the adiabatic processes in the atmosphere;
6) What are the anthropogenic and the natural contributions to the CO_2 concentration increase;
7) What is the natural sink rate of CO_2 (into the oceans and the soil), which determines the effective residence time of the emitted CO_2.

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Those are just the most important questions regarding the influence of CO_2 on global temperature. There are also numerous influences of other compounds and other processes, either as separate or in various mutual combinations. To describe them all we would probably require a large book, so we leave the treatment of most of those for another opportunity, and focus on only the points 6) and 7).

Comparing antropogenic CO2 emissions to atmospheric concentration increase

To tackle the problem we need to know these three key parameters:

a) The total amount of CO_2 in the atmosphere and the amounts exchanged naturally between the ocean surface, the land, and the atmosphere;

b) The yearly emitted amounts of CO_2 as a consequence of anthropogenic activity;

c) The average CO_2 residence time the eco-system needs to absorb the emitted quantity.

For a) we refer to the already available results gathered over many years, many of which are also listed as references in IPCC Assessment Reports (AR1 to AR5; the last one was published in 2014, in preparation is AR6, scheduled for 2020). Those results are best presented in graphics form in a simplified but sufficiently accurate schematic of Fig.1, which we borrowed form a US DOE publication in 2008 [2]; similar presentations are also available in IPCC ARs [3] and elsewhere.

In Fig.1, various carbon (C – not CO_2!) natural and anthropogenic sinks and sources, as well as accumulated quantities, are shown directionally and numerically in units of billions of metric tons (gigatons, Gt, or 10^9 tons, or 10^{15} g, or petagrams, Pg) per year. Note that to convert C into CO_2 we have to multiply the numbers shown by 3.667, which is the atomic mass ratio: $(12+2×18)/12$. Note that not all carbon ends up as CO_2, but for simplicity we shall assume so. The numbers shown were valid in 2008, the year of publication; today, in 2018, the numbers are slightly different, i.e., the yearly anthropogenic emissions are close to 10 GtC (36 Gt CO_2), but to acquire a comprehensive picture of the natural circulation processes this is not very important. We shall of course use the most recent numbers in our calculations later.

At a first glance, Fig.1 looks logical and acceptable. But there are a few problems with such presentation. First, all the numbers related to natural quantities are only coarse estimates based on known small scale physical and bio-chemical processes extrapolated to large scale. The only quantities known sufficiently accurate are the anthropogenic emissions, since they represent the use of energy, which plays an important role in our economy, so the cost of energy is carefully recorded.
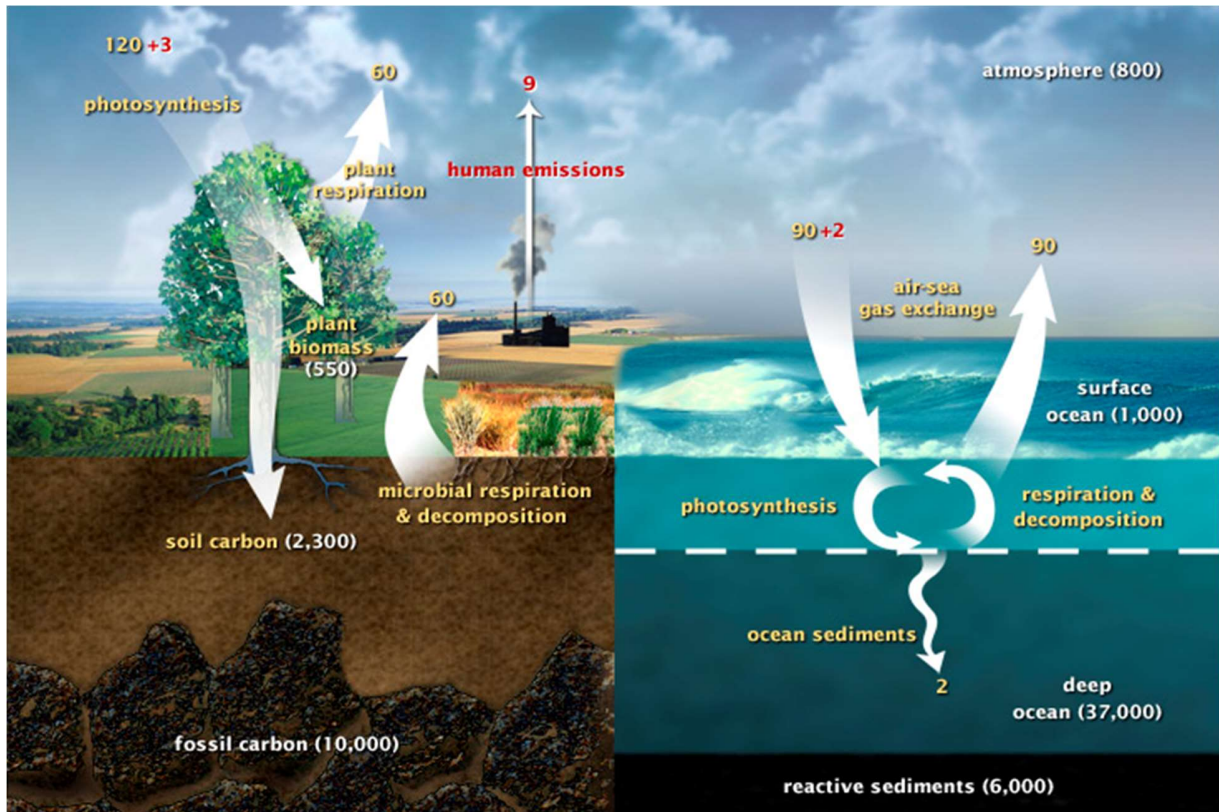
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Fig.1: Schematic presentation of yearly carbon circulation in nature (source US DOE). Natural sinks and sources are shown by nubers in yellow. The numbers in white in parentheses are long term accumulated quantities. The numbers in red are anthropogenic emissions and their relevant parts in the total sink. Note that about ¼ (210 GtC) of the total carbon in the atmosphere (800 GtC) is exchanged with the oceans and the ground each year. Athropogenic emissions are 9 GtC, about 5 GtC of those being absorbed by the ocean and the ground, and only about 4 GtC remain in the atmosphere.

A second problem is that all the numbers add up well, creating the impression that nature is in perfect balance and only humans are the disruptive element. However, natural processes are seldom balanced, there can be long periods when one process prevails over others and periods where a different process dominates. For example, it is well known that oceans absorb atmospheric gases when the surface temperature is low and release them back when the temperature is higher. Similarly, the oceanic phytoplankton and the bacterial metabolism in the ground and plants metabolism follow variable conditions (presence of nutrients, soil moisture, sunlight, temperature, CO_2 in the air, etc.). From historic records and proxy data we know that there where many natural variations [4] in both temperature and CO_2 content before humans started to modify the environment.

Thus, and in the evidence of large natural annual CO_2 exchange, it is reasonable to assume that relatively small natural variability can easily outperform anthropogenic emissions for long periods. So we should take such presentations as Fig.1 with caution.

A third problem arises from accounting for carbon (C) emissions instead of CO_2. It is not clear whether it is just some careless shorting of the full term (carbon dioxide), is it a purposely simplified expression for the media to create an emotional response (because the word "carbon" is associated with "dirty" coal), is it a consequence of some simplification for calculation

purposes, or is it an intentional manipulation (because under "carbon" it is possible to include other substances which contain carbon, not just CO_2). Or maybe it is all of the above. There are many substances in anthropogenic waste materials that contain carbon in large quantities (like plastics, etc.) which decay rather slowly, so not all of the released carbon ends up as CO_2. Likewise, many products of the fraction distillation of oil are compounds for other products in the chemical industry, and the remaining tar is used for asphalt. So a large part of oil is not burned; of course, road surface covered in asphalt absorbs sunlight and heats the air substantially during the day, and consequently participates in climate change, however this influence should be considered as land use change, not in the greenhouse effect. Sooth and other aerosols in the air prevent sunlight to reach the ground, so their effect is dominantly cooling the planet. On the other hand, when sooth falls on snow, it increases the albedo, causing snow to melt at a faster rate, and eventually expose the ground, which further changes the albedo, resulting in a warming effect. Again, all this has to be treated separately, not as part of the greenhouse effect. However in the calculation of carbon release, this is taken as if all end up as CO_2. This means that those 9 GtC shown in Fig.1 are actually lower; but in our calculation we shall ignore it and take it all as given in Fig.1.

To make the comparison easier we shall transform all the relevant quantities into a mass part of CO_2. As already mentioned this is achieved by simply multiplying each quantity by 3,667 (the CO_2 to C atomic mass ratio). Also, the current emissions are somewhat higher than they were in 2008, they amount to about 10 GtC, which transforms into 36 Gt CO_2.

Note that most often the atmospheric concentration of CO_2 is specified as a volume ratio in parts per million (ppmv), which is currently (in 2018) about 410 ppmv. A cubic meter of air has one million cubic centimeters, so 1 m^3 of air contains about 410 cm^3 of CO_2. The mas of 1 m^3 of air at ground level is about 1.2 kg, and it falls linearly with height, so the total mass of the atmosphere is about 7.83×10^{15} tons. One ppmv of CO_2 in the atmosphere then represents about 2.13 Gt of carbon (C), or 7.83 Gt of CO_2. So the atmosphere contains about 3210 Gt of CO_2, or about 875 Gt of carbon. The global mean CO_2 concentration is currently increasing by about 2 ppmv/year (16 Gt), with a large annual fluctuation: the level drops by some 6 to 7 ppmv (about 50 Gt) from May to September, and then increases by about 8 to 9 ppmv in the following months. The northern hemisphere dominates the annual cycle because it has much greater land area (and thus plant biomass) than the southern hemisphere, but the oceanic surface temperature cycle also adds a notable contribution.

With this, we come to the point b), where we need to look at historical emissions data. Fig.2 shows those emissions by each source, and the total. Those data are collected annually by CDIAC [5]. We can see that the total emissions were about 6 Gt in 1950, which was the coal dominated era. Then oil consumption increased rapidly, but slowed down considerably after the first and second oil shock (1973, 1978). Later, after the year 2000, coal consumption became the dominant source of emissions owed to a rapid economic development of China, India, and a few other countries, which can be seen in another set of CDIAC data showing emissions per country (not shown here). Finally, after 2014 the emissions stabilized at some 36 Gt of CO_2 per year, probably owed to China using more hydro and nuclear power. But in accordance with the Paris agreement, coal will still remain a dominant fuel in China, India, and elsewhere, until 2030, even if increasing

at a slightly lower rate. In the US and the EU, the use of natural gas is already replacing coal mainly in electricity production, resulting in their total emission reduction, because natural gas has grater thermal efficacy. Renewable energy sources are on the increase, but they still do not make an appreciable impact on emissions.
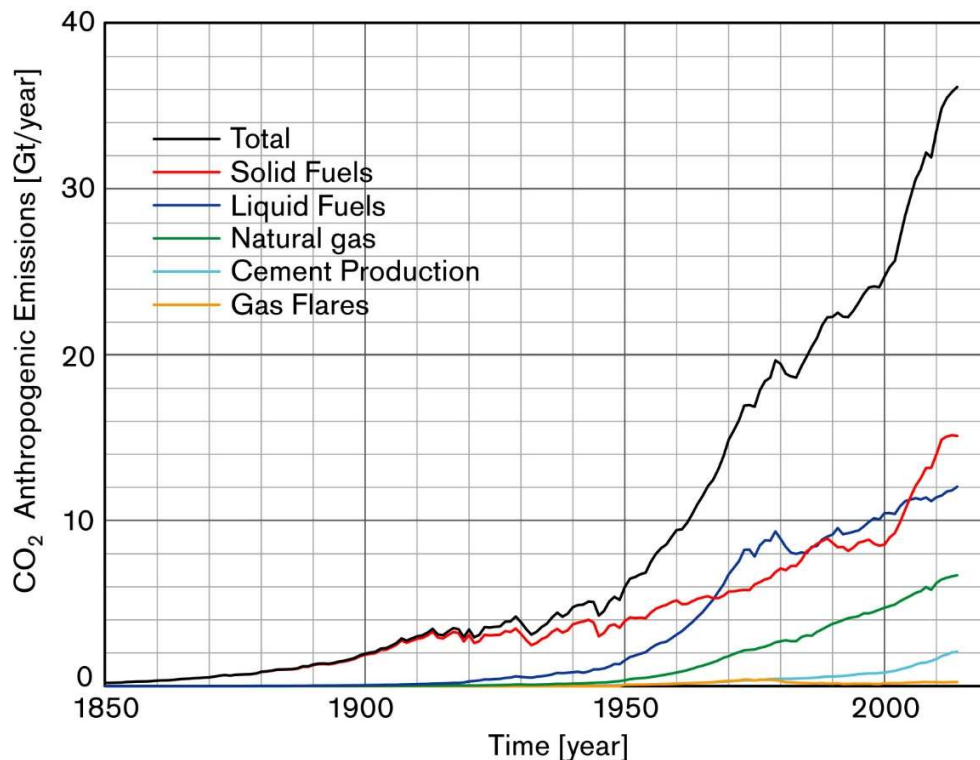

Fig.2: Yearly emissions of CO_2 by sources (data source CDIAC). It is possible to distinguish how many important historical events afected the energy consumption, and consequently the total emissions. Note the stagnation during the WWI (1914-1918), the stock market collapse (1929), the recession during the last years of WWII (1944-1945), the subsequent economic recovery (1950s and 1960s) based on the increase of oil use for transport, the first (1973) and second (1978) oil shock, the Gulf war and the collapse of the Soviet Union (1990s), the China steep economic growth (after 2000), the economic crisis of 2008, and the economic slowdown after 2014. In 100 years (1850-1950) the emissions increased to 6 Gt, which then quadrupled (24 Gt) in the next 50 years (to 2000), and reaching 36 Gt recently.

Such a steep increase in emissions caused concern among the environmentalist groups around the world, requesting emission reductions and a transition to a less polluting economy. It also increased the concern and confirmed the belief that the increasing CO_2 concentration in the atmosphere was the consequence of this increase in emissions, which then caused the observed slight increase in global temperature (by about 0.6°C from 1950 to 2018).

Let us see if this concern can be justified mathematically. We need to know where the assumption for a yearly sink of those 5 GtC (18 Gt CO_2) of anthropogenic origin (shown in Fig.1) comes from. The IPCC AR5 (2014) shows the following graph, Fig.3, where all yearly sources and sinks of CO_2 are shown. Obviously the dynamics of natural sinks reflects the sources, which – as already seen in Fig.1 - stems from the IPCC assumption that natural processes are all well balanced, and consequently the amount of CO_2 remaining and accumulating in the atmosphere is attributed

exclusively to anthropogenic emissions. Note however that the increase of CO2 in the atmosphere exhibits large oscillations, whereas no such oscillations are present in the graphs of anthropogenic sources, the yearly emissions increase relatively smoothly with small excursions. What is the reason for this difference?
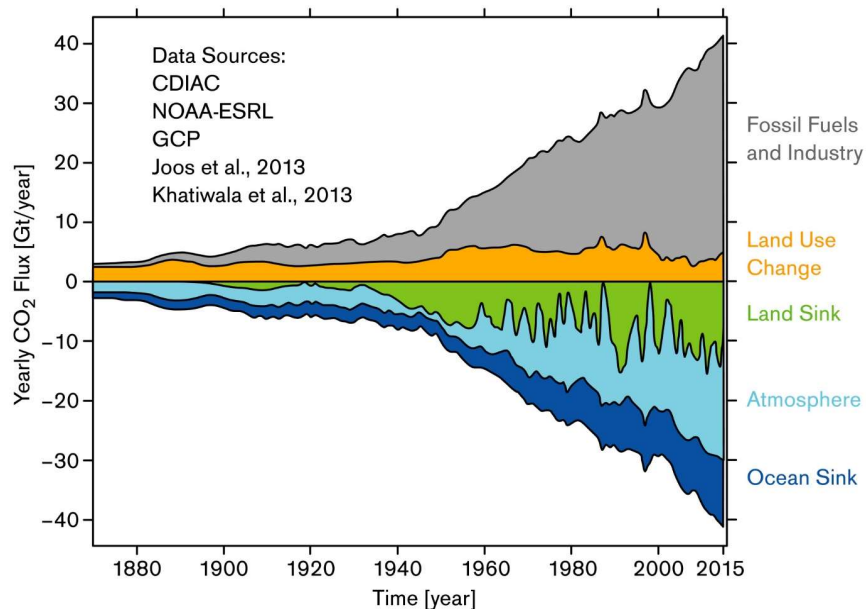

Fig..3: The history of yearly quantities of sources and sinks of CO_2 (IPCC AR5, 2014). Subtracting the influence of land use change (deforestation, etc.), the remaining source is identical to the total anthropogenic emissions of Fig.2. Congruent to the numbers in Fig.1, about 56% of those emissions sink into the oceans and ground, and 44% remains in the atmosphere. Note the large oscillations of the atmospheric part, which are not present in any source. A minor issue regarding this graph is that the oscillations of the atmospheric rate of change should be distributed between the oceans and the ground, instead of what is shown above, but for our analysis this is not important.

In order to explain those oscillations we nedd to inspect the measured values of CO_2 concentrations. As mentioned in the introduction, CO_2 concentration is being measured monthly from 1958 at Mauna Loa, Hawaii, and later at other stations around the world. The results from Mauna Loa are shown in Fig.4.

As already mentioned, there are relatively large oscillations superimposed on an increasing trend. Those oscillations are seasonal oscillations owed to the difference in CO_2 sinks and sources on the northern and southern hemisphere, because of the difference in land and ocean surfaces. Oceans absorb CO_2 (also oxygen and other gases) when the surface temperature is low, and release those gases when the surface warms, but oceans in the northern hemisphere do the same in opposite seasonal periods. Ocean phytoplankton thrives when there is more CO_2 in the water, creating an additional gradient in partial gas pressure, increasing the intake rate. The opposite occurs on land, because plants and bacteria in the ground thrive and absorb more CO_2 when the temperatures are higher, and release it when it is colder, again out of phase in the northern and southern hemisphere. So the seasonal oscillations we see in Fig.4 represent the difference of all the sinks and sources between the two hemispheres. The actual sink and source rate in each hemisphere is much higher than that, as the numbers in Fig.1 show.

It is important to realize that Fig.4 shows the cumulative CO_2 concentration, but Fig.3 shows the quantities exchanged each year. So in order to obtain the yearly changes and be able to compare those changes with anthropogenic emissions, we must first differentiate the cumulative quantities of Fig.4.
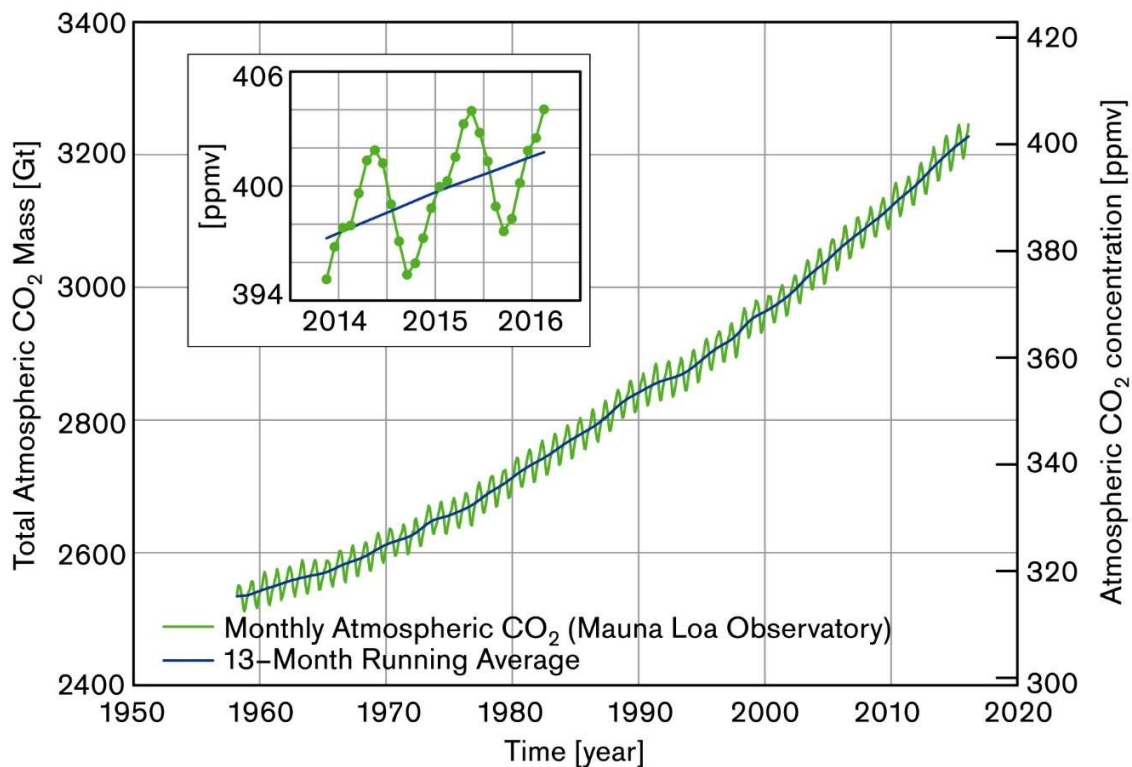

Fig.4: CO_2 concentration measured at Mauna Loa from 1958 on. The vertical scale on the left hand side represents the total mass of atmospheric CO_2 (in Gt), the scale on the right hand side represents the volumetric ratio in parts per million (ppmv). The monthly data exhibit seasonal oscillations (because of the difference in sinks and sources on the northern and southern hemisphere). The smoothed curve represents a 13 months arunning average, equivalent to the yearly trend.

The data published by the Mauna Loa Observatory are available form [6]. Since those represent a time integral of monthly variations, we need to differentiate them, and this is done simply by taking the difference between adjacent monthly data. We have now two problems: the monthly differential is 12 times larger than the yearly differential, but even after reducing the values by dividing by 12 we still have large variations from which it is impossible to determine any trend. In order to expose the trend we have to smooth the differential by, say, a 5-year running average. The comparison of the differential and the smoothed differential is show in Fig.5, exposing the increasing trend with oscillations similar to those shown in Fig.3.

From Fig.5 we note that the current rate of CO_2 increase during the last two decades was approaching some 2 ppmv/year. This we can confirm by looking at Fig.4: the concentration increased from 360 ppmv in 1996 to about 400 in year 2016, or 40 ppmv in 20 years. Now we can compare this with total yearly anthropogenic CO_2 emissions.
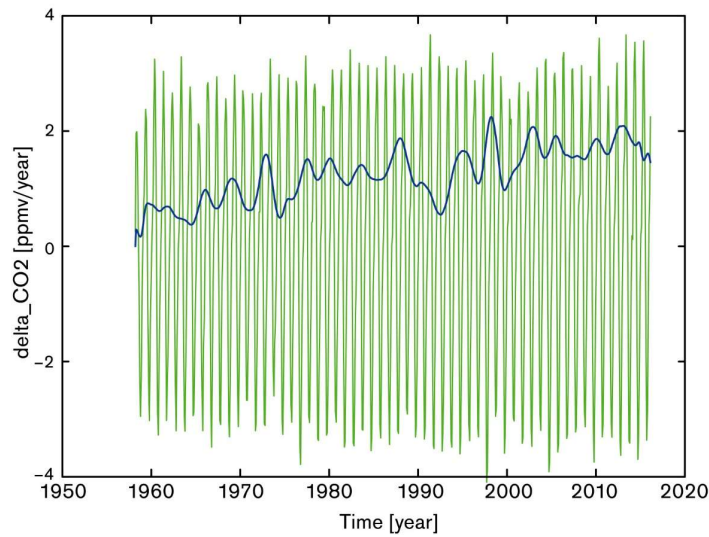
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Fig.5: The differential of the measured CO_2 concentration of Fig.4, adjusted for yearly values. The large seasonal oscillations can be smoothed by using a 5-year (60 months) running average in order to expose a long term trend. This graph is similar to the incremental air concentration of Fig.3, but flipped about the x-axis, because in Fig.3 it represents a sink. The difference in oscillation amplitude depends only on the length of the averaging period.
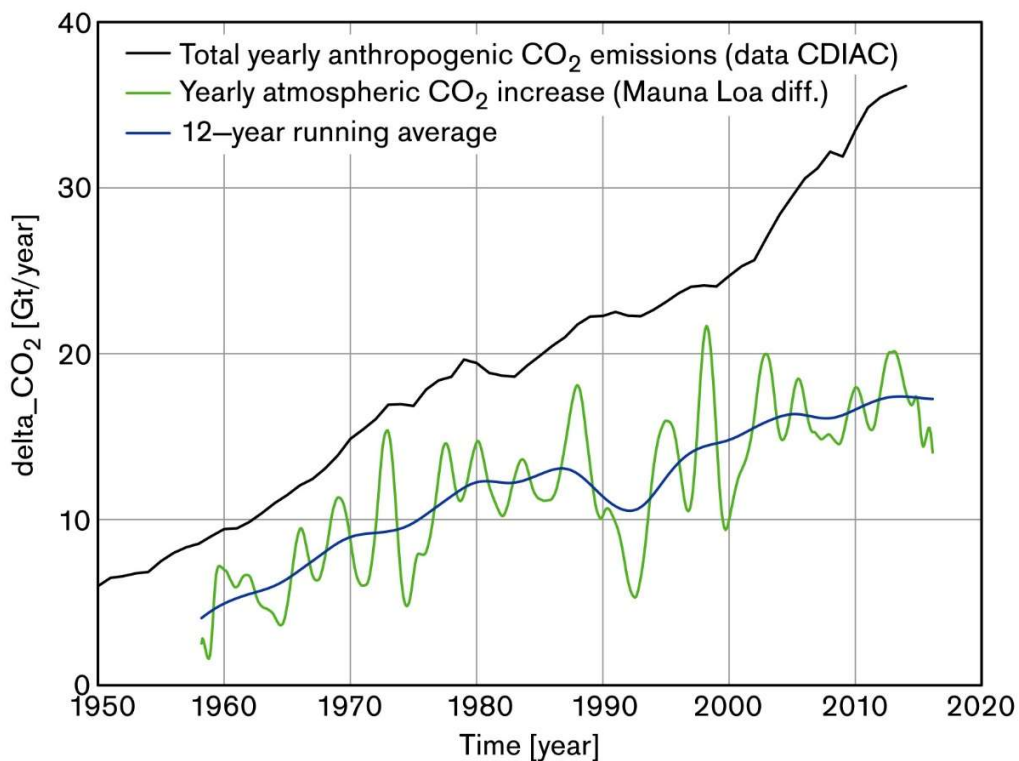

Fig.6: Comparison of yearly CO_2 emissions of anthropogenic origin with the measured yearly increase of CO_2 concentration in the atmosphere. Also shown is a 12-year average of the concentration increase, so that it is easier to compare the two trends. We note that both quantities were increasing at a similar rate from 1958 to about 2000, and the difference in the amount by factor of about 2× is attributed by the IPCC to the natural ocean and ground sinks (as shown in Fig.1). However after the year 2000, the rate of anthropogenic emissions doubled, while the measured concentration increase flattened to a value of about 18 Gt CO_2 per year.

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Fig.6 shows the comparison, with a further smoothing using a 12-year average to expose the difference in long term trends. We note that before the year 2000 the two quantities were both increasing at a similar rate: in 10 years (1970-1980) the anthrpogenic emissions have increased from 15 to 20 Gt/year, or by 5 Gt/year, and in the same period the atmospheric concentration increased from 9 to 12 Gt/year, or by 3 Gt/year. This relatively good correlation prompted James Hansen (NASA GISS) in 1988 to conclude that athropogenic emissions are the cause for the atmospheric CO_2 concentration increase [Hansen, 1988]. The slight difference in the rates was attributed to the oceans and ground natural sinks (about 56%), and the remaining amount (44%) was accumulating in the atmosphere. This led to the construction of diagrams similar to the one in Fig.1, and this explanation still prevails in all IPCC documents to this day.

However, after year 2000 we see no correlation, in fact there is a clear anti-correlation: in 10 years (2000-2010) the yearly rate of anthropogenic emissions has nearly doubled, from the previous 5 to the current 9 Gt/year (24 to 33 Gt/year), but the CO_2 concentration rate slowed down, from the previous 3 to currently only 1.5 Gt/year (14.5 to 16 Gt/year). From this it is obvious that something must be fundamentally wrong with the Hansen's model.

Anyway, most importantly: **in science, we look for possible causal relations whenever we note either a correlation or an anti-correlation between two variables. But when we have a correlation in one period, and an anti-correlation in the next period, than obviously no causal relation can exist between the two – or if it does exist, it must be very weak, and some other process dominates.**

Clearly, from just the rate of increase we cannot establish a relationship between the anthropogenic emissions of CO_2 and its atmospheic concentration. In order to find what part of CO_2 in the atmosphere is actually of anthropogenic origin, we will have to integrate its rate and compare it to the cumulative amount of CO_2 as measured at Mauna Loa. This is done in the following part of his article.

As we have seen, the Hansen's model requires that part of the anthropogenic CO2 is absorbed by land and the oceans, and part remains in the atmosphere. But it is nonphysical to assign fixed parts (however averaged) in this process on a yearly basis, especially in the presence of a large existing quantity. If anything, the same natural absorption and release processes must act on all the present and added quantity, not just the added one. Then these processes must be modeled dynamically. Because the industrial revolution started in 1850, long before there were reliable CO2 concentration measurements, to be able to compare the quantities in question over the whole period we need to find what were the concentrations in those days.

As mentioned, before 1958 there were some sporadic measurements of CO2 concentration using chemical methods, but for various reasons those results are considered unreliable (mostly because of large variations between various researchers, even if there were a few Nobel laureates among them). What we do have are proxy (indirect) measurements by analyzing other natural deposits of CO_2, for example in polar ice, lakes and sea sediments, carbonate deposits in caves, tree rings, etc. By measuring the concentration ratios of various isotopes of certain characteristic

elements it is possible to reconstruct the past variations of atmospheric concentrations of gases and the temperature, and for many thousands or even millions of years ago. However it is important to stress that the transition between individual layers is not sharp, so the time resolution is rather coarse, sometimes years, decades or even centuries. The consequence is that short term variations are lost, and what we recover it a long term average. Likewise, various analysis methods used for various materials may also have large variations in resolution and confidence bands, and even different resolutions for recent and more distant past. And calibration between the various methods is always of concern. This means that we must take those reconstructions with some caution. Nevertheless, when we obtain comparable results by different methods, or from samples from different sites, our confidence in the reconstruction increases.

Fig.7 shows a composite CO_2 concentration for the period between 1840-2018, with the older series based on the analysis of air bubbles trapped in the polar region ice core drilled at the Law Dome, Antarctica, followed by direct measurements at Mauna Loa.
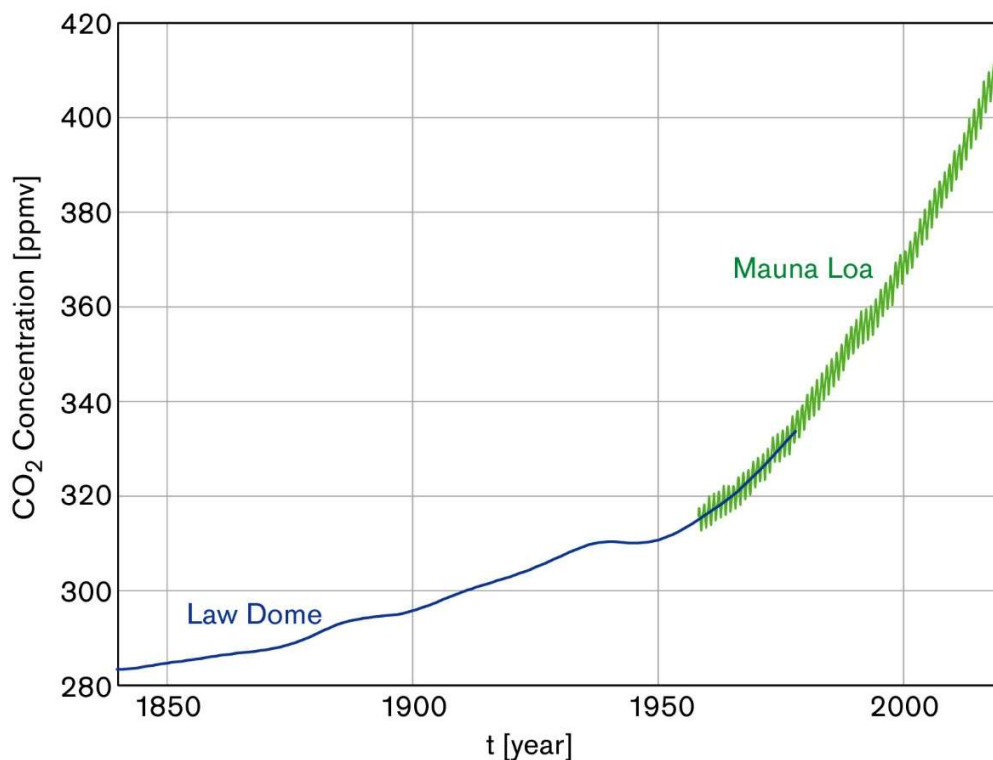

Fig.7: Reconstruction of the CO_2 concentrations in air for the period between 1840-2018. During the period between 1958-1978 the data obtained from the Law Dome ice core match well with the Mauna Loa data, so we can take the Law Dome data set as a reasonably accurate representation of the long term average CO_2 concentration. However we must also note that some researchers dispute this because the age of the ice layers and the age of the air bubbles do not match well, there is some 85 years difference in the data.

We can now compare the composite data of Fig.7 with the cumulative (time integral) values of anthropogenic CO_2 emissions.

But before we do that, we must find out what is the residence time of the added CO2 in the atmosphere by consulting the various studies by various researchers. The residence time is defined as the time taken by a system (a very dynamic and complex system of sinks and sources as the Earth with its oceans and its atmosphere certainly is) to adapt to some added amount of active substance, in this case CO_2. However, different authors use different definitions of the characteristic time constant, some use ½ of the added amount as the half-life constant, others use the 1/e level (e is the Euler natural number, e=2,71818....). That depends of the mathematical function type the authors are using to fit the measured data. Most authors use a limited environment volume within which they perform the experiment, but each model is specific in regard to the dynamics of natural sinks and sources, based on the estimates of the influence of physical and biological processes involved. Numerous factors influence the model, and each author estimates those to the given experimental setup conditions the best they know.
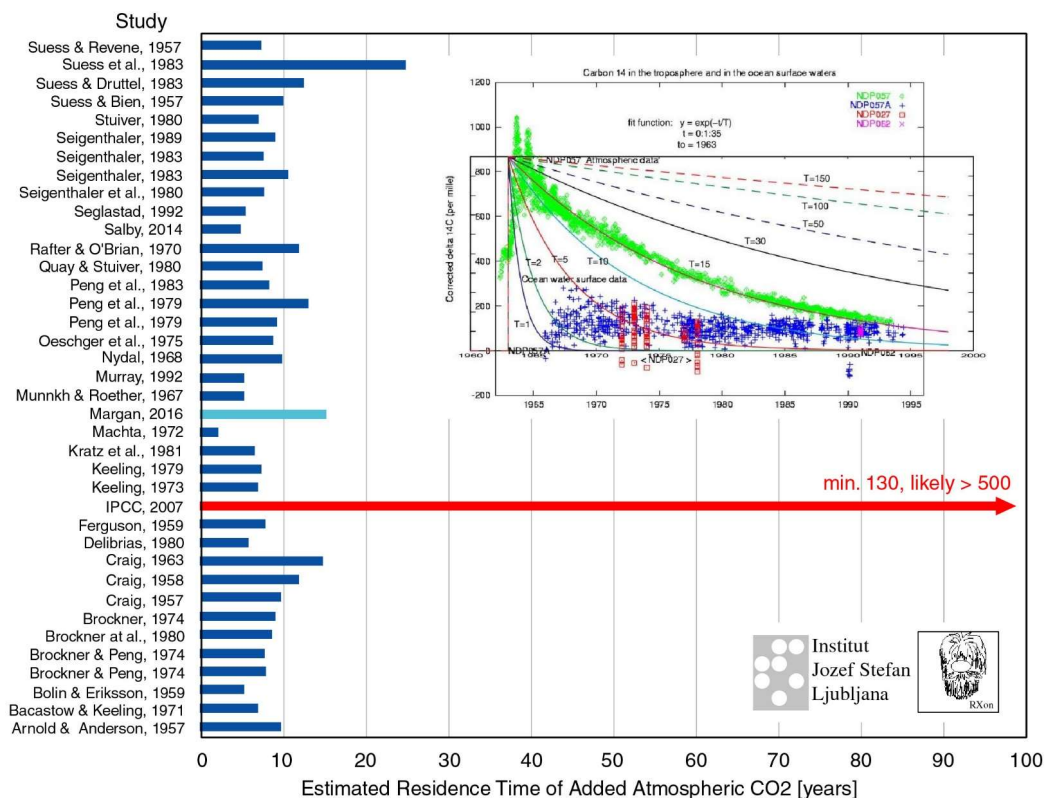

Fig.8: A review of the literature regarding estimates of the residence time of CO_2 in the atmosphere. The results span from 3 to 24 years, except for the IPCC, in its documents a suspiciously long value of at least 130 years is used, but it may well be up to 500 years or beyond. My own result, obtained by analyzing ^{14}C concentration decay after the ban of atomic explosions in the atmosphere in 1963, is about 15 years, and is the second largest. Authors who have arrived at low values justify their results by the seasonal dynamics of the system, which is capable of exchanging 50 Gt of CO2 within just 6 months.

Fig.8 shows the values of residence time obtained by many different authors (listed in alphabetic order). Note that the value used by all IPCC documents was estimated to be very high, at least 130 year, but possibly up to 500 years or more. The explanation goes something like the following: if a molecule that was added to the atmosphere is absorbed by, say, the ocean, and is replaced by a molecule emitted by the ocean, the condition for the atmosphere remains unchanged. The

IPCC justifies this by saying that by this the best fit of calculated to the measured data is achieved. At first glance this seems logical, but we shall soon see that it is not.

In contrast, all other authors have obtained results between 3 and 24 years, the average (excluding the IPCC value for obvious reasons) is about 7 years. Here I draw the reader's attention to two studies by Keeling (1973, 1979), who obtained results of about 7 years. Another interesting study with a result of about 6 years is the one by Bolin and Eriksson (1959), namely Bert Bolin later became the first president of the IPCC, Eriksson was his mentor. This certainly gives some weight to the average value of the results listed here.

It is important to realize that the Hansen's 1988 model, on which the IPCC's long residence time value is based, cannot be physically justified. Natural processes cannot make a difference between a molecule of CO_2 that has been recently added to the air, and a molecule that has been already in the air from whichever source, anthropogenic or natural. It is therefore unreasonable to expect that natural processes will extract 56% of the added CO_2 within the very same year, and leave the remaining 44% to accumulate in the atmosphere for the next 130 years or more. As we have already seen in Fig.1, natural processes exchange each year some 770 Gt of CO_2 (210 GtC), which is about ¼ of the total CO_2 content in the atmosphere, and the atmosphere is mostly well mixed, so the absorption of molecules occurs in a stochastic manner. Therefore we must use some other way to model the residence time.

How do we model such a process? In mathematics this problem has already been solved some 260 years ago by D'Alembert, in 1754 (the method has been later improved and generalized by many other French mathematicians, Lacroix, Laplace, Fourier, Poisson, ...), and this discovery we have been using ever since in numerous applications in physics, chemistry, biology, computer processing of signals and images, and even in economy and statistics. The procedure is known as the **convolution integral**, [7], or simply convolution, a brief explanation of which refers to Fig.9.
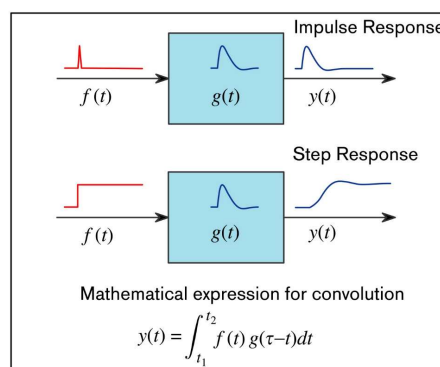

Fig.9: Convolution integral: a system characterized by its impulse response or a relaxation function g(*t*) and excited by an input function *f*(*t*) will respond with the output function *y*(*t*), which corresponds to the convolution integral of *f*(*t*) and g(*t*). The Latin *convolvere* means to fold, we are folding one of the integrated functions, usually g(*t*), about the starting time $t_1 = 0$ to negative time g(-*t*); a time constant *τ* is conveniently chosen to limit the system function length to a time at which the system relaxes to a value close to zero (otherwise a vertical offset error results). In this way the starting points of the input and the system function meet at the starting point, giving *y*(t_1). We then increment *t* to *t+dt*, multiply the input function by the convolved system function and sum it to the previous value, *y*(*t*), thus obtaining *y*(*t+dt*); integration is effectively a cumulative sum. By repeating this for every time step until $t = t_2$, we obtain the desired result y(t).

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The brief description in Fig.9 is necessary to understand the mathematical operations required. When analyzing a system we usually excite it by an impulse function to obtain the impulse response. Another very effective way is to excite the system by a unit step function and obtain the step response, then the impulse response is simply a time derivative if the step response. Once the impulse response is known, the response to an arbitrary input function is obtained using the convolution integral.

Analytically solving the convolution integral can be very complicated even for some relatively simple mathematical functions. But numerical solutions using a computer with the appropriate algorithm is easy, we only need to be careful when specifying the initial conditions and the required tie resolution dt. Since the data for CO_2 concentration is already in numerical form as either yearly or monthly average values, we only need to download the tabulated values from the official site, such as [Ref] and choose a suitable computer program to do the job. There are many such programs; for this article I was using Matlab (by The MathWorks), but the open source GNU Octave may be preferred by some readers. Both have the convolution algorithm built in, called CONV, see the program Help for additional information, or the script [Ref] where the complete procedure for plotting the processed data is written. The only problem that remains is how do we determine the impulse response function of such a complex system as the Earth.

Fortunately (or not!), we have the data already. In the late 1940s the carbon dating method was developed using the radioisotope ^{14}C decay. This isotope is being created in the upper atmosphere by fast neutrons from cosmic rays interacting with the atmospheric nitrogen ^{14}N, and has a decay half-life of about 5730 years, so the ratio to ordinary ^{12}C is fairly constant. But in the years that followed, researches started noticing a steep increase in the ^{14}C concentration, and this was attributed to atomic bomb tests in the atmosphere. In 1963 an agreement was reached between the USA, UK, and the Soviet Union to ban atmospheric tests. Other nuclear countries later also stopped such tests, even if many did not sign the treaty, except France and China who had a few more test explosions, but finally they too complied in 1974 and 1980 respectively. Nuclear tests continued underground, but this had no impact on atmospheric ^{14}C level.

The result was that the concentration of ^{14}C jumped from the natural level of about 1000 atoms to about 2000 atoms in one quadrillion or 10^{15} of ordinary ^{12}C atoms by 1963, and started to fall back to the natural level, reaching it by approximately mid 1990s. This reduction is shown in Fig.8 in the small graph, along with a set of exponentially decaying functions of the form $e^{(-t/T)}$, with different characteristic time constants T ranging from 1 year to 150 years. It can be seen that the function which fits best the measured ^{14}C concentration data has the value T = 15 years. Note that this reduction rate is the average of a large number of sources and sinks of the atmospheric carbon content, not a single one. Therefore this exponential function accurately represents the natural response of the Earth's carbon cycle system. It is true that certain processes have slightly different absorption rates for ^{14}C and ^{12}C, but the differences are not large and do not modify the effective time constant significantly. Consequently we can take this T = 15 year exponent denominator as a good estimate of the CO_2 residence time.

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It would be also interesting to compare it with other calculated residence times. Since the calculation will be executed by a computer algorithm, it is only a matter of changing the residence time T in the system response $g(t) = e^{-t/T}$ and then compare the various outcomes. So let us take the values proposed by the IPCC of 500, as well as the minimum 130 year, then the same 130 year scenario reduced by 56% as in Hansen's version, the 15 year case, and the 6 year case representing the literature average.

Our input function $f(t)$ will be the sum of all CO_2 emissions in units of Gt/year (as in Fig.4). The time t will be in yearly increments from 1850 to 2018, but in order to compare the results with the actual CO_2 atmospheric content we need to add the starting CO_2 value, which in 1850 was slightly over 2300 Gt, or about 282 ppmv, as measured from the ice core records. The results of the convolution integration for all residence time cases are compared in Fig.10.
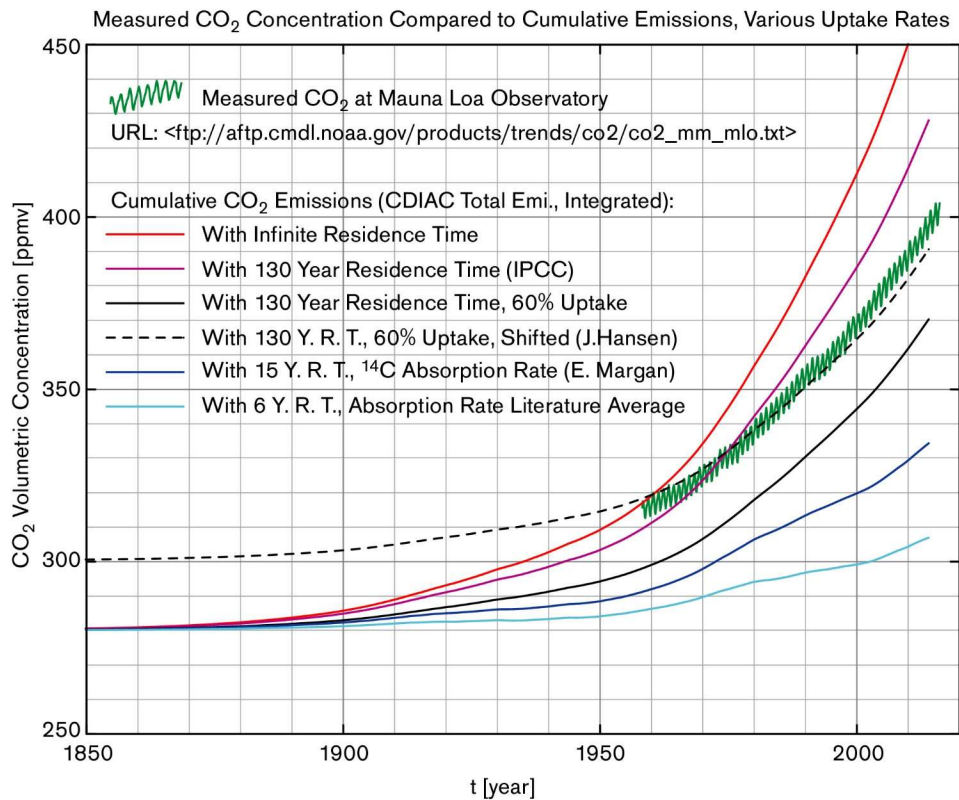

Fig.10: Comparison of the convolution of the sum of all anthropogenic CO_2 emissions for various residence time scenarios with the actual historical CO_2 records. The vertical scales are given in both total atmospheric CO_2 mass in Gt and the concentration in ppmv. Because the residence times proposed by the IPCC (500 and 130 years) result in CO_2 values that exceed the actually measured values by a large amount already after 1950 and 1965 respectively, we can dismiss such scenarios as unrealistic. The result obtained after the proposal by James Hansens (130 years with a 56% natural yearly absorption) fits the measured values well only in a relatively short period between 1960-1980, and only if the starting level of 1850 is increased to slightly above 2400 Gt (about 301 ppmv), which we know was not the case. The results for T=15 and T=6 years, which represent the realistic maximum estimate and the average of measured values given in the literature both indicate that the cumulative part of atmospheric CO_2 attributed to anthropogenic emissions is relatively small, 35% and 15% of the observed CO_2 increase in the period shown.

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Based on the plots in Fig.10 we can dismiss the IPCC scenarios as wrong with high confidence. Likewise, the Hansen's version, which fits the measured data over a limited period of only 20 years, cannot represent the real situation. It might be possible to bend this curve to fit the data over 30 years or so, bu then it would also require a higher initial conditions and would diverge above the current levels (2018). Before 1950 the concentration was increasing much faster than the anthropogenic emissions under any scenario, even with infinite residence time, therefore the increase in this period must be attributed exclusively to natural processes. But for the realistic values of the residence time, the results are low: even for the most conservative value of 15 years, the cumulative value (the blue curve) increase between 1850-2018 went from 285 to 339 ppmv (by 54 ppmv), which is only 45% of the total measured increase in the same period (from 285 to 405 ppmv, or by 120 ppmv). For the average residence time of 6 years of the values reported in literature, the increase is only from 285 to 312 ppmv, or 27 ppmv, which is 22.5% of the total increase. In other words, the current atmospheric CO_2 of anthropogenic origin is only 13%, or 6.7% of the total content, for T=15 years and T=6 years, respectively.

Concluding Remarks

As we have seen in Fig.1, each year about ¼ (or 770 Gt) of the total atmospheric CO_2 content is exchanged with the oceans and the ground. In comparison with this, the yearly anthropogenic emissions represent just 4.3% (33 Gt). On the low anthropogenic part we can also conclude from direct measurements in [8].

We have compared the differential yearly increase of anthropogenic emissions with the yearly measured increase of atmospheric CO_2 concentration, as well as the cumulative (integral) values of those same quantities, and we have demonstrated that there is a gross mismatch with what is claimed by the IPCC. We have thus demonstrated that it is physically impossible that anthropogenic emissions dominantly influence the climate change (what little of it we have seen so far). Given that, it is also unrealistic to expect larger influences in both near and remote future.

Accusing anthropogenic CO_2 emissions of high environmental impact is thus groundless. What action is necessary is to reduce all other byproducts of fossil fuel burning, such as sooth, SO_2, NOx, cyclic aromates, and other highly noxious compounds, but this can be addressed by filters, fuel preconditioning, or other simple methods, and at just a fraction of the cost of current CO_2 reduction attempts. This will be resolved by the technological advancement in the following decade or two.

Regarding the impact on global temperature, if we assume that the rather conservative T=15 years residence time is correct, and by assuming that CO_2 is indeed the cause for the observed temperature increase of about 1°C from 1850 to 2018 (as assumed by the IPCC), we may conclude that by the 13% of current CO_2 content being of anthropogenic origin, we should be responsible for not more than 0.13°C. Note that this is well below the temperature measurement uncertainty interval, which is ±0.25°C.

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Likewise, by assuming that the current rate of CO_2 increase of 2 ppmv/year will continue for the next 80 years (till 2100), the atmospheric concentration will increase by some 160 ppmv, or to 570 ppmv in total. Thus the current concentration (410 ppmv in 2020) will not even double. And as we know, the temperature dependence on CO_2 follows a logarithmic law, so that each doubling in concentration increases the temperature by between 1 and 1.2°C. This means that in year 2100, if everything else remains the same, we should experience a temperature increase of less than 0.5°C. Which means that by taking no action to limit our CO_2 emissions whatsoever, we will still be well within the limits recommended by the Paris Agreement.

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