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# Understanding Increasing Atmospheric CO<sub>2</sub>

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## Abstract

The carbon cycle is of fundamental importance to estimate the influence of anthropogenic emissions on the atmospheric CO<sub>2</sub> concentration, and thus, to classify the impact of these emissions on global warming. Different models have been developed, which under simplified assumptions can well reproduce the observed CO<sub>2</sub> concentration over recent years, but they also lead to contradictory interpretations of the human impact. Here we consider, how far such suppositions are substantiated or must be made responsible for significant misinterpretations. We present detailed own calculations based on the Conservation Law, which reproduce all details of the measured atmospheric CO<sub>2</sub> concentration over the Mauna Loa Era. In particular, they allow to deduce an upper limit of 35% for the anthropogenic contribution to the observed increase of CO<sub>2</sub> over the Mauna Loa Era, and a more likely value of 14%. Under non-equilibrium conditions between the Earth's surface and troposphere this even gives a lower bound of only 3.5%. The importance of only one unitary time scale for the removal of anthropogenic and natural CO<sub>2</sub> emissions from the atmosphere, characterized by an effective absorption time, is discussed.

**Keywords:** Carbon cycle; absorption time; anthropogenic emissions; natural emissions

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## 1. Introduction

In climate sciences too often half-truths and politically driven illusions are spreading around at lightning speed and are presented on social media or blogs as facts. Deviating findings from the mainstream or from the own conviction of bloggers are dismissed as errors or misconceptions without justification. Often this goes along with unqualified or ad hominem attacks.

A Comment (Andrews 2023) on three recently published papers in this journal (Harde & Salby 2021; Berry 2021, Schröder 2022) and in another journal (Skrable et al. 2022a, 2022b), apparently tries to imitate this style of social media by attacking these authors without presenting serious arguments against their findings. Instead, superficial considerations are used to persuade other laymen that only human activities such as burning of fossil fuels have caused the rise of atmospheric CO<sub>2</sub> concentration during the Industrial Era.

The Comment is titled "Clear Thinking about Atmospheric CO<sub>2</sub>", and obviously this means:

- to embezzle any temperature dependent native emissions, although already from paleoclimatic data it is well known that without any human impact the concentration of greenhouse gases in the atmosphere is changing with the surface temperature (e.g., Petit et al. 1999),
- to ignore any actual studies, which clearly show that the partial pressure of dissolved CO<sub>2</sub> in seawater, the respiration of the biosphere, soil emission and thaw of permafrost are significantly controlled by the temperature (e.g., Lloyd & Taylor 1994; Savage & Davidson 2001; Wood et al. 2013; Nottingham et al. 2018; Brechet et al. 2017; Palmer et al. 2019),
- to ignore any volcanic activities, although from global estimate of about one million submarine volcanoes perhaps many thousands of these volcanoes are active (Oregon State University 2023),

- and to consider only anthropogenic emissions, this on the grounds that the observed CO<sub>2</sub> increase is lower than the estimated fossil fuel emissions (FFE) and land use change (LUC), from which *clear thinkers* follow that nature must be a net sink and therefore cannot be responsible for any increasing CO<sub>2</sub> concentration.

Andrews (2023) alleges, all the papers cited above would present misconceptions and "*the errors need to be clearly spelled out in front of those same lay audiences, to ensure that the development of public policy is based on sound science*".

In one aspect Andrews is right: His Comment is only for a lay audience and not for readers of this journal, who are interested in serious science. Referring to a consensus among climate scientists as an argument for the validity of his thinking and the anthropogenic global warming hypothesis, is more than questionable, knowing the fraudulent consensus papers of Cook et al. (2013) and Powell (2016), which are meanwhile refuted (Legates et al. 2013, 2015; Fiedler 2020). Science advances not by consensus but by questioning the established paradigms.

It is not the intention of this contribution to reply to all of Andrews' allegations, who apparently is more interested in provoking and inciting statements than exchanging factual arguments. But we use this occasion, to clarify some main misinterpretations and misleading arguments in connection with the thesis that nature is a net sink. This will be considered in Section 2, and in Section 3 further discussed, how nature responds to emissions. Based on the Conservation Law for atmospheric CO<sub>2</sub>, we study in Section 4 the influence of anthropogenic and natural emissions on the CO<sub>2</sub> concentration in the atmosphere and compare this with observations over the Mauna Loa Era. Particularly the dependence on the absorption processes at the Earth's surface, characterized by the effective absorption time, is investigated. For the anthropogenic contribution to the observed CO<sub>2</sub> increase over the Mauna Loa Era we derive an upper limit of 35%, a lower bound of 3.5% and a more conservative value of 14% in agreement with previous studies (Harde 2017; Harde 2019; Harde & Salby 2021). We conclude with a summary in Section 5.

## 2. Is Nature a Net Sink?

From estimates of the anthropogenic emission rate  $e_A$  (see, Global Carbon Budget - GCB 2022) and the observed increase  $\Delta C_{CO_2}$  of the atmospheric CO<sub>2</sub> concentration  $C_{CO_2}$  per time  $\Delta t$  at Mauna Loa (Carbon Dioxide Information Analysis Center - CDIAC 2022) it is widely inferred that about 44% of these emissions (or an equivalent mass) as so-called Airborne Fraction  $AF$  remains in the atmosphere, while the rest is ostensibly absorbed by extraneous reservoirs (IPCC, Sixth Assessment Report - AR6 2021, Chap. 5, Fig 5.7). But does this also mean that nature cannot additionally contribute to the observed increasing atmospheric CO<sub>2</sub> concentration?

According to the Conservation Law of atmospheric CO<sub>2</sub> any concentration changes are controlled by a competition between the total emission rate  $e_{Tot}$  and its removal through a native absorption rate  $a_N$  (up to now artificial uptake does not make any difference):

$$\frac{dC_{CO_2}}{dt} = e_{Tot} - a_N = e_A + e_N - a_N, \quad (1)$$

with  $e_{Tot}$  as integral of all anthropogenic emissions  $e_A$  and all native emissions  $e_N$ . Under equilibrium conditions with  $dC_{CO_2}/dt = 0$  and with a constant emission rate  $e_{T0}$ , generally of native origin,  $e_{T0} = e_{N0}$ , also a constant absorption rate  $a_{N0}$  is expected:

$$\frac{dC_{CO_2}}{dt} = 0 = e_{T0} - a_{N0} = e_{N0} - a_{N0}. \quad (2)$$

In this context we note that unfortunately some people confuse absorption and emission at the surface with simple mixing of two liquids. CO<sub>2</sub> is mixing in the atmosphere with the other gases but at the surface it is absorbed, partially even changing its compound in seawater or in the

biosphere and is again released decades to thousands of years later, strongly dependent on chemical and biological reactions, which on their part are controlled by temperature and humidity.

With an additional perturbation  $e_P$ , of natural or anthropogenic origin or both, (1) can also be written as:

$$\frac{dC_{CO_2}}{dt} = e_{T0} + e_P - a_N = e_{N0} + e_P - a_{N0} - a_P = e_P - a_P, \quad (3a)$$

or

$$\frac{dC_{CO_2}}{dt} - e_P = e_{N0} - a_N = -a_P. \quad (3b)$$

It is obvious that in a linearly responding system without some virtual amplification the changes  $dC_{CO_2}/dt$  cannot be greater than the perturbation itself, and that these changes are responding with some time delay to the emissions. So, with the left-hand side of (3b) negative, also the right-hand side is negative, and compared to the previous equilibrium the environmental uptake must have increased by an amount  $a_P$ . From this right statement, so-called *clear thinkers* deduce that the environment must have acted as a net sink throughout the Industrial Era, and thus, nature could not have been the reason for any observed CO<sub>2</sub> increase (see also Annotations).

As justification reference is made to the IPCC reports AR5 (2013) and AR6 (2021):

- presupposing steady state conditions before 1750 (in first approximation also before 1850) with a CO<sub>2</sub>-concentration of  $C_{CO_2}(1750) \approx 280$  ppm and with constant natural emission and absorption rates  $e_{N0} = a_{N0}$  of about 93 ppmv/yr (AR5, Chap.6-Fig.6.1),
- also, assuming steady state conditions for natural emissions over the Industrial Era,
- almost exclusively considering a balance for the anthropogenic emissions with a fractional absorption, proportional to the emission rate  $e_A(t)$  with a proportionality factor  $(1-AF)$ , and
- a cumulating contribution in the atmosphere, the airborne fraction  $AF$ , alone responsible for the increasing CO<sub>2</sub>-concentration.

Under such hypotheses, when nature is explicitly excluded as additional emitter, it is clear that it cannot be the reason for any observed CO<sub>2</sub> increase. The Conservation Law then reduces to:

$$\frac{dC_{CO_2}}{dt} = e_A(t) - (1 - AF) \cdot e_A(t) = AF \cdot e_A(t) \quad (4a)$$

with the solution:

$$C_{CO_2}(t) = C_{CO_2}(1750) + AF \cdot \int_{1750}^t e_A(t) \cdot dt. \quad (4b)$$

As already previously demonstrated (Harde 2019), can the annually averaged Mauna Loa series well be reproduced, only considering these anthropogenic emissions  $e_A(t)$  (GCB 2022). Plotted in Fig. 1 is a simulation of the atmospheric CO<sub>2</sub>-concentration for  $AF = 46\%$  (Magenta Diamonds) together with the monthly Mauna Loa measurement (CDIAC 2022, Blue Triangles). Also plotted is  $AF(t)$  over time (Green Squares) as increase  $\Delta C_{CO_2}/\Delta t$  relative to  $e_A(t)$ . The concentration in 1960 was assumed to be 314 ppmv.

Indeed, can this good agreement be seen as confirmation of only human emissions being responsible for the increasing CO<sub>2</sub>-concentration. But a high correlation is no evidence, particularly not, when in advance native sources are excluded and some basic physical principles (see below) are ignored.

Apparently, some experts are not aware that nature is always responding to increased emissions, independent of the *origin*. As long as the perturbation  $e_P$  is larger than the additional uptake  $a_P$ , the concentration is ascending, till a new quasi equilibrium has established. An observed increasing absorption  $a_P$  per se is not equivalent with a net sink. Following the argument of the *clear*

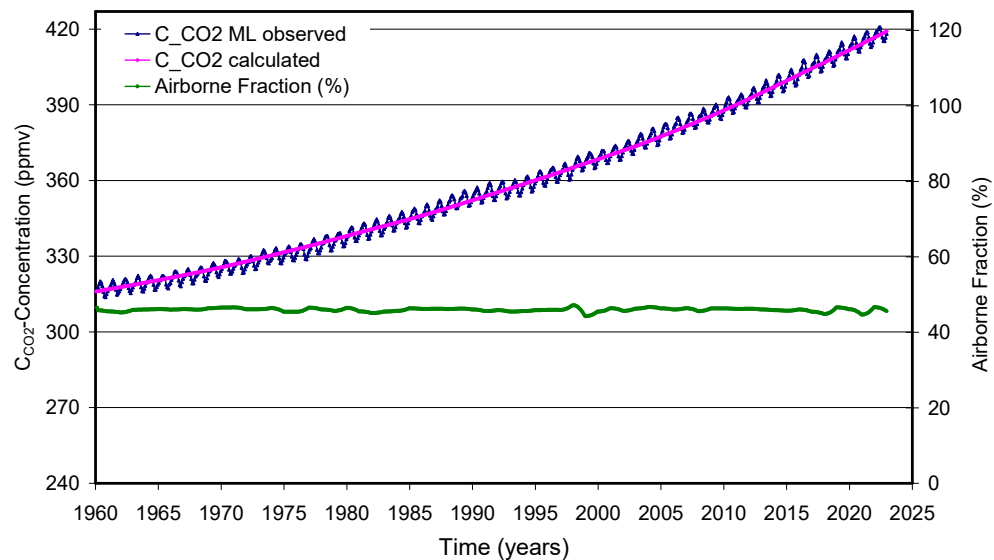


Figure 1: Observed monthly CO<sub>2</sub> concentration at Mauna Loa (Blue Triangles) together with a calculation, only considering anthropogenic emissions  $e_A(t)$  and a concentration  $C_{CO_2}(1960) = 314$  ppmv (Magenta Diamonds). Also plotted is the airborne fraction AF (Green Squares).

*thinkers*, even a net emission caused by a volcanic eruption or an El Niño as pure native events, nevertheless would classify nature as a net sink, since the absorption was increasing.

We have also to remind that emission and absorption are largely independent processes. In tropical areas we find a stronger net emission, in polar regions we have a net absorption, both controlled by the temperature (see, Salby & Harde Part II 2021 and Part III 2022, hereafter SH2 and SH3). Numerical simulations based on the observed tropical temperature reproduce the observed evolution of atmospheric CO<sub>2</sub>, including its annual cycle.

This also follows empirically from the observed covariance and high correlation between tropical temperature and *net* emission of CO<sub>2</sub>, the component of emission that actually changes CO<sub>2</sub>. With a correlation of 0.78 the correspondence holds for interannual fluctuations of net emission, notably during the El Niños of 1973, 1997, and 2016, as well as for its long-term intensification, wherein net emission intensified from  $\sim 0.7$  ppmv/yr to almost 2.5 ppmv/yr (see: SH3, Fig. 8).

The robust coherence between those observed features is also no evidence, but it is in agreement with fundamental physical laws, and this coherence establishes that the changes of tropical temperature do not follow from changes of CO<sub>2</sub>, but rather produce them.

An actual study about freshwater CO<sub>2</sub> emissions (Pollard 2022) confirms our results of stronger natural emissions. From in situ measurements at freshwater lakes and rivers this study found a slightly exponential increase of the emissions with temperature, and even more important, that global freshwater lakes are outgassing CO<sub>2</sub> at a rate of 27.5 ppmv/yr, which is of the same size as the mean seasonal emissions with 27.3 ppmv/yr and five times larger than actual anthropogenic emissions with 5.5 ppmv/yr.

These observations are supported by other authors (Ward et al. 2017; Tanentzap et al. 2019), while the IPCC in its preliminary report (AR6-Chap.5, Figure 5.12) specified a mere 0.14 ppmv/yr. This is 200 times less than the estimates from the in-situ measurements. After all, in the final IPCC report a few months later this value has now been increased by a factor of 5, but is still a factor of 40 lower than the actual measurements.

So, obviously it is too *simple thinking* to infer from an increased absorption, relative to a previous level at lower emission, that nature cannot simultaneously be a stronger emitter. With such theses spreading around the globe, together with catastrophic scenarios, how human emissions would endanger our planet, it is indeed high time, that some *dissenters* try to stop such *confused thinking*.

### 3. Response of Nature to Emissions

A fundamental prerequisite for a consistent description of the emission and absorption processes at the Earth's surface is to rely on well-established physical principles and to integrate them in the Conservation Law. But apparently *clear thinkers* are applying their own principles, which we have to contemplate briefly and to oppose to scientific standards.

#### 1. Absorption Assumed Proportional to Emission

Carbon-cycle models favored by the IPCC rest upon the premise that absorption of anthropogenic CO<sub>2</sub> is proportional, not to its instantaneous abundance, but to its instantaneous emission rate (see eq.(4a) and, e.g., Joos et al., 1996) – irrespective of how much CO<sub>2</sub> is actually in the atmosphere. It is presumed that only some part of the emissions is absorbed, the rest as airborne fraction  $AF$ , remains in the atmosphere. A consequence of this premise is that CO<sub>2</sub> continuously accumulates in the atmosphere almost for ever, regardless of its actual abundance.

How could nature have stabilized to any natural emissions with continuous seasonal cycles or glacial periods over millions of years assuming such an absorption? In the presence of real absorption, such behavior is impossible. For constant emission, CO<sub>2</sub> would eventually reach an equilibrium level, at which it is removed through absorption as fast as it is introduced by emission (Essenhigh 2009; Salby 2016; Harde 2017; Harde 2019; Berry 2019; Harde & Salby 2021; Salby & Harde Part I 2021 (SH1); SH2; SH3; Berry 2021; Schröder 2022). Such equilibrium is only possible with an absorption rate proportional to the instantaneous atmospheric concentration  $C_{CO_2}$ , as this is confirmed by the exponential decay of radioactive carbon after the stop of the bomb tests (Levin et al. 2013, Harde & Salby 2021).

#### 2. Division in Anthropogenic and Natural Parts

Another physical inconsistency of carbon cycle models is its arbitrary division of the carbon budget into a native part, which is presumed to have remained constant before the Industrial Era, and an anthropogenic part, which is presumed to be solely responsible for increasing CO<sub>2</sub> (see above). The two arbitrarily-defined components are presumed to be independent and, somehow, distinguished by separate absorption processes. A consequence of the different treatment of these arbitrarily-defined components is that, when recombined, they no longer satisfy the Equivalence Principle of physics and the Conservation Law of atmospheric CO<sub>2</sub> - physical laws that *are* satisfied by CO<sub>2</sub> in the real atmosphere (Salby 2018; Harde 2019).

A division into a constant natural part and a separate anthropogenic part, the latter alone considered to be responsible for increasing CO<sub>2</sub>, is circular reasoning. Obviously, Andrews (2023) did not read our previous papers, how otherwise can he allege that we would focus on anthropogenic and natural carbon separately.

#### 3. Different Time Scales

Generally different extraneous reservoirs like the oceans, soil or the vegetation are characterized by significantly different absorption rates, distinguished by different absorptivities  $\alpha_i$  or their reciprocals, the absorption times  $\tau_i$ .

Some models (e.g., Bern-Model, Joos et al. 1996) even consider up to five individual time scales with separate absorption and decay processes. They distinguish between a shorter residence or turnover time of about 4 yrs, mainly controlling the pre-industrial carbon cycle, and on the other hand between different adjustment times - one even lasting infinite - for the additional uptake caused by the anthropogenic emissions. These adjustments are considered to work essentially in series, where the final absorption is determined by the slowest process. However, as discussed previously (Harde 2017; Harde 2019; Harde & Salby 2021), the different absorption channels at the Earth's surface operate in parallel. Their collective impact on atmospheric CO<sub>2</sub> is represented in the total absorptivity:

$$\alpha = \alpha_1 + \alpha_2 + \dots + \alpha_k. \quad (5a)$$

Its inverse is the *direct absorption time* of atmospheric CO<sub>2</sub>,  $\tau$ , which characterizes its direct removal from the atmosphere:

$$\tau = \alpha^{-1} = (\alpha_1 + \alpha_2 + \dots + \alpha_k)^{-1} = (1/\tau_1 + 1/\tau_2 + \dots + 1/\tau_k)^{-1}. \quad (5b)$$

Because CO<sub>2</sub> is virtually conserved in the atmosphere, it is produced and destroyed only at the Earth's surface. The direct absorption time of CO<sub>2</sub> is therefore equal to its *residence time*, and different adjustment times, invented by the IPCC, are incongruous with the physics that controls atmospheric CO<sub>2</sub>.

After these annotations on *clear thinking* we derive, based on the physical principles, an absorption rate that is determined by the instantaneous concentration  $C_{CO_2}$  and the direct absorption time  $\tau$ :

$$a_N = \frac{C_{CO_2}}{\tau}. \quad (6)$$

Then the Conservation Law (3a) converts to:

$$\frac{dC_{CO_2}}{dt} = e_{N0} + e_P - \frac{C_{CO_2}}{\tau}. \quad (7)$$

This equation is valid for describing the natural carbon cycle in pre-industrial times in the same way as a cycle with additional human emissions. Common in physical systems, the dependence of CO<sub>2</sub> removal on CO<sub>2</sub> abundance by one unitary absorption time is an empirical feature of atmospheric carbon dioxide. It is documented in the monotonic decline of nuclear-perturbed carbon 14 (Salby 2013). Following the 1963 Limited Test Ban Treaty, <sup>14</sup>CO<sub>2</sub> declined exponentially with a single absorption time of about 10 yrs (Levin et al. 2013; Harde & Salby 2021).

For the further considerations it is helpful to distinguish between a direct absorption, which can take place on a time scale even as short as one year, and on the other hand an effective absorption, which can slow down the observed uptake up to one decade (see also: Annotations as reply to some devious comments of Andrews concerning this effective absorption and the <sup>14</sup>C-decay).

Generally, we distinguish between a constant, primarily native emission term  $e_{N0}$  and the perturbation term  $e_P$ . But in addition or in combination with these emissions some fraction,  $\beta$ , of directly absorbed and already removed CO<sub>2</sub> is returned to the atmosphere through re-emission from the Earth's surface (e.g., via outgassing and decomposition of vegetation). This re-emission can be integrated in the other terms or separately considered as an additional source term in the total balance. It is proportional to the instantaneous direct absorption:

$$e_R = \beta \cdot \frac{C_{CO_2}}{\tau}, \quad (8)$$

and in this way partially compensating direct absorption. This opposing influence gives a net absorption, which operates with an effective absorption time  $\tau_{eff}$  and is slowing down the direct absorption from  $\tau$  to  $\tau_{eff}$ . Particularly for radiocarbon, which due its radioactivity, can separately be traced in observations, it is necessary for the right interpretation of the carbon cycle to distinguish between re-emission from a temporary reservoir (before sequestration or a further dilution takes place) and a constant basic emission rate  $e_{N0}$  from long time storage reservoirs.

This re-emission can well be compared with an induced photonic emission between different excited molecular states, causing transitions and a repopulation between these states, before transitions to a lower state take place and stop this interaction. Such system is generally described by a coupled balance equation system.

With (8) integrated in the total balance, (7) finally becomes:

$$\frac{dC_{CO_2}}{dt} = e_{N_0} + e_P + \beta \frac{C_{CO_2}}{\tau} - \frac{C_{CO_2}}{\tau} = e_{N_0} + e_P - (1 - \beta) \frac{C_{CO_2}}{\tau} \quad (9a)$$

or

$$\frac{dC_{CO_2}}{dt} = e_{N_0} + e_P - \frac{C_{CO_2}}{\tau_{eff}}, \quad (9b)$$

with  $\tau_{eff} = \tau / (1 - \beta)$  and a respectively adapted native emission term  $e_{N_0}$ .

For a constant perturbation  $e_P$ , natural or anthropogenic origin or both, the general solution of (9) is:

$$C_{CO_2}(t) = C_{CO_2}(0) \cdot e^{-t/\tau_{eff}} + (e_{N_0} + e_P) \cdot \tau_{eff} \cdot (1 - e^{-t/\tau_{eff}}), \quad (10)$$

and with  $C_{CO_2}(0) = e_{N_0} \cdot \tau_{eff}$  as the equilibrium concentration at constant emission  $e_{N_0}$ , the excess concentration  $\Delta C_{CO_2}(t) = C_{CO_2}(t) - C_{CO_2}(0)$  becomes

$$\Delta C_{CO_2}(t) = e_P \cdot \tau_{eff} \cdot (1 - e^{-t/\tau_{eff}}). \quad (11)$$

#### 4. Anthropogenic versus Natural Emissions over the Mauna Loa Era

In general  $e_P$  is a function of time and consists of a combination of anthropogenic and native emissions:

$$e_P(t) = e_A(t) + e_S(t) + e_T(\Delta T, t). \quad (12)$$

Anthropogenic emissions  $e_A(t)$  are prescribed from the time-varying record of FFE and LUC (GCB 2022).

The seasonal emissions  $e_S(t)$  can well be represented by (see Harde & Salby 2021):

$$e_S(t) = \frac{e_{S0}}{2} \cdot \{1 + \cos(\omega(t - t_0) + \varphi_e + m \cdot \sin \omega(t - t_0))\}, \quad (13)$$

where  $e_{S0}$  is the amplitude of the seasonal modulation,  $\varphi_e$  is its constant background phase and  $m \cdot \sin \omega(t - t_0)$  a phase modulation term that recovers the asymmetric shape of the observed seasonality.

The temperature dependence of emission is defined to be slightly nonlinear (see, Harde 2019):

$$e_T(\Delta T, t) = \beta_e \cdot \Delta T(t)^{1.35}, \quad (14)$$

with  $\beta_e$  as the coefficient of temperature response. For anomalous temperature,  $\Delta T(t)$ , we rely on the record of annual-mean tropical temperature observed at Hawaii (NOAA 2020), which underwent systematic warming (trend) during the Mauna Loa era of 0.13°C/decade.

We note that the time and temperature dependent net emission as derived from tropical temperatures (see: SH3), including seasonal cycles, is in close agreement with this approach.

Together with the basic emission rate  $e_{N_0}$ , (13) and (14) define the direct native emissions:

$$e_N(t) = e_{N_0} + e_S(t) + e_T(\Delta T, t). \quad (15)$$

Inserting (12) in (9b) the numerical integration then can directly be compared with the observed monthly CO<sub>2</sub>-concentration series at Mauna Loa (CDIAC 2022) (see also Harde & Salby 2021).

##### 4.1 Stepwise Approach to Reality

As already demonstrated in Section 2, can the annually averaged Mauna Loa series well be reproduced, considering only the anthropogenic emissions  $e_A(t)$ . In a first step, again we only regard

FFE and LUC emissions, but now for an absorption rate proportional to the instantaneous concentration and controlled by an effective absorption time  $\tau_{eff} \leq 210$  yrs. Plotted in Fig. 2a is a simulation of the atmospheric CO<sub>2</sub>-concentration for  $e_{N0} = e_{S0} = e_T = 0$  and  $\tau_{eff} = 210$  yrs (Magenta Diamonds) together with the monthly Mauna Loa measurements (Blue Triangles). Larger deviations only become apparent after 2010, which to some smaller part may be explained by the less accurate estimates of LUC. Additionally shown is the airborne fraction  $AF$  as calculated atmospheric CO<sub>2</sub> increase relative to the anthropogenic emissions per year (Green Dots).

Nearly perfect agreement with the general trend of the Mauna Loa measurement is found for a simulation with an effective absorption time  $\tau_{eff} = 50$  yrs (Fig. 2b), again assuming anthropogenic emissions  $e_A(t)$  and  $e_{N0} = e_T = 0$  with a start concentration  $C_{CO_2}(1960) = 314$  ppmv, but an additional seasonal modulation amplitude  $e_{S0} = 7.6$  ppmv/yr (Magenta Diamonds). The  $AF$ -graph (Green) with smaller variations around 45% shows also close coincidence with observations. Different to Fig. 1, this simulation does not differentiate between anthropogenic and natural contributions, and it uses a first order absorption term with one single timescale for all emissions.

The same good agreement can be obtained with an amplitude  $e_{S0} = 0$ , but  $e_{N0} = 5.22$  ppmv/yr, equivalent to an annual mean emission  $\langle e_S(t) \rangle = 5.22$  ppmv/yr at an amplitude  $e_{S0} = 7.6$  ppmv/yr and in its size directly comparable to the anthropogenic fraction with a mean  $\langle e_A(t) \rangle \approx 3.4$  ppmv/yr

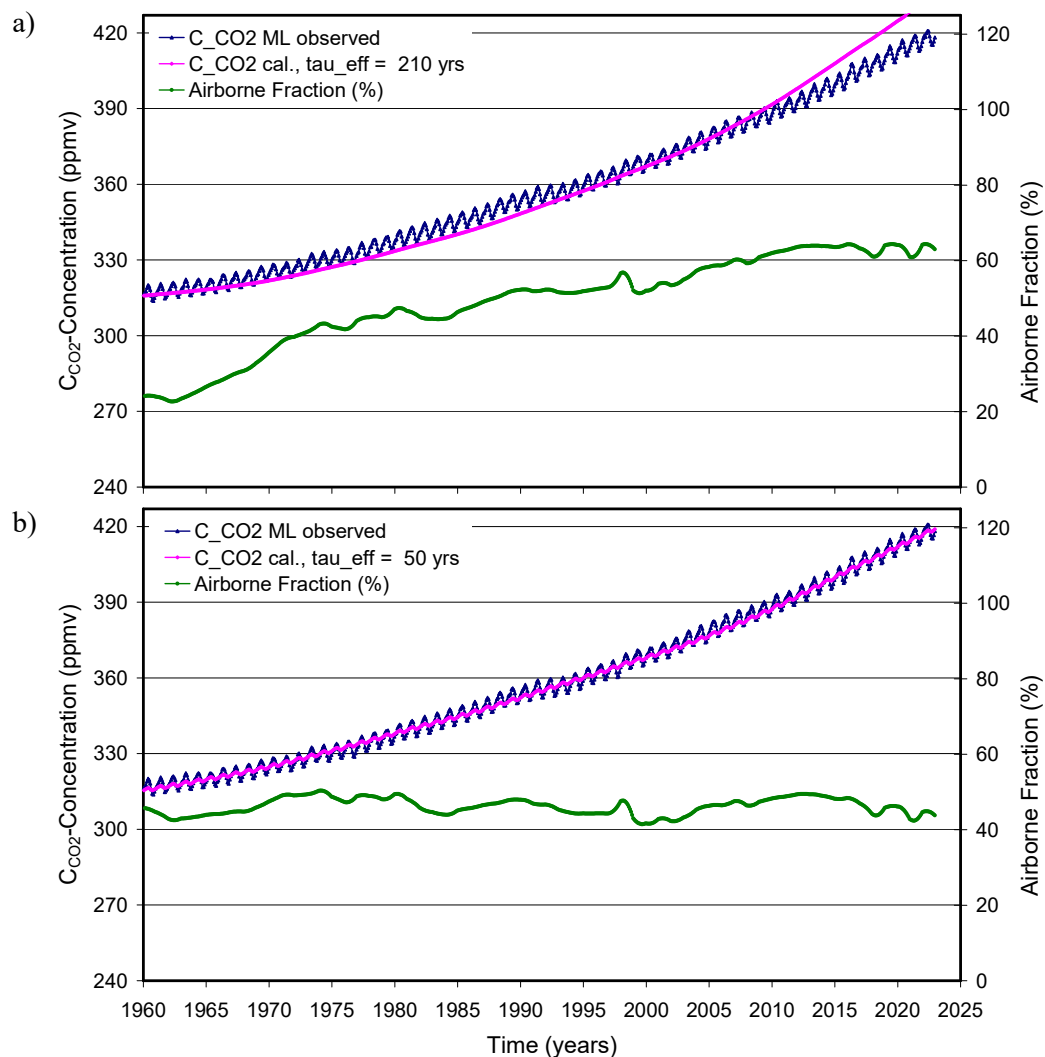


Figure 2: a) Observed monthly CO<sub>2</sub> concentration at Mauna Loa (Blue Triangles) together with a calculation for  $\tau_{eff} = 210$  yrs, only anthropogenic emissions  $e_A(t)$  and a concentration  $C_{CO_2}(1960) = 314$  ppmv (Magenta Diamonds). Also plotted is the airborne fraction (Green Dots). b) Respective calculations for  $\tau_{eff} = 50$  yrs,  $e_A(t)$  and  $e_{S0} = 7.5$  ppmv/yr.



(over the Mauna Loa Era) and an actual emission of  $e_A \approx 5.5$  ppmv/yr. Also, assuming a slightly larger or lower  $\tau_{eff}$  and then a respectively smaller or larger seasonal modulation amplitude or basic emission rate  $e_{N0}$  gives this good agreement.

However, with these emission rates there exists a significant discrepancy to the emission rates specified in (AR6, Fig.5.12). The mean rates of natural and anthropogenic emissions over the period from 2010-2019 are estimated as  $e_{Tot} \approx 226.9$  PgC/yr  $\approx 832.7$  PgCO<sub>2</sub>/yr  $\approx 106.8$  ppmv/yr, while under the conditions of Fig. 2b we obtain not more than  $\langle e_A(t) \rangle \approx 5.2$  ppmv/yr over this period, and together with  $\langle e_S(t) \rangle = 5.2$  ppmv/yr not more than  $\approx 10.4$  ppmv/yr, an order of magnitude less. Accordingly, also the respective residence time of CO<sub>2</sub> in the atmosphere, as derived from AR6, and the effective absorption time from Fig. 2b, differ by about one order of magnitude.

Pragmatically this dilemma is solved in some hybrid models by introducing a two-box model, one for the natural cycle as in pre-industrial times with a residence time of 3 to 4 yrs, and an anthropogenic box with an adjustment time between 50 yrs and more than 100 yrs (e.g.: Siegenthaler & Sarmiento 1993; Dietze 2001; Cawley 2011; Lüdecke & Weiss 2016). At least this results again in different timescales and an effectively separate treatment of natural and anthropogenic emissions in these models (see: Harde 2019, Subsec. 5.1).

And there exist three further significant discrepancies with observations:

- From the exponential decay of radioactive carbon after the stop of the bomb tests in 1963 we know that  $\tau_{eff}$  cannot be larger than 10 yrs (Harde & Salby 2021).
- The monthly Mauna Loa data with the typical seasonal oscillations can only be reproduced with a modulation amplitude  $e_{s0} = 40$  ppmv/yr and an effective absorption time  $\tau_{eff} \leq 11$  yrs (Harde & Salby 2021).
- The strong correlation between CO<sub>2</sub> emissions and temperature changes, as found on shorter and longer time scales, particularly in the tropics, indicates a systematic variation of the atmospheric CO<sub>2</sub> level with temperature (Palmer et al. 2019; SH2 and SH3; Pollard 2022).

#### 4.2 Consistent Replication of Growing Atmospheric CO<sub>2</sub>

A comprehensive analysis and reproduction of the atmospheric CO<sub>2</sub> evolution requires to include these observations and to treat all emissions in a consistent manner.

Plotted in Fig. 3a is the simulated atmospheric CO<sub>2</sub>-concentration over the Mauna Loa Era for an effective absorption time  $\tau_{eff} = 10$  yrs, a constant background emission  $e_{N0} = 3$  ppmv/yr, a seasonal modulation amplitude  $e_{s0} = 40$  ppmv/yr, and a temperature coefficient  $\beta_e = 10.3$  ppmv/yr/°C<sup>1.35</sup> (Magenta Diamonds). It tracks almost exactly the observed evolution of CO<sub>2</sub>, which is superimposed (Blue Triangles). Different to Fig. 2b this calculation reproduces precisely the seasonal oscillations in amplitude and shape, this with a single absorption or residence time, which is controlling the long-time variations in the same way as the seasonal oscillations, and which does not differentiate between human or native emissions. The asymmetric shape of the oscillations is recovered by a phase modulation with a background phase  $\varphi_e = \pi$  and a phase modulation amplitude of  $m = 0.8$ .

Also shown in Fig. 3a is the airborne fraction  $AF(t) = (\Delta C_{CO_2}(t)/\Delta t) : e_A(t)$  as calculated concentration changes per year relative to the published FFE and LUC data (Green Dots), which despite of increasing anthropogenic and native emissions is slightly declining and by far does not reveal any saturation of the sinks; just opposite it indicates a faster growing uptake of the extraneous reservoirs with rising human and natural emissions. As fraction of the concentration changes to the total varying emissions  $(\Delta C_{CO_2}(t)/\Delta t) : (e_A(t) + e_T(t))$ , including the thermal emissions, it even declines to 17.3% in 2022 (not shown).

The fraction of anthropogenic to natural emissions  $ANF (\%) = e_A(t) / e_N(t) \cdot 100$  with  $e_N(t) = e_{N0} + e_S(t) + e_T(t)$ , see (15), directly reflects the human contribution relative to the natural emissions

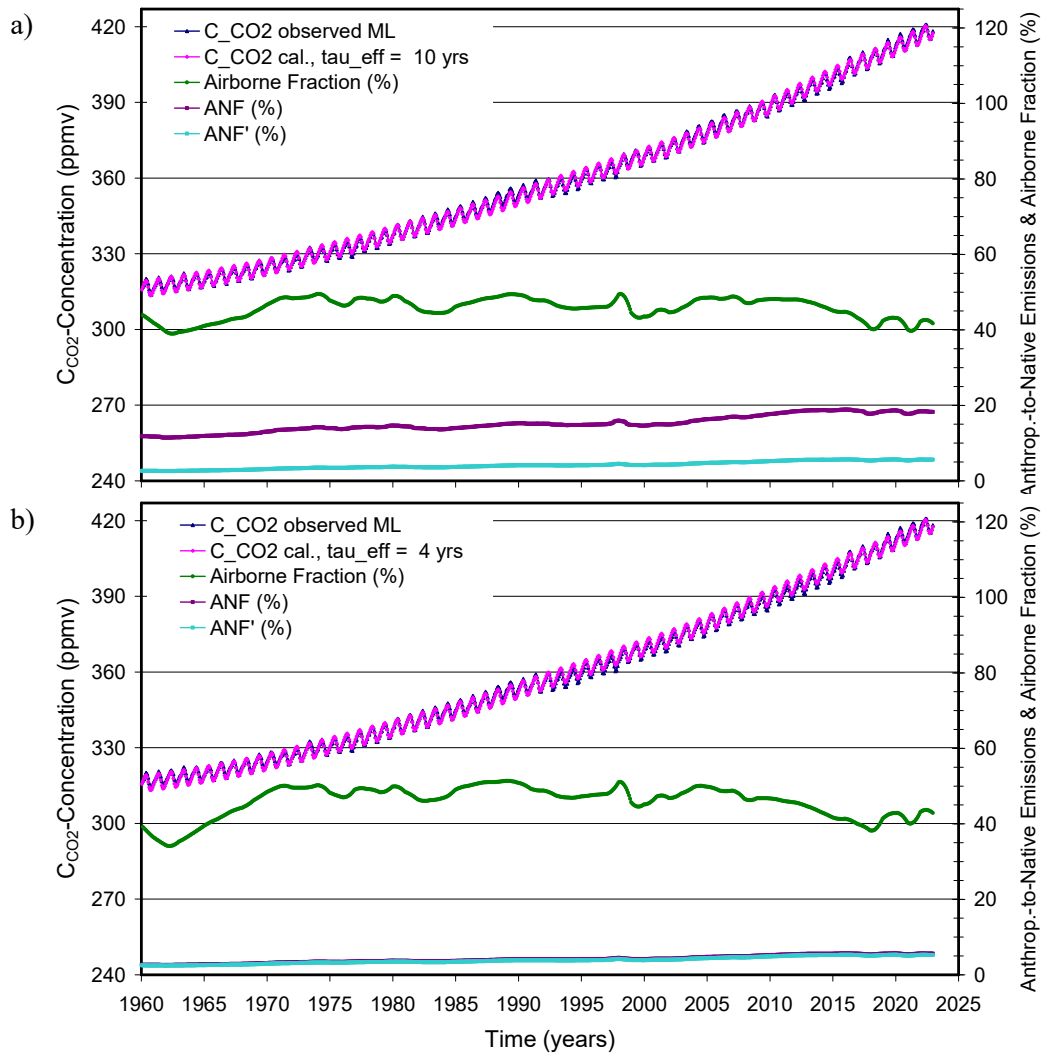


Figure 3: a) Observed monthly CO<sub>2</sub> concentration at Mauna Loa (Blue Triangles) together with a calculation for  $\tau_{\text{eff}} = 10$  yrs with natural and anthropogenic emissions (Magenta Diamonds). Also plotted is the airborne fraction (Green Dots) and the anthropogenic to natural emissions ANF (Violet Squares) and ANF' (Aqua Squares). b) Respective calculations for  $\tau_{\text{eff}} = 4$  yrs.

(Violet Squares). It is slightly increasing over the Mauna Loa Era from 12 to 18%, as the anthropogenic emissions are rising faster than the respective native emissions.

We note that the re-emission of absorbed CO<sub>2</sub>, mostly emitted by natural sources, is implicitly included in the effective absorption time, see (8) and (9). With  $\beta = 0.6$  ( $\tau = 4.0$  yrs) and  $\langle C_{\text{CO}_2} \rangle \approx 400$  ppm over the last decade, mean re-emission is then  $\langle e_R \rangle = \beta \cdot \langle C_{\text{CO}_2} \rangle / \tau = 60$  ppmv/yr.

The seasonal oscillations with its asymmetric form contribute to an annual-mean emission of  $\langle e_S(t) \rangle = 27.3$  ppmv/yr, and the temperature dependence increases emission by 6.9 ppmv/yr, with an average of  $\langle e_T \rangle = 6.8$  ppmv/yr from 2010 - 2019. Collective emission from all natural and anthropogenic sources then even adds up to:  $\langle e_{N0} \rangle + \langle e_S \rangle + \langle e_T \rangle + \langle e_R \rangle + \langle e_A \rangle \cong 3 + 27.3 + 6.8 + 60 + 5.2 \cong 102.3$  ppmv/yr. It corresponds to a total emission of 106.8 ppmv/yr that was estimated by the IPCC (AR6 2021, Fig. 5.12) over the period 2010 - 2019; and in contrast to any temperature and time dependence is the native portion presumed to have been constant.

The respective fraction of anthropogenic to natural emissions  $ANF'(\%) = e_A(t) / \{e_N(t) + e_R(t)\} \cdot 100$ , including re-emissions, is also plotted over the Mauna Loa Era for  $\beta = 0.6$ , respectively  $\tau = 4$  yrs (Aquamarine Squares). It increases monotonically from 2.6 to 5.6%, and the anthropogenic to total emissions as

$$ATF'(\%) = \frac{e_A}{e_A + e_N + e_R} \cdot 100 = \frac{ANF'}{ANF' + 100} \cdot 100 \quad (16)$$

is varying from 2.5 to 5.2%. So, the actual human emissions of  $e_A \approx 5.5$  ppmv/yr contribute less than 6% to the total emissions, and as average over the Mauna Loa Era with  $\langle e_A \rangle = 3.4$  ppmv/yr less than 4%.

The observed evolution of the CO<sub>2</sub>-concentration in Fig. 3a can, within bounds, also be recovered for other values of emission. This is a direct consequence of the local mean of CO<sub>2</sub> being determined by the product of total emission and the absorption time (see Eq. (10)). A change in one can therefore be compensated by a change in the other. However, the observed evolution of CO<sub>2</sub> is recovered only for  $\tau_{eff}$  shorter than 11 yrs, regardless of temperature dependence or seasonal emission, slower absorption ( $\tau_{eff} > 11$  yrs) does not recover the long-term increase and the seasonality of observed CO<sub>2</sub> (see, e.g., Figs 2a and 2b). Such calculations provide an upper bound on the absorption time, independent of but consistent with the value revealed by the decline of anomalous <sup>14</sup>CO<sub>2</sub>. Together, they provide an upper bound on the anthropogenic perturbation of atmospheric CO<sub>2</sub>.

However, absorption can be faster than this limiting absorption. Fig. 3b displays a simulation of the atmospheric CO<sub>2</sub>-concentration for an effective absorption time of  $\tau_{eff} = 4$  yrs, with a larger undisturbed emission rate  $e_{N0} = 50$  ppmv/yr and larger thermal coefficient  $\beta_e = 30.1$  ppmv/yr/°C<sup>1.35</sup>, but an identical seasonal modulation amplitude of  $e_{S0} = 40$  ppmv/yr (Magenta Diamonds). Again, it tracks almost exactly the observed evolution of CO<sub>2</sub> (Blue Triangles). Also, the airborne fraction *AF* (Green) reflects similar behavior as in Fig. 3a. With thermal emissions included it even declines to 8.3% in 2022.

While the average seasonal emissions with  $\langle e_S(t) \rangle = 27.3$  ppmv/yr are the same as in the previous case, is the basic emission rate with  $e_{N0} = 50$  ppmv/yr significantly larger and also the average thermal emission over the period 2010 - 2019 increases to  $\langle e_T \rangle = 20.0$  ppmv/yr. Together this adds up to  $\langle e_{N0} \rangle + \langle e_S \rangle + \langle e_T \rangle + \langle e_A \rangle \cong 50 + 27.3 + 20.0 + 5.2 = 102.5$  ppmv/yr, and is almost identical with the previous simulation for  $\tau_{eff} = 10$  yrs and  $\beta = 0.6$  ( $\tau = 4$  yrs).

Under these conditions the anthropogenic-to-native fractions *ANF* (Violet Squares) and *ANF'* (Aquamarine Squares) coincide, slightly increasing from 2.5 to 5.3% over the Mauna Loa Era.

But it should also be clear that the total emission rate of approximately 107 ppmv/yr, as specified in AR6, is generally the most uncertain parameter of the guessed rates. When the total rate can be assumed to be even larger, the effective and direct absorption times are further reducing, and in the same way is the anthropogenic to natural fraction further declining.

### 4.3 Impact of Anthropogenic Emissions on Atmospheric CO<sub>2</sub>-Concentration

From the Conservation Law (9) or its solution (10) we see that the anthropogenic and natural emissions are adding up linearly to a total rate, and thus, at least under equilibrium conditions also their relative impacts on atmospheric CO<sub>2</sub> will essentially respond linearly to these rates.

*Relative Concentration:* For a constant perturbation  $\bar{e}_P$  the CO<sub>2</sub>-concentration achieves an equilibrium level

$$C_{CO_2}^{eq} = (e_{N0} + \bar{e}_P) \cdot \tau_{eff}, \quad (17a)$$

and with the definitions (12) and (15) for constant rates  $\bar{e}_A$  and  $\bar{e}_N$  this gives:

$$C_{CO_2}^{eq} = C_{A,CO_2}^{eq} + C_{N,CO_2}^{eq} = (\bar{e}_A + \bar{e}_N) \cdot \tau_{eff} = \bar{e}_N \cdot (\bar{e}_A / \bar{e}_N + 1) \cdot \tau_{eff}. \quad (17b)$$

Then, at equilibrium, the relative concentration, caused by anthropogenic emissions to the total concentration, is equivalent to the emission rate  $\bar{e}_A$  relative to the total rate  $\bar{e}_A + \bar{e}_N$ , independent of the absorption time, and in analogy to (16) can be expressed as:

$$\frac{C_{A,CO_2}^{eq}}{C_{CO_2}^{eq}} (\%) = \frac{\bar{e}_A \cdot \tau_{eff}}{(\bar{e}_A + \bar{e}_N) \cdot \tau_{eff}} \cdot 100 = \frac{\bar{e}_A / \bar{e}_N}{\bar{e}_A / \bar{e}_N + 1} \cdot 100 \approx ATF(\%). \quad (17c)$$

In this context we emphasize that the concentrations,  $C_{A,CO_2}$  and  $C_{N,CO_2}$ , represent the respective fractions to the total concentration in mass or mol units per volume, caused by these emissions and their impact on the total balance. This is independent from any dilution or exchange of molecules from anthropogenic emissions by molecules from natural emissions or vice versa. So, when we consider an anthropogenic fraction  $C_{A,CO_2}$  to the CO<sub>2</sub>-concentration in the atmosphere, here and elsewhere, this is the repercussion on the total concentration and has nothing to do with any isofluxes between reservoirs, as considered by Andrews (2023) in his Comment and his analogy in Subsection 3.5.

*Absolute Concentrations:* At equilibrium the absolute contributions to the CO<sub>2</sub>-concentration are determined by the emission rates and the absorption time (see Eq.(17b)). For conditions as assumed in Fig. 3a with  $\tau_{eff} = 10$  yrs we find for constant rates

$$\begin{aligned} \text{in 1960: } & C_{A,CO_2}^{eq} = 19.8 \text{ ppmv}; C_{N,CO_2}^{eq} = 303.4 \text{ ppmv} \Rightarrow C_{CO_2}^{eq} = 323.2 \text{ ppmv}, \\ \text{in 2022: } & C_{A,CO_2}^{eq} = 55.5 \text{ ppmv}; C_{N,CO_2}^{eq} = 384.5 \text{ ppmv} \Rightarrow C_{CO_2}^{eq} = 440.0 \text{ ppmv}. \end{aligned}$$

In 1960 this is 8 ppmv more, and in 2022 about 25 ppmv more than actually observed. These differences represent the additional increase, which still has to be expected till equilibrium has established, i.e., for emissions on the same level as in 2022 the CO<sub>2</sub> concentration will have stabilized within about two decades at 440 ppmv. The calculated temporal increase is plotted in Fig. 4 (Magenta Diamonds) together with the observations (Blue Triangles), the latter till 2022. This calculation differs significantly from the IPCC Representative Concentration Pathways (AR5-Chap6, p.468), prognosticating a further strong CO<sub>2</sub> and temperature increase even for constant future emission rates.

For Fig. 3b with  $\tau_{eff} = 4$  yrs we get:

$$\begin{aligned} \text{in 1960: } & C_{A,CO_2}^{eq} = 7.9 \text{ ppmv}; C_{N,CO_2}^{eq} = 309.4 \text{ ppmv} \Rightarrow C_{CO_2}^{eq} = 317.3 \text{ ppmv}, \\ \text{in 2022: } & C_{A,CO_2}^{eq} = 22.2 \text{ ppmv}; C_{N,CO_2}^{eq} = 403.1 \text{ ppmv} \Rightarrow C_{CO_2}^{eq} = 425.3 \text{ ppmv}, \end{aligned}$$

which is 2 ppmv more in 1960 and 10 ppmv more in 2022 than observed. In this case, with emission rates like 2022, the total CO<sub>2</sub>-concentration will have stabilized within one decade at about 425 ppmv (Green Crosses).

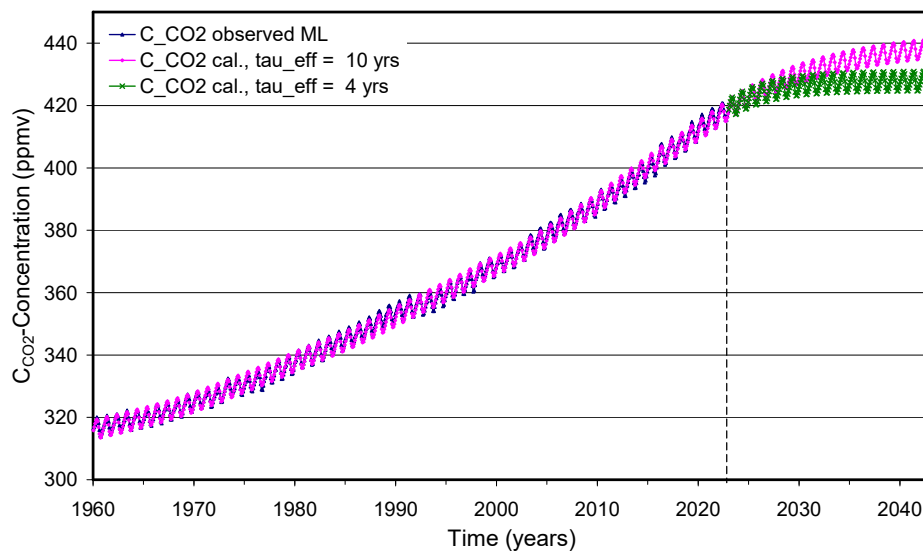


Figure 4: Observed CO<sub>2</sub> concentration at Mauna Loa (Blue Triangles) together with a calculation for  $\tau_{eff} = 10$  yrs at constant anthropogenic and thermal emissions after 2022 (Magenta Diamonds) and respective calculation for  $\tau_{eff} = 4$  yrs (Green Crosses).

Due to the larger absorption time in Fig. 3a also the deviations to the observed concentrations are larger. Nevertheless, give these calculations already a good estimation for the absolute and relative fraction of anthropogenic emissions. So, for the limiting case with an effective absorption time of  $\tau_{eff} = 10$  yrs, in 1960 the anthropogenic fraction to the total concentration was 6.2% or 19.8 ppmv and in 2022 it doubled to 12.6% or 55.5 ppmv.

With an absorption time  $\tau_{eff} = 4$  yrs this further reduces to 2.5% or 7.9 ppmv in 1960 and to 5.2% or 22.2 ppmv in 2022 and is already well represented by the anthropogenic to natural emission fraction  $ANF = ANF'$  in Fig. 3b. For still shorter absorption times (see SH3 and Subsec. 4.3.2) this further drops to about 2%.

#### 4.4 Anthropogenic and Natural Contribution to Atmospheric CO<sub>2</sub> Increase

An analysis considering the dynamic evolution of atmospheric CO<sub>2</sub>, before equilibrium can be established, requires a direct comparison of simulations with and without anthropogenic emissions. This is plotted in Fig. 5a for  $\tau_{eff} = 10$  yrs. The calculation with FFE+LUC emissions included (Magenta Diamonds) is identical with Fig. 3a. It exactly traces the Mauna Loa measurement (Blue Triangles). Additionally plotted is the calculation without anthropogenic emissions (Green Dots), representing the fraction  $C_{N,CO_2}$  caused only by natural emissions (left axis). The difference of both calculations is the CO<sub>2</sub> increase  $C_{A,CO_2}$  (Aquamarine Triangles, right axis) caused by the additional anthropogenic emissions (Violet Squares) to the atmosphere.  $C_{A,CO_2}$  continually increases from 14.1 ppmv to 49.8 ppmv and is in 2022 still 6 ppmv smaller than the equilibrium case.

The difference  $\Delta C_{A,CO_2} = C_{A,CO_2}(2022) - C_{A,CO_2}(1960) = 35.7$  ppmv can directly be compared with the growth of the total concentration over this period:  $\Delta C_{CO_2} = C_{CO_2}(2022) - C_{CO_2}(1960) = 417.1 - 315.6 = 101.5$  ppmv. The ratio  $\Delta C_{A,CO_2} / \Delta C_{CO_2}$  then represents the relative anthropogenic fraction to the observed CO<sub>2</sub> increase over the Mauna Loa Era with:

$$\Delta F_A = \frac{\Delta C_{A,CO_2}}{\Delta C_{CO_2}} \cdot 100 = \frac{C_{A,CO_2}(2022) - C_{A,CO_2}(1960)}{C_{CO_2}(2022) - C_{CO_2}(1960)} \cdot 100 = 35 \% . \quad (18)$$

This is in full agreement with our previous estimate for an upper limit of the anthropogenic fraction to the increase (Harde & Salby 2021, eq. (18) and Appendix).

The respective plots for an effective absorption time  $\tau_{eff} = 4$  yrs are displayed in Fig. 5b and can again be compared with the Mauna Loa measurement (Blue Triangles). The calculations for the CO<sub>2</sub>-concentrations with anthropogenic emissions (Magenta Diamonds) and without these emissions (Green Dots) move closer together, and the difference  $C_{A,CO_2}$  as anthropogenic fraction shrinks to 7.0 ppmv in 1960 and to 21.5 ppmv in 2022 (note the increased scale versus Fig. 5a).

$C_{A,CO_2}$  follows closely the anthropogenic emission rate (Violet Squares). With a difference  $\Delta C_{A,CO_2} = 14.5$  ppmv now the respective anthropogenic fraction, causing the CO<sub>2</sub> growth over the Mauna Loa Era, reduces to  $\Delta F_A = 14.3\%$ .

Comparison of Figs 5a and 5b illustrates, how the anthropogenic emissions contribute to the atmospheric CO<sub>2</sub>-concentration and how this increase is controlled by the effective absorption time. While Fig. 5a displays the limiting case with  $\tau_{eff} = 10$  yrs, and thus, a maximum anthropogenic fraction to the CO<sub>2</sub> incline of  $\Delta F_A = 35\%$ , from the total budget of natural and anthropogenic emissions and absorptions, as compiled in AR6, Fig. 5.12, the residence time of atmospheric CO<sub>2</sub> can be estimated between 3 and 4 yrs (Harde 2017). Therefore, we expect that the simulation in Fig. 5b with a common absorption time  $\tau_{eff} = 4$  yrs for natural and anthropogenic emissions, and  $\Delta F_A = 14\%$ , provides quite realistic conditions of effective absorption.

The preceding considerations are intended to make clear that obviously it is too simple thinking to surmise from an atmospheric CO<sub>2</sub> growth, which is smaller than the anthropogenic emission rates, that nature is not contributing to any increase. Although in both examples, for  $\tau_{eff} = 10$  yrs

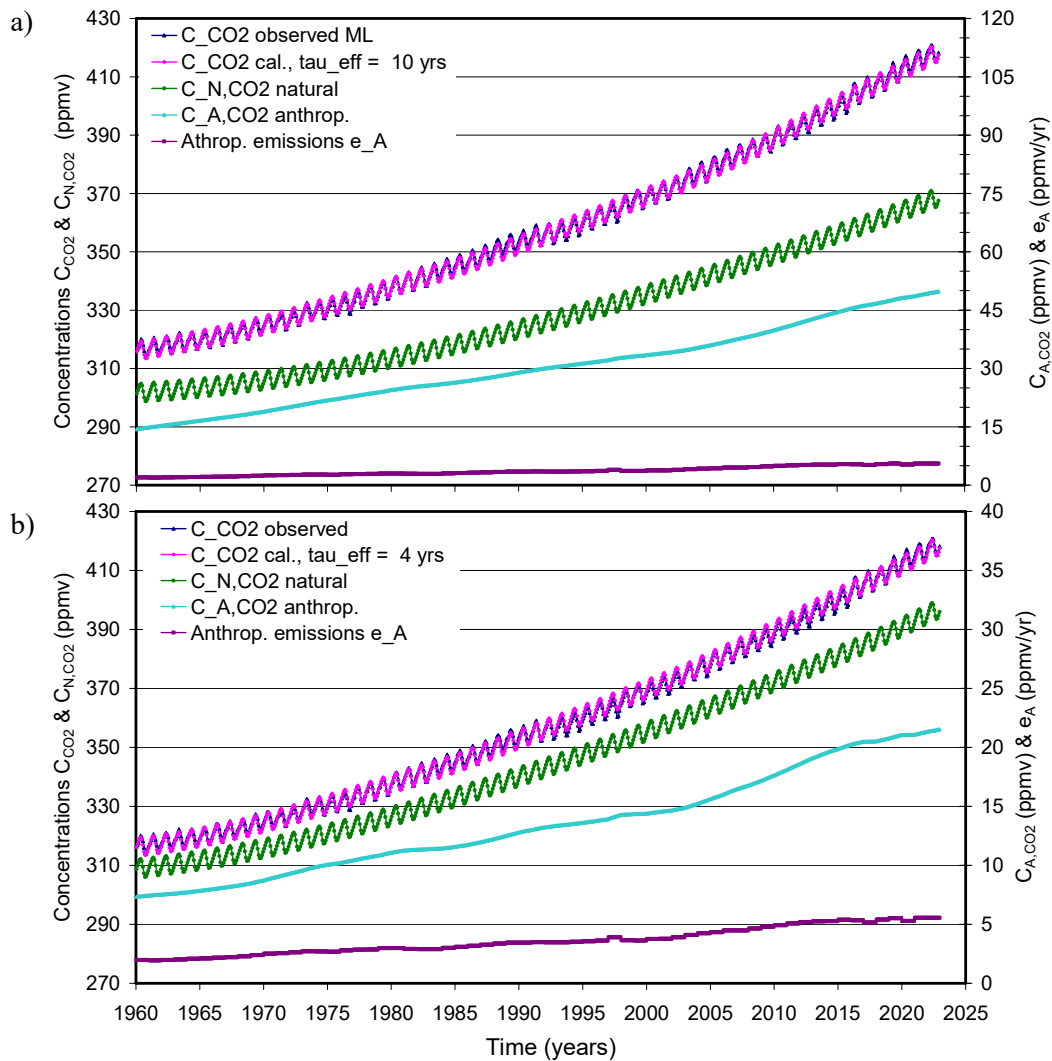


Figure 5: a) Observed monthly CO<sub>2</sub> concentration at Mauna Loa (Blue Triangles) together with a calculation for  $\tau_{eff} = 10$  yrs, including anthropogenic and natural emissions (Magenta Diamonds). Also plotted is the concentration  $C_{N,CO2}$  (Green Dots) only caused by natural emissions  $e_N(t)$ , and  $C_{A,CO2}$  (Aqua Triangles) caused by the anthropogenic emissions  $e_A(t)$  (Violet Squares). b) Respective calculations for  $\tau_{eff} = 4$  yrs.

and 4 yrs, the airborne fraction, generally understood as CO<sub>2</sub> increase only related to anthropogenic emissions, is varying around 45% (see Fig. 3), in Fig. 5a nature contributes with 65 ppmv twice as much to the incline (Green Dots) and in Fig. 5b with 86 ppmv even six times more than human emissions. So, despite a larger uptake than 1960 it would be strange and misleading to designate nature as a net sink, when it significantly amplifies the CO<sub>2</sub> increase over the Mauna Loa Era. Altogether, the natural emissions are growing faster than the absorption, and together with the anthropogenic emissions they pretend an almost constant airborne fraction.

#### 4.5 Fast Absorption of Anthropogenic Emissions

From faster oscillations on the <sup>14</sup>CO<sub>2</sub> decay (SH1) and a cross-correlation analysis of interannual CO<sub>2</sub> and temperature fluctuations (Humlum et al. 2013; Salby 2013) it even follows that the direct absorption time  $\tau$  can be as short as about 1 yr, which under respective conditions also ties down the effective absorption time.

Unlike thermally-induced emission from the surface, anthropogenic emission operates directly in

the atmosphere. For re-emission of CO<sub>2</sub> to amplify and slow effective absorption of CO<sub>2</sub>, anthropogenic emission must enrich CO<sub>2</sub> in the surface layer relative to that in the atmosphere. As detailed in SH1 and SH3, however, a slightly growing and continuous re-supply of anomalous CO<sub>2</sub> in the atmosphere maintains the troposphere and surface layer out of equilibrium. Thereby, it limits re-emission and its offset of direct absorption, leaving  $\tau_{eff}$  fast.

A simulation of the monthly Mauna Loa curve with an effective absorption time for the natural emissions of  $\tau_{eff} = 3.8$  yrs and for the human emissions of  $\tau = 1$  yr is displayed in Fig. 6 (Magenta Diamonds), which again completely covers the measurement (Blue Triangles).

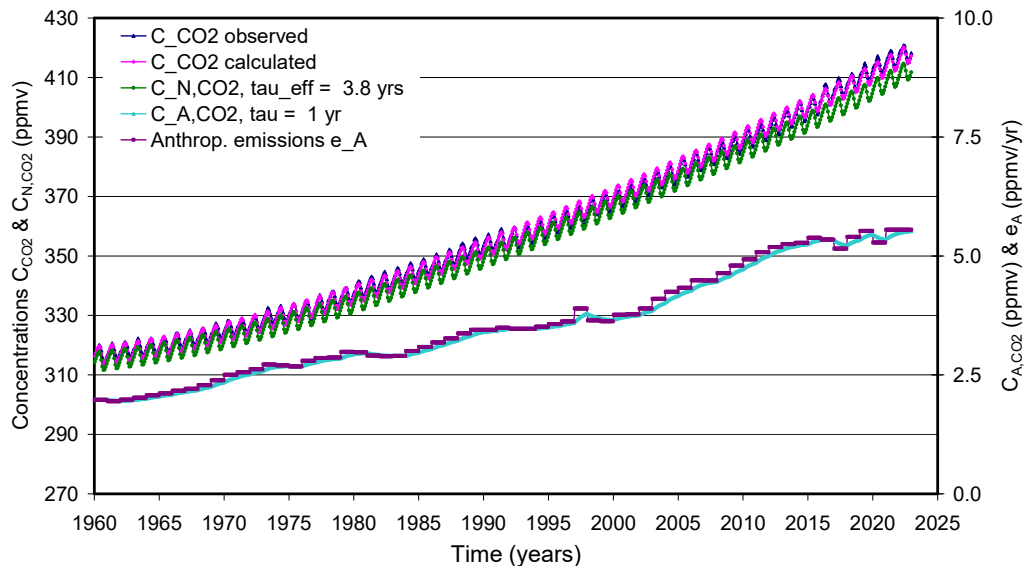


Figure 6: Observed monthly CO<sub>2</sub> concentration at Mauna Loa (Blue Triangles), almost completely covered by a calculation for the natural and anthropogenic emissions together (Magenta Diamonds). Also plotted is the concentration  $C_{N,CO_2}$  (Green Dots) for  $\tau_{eff} = 3.8$  yrs, caused by natural emissions  $e_N(t)$  alone, and  $C_{A,CO_2}$  (Aquamarine Triangles) for  $\tau = 1$  yr, caused only by the anthropogenic emissions  $e_A(t)$  (Violet Squares).

Almost as closely is the natural component  $C_{N,CO_2}$  tracking the observed CO<sub>2</sub> concentration (Green Dots). The effective absorption time of  $\tau_{eff} = 3.8$  yrs represents a combination of the slower temperature induced CO<sub>2</sub> changes over one decade, and on the other hand the faster interannual fluctuations with an absorption time less than 1 year (SH3). The anthropogenic component  $C_{A,CO_2}$  (Aquamarine Triangles) with a direct absorption time  $\tau = 1$  yr exactly tracks the anthropogenic emission rate  $e_A(t)$  (Violet Squares).

The basic natural emission with  $e_{N0} = 55.6$  ppmv/yr and the temperature dependent emission over 2010 - 2019 with  $\langle e_T \rangle = 23.4$  ppmv/yr ( $\beta_e = 33.3$  ppmv/yr/ $^{\circ}C^{1.35}$ ) are only slightly larger than in Fig. 5b, while the average seasonal emission with  $\langle e_S \rangle = 27.3$  ppmv/yr is the same. Together with the human fraction these emissions are causing an average of 111.5 ppmv/yr, in close agreement with the IPCC estimates of total emissions.

The anthropogenic part  $C_{A,CO_2}$  increases from 2 ppmv in 1960 to 5.5 ppmv in 2022 and under these conditions only contributes to the CO<sub>2</sub> increase over the Mauna Loa Era the fraction  $\Delta F_A = 3.5\%$ , declining almost proportional with  $\tau$  (see also SH3, Fig. 11). The respective fraction  $C_{A,CO_2} / C_{CO_2}$  in 2022 reduces to less than 1.5%.

## 5. Conclusion

The carbon cycle is of fundamental importance to estimate the influence of anthropogenic



emissions on the atmospheric CO<sub>2</sub> concentration, and from this to derive the impact of these emissions on global warming. Different models of the carbon cycle, using quite different approaches, can well reproduce the observed CO<sub>2</sub> concentration over recent years, but they also lead to contradictory interpretations of the human impact. Therefore, in this contribution we consider, how far some of these suppositions are substantiated or must be made responsible for significant misinterpretations. We compare these different approaches with own calculations.

Motivation for this study was a critical Comment (Andrews 2023) titled "Clear Thinking about Atmospheric CO<sub>2</sub>", in which the author of this article and some other scientists are addressed as *dissenters* or even as *mavericks*, and are accused to distribute misconceptions and errors when publishing an only moderate contribution of anthropogenic emissions to the increasing concentration of atmospheric CO<sub>2</sub>. It is not worth to respond to all the strange allegations and inciting statements in this Comment, but to clarify some main misinterpretations and misleading arguments, spreading around in this important discussion.

We present detailed calculations based on the Conservation Law, which reproduce all details of the measured atmospheric CO<sub>2</sub> concentration over the Mauna Loa Era. They clearly demonstrate that nature can be a net emitter, this in contradiction to some *confused thinking* that the environment could not be responsible for any increased CO<sub>2</sub> concentration in the atmosphere. Our studies show the direct influence of the absorption processes at the Earth's surface, which are characterized by a unitary time scale and can be represented by an effective absorption time  $\tau_{eff}$ , including re-emissions from extraneous reservoirs back to the atmosphere.

In particular, they allow to deduce an upper limit of 35% for the anthropogenic contribution to the observed increase of CO<sub>2</sub> over the Mauna Loa Era, but also a lower bound with 3.5%, one order of magnitude smaller, which has to be explained by a continuous re-supply of anomalous CO<sub>2</sub> in the atmosphere, maintaining the troposphere and surface layer out of equilibrium. This limits re-emission and its offset of direct absorption, leaving  $\tau_{eff}$  fast (SH3).

But even a more conservative consideration allowing stronger re-emission and thus a larger absorption time  $\tau_{eff} \approx 4$  yrs - this also based on the actually estimated CO<sub>2</sub> fluxes in and out of the atmosphere -, gives an anthropogenic fraction to the CO<sub>2</sub> growth over the Mauna Loa Era of about 14%, in agreement with our previous studies.

The calculations reveal that the presented approach is in full agreement with all observations, including the seasonal cycles and temperature induced emissions. It is based on well-known physical principles, and in this aspect, indeed differs from nebulous expositions of so-called *clear thinking*, which try to convince laymen with misleading conceptions that nature is a net sink, and thus, would not contribute to increasing CO<sub>2</sub>, or the emission and absorption processes at the Earth's surface would be a simple mixing process like liquids with different alcoholic concentrations.

Would be illuminating to see how *clear thinkers* can explain the whole dynamic of emission and absorption, including all anthropogenic and natural fluxes with the seasonal cycles and observed temperature dependent emissions, this without violating basic physical principles.

Our analysis of the carbon cycle, which uses data for the CO<sub>2</sub> concentrations and fluxes as published in AR6, shows that also a completely different interpretation of these data than favored by the IPCC is possible, this in complete conformity with all observations and natural causalities. Science advances not by consensus but by questioning the established paradigm.

## Annotations

This article is no Reply to Andrews' attacks and his Comment (2023), which is more a feat of hubris fuelled by vanity and political delusion and has far removed from any serious disputation. Otherwise, he would have taken a closer look at the arguments made in our previous papers, where we have extensively discussed what speaks against an interpretation of the carbon cycle as



avored by the IPCC. It is not worth to comment on all of Andrews' false claims and misinterpretations, but his most unqualified assertions cannot be left unchallenged and, although to some part already addressed above, they are here briefly summarized with some additional annotations.

#### *Net Global Uptake*

In his summary Andrews writes: "*Like the other papers critiqued, Salby & Harde (2022) ignore the well-established fact that Net Global Uptake is solidly positive in the current era as the authors should know. All credible models need to be constrained by this simple observation*".

The answer to this assertion is given in Section 2 and further demonstrated by the calculations in Subsection 4.4. Already in a preceding paper (Harde 2019, Subsection 5.3) this has been discussed extensively. *Clear thinkers* overlook that an increasing emission causes a delayed increase of the atmospheric CO<sub>2</sub> concentration. They derive from this increase, relative to the anthropogenic emissions, an increased absorption of nature. But independent of the fact that also the actual absorption is responding with some delay, from an increasing absorption relative to a previous level at lower emissions, we cannot automatically follow that nature would not contribute to the increasing CO<sub>2</sub> level, particularly not when in forehand only anthropogenic emissions are considered and native contributions, often not well known, have been neglected. This is an obvious case of circular reasoning. A complete balance requires to include all emissions and absorption.

#### *Isoflux-Model*

Andrews writes: "*Isoflux effects can change carbon isotope distributions without changing total carbon distributions. These authors ignore them and mistakenly believe that total carbon changes mimic isotope changes. See the appendix for further criticism of the radiocarbon model of these authors*".

Obviously, Andrews did not realize that his isoflux model is a bad copy of our description of effective absorption, which considers re-emission from previously absorbed CO<sub>2</sub>. In distinction to a simple mixing effect like liquids of different concentration (a bad and misleading comparison) we consider real absorption and emission processes at the Earth's surface, as they are authentically observed and which include a partial and/or delayed sequestration of CO<sub>2</sub>. These processes determine the actual exchange of CO<sub>2</sub> with the oceans or the biosphere.

For this uptake and release of CO<sub>2</sub> it is reasonable to distinguish between direct absorption processes on a timescale even as short as about one year, as this follows from observations of the faster oscillations on the <sup>14</sup>CO<sub>2</sub> decay (SH1) and also from cross-correlation analyses of interannual CO<sub>2</sub> and temperature fluctuations (Humlum et al. 2013; Salby 2013), and on the other hand between an effective absorption on an extended timescale, which is determined by re-emission from extraneous reservoirs. This re-emission is assumed to be proportional to a previous absorption by these reservoirs and represents a good approximation for a coupled balance scheme of adjacent reservoirs with the atmosphere.

Our description in no way ignores any two-way exchanges between different carbon inventories, which can happen without real changes of these reservoirs, as the total concentration and also the composition of the different CO<sub>2</sub> isotopologues in the atmosphere is completely controlled by these processes. So, the <sup>14</sup>CO<sub>2</sub>-decay after the stop of the bomb tests in 1963 is the result of real absorption and emission cycles, this indeed without net concentration change, from which we can learn, on which timescale they are taking place.

Radiocarbon is an ideal tracer, which obeys the same rules as the main isotopologues, and thus can be well used to study temporal carbon mixing and exchange processes. Of course, indicates this <sup>14</sup>CO<sub>2</sub>-decay curve that the absorption rate of all CO<sub>2</sub> is proportional to the instantaneous concentration in the atmosphere and reciprocal to an effective absorption time (e-folding time) of  $\tau_{eff} \approx 10$  yrs, which simultaneously defines an upper limit for the direct absorption time  $\tau$ . Independently this also follows from an analysis of the seasonal cycles (Harde & Salby 2021).

A more serious study of our approach and clear thinking about coupled systems would have shown Andrews that our description does not ignore, what he simply explains as mixing, but includes such processes and quantifies them on a scientifically confirmed basis. Instead, Andrews apparently ignores real science and tries to explain everything by isofluxes in his artificial universe.

#### *Interpretation of the <sup>14</sup>C-decay*

The Appendix of Andrews' Comment is only aimed at defaming without any new content. It is a repeat of his earlier unqualified claims, to which we were already responding elaborately (Harde & Salby, 2021). Continuously he stresses that we and others have misinterpreted the <sup>14</sup>C-decay, and that it required his enlightenment to point out the correct interpretation of this decay together with the right description of the carbon cycle.

He writes: "*As an example of authors' clinging to old and discredited ideas, we will describe (Harde and Salby 2021)'s attempt to salvage Harde's model by designing (inventing?) a background to transform the true concentration curve (red in Figure 2) to the curve they originally thought was the concentration (green in Figure 2)*".

Here only a few additional remarks for clarification. First of all, we never thought or were anywhere writing that the fractionation corrected ‰-deviation  $\Delta^{14}\text{C}$  from the International Standard activity (green graph in Andrews' Fig. 2) would be the concentration of <sup>14</sup>C in the atmosphere. But indeed, can we derive from such data the residence time, respectively the effective absorption time of <sup>14</sup>CO<sub>2</sub>. The only question is, under which conditions such data were collected and evaluated.

The  $\Delta^{14}\text{C}$ -measurements of Levin et al. (1980 and 1994), we were using for our analyses, were performed by taking air samples of 15 m<sup>3</sup>, and after an extraction and cleaning procedure the activity of the samples was recorded by conventional counting techniques. Over the first two decades after the bomb test stop it was standard to normalize the measured activities to the sampling volume or the air density (see also Stuiver & Polach 1977). Under such condition the measured activity directly reflects the <sup>14</sup>CO<sub>2</sub>-concentration changes over time. Since the 80s many groups are using additionally or parallel accelerator mass spectrometry (AMS), which relies on counting the relative abundance of the carbon isotopes directly in terms of the isotope ratios <sup>14</sup>C/<sup>12</sup>C. In this case, due to the increased <sup>12</sup>CO<sub>2</sub>-concentration in the atmosphere over the observation period a further correction is necessary, to determine the correct decline of <sup>14</sup>C. The publications (Levin et al. 1980 and 1994) give no hint of using AMS or applying additional corrections. Nevertheless, Andrews (2020) states:

*"Unconventional models motivated by a misinterpretation of the isotope ratio variable " $\Delta^{14}\text{C}$ " are excluded when the error is corrected ... Harde and Berry erroneously concluded that after atmospheric nuclear testing ceased, the "pulse" of extra <sup>14</sup>C introduced by the tests exponentially disappeared from the atmosphere with a time constant of approximately 16 years"*.

In Harde & Salby (2021) we explicitly show that the increasing CO<sub>2</sub> concentration in the analysis of the  $\Delta^{14}\text{C}$ -data, either based on the original activity measurements or using AMS with or without further correction of the increased <sup>12</sup>CO<sub>2</sub>-concentration, only results in a marginal correction for the decay time. In both cases we deduce for <sup>14</sup>CO<sub>2</sub> an effective absorption time of about 10 yrs, only on a different background, which for several reasons cannot be assumed to be the same today as before the Test Ban Treaty (see also Levin et al., 2010). In any way, the artificially constructed background in Andrews' Fig. 3 has nothing to do with our calculation and explanation, which unambiguously confirms our previous conclusion that the observed exponential decay of <sup>14</sup>C represents an upper limit for the absorption time of CO<sub>2</sub> in the atmosphere.

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### References

- Andrews, D. E., 2020: *Correcting an Error in Some Interpretations of Atmospheric <sup>14</sup>C Data*, Earth Sciences, Vol. 9, No. 4, pp. 126-129, <https://doi.org/10.11648/j.earth.20200904.12>.
- Andrews, D. E., 2023: *Clear Thinking about Atmospheric CO<sub>2</sub>*, Science of Climate Change, Vol. 3.1, pp. 33 - 45, <https://doi.org/10.53234/scc202301/20>
- Berry, E., 2019: *Human CO<sub>2</sub> Emissions Have Little Effect on Atmospheric CO<sub>2</sub>*, Intern. J. Atmospheric and Oceanic Sciences, Vol. 3(1), pp. 13-26, <https://doi:10.11648/j.ijaos.20190301.13>.
- Berry, E., 2021: *The Impact of Human CO<sub>2</sub> on Atmospheric CO<sub>2</sub>*, Science of Climate Change, Vol. 1, No. 2, pp. 213 - 249, <https://doi.org/10.53234/scc202112/13>
- Brechet, L., Lopez-Sangil, L., George, C., Birkett, A., Baxendale, C., Trujillo, B., and E. Sayer, 2018: *Distinct responses of soil respiration to experimental litter manipulation in temperature woodland and tropical forest*, Ecol and Evolution, 8, 3787-3796.
- Carbon Dioxide Information Analysis Center (CDIAC), 2022: [https://cdiac.ess-dive.lbl.gov/trends/co2/recent\\_mauna\\_loa\\_co2.html](https://cdiac.ess-dive.lbl.gov/trends/co2/recent_mauna_loa_co2.html)
- Cawley, G. C., 2011: *On the Atmospheric Residence Time of Anthropogenically Sourced Carbon Dioxide*, Energy Fuels, Vol. 25, pp. 5503–5513, <https://doi.org/10.1021/ef200914u>
- Cook, J., et al., 2013: *Quantifying the consensus on anthropogenic global warming in the scientific literature*, Environ. Res. Lett. 8 024024 (7pp), <https://doi.org/10.1088/1748-9326/8/2/024024>
- Dietze, P., 2001: *IPCC's Most Essential Model Errors*, Carbon Model Calculations, <http://www.john-daly.com/dietze/cmodcalc.htm>.
- Essenhigh, R. E., 2009: *Potential dependence of global warming on the residence time (RT) in the atmosphere of anthropogenically sourced carbon dioxide*, Energy Fuel 23, pp. 2773–2784, <http://pubs.acs.org/doi/abs/10.1021/ef800581r>.
- Fiedler, M. 2020: *Die 97% Einigkeit unter Wissenschaftlern, die es nie gegeben hat*, <https://markus-fiedler.de/2020/01/02/die-97-einigke-iter-wissenschaftlern-die-es-nie-gegeben-hat/>
- Global Carbon Budget (GCB) 2022: <https://www.carbonbrief.org/analysis-global-co2-emissions-from-fossil-fuels-hit-record-high-in-2022/>
- Harde, H., 2017: *Scrutinizing the carbon cycle and CO<sub>2</sub> residence time in the atmosphere*, Global and Planetary Change 152, pp. 19-26, <http://dx.doi.org/10.1016/j.gloplacha.2017.02.009>.
- Harde, H., 2019: *What Humans Contribute to Atmospheric CO<sub>2</sub>: Comparison of Carbon Cycle Models with Observations*. Earth Sciences, Vol. 8, No. 3, pp. 139-158, <https://doi.org/10.11648/j.earth.20190803.13>.

Harde, H., M. L. Salby, 2021: *What Controls the Atmospheric CO<sub>2</sub> Level?* Science of Climate Change, Vol. 1, No.1, pp. 54 - 69, <https://doi.org/10.53234/scc202106/22>.

Humlum, O., K. Stordahl, and J.-E. Solheim, 2013: *The phase relation between atmospheric carbon dioxide and global temperature*, Global and Planetary Change, vol. 100, pp. 51–69.

IPCC Fifth Assessment Report (AR5), 2013: T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P. M. Midgley (Eds.): *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC Sixth Assessment Report (AR6), 2021: V. Masson-Delmotte, P. Zhai, A. Pirani et al.: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press.

Joos, F., M. Bruno, R. Fink, U. Siegenthaler, T. F. Stocker, C. Le Quéré, J. L. Sarmiento, 1996: *An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake*, Tellus B 48, pp. 397–417, <https://doi.org/10.1034/j.1600-0889.1996.t01-2-00006.x>

Legates, D. R., W. Soon, W. M Briggs, 2013: *Learning and Teaching Climate Science: The Perils of Consensus Knowledge Using Agnotology*, Science & Education 22, 2007–2017, <https://doi.org/10.1007/s11191-013-9588-3>

Legates, D. R., W. Soon, W. M. Briggs, et al., 2015: *Climate Consensus and ‘Misinformation’: A Rejoinder to Agnotology, Scientific Consensus, and the Teaching and Learning of Climate Change*, Science & Education 24, 299–318, <https://doi.org/10.1007/s11191-013-9647-9>

Levin, I., K. O. Münnich, W. Weiss, 1980: *The Effect of Anthropogenic CO<sub>2</sub> and <sup>14</sup>C Sources on the Distribution of <sup>14</sup>C in the Atmosphere*, Radiocarbon, Vol. 22, No. 2, pp. 379-391.

Levin, I., B. Krömer, H. Schoch-Fischer, M. Bruns, M. Münnich, D. Berdau, J.C. Vogel, K.O. Münnich, 1994: *Atmospheric <sup>14</sup>CO<sub>2</sub> measurements from Vermunt, Austria, extended data up to 1983*, <https://cdiac.ess-dive.lbl.gov/ftp/trends/co2/vermunt.c14>

Levin, I., T. Naegler, B. Krömer, M. Diehl, R. J. Francey, A. J. Gomes-Pelaez, L. Paul Steele, D. Wagenbach, R. Weller, D. E. Worthy, 2010: *Observations and modelling of the global distribution and long-term trend of atmospheric <sup>14</sup>CO<sub>2</sub>*, Tellus B: Chemical and Physical Meteorology, 62:1, pp. 26-46, <https://doi.org/10.1111/j.1600-0889.2009.00446.x>.

Levin, I., B. Krömer, and S. Hammer, 2013: *Atmospheric  $\Delta^{14}\text{CO}_2$  trend in Western European background air from 2000 to 2012*, Tellus B: Chemical and Physical Meteorology, 65(1), p. 20092, <http://doi.org/10.3402/tellusb.v65i0.20092>

Lloyd, J. and J. Taylor, 1994: *On the temperature dependence of soil respiration*, Functional Ecology, 8 315-323.

Lüdecke, H.-J., C. O. Weiss, 2016: *Simple Model for the Anthropogenically Forced CO<sub>2</sub> Cycle Tested on Measured Quantities*, JGEESI, Vol. 8, No. 4, pp. 1-12, <https://doi.org/10.9734/JGEESI/2016/30532>.

Nottingham, A., Baath, E., Reischke, S., Salinas, N., and P. Meir, 2018: *Adaptation of soil microbial growth to temperature: Using a tropical elevation gradient to predict future changes*, Glob. Change Biol., 25, 827-838.

Oregon State University, 2023: <https://volcano.oregonstate.edu/submarine-eruptions>

Palmer, P., L. Eng, D. Baker, F. Chevallier, H. Bosch and P. Somkuti, 2019: *Net carbon emissions from African biosphere dominate pan-tropical atmospheric CO<sub>2</sub> signal*, Nature Comm.,

<https://doi.org/10.1038/s41467-019-11097-w>.

Petit, J.-R., J. Jouzel, D. Raynaud, N. I. Barkov, J.-M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, et al., *Climate and Atmospheric History of the past 420,000 Years from the Vostok Ice Core, Antarctica*, Nature, vol. 399, no. 6735, pp. 429–436 (1999).

Pollard, P. C., 2022: *Globally, Freshwater Ecosystems Emit More CO<sub>2</sub> Than the Burning of Fossil Fuels*, Front. Environ. Sci., Vol. 10, p. 904955, <https://doi.org/10.3389/fenvs.2022.904955>

Powell, J. L., 2016: *The Consensus on Anthropogenic Global Warming Matters*, Bulletin of Science, Technology & Society, Vol. 36, issue 3, pp 157-163, <https://journals.sagepub.com/doi/10.1177/0270467617707079>

Salby, M. L., 2013: *Relationship Between Greenhouse Gases and Global Temperature*, Video Presentation, April 18, 2013, Helmut-Schmidt-University Hamburg, [https://www.youtube.com/watch?v=2ROw\\_cDKwc0](https://www.youtube.com/watch?v=2ROw_cDKwc0).

Salby, M. L., 2016: *Atmospheric Carbon: Why It's Not Pollution and Why Humans Cannot Regulate It*, Video presentation, 18 July, University College London, [https://youtu.be/3q-M\\_uYkpT0?t=1330](https://youtu.be/3q-M_uYkpT0?t=1330).

Salby, M. L., 2018: *What is Really Behind the Increase of Atmospheric CO<sub>2</sub>?* Helmut-Schmidt-University Hamburg, 10. October 2018, <https://youtu.be/rohF6K2avtY>

Salby, M. L., H. Harde, 2021 (SH1): *Control of Atmospheric CO<sub>2</sub> - Part I: Relation of Carbon 14 to Removal of CO<sub>2</sub>*, Science of Climate Change, Vol. 1, No.2, pp. 177 - 195, <https://doi.org/10.53234/SCC202112/30>

Salby, M. L., H. Harde, 2021 (SH2): *Control of Atmospheric CO<sub>2</sub> - Part II: Influence of Tropical Warming*, Science of Climate Change, Vol. 1, No.2, pp. 196 - 212, <https://doi.org/10.53234/scc202112/12>

Salby, M. L., H. Harde, 2022 (SH3): *Theory of Increasing Greenhouse Gases*, Science of Climate Change, Vol. 2, No.3, pp 212 - 238, <https://doi.org/10.53234/scc202212/17>.

Savage, K. and E. Davidson, 2001: *Interannual variation of soil respiration in two New England forests*, Glob. Biogeochem. Cycles, 15, 337-350.

Schröder, H., 2022: *Less than half of the increase in atmospheric CO<sub>2</sub> is due to the burning of fossil fuels*, Science of Climate Change, Vol. 2, No.3, pp 1 - 19, <https://doi.org/10.53234/scc202111/17>

Siegenthaler, U., J. L. Sarmiento, 1993: *Atmospheric carbon dioxide and the ocean*, Nature 365, pp. 119-125.

Skrable, K., Chabot, G., French, C., 2022a: *World Atmospheric CO<sub>2</sub>, Its <sup>14</sup>C Specific Activity, Non-fossil Component, Anthropogenic Fossil Component, and Emissions (1750-2018)*, Health Physics, Vol. 122, No. 2 - pp. 291-305, <https://doi.org/10.1097/HP.0000000000001485>

Skrable, K., Chabot, G., French, C., 2022b: *Components of CO<sub>2</sub> in 1750 through 2018 Corrected for the Perturbation of the <sup>14</sup>CO<sub>2</sub> Bomb Spike*, Health Physics, Vol. 123, No. 5, p. 392, <https://doi.org/10.1097/HP.0000000000001606>.

Stuiver, M. and H. Polach, 1977: *Discussion: Reporting of <sup>14</sup>C data*, Radiocarbon, Vol. 19, No. 3, pp. 355-363.

Tanentzap, A. J., A. Fitch, O. Cole, 2019: *Chemical and Microbial Diversity Covary in Fresh Water to Influence Ecosystem Functioning*, Proc. Natl. Acad. Sci., Vol. 116, p. 24689, <https://doi.org/10.1073/pnas.1904896116>

Ward, N. D., T. Bianchi, M. Seidel, 2017: *Where Carbon Goes when Water Flow: Carbon Cycling across the Aquatic Continuum*, Front. Mar. Sci., Vol. 4, pp. 1-27, <https://doi.org/10.3389/fmars.2017.00007>

Wood, T., Detto, M., and W. Silver, 2013: *Sensitivity of soil respiration to variability in soil moisture and temperature in a humid tropical forest*, *PLOS ONE*, 8, <https://doi.org/10.1371/journal.pone.0080965>.