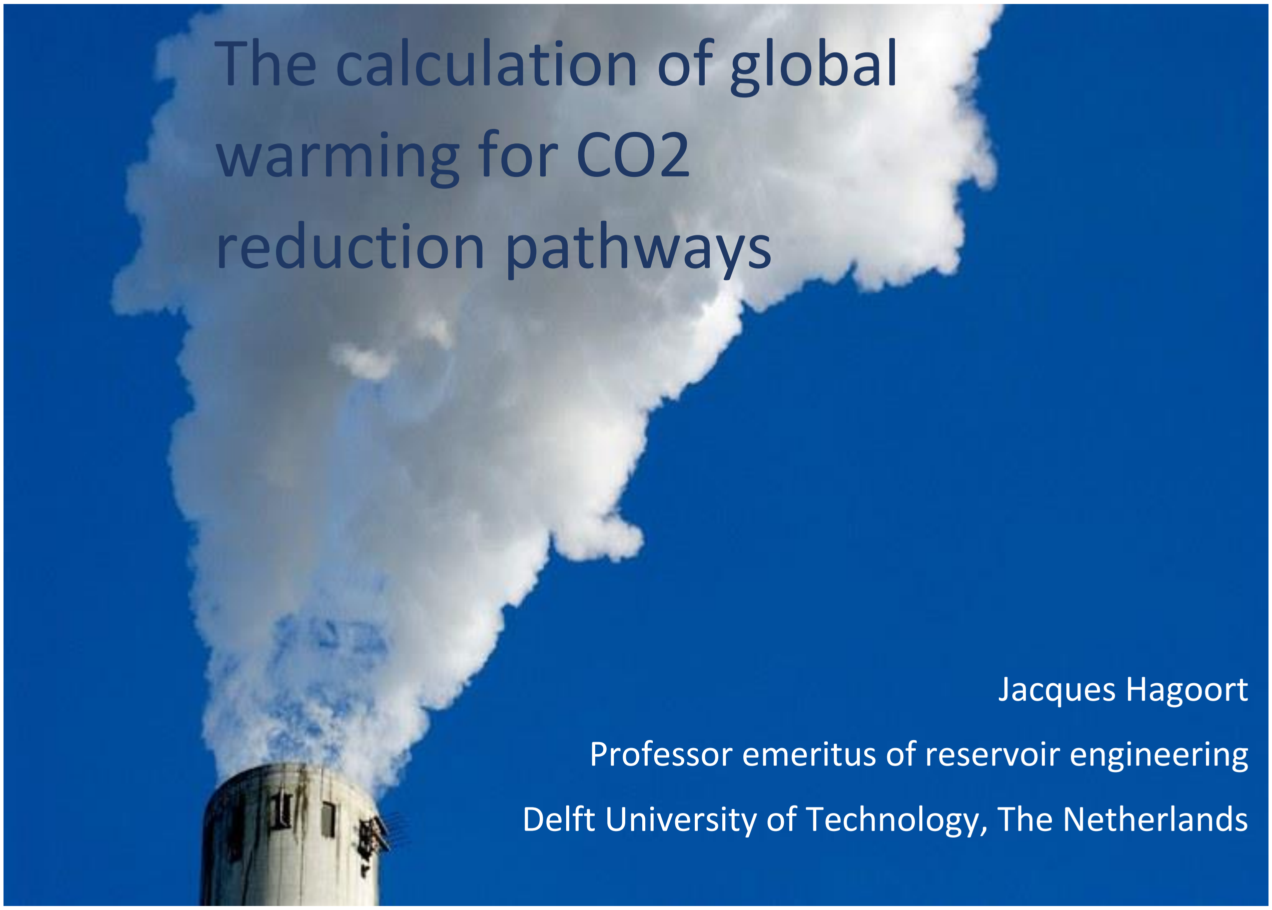


Version 1.0

Released: August 1, 2024

From the preamble of the European Climate Law passed by the European Parliament on July 21, 2021 (emphasis added):

The existential threat posed by climate change requires enhanced ambition and increased climate action by the Union and the Member States. The Union is committed to stepping up efforts to tackle climate change and to delivering on the implementation of the Paris Agreement adopted under the United Nations Framework Convention on Climate Change (the 'Paris Agreement') (4), guided by its principles and ***on the basis of the best available scientific knowledge****, in the context of the long-term temperature goal of the Paris Agreement.*

Contents

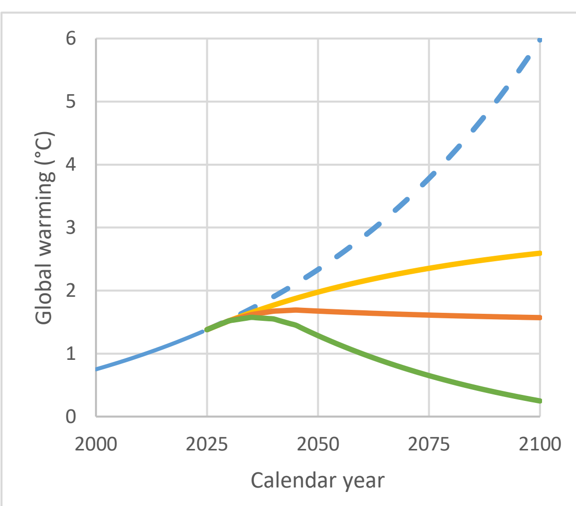
Abstract

To mitigate the negative impacts of global warming, the UN Intergovernmental Panel on Climate Change (IPCC) has called for a reduction of CO2 emissions to *Net Zero* in 2050 and an intermediate reduction in 2030 of 45% relative to the 2010 level. This *Net Zero* pathway is intended to keep global warming limited to 1,5°C compared to the pre-industrial level, in line with the strictest global warming goal in the Paris Climate Agreement from 2015.The IPCC also claims that once net-zero emission has been achieved in 2050, global warming will stay put at 1,5°C forever. *Net Zero* climate policy has now been widely adopted in most rich industrialized countries.

The problem with *Net Zero* is that the underlying science is wrong. The IPCC assumes that past and future global warming depends linearly on cumulative CO2 emission. However, this is an accidental relationship that is approximately true in the past, when emissions were rising exponentially, but it is definitely not valid in the future when emissions will be reduced and perhaps stopped altogether. The linear model is also physically unrealistic as it ignores future natural uptake of CO2 by the biosphere and the oceans and as a result leads to overly restrictive climate goals.

In this report we present an alternative model to calculate global warming for CO2 reduction pathways that is scientifically more robust. The model calculates the CO2 concentration in the atmosphere for a given CO2 emission profile by assuming that CO2 decays exponentially with an empirically calibrated decay time of 55 years. Subsequently, this calculated CO2 concentration is converted to global warming by an empirical correlation derived from observed global warming and observed CO2 concentrations.

Using the alternative model we have calculated future global warming for four scenarios with different future CO2 emission profiles, all starting in 2025. The first scenario represents a 'worst case' in which the emission continues to grow at the historically observed exponential growth rate. The other three scenarios represent CO2 reduction scenarios with an increasing degree of CO2 reduction: (1) continuation of the emission at a constant emission rate of 45 GtCO2/year, (2) linear reduction of the emission rate to a constant rate of 26 GtCO2/year in 2050, and (3) linear reduction of the emission rate to net-zero in 2050 as advocated by the IPCC.



In the 'worst case' scenario (dashed blue) global warming rises to almost 6°C at the end of the century, which clearly illustrates the need for a drastic reduction of CO2 emissions. In the scenario with a constant rate of 45 GtCO2/year from 2025 onwards (gold), global warming increases steadily at decreasing rates and reaches a maximum of about 3°C somewhere in the next century. The scenario for the constant rate of 26 GtCO2/year after 2050 (orange) shows an initially increasing global warming up to a maximum of 1,7°C followed by a slow but steady cooling, down to a little over 1,5°C in 2100. The net-zero scenario (green) shows an initial warming up to a maximum of 1,6°C and a strong cooling thereafter until 0,2°C at the end of the century.

The two most important takeaways from the report are:

- The IPCC advocated net-zero-in-2050 pathway to limit global warming to 1,5°C lacks a sound scientific basis, ignores the natural uptake of CO_2 and as a result is needlessly restrictive.
- The 1,5°C warming goal of the Paris Climate Agreement can be achieved by transitioning from the current emission rate of about 40 $GtCO_2$/year to a constant rate of 26 $GtCO_2$/year in 2050.

1. Introduction

There is little doubt that the global warming since the middle of the last century is largely caused by the anthropogenic emission of greenhouse gases, in particular carbon dioxide (CO_2)[1]. It is also beyond question that unbridled anthropogenic emission will adversely affect the earth's global climate. To mitigate the negative impacts of global warming, emissions of greenhouse gases must therefore be reduced to a safe level or stopped altogether.

The CO2 reduction pathway advanced in 2018 by the Intergovernmental Panel on Climate Change (IPCC), the UN body that periodically assesses the state of the global climate and climate science, calls for a worldwide *Net Zero* emission in 2050 and an intermediate reduction in 2030 of about 45% relative to the emission in 2010.[2] This pathway is intended to keep global warming limited to 1,5°C compared to the pre-industrial level, in line with the strictest global warming goal in the Paris Climate Agreement from 2015.The IPCC also claims that once *Net Zero* has been achieved in 2050, global warming will stay put at 1,5°C forever.

All major rich industrial countries that are part of the G7 have committed themselves to the 1,5°C global warming goal of Paris and to the associated *Net Zero* pathway. The most committed of all is the European Union that in 2019, 4 years after the Paris Agreement, launched the European Green Deal with the promise to become the first climate-neutral continent in the world by 2050. Europe's climate goals were even codified into European law in 2021. Since then the European Union has become the world's most ardent defender of *Net Zero*.

The only problem is that the science that underlies *Net Zero* is highly questionable, if not outright wrong. It assumes that past and future global warming depends linearly on the cumulative emission of CO2 since the beginning of the industrial era. This linear relationship can indeed be observed in the past when emissions were increasing exponentially. In the future, however, when emissions will decrease or stay constant, such a linear relationship will almost certainly not exist.

The assumption that the linear relationship observed in the past will also hold in the future under different conditions is scientifically indefensible and leads to results that are physically highly improbable. Specifically, the linear model ignores the future natural uptake of CO2 by the biosphere and the oceans. As a result, CO2 reduction pathways that are based on the linear model, such as the *Net Zero* pathway, are not only physically unrealistic but, since natural uptake is excluded, also overly restrictive.

In this report we present an alternative model for the calculation of past and future global warming that is scientifically more robust. The model comprises two distinct parts. The first part calculates the CO2 accumulation in the atmosphere as a function of time for a given CO2 emission rate profile. In the second part this CO2 accumulation profile is converted to a global warming profile.

The calculation of the CO2 accumulation assumes that natural uptake is governed by a simple exponential decay equation with a characteristic decay constant that can be derived from the historically observed CO2 concentrations. In the special cases of a constant emission rate and an exponentially increasing emission rate, the CO2 accumulation over time can be expressed in relatively simple analytical formulas. The exponential case is of direct practical relevance as the CO2 emission rates since the beginning of the industrial era have, to a very good approximation, grown exponentially. This historical exponential profile can be extended with a future emission reduction profile by using the superposition principle with the analytical formulas for a constant rate and an exponential rate as basic building blocks.

The second part of the model that translates CO2 accumulation into global warming is based on an empirical correlation between observed global warming and observed CO2 concentration since the middle of the last century. It is thus assumed that the observed global warming can be entirely attributed to the emission of CO2, which overstates the role of CO2. Therefore, the model calculated CO2 reduction pathways err on the safe side.

Just like the linear IPCC model, the new model predicts global warming in the short- and medium-term, say, until the end of this century. This is the time period that is of most interest to policy makers. Global warming in this period is called 'transient', which indicates that there is more warming 'in the pipeline' as it will take many centuries if not millennia for the oceans to reach complete thermal equilibrium. Predictions of global warming on a multi-century or centennial scale are beyond the scope of the report.

The layout of the report is as follows.

In Section 2 we first set out why the linear IPCC model for calculating CO2 reduction pathways is scientifically flawed.

The following Sections 3 – 6 are all devoted to the first part of the alternative model: the calculation of the CO2 accumulation in the atmosphere for given emission rates. In Section 3 we derive analytical formulas for CO2 accumulation for constant and exponentially increasing emission rates. Because historical emission rates have increased exponentially, we discuss this case in more detail in Section 4. Section 5 deals with the calibration of the CO2 decay constant using the historically observed CO2 concentrations. In Section 6 we show how future CO2 reduction pathways can be incorporated by using the superposition principle.

Section 7 is about the second part of the model and describes the empirical correlation between global warming and CO2 concentration that is used to convert the calculated CO2 accumulation in the first part to a final global warming profile.

In Section 8 we apply the alternative model to 4 different future CO2 emission scenarios: a reference scenario with no limit on future CO2 emissions and three different emission reduction scenarios with an increasing degree of reduction.

We conclude by listing the major and minor findings of the report.

---

[1] IPCC, 2014: Climate Change 2014: Synthesis Report. (https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf)

[2] IPCC, 2018*:* Global Warming of 1.5°C (SR15).(https://www.ipcc.ch/sr15/download/)

2. Why the IPCC global warming model is scientifically flawed

The model that the IPCC employs for the prediction of past and future global warming is a simple linear relationship between global warming and cumulative CO2 emission given by

$$\Delta T = a + bE \qquad (1)$$

where ΔT is the global warming relative to the pre-industrial period, E is the cumulative CO2 emission since the beginning of the industrial period and a and b are constants. The constant b is known as the *Transient Climate Response to Cumulative Emission* (TCRE). According to the most recent IPCC assessment report (AR6), the best estimate of the TCRE is 0,000588°C/GtCO2 (Gt = Gigatonnes) with a standard deviation of roughly 25%.[3] Hence, at the current yearly CO2 emission rate of about 40 GtCO2, global warming will increase by 0,24°C/year.

Equation (1) is essentially an empirical correlation based on the results of a large number of computer simulations with advanced, complex climate models of the historical CO2 emissions and of the future for a variety of CO2 emission scenarios. These results showed that global warming with respect to the pre-industrial level is about linearly proportional to cumulative CO2 emission, irrespective of the emission scenario.

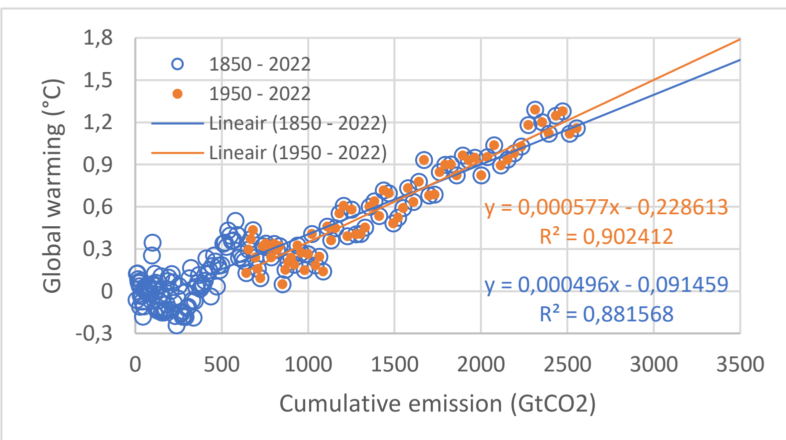


Figure 1 - Global warming versus cumulative CO2 emission

Observed past global warming in the real physical world also confirms this linear trend as shown in Fig. 1. Here we have plotted the global warming with respect to the average warming form 1800 to 1850 versus the cumulative CO2 emission. For the global warming data we have used the HadCRUT5 temperature database compiled and processed by the Hadley Centre of the UK Met Office and the Climate Research Unit at the University of East Anglia.[4] It is the oldest official temperature record for worldwide temperatures and goes back to 1850. Other temperature series show very similar results. We have determined the cumulative CO2 emissions from the CO2 emission database of the Global Carbon Project (GCP), an international consortium of climate scientists.[5] This GCP database goes back to 1750.

The open blue circles represent the data from 1850 up to and including 2022. The orange dots represent a later subset from 1950 to 2022. The straight lines are the best linear fits through the two data sets. The slope of the straight line through the orange dots (0,000577) comes close to the official IPCC slope of 0,000588. If all data since 1850 are included the slope of the straight line is somewhat less steep.

The term *Transient* in the definition of TCRE refers to the short- and medium-term timescale of global warming, the timescale of interest to policy makers, roughly until the end of the century. *Transient* indicates that there is more warming to come ('warming in the pipeline') even after a complete cessation of CO2 emission in the near or more distant future. This is because temperature equilibration of the vast oceans with their huge heat capacities is an extremely slow process that may take centuries to a millennium or more, be it at ever-decreasing rates of equilibration.

A measure for the short- and medium-term climate response to CO2 emission is the *Transient Climate Response* (TCR), defined as the increase in global warming due to a doubling of the CO2 concentration after a period of 70 years with a linearly increasing CO2 concentration of 1% per year. According to the latest AR6 report, TCR ranges from 1,4 to 2,2°C with a central value of 1,8°C. On the other hand, the increase in global temperature due to a doubling of the CO2 concentration on a time scale of several centuries to a millennium or more, denoted by the *Equilibrium Climate Sensitivity* (ECS), ranges from 2,6 to 4,0°C with a central value of 3°C.

The putative universal linear relationship Eqn (1) has spawned the important and widely accepted Carbon Budget concept.[6] A Carbon Budget is the maximum amount of CO2 that can be emitted from a certain date so that global warming stays below a certain level. For instance, '1,5 C' or 'well below 2C', the two global warming goals in the Paris Agreement. According to the AR6 report, the best estimate of the carbon budget per 01-01-2020 for 1,5 and 2°C is 500 and 1350 GtCO2, respectively. The notion of a Carbon Budget implies that to meet the Paris goals, emission rates must go down all the way to zero; no CO2 emission is allowed anymore if the Carbon Budget has been used up.

The Carbon Budget has become a very popular metric in the climate policy community. It is easy to understand (a simple straight line), intuitively appealing (evil things should be rooted out radically), and refers to a common everyday experience (making ends meet). If the Carbon Budget for a selected global warming limit is exceeded, the resulting overshoot of the global warming can be directly estimated from Eqn (1).

Figure 2 shows the IPCC pathway and associated global warming for the 1,5°C global warming limit for an emission scenario in which global warming always stays below the 1,5°C limit (*no overshoot*). This pathway is the basis for the net-zero policies adopted by the major industrial countries of the G7. The vertical axis on the left represents the CO2 emission rate, the vertical axis on the right the global warming. The horizontal axis represents the time in calendar years.

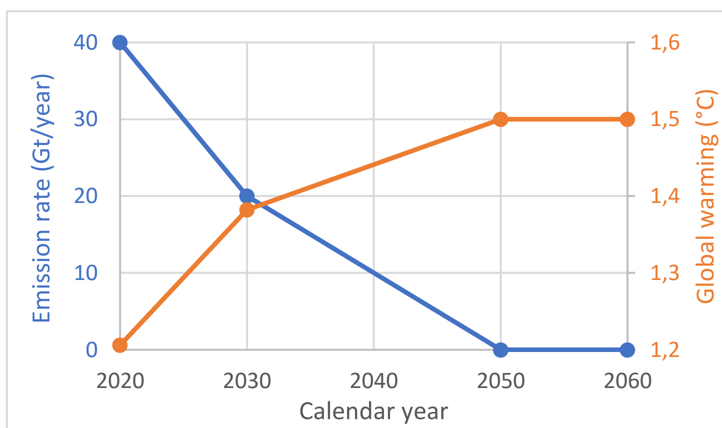


Figure 2 -Emission reduction pathway (blue) and associated global warming (orange) for 1,5C global warming goal without overshoot

The pathway starts in 2020 at a global CO2 emission rate of 40 GtCO2/year and a global warming of 1,2°C and ends in 2050 at a zero emission rate while the global warming has increased to 1,5°C. The emission rate in 2030 is 20 Gt/year, half the initial emission rate at 2020. The total amount of CO2 emitted from 2020 to 2050 equals the Carbon Budget of

500 GtCO2. Global warming increases from the initial level of 1,2°C in 2020 to the final goal of 1,5°C in 2050 and then stays at the 1,5°C level forever.

The problem with the linear relationship Eqn (1) is that it holds good for the past but certainly not for the future. There is no such thing as a universal linear relationship between global warming and cumulative emission. As we shall see in Section 4 under Accumulation versus cumulative emission, Eqn (1) is an accidental relationship that arises from the combination of exponentially increasing CO2 emission rates and an exponential CO2 decay rate. In the future, however, emission rates will no longer increase exponentially but decline or remain constant. Therefore, the observed linear relationship in the past may not be extrapolated into the future and subsequently be used for the calculation of Carbon Budgets and associated CO2 reduction pathways. Carbon Budgets and their CO2 reduction pathways are based on a false linear relationship and are meaningless. Carbon Budgets are also misleading in that they convey the notion of a finite maximum total emission limit to keep global warming in check.

That the linear relationship can't be universally true also follows from a simple thought experiment. Suppose we abruptly stop the emission of CO2. As the cumulative emission does not change anymore, global warming then stays put forever at the level at the time of the emission stop. And so does the CO2 concentration in the atmosphere. This then would spell an abrupt and definite end to the natural uptake of CO2 by the biosphere and the oceans, despite the much higher CO2 concentrations in the atmosphere than the equilibrium concentrations at the beginning of the industrial era. A physical oddity.

The amount of CO2 in the atmosphere is determined by the balance between emission of CO2 and the uptake of CO2 by the biosphere and the oceans. There is no physical reason to assume that natural uptake would stop the moment emission stops. On the contrary, natural uptake of CO2 will continue as long as the concentration in the atmosphere exceeds the equilibrium concentration in the atmosphere before anthropogenic CO2 emission started in the industrial era.

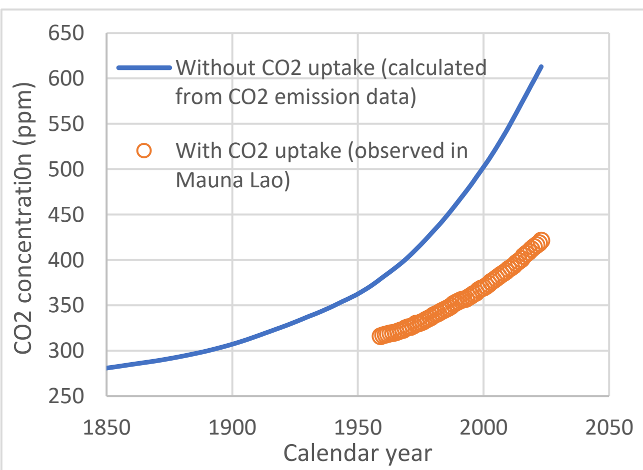


Figure 3 - CO2 concentration in atmosphere without (blue) and with (red) natural CO2 uptake

Natural uptake is not just a minor effect that can be safely ignored. Observed CO2 concentrations have proven unequivocally that natural uptake has a very strong impact on the accumulation of CO2 in the atmosphere. This is illustrated in Fig. 3 that shows the concentration of CO2 in the atmosphere in parts per million (ppm) as a function of time with (orange) and without (blue) natural uptake. The curve with natural uptake is based on the CO2 concentration measurements at the Manau Lao Observatory in Hawaii, which began in 1959.[7] We have calculated the hypothetical CO2 concentrations without natural uptake from the yearly CO2 emission rates taken from the CO2 emission database compiled by the Global Carbon Project, assuming a CO2 concentration before the industrial era of 280 ppm (parts per million). CO2 concentration, denoted by C_{CO2} and expressed in ppm, and cumulative CO2 emission, denoted by E and expressed in GtCO2, are then related by

$$C_{CO2} = 280 + E/CF \qquad (2)$$

where CF (=7,793 GtCO2/ppm) is a conversion factor to convert the CO2 concentration in ppm into a mass of CO2 in GtCO2.

In 2023 the hypothetical CO2 concentration without natural uptake is 613 ppm, whereas the actually observed concentration is 421 ppm. The effect of natural uptake is that less than half of the total emitted CO2 since 1850 has remained in the atmosphere ((421-280)/((613-280) = 0,42). Or, to put it differently, natural uptake has removed almost 60% of the total emitted CO2 since 1850 from the atmosphere, no small matter.

Any model for the calculation of global warming must therefore explicitly include the effect of natural uptake of CO2 by the biosphere and the oceans. If not, they are not fit for the purpose of calculating global warming by CO2 emission or, more specifically, CO2 reduction pathways to mitigate the adverse effects of global warming.

---

[3] IPCC, 2023: AR6 Synthesis Report, Climate Change 2023.(https://www.ipcc.ch/report/ar6/syr/)

[4] HadCRUT5 temperature series, 2024. (https://www.metoffice.gov.uk/hadobs/hadcrut5/)

[5] Global Carbon Project, 2023. (https://www.globalcarbonproject.org/; https://globalcarbonbudget.org/)

[6] IPCC, 2014: Climate Change 2014: AR5 Synthesis Report. (https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf)

[7] Manau Lao Observatory, 2024, (https://gml.noaa.gov/webdata/ccgg/trends/co2/)

3. Calculation of CO2 accumulation in the atmosphere

General accumulation equation

Let us picture the atmosphere as a gigantic reservoir filled with gases, amongst others the greenhouse gas CO2. CO2 is a well-mixed gas which is distributed uniformly in this reservoir. The reservoir has open boundaries and can exchange CO2 with the biosphere and the oceans.

Suppose we emit at time zero a mass pulse of 1 GtCO2 into the reservoir. This pulse instantaneously increases the concentration of CO2 in the atmosphere, denoted by C_{CO2}, to

$$C_{CO2}(t = 0) = C_{init} + 1/CF \quad (3)$$

where C_{init} is the initial CO2 concentration of the atmosphere prior to the pulse in ppm and CF is the conversion factor to convert a CO2 concentration, expressed in ppm, into a mass of CO2, expressed in GtCO2. Ultimately, this extra mass of CO2 above the mass of CO2 that is initially present disappears from the atmosphere because it is taken up by the biosphere and the oceans. Let us assume that at any one time the uptake rate of the emitted CO2 is proportional to the difference between the CO2 concentration at time t and the initial, equilibrium CO2 concentration prior to the emission of the pulse of CO2. Hence the rate at which the extra CO2 in the atmosphere disappears is given by

$$\frac{d(C_{CO2} - C_{init})}{dt} = -\alpha \quad (4)$$

where t is the time and α the proportionality constant. Integration of Eqn (4) from time zero to time t then yields the following function for the decay of the CO2 concentration created by the pulse of CO2 as a function of time

$$\frac{C_{CO2}}{C_{init}} = f(t) = e^{-\alpha t} \quad (5)$$

The function $f(t)$ is called the decay function and α the decay constant. The reciprocal of the decay constant is the decay time denoted by λ. The decay time is equal to the average lifetime or residence time of all the CO2 molecules that make up the emitted pulse of CO2. This can be seen as follows

$$\lambda = \int_0^\infty e^{-\alpha t} dt = \frac{1}{\alpha} \quad (6)$$

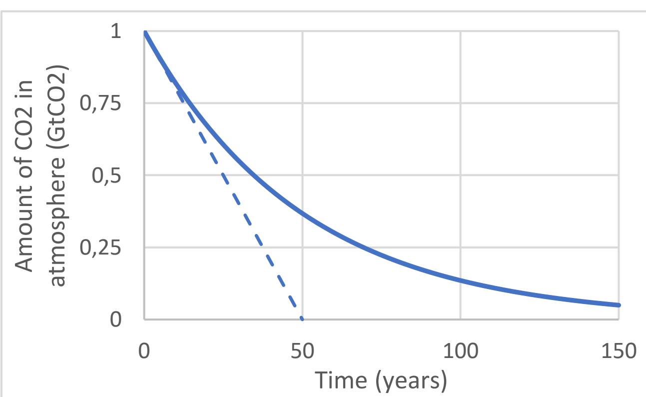
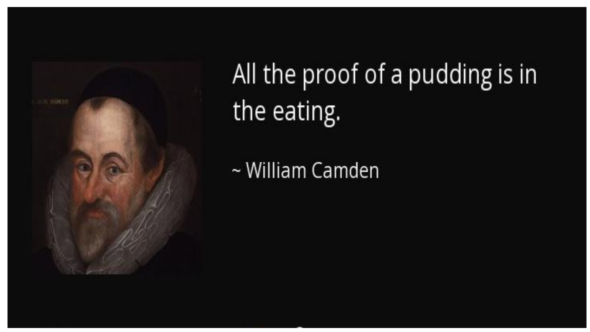


Figure 4 - Exponential decay function for a decay constant of 0,02/year

Figure 4 illustrates the decay function for the emission of a unit pulse of CO2 equal to 1 GtCO2 at time zero and a decay constant of 0,02 and thus an average lifetime of 50 years. The vertical axis represents the extra amount of mass of CO2 in the atmosphere in GtCO2 with respect to the initial amount at time zero and the horizontal axis the time in years. The CO2 in the atmosphere falls of from unity at time zero to zero after an infinite time. The slope of the decay curve at time zero intersects the horizontal axis at 50 years which is equal to the decay time. At this point the fraction of the original unit pulse that is still in the atmosphere is 0,37 (=1/e). At a time equal to twice the average lifetime (100 years) this fraction has reduced to 0,135. At four times the average lifetime there is less than 2 per cent of the original pulse left.

Characterizing the disappearance of CO2 in the atmosphere by a single exponential decay function is not new. Through the years many blog posts have appeared in the serious climate blogosphere on the exponential decay of CO2. As early as 1992 the German control engineer Peter Dietze developed a simple carbon budget model using an exponential decay function with a decay time of 55 years.[8] Since the beginning of this century the Belgium process engineer and frequent blog commenter Ferdinand Engelbeen has argued tirelessly that an exponential decay function with a decay time of about 50 years makes good physical sense.[9] In 2014 the Australian climate blogger and mathematician Nick Stokes showed that the observed constant airborne fraction of CO2 (see Section 4) can be explained by an exponential decay function with a decay time of about 50 years.[10] In 2020 the Dutch physicists Cees le Pair and Ad Huyser showed that the observational CO2 data can be very well described by assuming an exponential decay with a decay time of 53,5 years.[11] In 2022 the US climate blogger Willis Eschenbach wrote a blog article on the Bern model in which he showed an excellent fit of the CO2 concentration measurements for a decay time of about 49 years.[12] Finally, the US climate scientist Roy Spencer observed that nature removes the excess CO2 in the atmosphere at a rate of 2% per year which corresponds to a decay time of 50 years.[13]



Ultimately, the validity of the assumption of an exponential decay will have to be borne out by the observational record: actual and accurate measurements of CO2 concentrations in the atmosphere over a long time period. See Section 5.

Let a real emission rate profile be given by the continuous function $q(t)$, where q denotes emission rate. A continuous rate profile can be approximated by a series of successive pulses of different strengths and all starting at different times. See Fig. 5 where the real profile is depicted in orange and the approximation in blue. The response to this series of pulses at a certain time is the summation of all the individual responses. By letting the width of the individual responses go to zero, the summation changes to a special integral called convolution or Duhamel integral. For the total amount of CO2 that has accumulated in the atmosphere at time t, denoted by $N_{atm}(t)$, we may then write

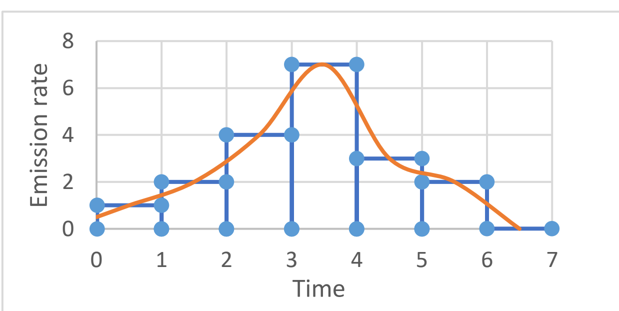


Figure 5- Approximation of a continuous rate profile (orange) by a series of successive discrete emission pulses (blue)

$$N_{atm}(t) = \int_0^t q(\tau)\, f(t-\tau) d\tau = \int_0^t q(\tau)\, e^{-\alpha(t-\tau)} d\tau \qquad (7)$$

where τ denotes the time of the zero-width CO2 pulse that runs from zero to t.

For the special cases of a constant emission rate and an exponential emission rate, Eqn (7) can be solved analytically in closed form.

Constant rate solution

In the case of a constant emission rate, the emission rate function reduces to

$$q(t) = q_c \tag{8}$$

where q_c denotes the constant rate.

The cumulative emission, denoted by E, at time t is then simply given by

$$E(t) = q_c t \tag{9}$$

Inserting Eqn (8) into Eqn (7) yields for the CO2 accumulation

$$N_{atm}(t) = q_c \int_0^t e^{-\alpha(t-\tau)} d\tau = q_c \frac{1-e^{-\alpha t}}{\alpha} \tag{10}$$

At early times Eqn (10) can be approximated by

$$t \ll \frac{1}{\alpha}: \qquad N_{atm}(t) = q_c \frac{1-1+\alpha t}{\alpha} = q_c t \tag{11}$$

At sufficiently long times Eqn (10) reduces to

$$t \gg \frac{1}{\alpha}: \qquad N_{atm}(t) = q_c \frac{1}{\alpha} \tag{12}$$

At early times the accumulation of CO2 in the atmosphere depends linearly on time t as it takes some time before the natural uptake becomes effective. At long times the accumulation approaches a constant value equal to the product of the constant emission rate and the reciprocal decay constant. The emission rate (q_c) is then equal to the natural uptake rate (αN_{atm}) so that the accumulation (or concentration) of CO2 in the atmosphere remains the same. By the same token, the accumulation of CO2 in the atmosphere at long times does not depend on cumulative CO2 emission.

Equation (12) has an important bearing on CO2 mitigation policy. It shows that the concentration of CO2 in the atmosphere can be stabilized by maintaining a constant emission rate. Hence global warming, which is proportional to CO2 concentration, can also be stabilized by keeping emission rates constant. Therefore, to limit the impact of global warming, CO2 emissions need not go all the way to zero as is commonly believed.

Stabilizing the CO2 concentration in the atmosphere by a constant CO2 emission rate has an exact analogue in the world of finance. Suppose we deposit each year a fixed amount into a Piggy Bank. As the deposited money is subject to inflation, the total value of the deposited money does not increase linearly but gradually bends over to a maximum value after an infinitely long time. For a yearly deposit of 100$ and an inflation rate of 2%/year, this maximum value is equal to 5000$, the yearly deposit divided by the yearly inflation rate (100/0,02). At infinity the yearly depreciation of the total deposited money in the bank (0,02x5000) is then exactly compensated by the yearly deposit of 100$. After 100 years the total value of the deposited money in the bank is about 86,5% of the final value.

Exponential rate solution

The emission rate in the case of an exponentially growing emission is mathematically represented by

$$q(t) = be^{\beta t} \tag{13}$$

where b is the initial emission rate at time zero and β the emission growth constant.

The cumulative emission as a function of time follows from integrating Eqn (13) from time zero to time t and is given by

$$E(t) = \int_0^t b\, e^{\beta\tau} d\tau = \frac{b}{\beta}(e^{\beta t} - 1) \tag{14}$$

At sufficiently long times the cumulative emission becomes

$$e^{\beta t} \gg 1: \qquad E(t) = \frac{b}{\beta} e^{\beta t} \tag{15}$$

Hence the cumulative emission after a sufficiently long time grows exponentially with a growth constant of β and an apparent initial growth rate of $\frac{b}{\beta}$.

Substitution of Eqn (13) into Eqn (7) and evaluation of the integral yields

$$N_{atm}(t) = b \int_0^t e^{\beta t}\, e^{-\alpha(t-\tau)} d\tau = \frac{b}{\alpha+\beta}(e^{\beta t} - e^{-\alpha t}) \tag{16}$$

At early times Eqn (16) can be approximated by

$$t \ll \frac{1}{\beta} \text{ and } t \ll \frac{1}{\alpha}: \qquad N_{atm}(t) = \frac{b}{\alpha+\beta}(1 + \beta t - 1 + \alpha t) = bt \tag{17}$$

At sufficiently long times Eqn (16) reduces to

$$e^{\beta t} \gg e^{-\alpha t}: \qquad N_{atm}(t) = \frac{b}{\alpha+\beta} e^{\beta t} \tag{18}$$

At early times the accumulation is equal to the initial emission rate times time t and thus not affected by the emission growth constant and the CO2 decay constant. The CO2 accumulation at long times shows an exponential growth with the same growth rate as the CO2 emission rate but at a reduced apparent initial growth rate of $\frac{b}{\alpha+\beta}$. This reduction is the result of the natural uptake of CO2 by the biosphere and the oceans.

---

[8] Peter Dietze (1999): Carbon Model Calculations (Carbon Model Calculations (john-daly.com))

[9] Ferdinand Engelbeen (2007): Origin of the recent CO2 increase in the atmosphere, section 3 (https://www.ferdinand-engelbeen.be/klimaat/co2_origin.html)

[10] Nick Stokes (2015):Why is cumulative CO2 Airborne Fraction nearly constant? (https://moyhu.blogspot.com/2015/11/why-is-cumulative-co2-airborne-fraction.html)

[11] Cees Le Pair and Ad Huijser (2020): How does CO2 escape? (https://www.clepair.net/oceaanCO2-4.html)

[12] Willis Eschenbach (2022): Feeling the Bern (Feeling The Bern – Watts Up With That?)

[13] Roy Spencer (2023): ENSO Impact on the Declining CO2 Sink Rate (enso-impact-on-the-declining-co2-sink-rate.pdf (opastpublishers.com))

4. CO2 accumulation for exponentially increasing emission rates

The analytical formula for exponentially increasing emission rates (Eqn 16) is of direct relevance to the global warming problem because historical worldwide CO2 emission rates since 1850 have grown exponentially until the present day. See Section 5. The amount of CO2 that has accumulated in the atmosphere since 1850 is thus given by a single mathematical formula. Below we take a closer look at the characteristics of the accumulation of CO2 for exponentially increasing emission rates.

Effect of growth constant β

Figures 6 and 7 illustrate the effect of the growth constant β on the build-up or (build-down) of the CO2 accumulation in the atmosphere for an exponentially growing emission as predicted by Eqn (16). The vertical axis represents the CO2 accumulation expressed in GtCO2 and the horizontal axis represents the time in years from the moment the emission begins. For the CO2 decay constant we have taken 0,02/year, corresponding to a decay time of 50 years (=1/0,02). For the initial emission growth rate we have taken 1 GtCO2/year and for the growth constant of the emission we have taken 0,01, 0,0, -0,2 and -0,4/year. A positive growth constant means emission growth, a negative growth constant means emission decline. A growth constant of zero (orange) represents emission at a constant rate $q_c = b$.

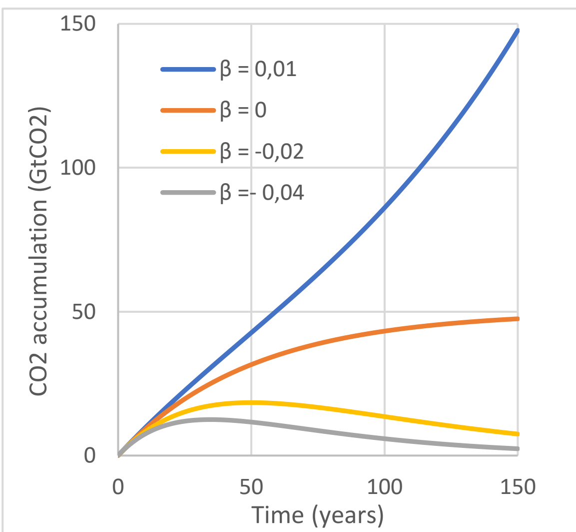


Figure 6 - CO2 accumulation in atmosphere for a CO2 decay time of 50 years and various emmision rate growth constant

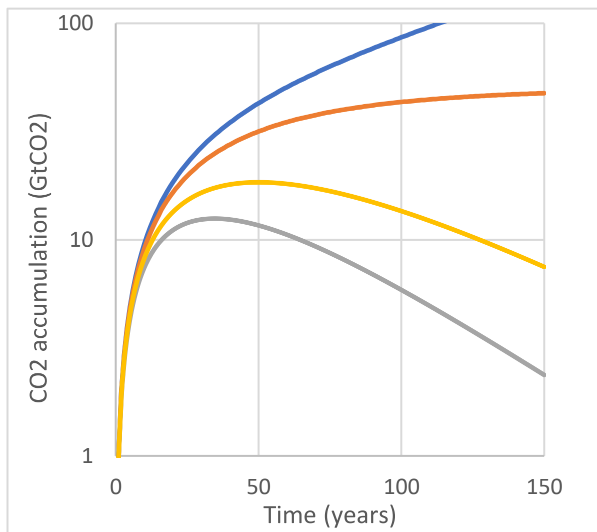


Figure 7 - Same as 2a but now displayed with a logarihmic vertical axis

All curves take off at time zero with a unit slope of 1 GtCO2/year, the yearly emission rate at time zero. The CO2 accumulation for the positive growth rate begins linearly but eventually transitions to an exponential growth with a growth constant equal to the growth constant of the emission rate. The accumulation for a constant emission rate ($\beta = 0$) levels off to 50 GtCO2, equal to the CO2 emission rate (1 GtCO2/year)divided by the decay constant (0,02/year). See Eqn (12).

The curves for the negative growth constant begin with a unit slope, increase to a maximum and then fall off as an exponential decline curve. In the case where the decline equals the decay, the maximum lies at a time equal to the decay time of 50 years. For smaller negative growth constants the maximum moves to the left, for larger negative growth constant it moves to the right.

Accumulation versus cumulative emission

Figures 8 and 9 both display CO2 accumulation and CO2 cumulative emission as a function of time for an exponential emission rate profile in a single graph. The initial growth rate $b = 1$ GtCO2/year, the growth constant β =0,01/year and the decay constant $\alpha = 0{,}02$/year. Figure 9 is the same as Figure 8 except for the vertical axis which is logarithmic.

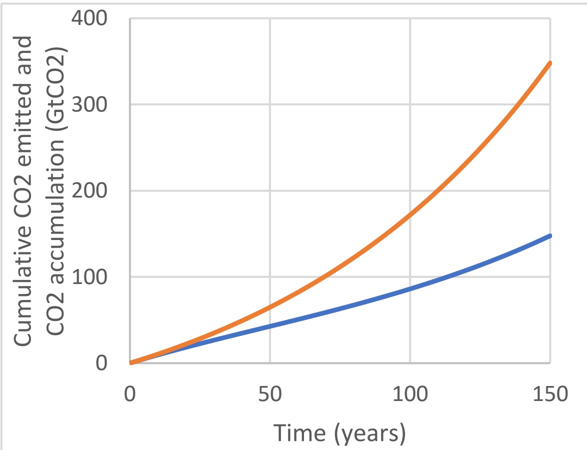


Figure 8 - Cumulative emission of CO2 (orange) and CO2 accumulation in atmosphere (blue)

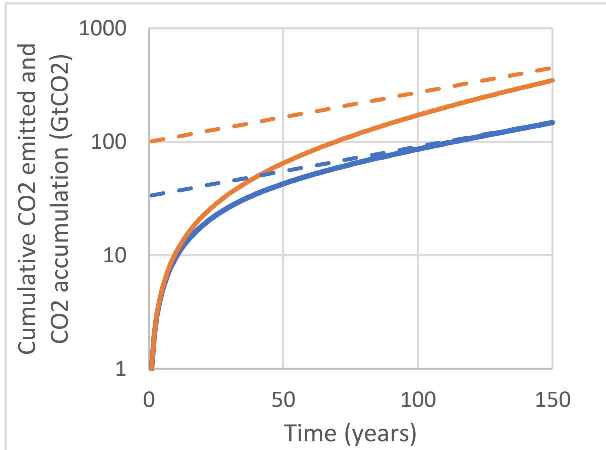


Figure 9 -Same as figure 7 but with logarithmic vertical axis. Dashed lines are the long time asymptotes

Both the cumulative injection and accumulation are continuously increasing. The increasing divergence of the two curves reflects the increasing natural uptake of CO2 for exponentially increasing emission rates. After sufficiently long times both curves approach a constant exponential increase as indicated by the parallel straight lines in the graph with the logarithmic scale. The slope of the two straight lines is equal to the growth constant of the emission rate of 0,01. See Eqns (15) and (18). The level of the accumulation straight line is lower than the emission straight line because of the uptake of the CO2 by the biosphere and the oceans.

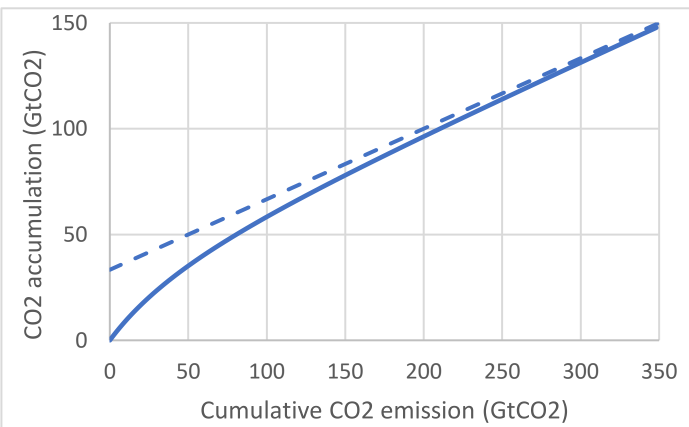


Figure 10 -CO2 accumulation in atmosphere versus cumulative CO2 emission. The dashed straight line is the long-time asymptote

We may also plot CO2 accumulation as a function of cumulative CO2 emission rather than time. See Fig. 10. The curve is slightly concave to the right and approaches a straight line after a sufficiently long time as shown by the dashed blue line. The fact that a straight line emerges after a sufficiently long time can be seen as follows. Using Eqn (14) we can express the exponential growth term $e^{\beta t}$ in the cumulative emission E. That gives $e^{\beta t} = \frac{\beta}{b} E(t) + 1$. Substitution of this growth term into Eqn (16) gives

$$N_{atm}(t) = \frac{b}{\alpha+\beta}\left(\frac{\beta}{b}E(t) + 1 - e^{-\alpha t}\right) = \frac{\beta}{\alpha+\beta}\left(E(t) + \frac{b}{\beta}(1 - e^{-\alpha t})\right) \qquad (19)$$

At long times Eqn (19) becomes

$$e^{-\alpha t} \ll 1: \qquad N_{atm}(E) = \frac{\beta}{\alpha+\beta}E + \frac{b}{\alpha+\beta} \qquad (20)$$

Thus, a linear plot of N_{atm} against E at long times takes on the shape of a straight line with a slope of $\frac{\beta}{\alpha+\beta}$ and an intercept with the N_{atm} axis of $\frac{b}{\alpha+\beta}$. For the parameters used in Fig. 10, the slope is 0,01/(0,02+0,01) = 1/3 and the intercept is 1/(0,02+0,01) = 33,333.

The linear relationship between CO2 accumulation (or CO2 concentration) and cumulative emission explains why observed global warming depends linearly on cumulative CO2 emission (see Section 2). This is because observed global warming is, to a good approximation, linearly proportional to the observed concentration (see Section 7) and thus according to Eqn (20) to the cumulative emission. But this is true only in the special case of exponential emission growth in combination with the exponential decay of CO2 in the atmosphere, and at long times.

Airborne Fraction

The fraction of the yearly emitted CO2 that remains in the atmosphere is known as Airborne Fraction, commonly abbreviated to AF. It is defined as the ratio of the CO2 accumulation rate in the atmosphere ($\frac{dN_{atm}}{dt}$) and the CO2 emission rate q. Using Eqn (16) and Eqn (13) we can write for the airborne fraction AF

$$AF(t) = \frac{dN_{atm}/dt}{q} = \frac{1}{\alpha+\beta}\frac{\beta e^{\beta t}+\alpha e^{-\alpha t}}{e^{\beta t}} \qquad (21)$$

At sufficiently long times, AF approaches the asymptotic value of

$$\beta e^{\beta t} \gg \alpha e^{-\alpha t}: \qquad AF = \frac{\beta}{\alpha+\beta} \qquad (22)$$

This asymptotic value is equal to the slope of the graph of CO2 accumulation versus cumulative CO2 emission at long times. See Fig. 10 and Eqn 20.

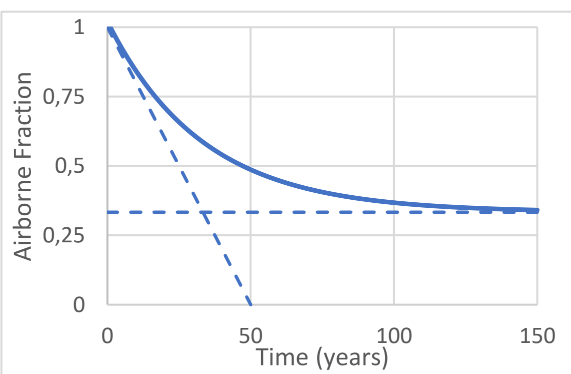


Figure 11 – Airborne Fraction as a function of time

Figure 11 shows the AF as a function of time for the same parameters as used in Fig. 10, viz. b =1 GtCO2/year, β = 0,01/year and α = 0,02/year. At time zero AF equals unity (all emission remains in the atmosphere) and then falls off to the asymptotic value of 1/3 (=0,01/(0,02+0,01). The slope of the curve at time zero is $-\alpha$. Hence for the assumed decay constant of 0,02/year the tangent to the AF curve at time zero intersects the horizontal axis at 50 years (=1/0,02).

The constant AF is not a property of the earth system but the result of the coincidence of an exponentially increasing emission rate and an exponential decay of CO2 in the atmosphere and only after a sufficiently long time. AF is an emergent characteristic of the response of the atmosphere to CO2 emission and depends on the CO2 emission rate profile. In the case of a constant emission rate the CO2 accumulation in the atmosphere approaches a constant value (see Eqn 11) and the AF reduces to zero: all of the emission is then absorbed by the earth system.

In the real physical world, a constant AF of 0,48 has been observed since the CO2 measurements began in Manau Lao in 1959[14]. As we shall see in Section 5, the historical exponential emission growth constant is 0,0165/year and the best estimate of the exponential CO2 decay constant is 0,0182/year. According to Eqn (22) that gives an AF of 0,48 [0,0165/(0,0165+0,0182)], in excellent agreement with the observed AF in ref. 14.

---

[14] Mikkel Bennedsen, Eric Hillebrand, Siem Jan Koopman (2023): A New Approach to the CO2 Airborne Fraction: Enhancing Statistical Precision and Tackling Zero Emissions.(https://doi.org/10.48550/arXiv.2311.01053)

5. Calibration of the CO2 decay constant

The critical parameter in the alternative model is the decay constant α of the emitted CO2. This decay constant can be calibrated by fitting the observed CO2 concentration profile recorded at the Manau Lao Observatory with the model calculated CO2 concentration profile for the recorded CO2 emission history.

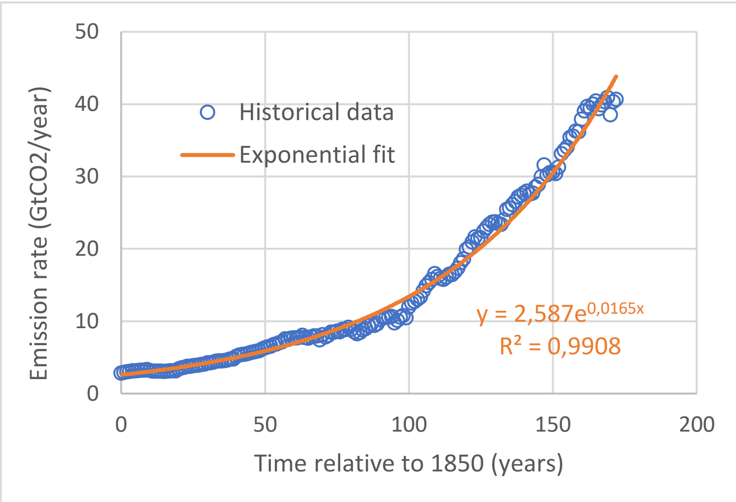


Figure 12- Exponential fit of historical CO2 emission rates

As mentioned before, it so happens that the historical annual CO2 emission rates since 1850 can be very well described by an exponential function as given by Eqn (13). Figure 12 shows the historical yearly emission rates since 1850 as a function of time along with an exponential fit of the yearly emission rates as performed with the Excel spreadsheet program.[15] The source for the historical emission rates is the CO2 emission database compiled by the Global Carbon Project. The CO2 emission rates include CO2 released by the burning of fossil fuels, by cement production and industry, by carbonation of cement and by changes in land use. The goodness of the fit is excellent and yields for the initial rate b = 2,587 GtCO2/year and for the growth constant β =0,0165/year.

The excellent exponential fit means that the CO2 accumulation since 1850 can be calculated by the analytical formula for the CO2 accumulation N_{atm} for exponential emission rates Eqn (16) with b = 2,587 GtCO2/year and β = 0,165 and with α as the only unknown parameter. Given the CO2 accumulation N_{atm} as a function of time t, the CO2 concentration profile then follows from

$$C_{CO2}(t) = N_{atm}(t;\alpha)/CF + C_{init} \qquad (23)$$

where C_{init} is the reference CO2 concentration in ppm in the pre-industrial period and CF the conversion factor to convert ppm to GtCO2. Hence the calculated CO2 concentration profile depends on the two parameters α and C_{init}.

Fitting the observed concentration profile with the calculated profile is essentially a trial and error procedure. It starts with the calculation of the concentration profile for a reasonable first estimate of the two unknown parameters. This calculated profile is then compared with the observed one. Subsequently a new parameter combination is chosen that results in a closer agreement. And so on, until the new combination makes no noticeable difference anymore. As an objective measure of how well the calculated CO2 profile fits the observed CO2 concentration profile we have chosen the average absolute error of the fit denoted by A_e and defined as

$$A_e = \frac{1}{N}\sum_{n=1}^{N} |C_{CO2}^{calc}(t_n;\alpha, C_{init}) - C_{CO2}^{obs}(t_n)| \qquad (24)$$

where N is the total number of yearly CO2 observations since 1959 (=64) and C_{CO2}^{calc} and C_{CO2}^{obs} are the calculated and observed CO2 concentrations at time t_n, repectively. The best fit then is a combination of α and C_{init} that minimizes the absolute error A_e.

We have performed the minimization by means of the Solver add-in program of the Excel spreadsheet.[16] Using Solver one can determine the minimum value of a spreadsheet cell that contains a formula [Eqn (24)] by changing other cells that contain the parameter values of the formula (α and C_{init}).

The results of the minimization are listed in the table on the right. As we can see the absolute error of the best fit is very small indeed, no more than 0,6 ppm. The decay constant α of 0,0182 corresponds to a an average life time of CO2 of almost 55 years (=1/0,0182). The initial CO2 concentration C_{init} of 257,63 ppm is close to the commonly accepted value of 280 ppm derived from ice-core measurements, be it on the low side (-7%). The excellent fit is also clear from Fig. 13 below which shows the observed concentration profile (blue open circles) along with the best fit concentration profile (uninterrupted orange curve).

Results best fit	
α	**0,0182/year**
C_{init}	**257,63 ppm**
A_e	**0,56 ppm**

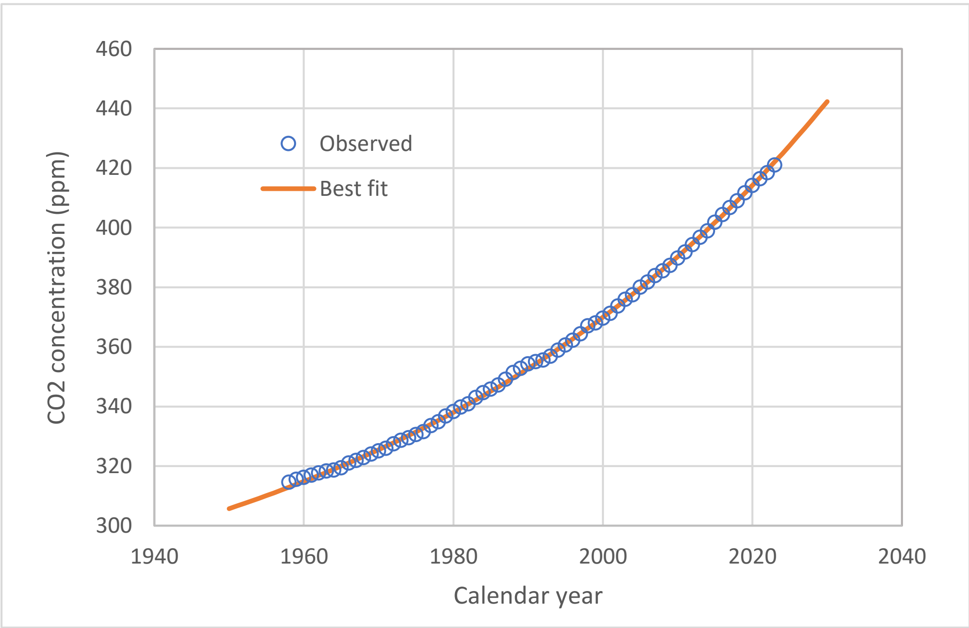


Figure 13- Best fit of observed CO2 concentration profile

The excellent fit demonstrates that the assumption of an exponential decay of CO2 is fully supported by the observational evidence of the last 65 years or so. We are therefore confident that in the near and more distant future uptake of CO2 will also be governed by the same exponential decay as in the past. Of course, past performance is no guarantee for future performance, but so far there is no evidence for a change in uptake behavior.

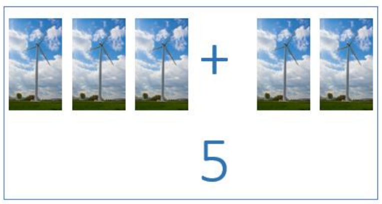
---

[15] Microsoft: https://www.microsoft.com/en-us/microsoft-365/excel

[16] Microsoft, Define and solve a problem by using Solver: https://support.microsoft.com/en-us/office/define-and-solve-a-problem-by-using-solver-5d1a388f-079d-43ac-a7eb-f63e45925040

6. Incorporation of future CO2 reduction pathways

In Section 5 we have shown that the observed CO2 concentration in the atmosphere can be very well reproduced by the analytical function for exponentially increasing emission rates and an exponential decay function for CO2 in the atmosphere. In the future this increasing emission will at some point stop and then decline in accordance with an agreed CO2 reduction pathway. The question then is how the declining emissions can be incorporated in the calculation of future CO2 concentrations. The answer is the *superposition principle,* by which we can extend the historical concentration profile by a future emission profile due to declining emission rates.



The superposition principle states that in linear systems the response of a system subjected to various individual stimuli is equal to the sum of the individual responses to the individual stimuli. Here the stimulus is a CO2 emission rate profile and the response is the CO2 concentration profile. Hence, future CO2 concentration profiles can be constructed by adding concentration profiles of known individual concentration profiles or building blocks. In our case these building blocks are the constant rate solution Eqn (10) and the exponential solution Eqn (16).

Figures 14 and 15 demonstrate how the superposition principle can be applied to an emission scenario where an exponentially increasing emission rate abruptly changes to a constant emission rate. The individual emission rate profiles are depicted in Fig. 14 on the left. It shows an exponential increase from time zero up to a certain time 20 in arbitrary time units (uninterrupted blue). At time 20 the exponential emission continues as before (dashed blue). To cancel this emission we add at time 20 a negative exponential emission profile (dark blue) with the same growth rate and an initial rate equal to the exponential rate at time 20. Finally, we add a constant rate profile that begins at time 20 with a constant rate equal to the exponential rate at time 20.

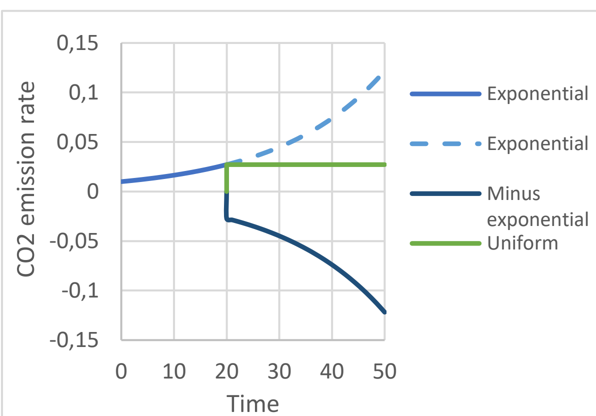


Figure 14 - Superposition scheme for CO2 emission rates

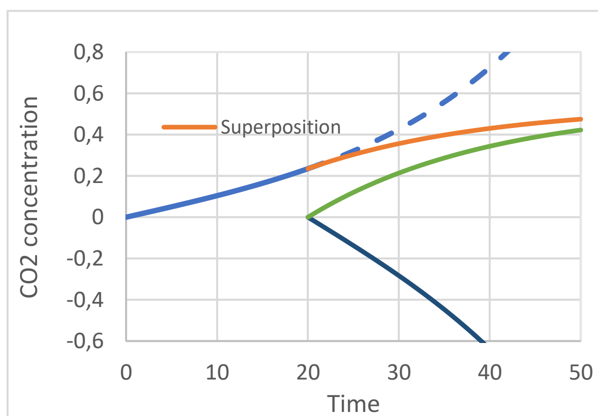


Figure 15 - CO2 concentrations for associated emission rates and final superposition (orange)

The responses to the individual rate profiles are shown in Fig. 15 on the right in the same color scheme. The overall response (orange) is just the sum of the individual responses. As we can see the overall response gradually approaches a constant concentration equal to the constant concentration of the constant rate response.

In some of the CO2 reduction scenarios we have included a period where the emission rate at the end of the exponential increase falls off linearly down to a constant rate. This profile in between the profile for the exponential rate and the constant rate can be approximated by a staircase reduction from the last exponential rate to the final constant rate. The response to the staircase profile is then equal to the summation of a series of constant rate responses each with its own starting time and magnitude of the rate.

Figure 16 schematically illustrates the constant rate profiles staircase approximation in the case the declining profile is approximated by 4 equidistant time steps. The transition profile starts at time 20 at a rate of 50 and ends at time 50 at a rate of 10. The response to this transition profile is then equal to the response of a positive rate starting at time 20 (gold) and 3 negative responses starting at time 30 (orange), 40 (grey) and 50 (green), respectively.

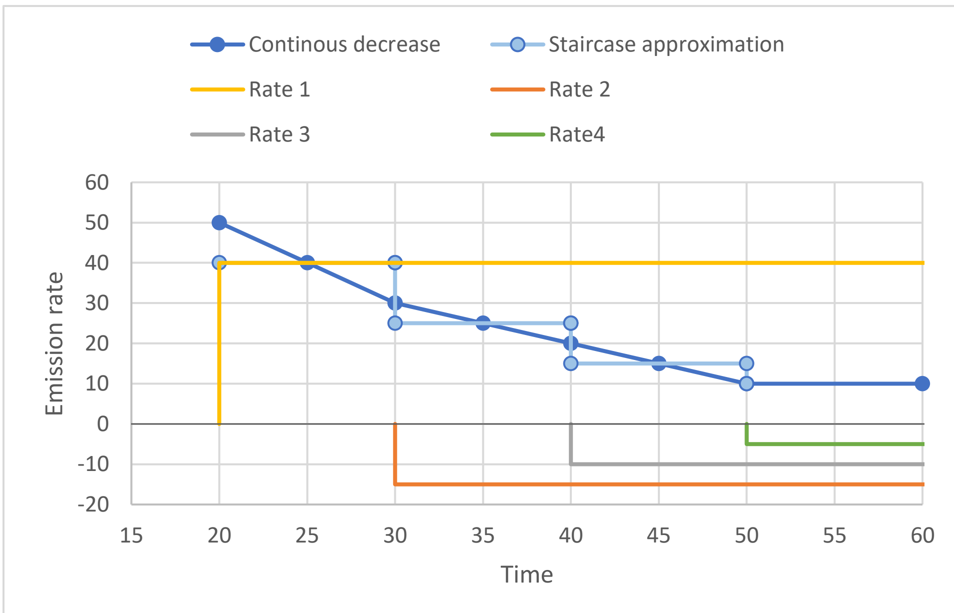
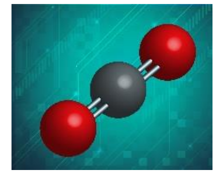


Figure 16 - Staircase approximation of continuously decreasing emission rate profile along with the constant rates

7. Calculation of global warming for a given CO_2 accumulation

The second and final part of the alternative global warming model consists of the calculation of global warming for a given accumulation (or concentration) of CO_2 in the atmosphere. For this calculation we employ an empirical correlation between observed global temperatures and observed global CO_2 concentrations. We thus assume that the observed global warming since the middle of the previous century can be entirely attributed to anthropogenic CO_2 emission. This overstates the role of CO_2 and would lead to CO_2 reduction pathways that are erring on the safe side.



For the global warming data we have used the temperature series of the HadCRUT5 global average temperature database. See Section 2. For the CO_2 concentrations we have used the Manau Lao data set of yearly CO_2 concentrations that we have used before in Sections 2 and 4. The temperature and concentration data set begin in 1959, the year that the CO_2 measurements in Manau Lao began, and end in 2023, covering a period of almost 65 years.

Figure 17 shows the yearly averaged global warming from 1959 up to 2023, relative to the average temperature during the period 1850 – 1900. Hence we assume that this average temperature represents the temperature level of the pre-industrial period. As we can see, the global warming shows a clear upward trend despite a considerable scatter, from about 0,1°C in 1959 up to about 1,2°C in 2023.

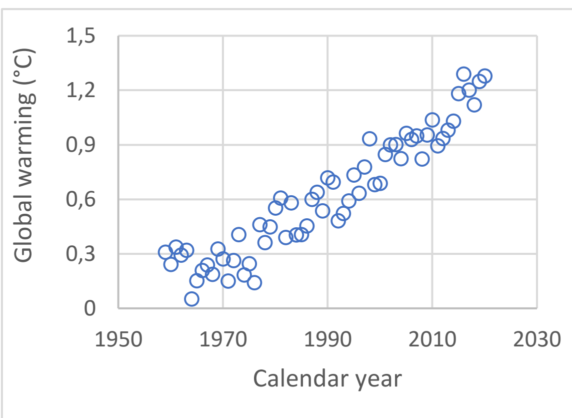


Figure 17-Yearly global warming from 1959 to 2024

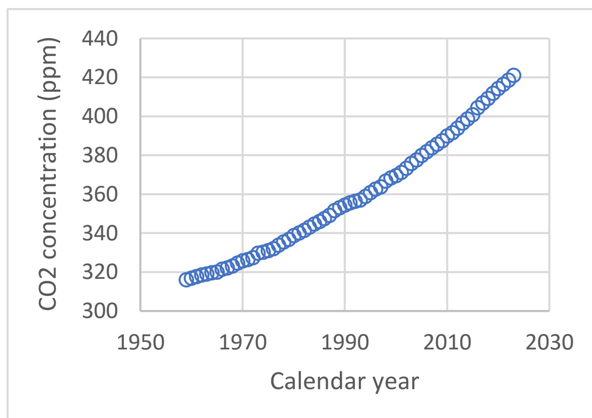


Figure 18 – Yearly CO2 concentrations from 1959 to 2024

Figure 18 shows the yearly averaged CO_2 concentrations in ppm as measured in the Manau Lao Observatory in Hawaii. The concentrations rise steadily from 316 ppm in 1959 to 423 ppm in 2023. The yearly CO_2 concentrations plot on a rather smooth curve that is slightly concave to the left, reflecting the exponentially increasing emission rates.

Figure 19 shows a cross-plot of the global warming and the CO_2 concentration data along with a best linear and logarithmic fit through the data points. A logarithmic relationship reflects the diminishing effect of CO_2 concentrations on the temperature, the so-called saturation effect. The goodness of the best fits as indicated by the R-squared is virtually the same for both the linear and the logarithmic fit. Again, there is a considerable scatter that can be entirely attributed to the global warming data.

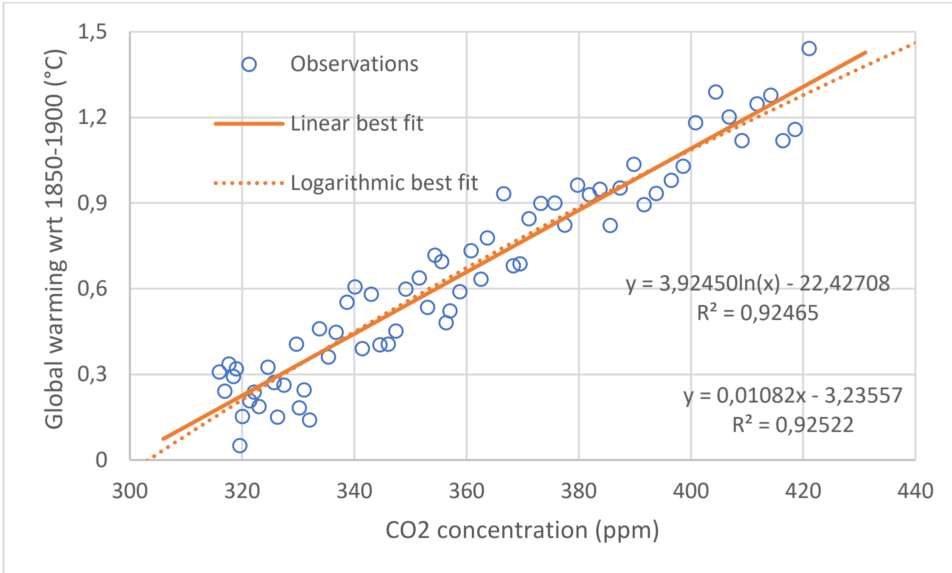


Figure 19 – Linear and logarithmic best fits of cross-plot of observed yearly global warming and observed CO2 concentration since 1959

To convert the model calculated concentrations to global warming we have chosen to use the simpler and more pessimistic (not counting on the favorable CO2 saturation effect) linear fit given by

$$\Delta T = cC_{CO2} + d \qquad (25)$$

where ΔT is the global warming with respect to the period 1850-1900 in °C, C_{CO2} the CO2 concentration in ppm, c = 0,0108°C/ppm and d = -3,2356°C. At 1,5°C global warming, Eqn (25) predicts a CO2 concentration of 438 ppm. Still 17 ppm (438 - 421) to go for the 1,5°C limit.

By using Eqn (25) we thus assume that the correlation also holds good for concentrations outside the cross-plot concentration range from 314 to 421 ppm. This is a fair assumption as the CO2 concentrations of realistic reduction pathways remain close to or within the correlation range as we will see in Section 8. Only for unbridled CO2 emission would the calculated CO2 concentrations and temperatures fall far outside the correlation range.

The logarithmic fit has a slope of 3.95, which corresponds to a climate sensitivity (the increase in global warming due to a doubling of the CO2 concentration) of 2,74 (=3,95xln(2)). This climate sensitivity is only 10% lower than the central value of the Equilibrium Climate Sensitivity (ECS) of 3.0 (see Section 3). This means that the predicted global warming for the short- and medium-term is already within 10% of the prediction for the long-term centennial timescale.

8. Future CO_2 emission scenarios

We have used the alternative global warming model to predict future global warming for four different global CO2 emission scenarios. All scenarios begin in 2025. Up to that time we assume exponentially increasing yearly emission rates from 1850, similar to the historically observed emission rates. In 2024 the emission rate is 45,4 GtCO2/year, the CO2 concentration is 424 ppm and the global warming is 1,35°C. These values are a little higher than expected for 2024, which is due to a slight overestimation of the emission rates in the period from 2020 to 2023. See Fig. 12.

The first scenario may be considered a reference scenario. It assumes that the emission rates continue to grow exponentially at the same growth rate as observed in the past. It is also a 'worst case' scenario with unbridled CO2 emission similar to the IPCC SSP5-8.5 worst case scenario discussed in the last IPCC assessment report AR6.

In the second scenario the exponentially increasing emission rate profile changes abruptly in 2025 to a constant rate of 45,4 GtCO2/year, equal to the emission rate in 2024.

In the third scenario the emission rate is reduced linearly from 45,4 GtCO2/year in 2024 to a constant value of 26 GtCO2/year in 2050. At this constant emission rate the final global warming satisfies the 1,5°C goal of the Paris Climate Agreement. This can be seen as follows. According to the empirical Eqn (25), a warming of 1,5°C corresponds to a CO2 concentration of 437,8 ppm. This concentration corresponds to a CO2 accumulation in the atmosphere of 1404 GtCO2 [(437,8-257,6)x7,79]. The constant emission rate that yields this CO2 accumulation is then equal to 25,55 GtCO2 (0,0182*1404). See Eqn (12) in Section 3.

Finally, the fourth scenario represents *Net Zero*. The emission rate is reduced linearly from 45,4 GtCO2/year in 2025 all the way down to zero in 2050.

The calculation of the global warming for the 'worst case' emission profile is straightforward, it is simply a continuation of the historical response until 2025. It is given by Eqn (16) for an initial emission rate b = 2,587 GtCO2/year, an emission growth constant β = 0,0165/year and a CO2 decay constant α = 0,0182/year.

To calculate the global warming for the other three scenarios, we have used the superposition principle with the exponential and constant rate responses as basic building blocks. See Section 5 for details. We have approximated the linear transition period from 2025 to 2050 in the last two scenarios by a stepwise rate reduction in 5 equidistant steps of 5 year.

The results of the scenario calculations are shown graphically below. Figure 20 on the left displays the emission rate profiles. Figure 21 on the right shows the resulting global warming for the corresponding emission profiles in the same color scheme as Fig. 20.

The 'worst case' scenario (dashed blue curve) is a truly worst case. At the end of the century the warming has risen to 6 degrees. It is another reminder that CO2 emissions must be reduced to a safe level.

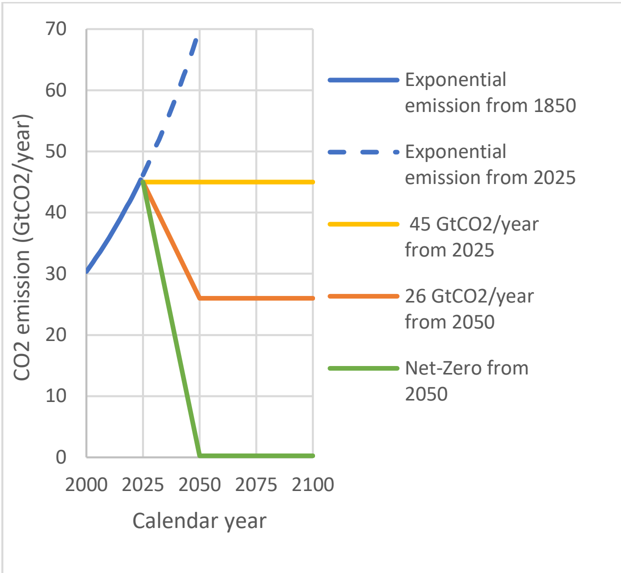


Figure 20 - Emission rate profiles for CO2 emission scenarios

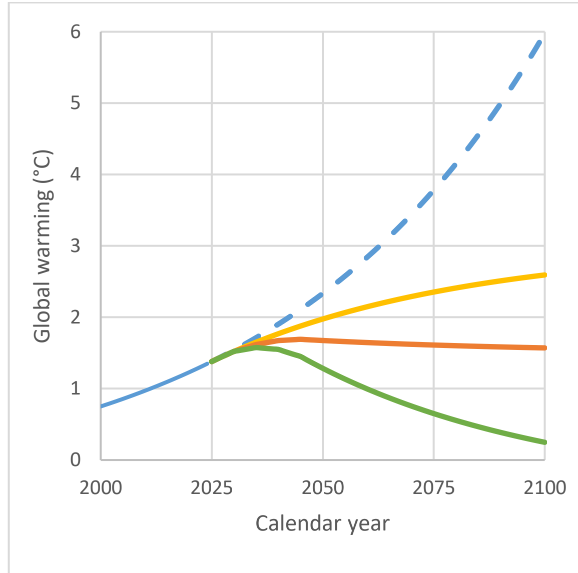


Figure 21 - Global warming for CO2 emission scenarios

As we can see in Fig. 21 it takes a while before the effect of emission reduction can be noticed. In all reduction scenarios the slope of the warming curve in 2025 is about the same and equal to the exponential warming curve. The delayed response is a consequence of the response to the previous exponentially increasing emission rates before 2025 that still make themselves felt after 2025.

Even for the drastic *Net Zero* scenario warming continues to increase after 2025, albeit at decreasing rates. The warming reaches a maximum in 2035 after which a period of steady cooling begins at declining rates. At the end of the century the warming with respect to the pre-industrial period is about 0,2°C, comparable to the warming in the fifties of the previous century. The cooling continues far into the next century until the CO2 concentration in the atmosphere has declined to pre-industrial levels.

The scenario with a constant emission rate of 45 Gt/year (gold) is least affected by the change in emission rate. The warming continues to increase and levels off to almost 3°C somewhere in the middle of the next century. The effect of the previous exponential emissions slowly dies out and is gradually overtaken by the effect of the constant rate emission. At the end of this century the warming is 2,8°C, which is well above the least stringent goal of 'well below 2°C' of the Paris Agreement. It shows that the current emission rates are unquestionably too high and must be reduced to meet the upper limit of the Paris global warming goals.

The global warming in the scenario with a constant yearly rate of 26 GtCO2 after 2050 closely approximates the 1,5 goal. This is no surprise as we have chosen this rate purposely to meet the 1,5 goal of the Paris Agreement. So to meet this goal there is no need for an extreme net-zero scenario. This is also the conclusion the US climate scientist Roy Spencer arrived at in a recent blog article.[17]

The extra warming that is still 'in the pipeline' can be estimated from the IPCC estimates of the transient climate response (TCR) and the equilibrium climate sensitivity (ECS) for the doubling of the CO2 concentration. The central values of TCR and ECS are 1,8 and 3,0°C, respectively. The best logarithmic fit of the empirical global warming correlation used in the model has a slope of 3,95°C (see Fig. 18). This corresponds to a climate sensitivity for a doubling of the CO2 concentration of 2,74°C (=3,95ln(2)), very close to the central ECS value of 3,0°C. As a first estimate of the extra warming after 2100 we may multiply the predicted global warming after 2100 by a factor 1,1 (3/2,74)

In the scenario with a constant yearly rate of 26 GtCO2 the predicted final temperature in 2100 is 1,55°C. The expected global warming on the very long term (multi-century to millennium time scale) is then approximately 1,7°C (1,1x1,55), which is still within the range of the global warming goals of the Paris Climate Agreement.

Finally, the above scenario calculations also clearly demonstrate the incapacity of the IPCC 'universal' linear relationship between global warming and cumulative emission for the prediction of future global warming. Figure 22 shows a plot of the global warming against the cumulative emission for the scenarios discussed above. At the start of the reduction pathways in 2025 the cumulative CO2 emission amounts to 2600 GtCO2 and the global warming is about 1,35°C.

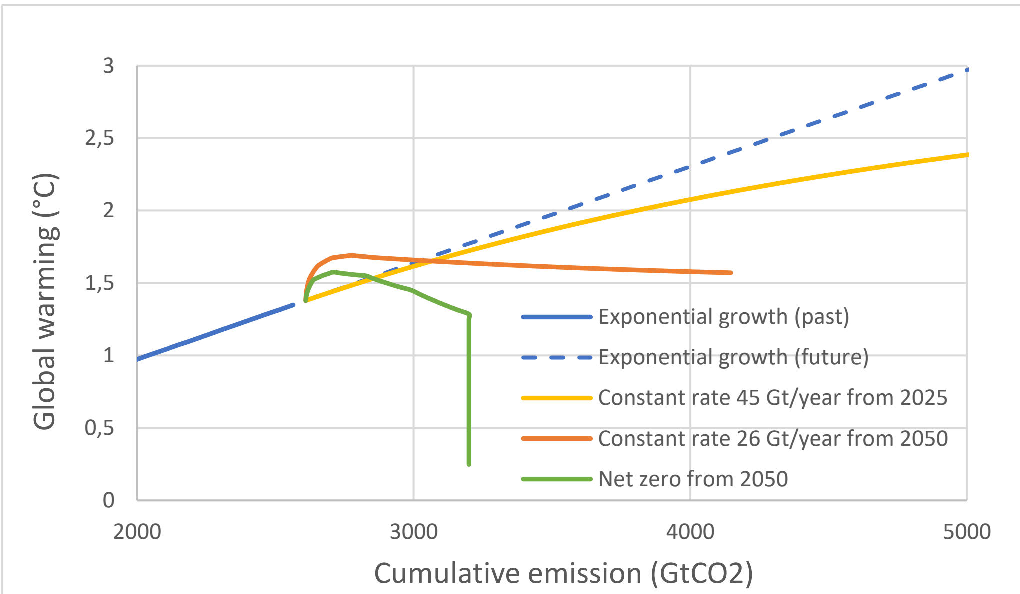


Figure 22 - Global warming vs. cumulative emission for the four future emission scenarios

According to the IPCC the individual scenario graphs should collapse into a single straight line from the beginning to the end. As expected, the reference exponential-growth scenario shows indeed a perfect straight line (see Section 4 under Accumulation versus cumulative emission). However, there is no question of a straight line for the three CO2 reduction scenarios. All three scenarios exhibit their own unique relationship that is dictated by the chosen reduction pathway. This is particularly true for the IPCC advocated net-zero pathway. Here the relationship between global warming and cumulative emission ends up in a vertical line at the net-zero point, reflecting a decreasing global warming while the cumulative emission remains the same.

[17] Roy Spencer (2024): Net zero CO2 emissions, A damaging and totally unnecessary goal (https://www.drroyspencer.com/2024/04/net-zero-co2-emissions-a-damaging-and-totally-unnecessary-goal/)

9. Major and minor findings

Major findings

- The IPCC advocated net-zero-in-2050 pathway to limit global warming to the 1,5°C goal of the Paris Climate Agreement lacks a sound scientific basis, ignores the natural uptake of CO_2 and as a result is needlessly restrictive.
- The 1,5°C warming goal of the Paris Climate Agreement can be achieved by transitioning from the current emission rate of about 40 $GtCO_2$/year to a constant emission rate of 26 $GtCO_2$/year in 2050.

Minor findings

- The linear relationship between observed past global warming and cumulative CO_2 injection is an accidental relationship that has no universal validity.
- The linear relationship holds true in the past when CO_2 emission rates were increasing exponentially but is meaningless in the future when emissions will be reduced or remain constant.
- A Carbon Budget is a meaningless and misleading concept.
- The linear relationship applied to future warming ignores the effect of future natural CO_2 uptake.
- Net-zero pathways are physically unrealistic and needlessly restrictive.
- A forever constant warming level after reaching net-zero as predicted by the linear relationship is a physically oddity.
- The observed CO_2 concentrations in the atmosphere can be accurately reproduced by assuming that CO_2 that is emitted in the atmosphere decays exponentially with a decay time of 55 years.
- CO_2 concentrations in the atmosphere can be stabilized by a constant emission rate.
- Observed global warming and observed CO_2 concentrations are linearly correlated with an R-squared of 0.92.
- An emission scenario with continued emission at the same exponential growth rate as in the past leads to a global warming at the end of the century of 6°C.
- Continued emission at the current constant rate of over 45 $GtCO_2$/year yields a stable global warming of almost 3°C sometime in the next century.
- A transition of the current 45 $GtCO_2$/year to a constant yearly emission rate of 26 $GtCO_2$ in 2050 stabilizes the global warming to 1,55°C at the turn of the century.
- The additional warming due to the thermal equilibration of the oceans will increase the long-term, multi-century warming with a few tenths of a degree.
- A transition to Net Zero emissions in 2050 leads to global cooling, down to 0,2°C in 2100, the same warming as observed in the middle of the last century.

Epilog

This report is intended as scientific underpinning of a series of columns on *Net Zero* that I have recently written for Wynia's Week, a popular and widely read Dutch political internet magazine founded by the Dutch journalist Syp Wynia. In these columns I have challenged the wisdom of the *Net Zero* climate policy, in particular the science behind *Net Zero*, which, I genuinely believe, is deeply flawed.

It behooves a challenger in a scientific debate to put all his cards on the table and, if at all possible, to come up with a more credible alternative. That is exactly what I have done in this report.

First of all, the report pinpoints where the science of *Net Zero* has taken a wrong turn. Condensed into a single sentence: the simple linear model that underlies the net-zero pathway does not exist. In addition, the report presents an alternative, scientifically more robust model to calculate the global warming for given CO2 reduction pathways. The detail of the report is such that all claims, calculations and conclusions can be readily traced, verified and reproduced.

Very little in this report is new or original. All I have done is to shamelessly borrow ideas and insights from professional and amateur climate scientists, climate policy makers, climate blog writers and climate blog commenters, and put these together in, I hope, a coherent technical/scientific report. The only thing I may perhaps take credit for is the method for calculating the efflux of CO2 from the atmospheric reservoir. But even this 'thing' I took straight from the textbooks on reservoir engineering, the engineering discipline I practiced in my professional career before I got interested in climate science and climate policy some 20 years ago.

I sincerely hope that the report will stimulate the discussions at the interface of climate policy and climate science and will contribute to a less ideological and a more rational approach to climate policy '*on the basis of the best available scientific knowledge'***.**

Amsterdam, August 1, 2024.

Illustrations in the report taken from public domain internet sites, Freeimages.com and freepik.com