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About the Origin of CO_2 in the Atmosphere:

Some Annotations to a Study of the CO_2 Coalition

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Abstract

A study published by the CO_2 Coalition claims that the rise in atmospheric CO_2 concentration is manmade. This claim is examined here and rejected.

There are two fundamental shortcomings in the study: It is based on an inappropriate model, that is far from reality, and it ignores that the atmosphere is an open system. In such a system the concentration cannot rise more than the inflow. Therefore, since the concentration has risen by 50 %, the inflow must have risen by at least 50 %. 5 % emissions from human activities are far too small, emissions from natural sources must have risen much more.

The study also emphasizes that the atmosphere accumulates less CO_2 than humans emit. Therefore, there is a net outflow to nature, nature acts as a net sink. And, as "a sink cannot be a source", the study concludes that the increase in concentration can only be caused by anthropogenic emissions. That sounds logical but does not stand up to scrutiny: Nature acts as both a source and a sink simultaneously, sometimes one prevails, sometimes the other. On its own, nature would have been a net source since 1750; only in combination with anthropogenic emissions has it become a net sink. Nevertheless, even as a net sink, nature can have, and actually has, contributed more to the rise in concentration than humans.

Another weakness of the study is its assumption that natural fluxes in and out of the atmosphere have remained unchanged for 250 years. Given the high variability of natural processes, this is extremely unlikely, and given the recent warming, it cannot be correct.

The study also puts forward several additional arguments to support its view of the exclusively anthropogenic causation of the CO_2 increase. It is shown that these arguments are also not viable.

Keywords: Adjustment time; ^{14}C; carbon cycle; climate change; CO_2-concentration; mass balance; residence time.

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1. Introduction

The atmospheric CO_2 concentration has risen from about 280 ppm in preindustrial times to about 420 ppm today. Most scientists, represented above all by the IPCC (see particularly [1] and [2]), consider anthropogenic emissions to be the sole cause, or at least the predominant cause by far. But not everyone agrees, many scientists believe that nature has contributed much more than mankind. A heated debate has arisen in scientific literature, e. g., [3 - 30].

In December 2024 the CO_2 Coalition published a new study [31], which renews the viewpoint of causation exclusively by anthropogenic emissions. That would necessarily result from the fact that about half of these emissions remain in the atmosphere. From this, [31] deduces that, if humans were to stop their emissions, the concentration would decline with a time constant (e-folding time) of about 50 years. However, at least in my opinion, [31] does not bring any new aspects and only repeats arguments that have already been rejected. The authors of [31] misinterpret some

special features of the carbon cycle and sometimes they fall victim to heuristic traps. Therefore, they come to wrong conclusions, as will be shown in this reply.

2. It's the model, stupid

We never know exactly how nature works: We can only examine it based on models that always have larger or smaller deviations from the real world. Of course, [31] also works with such a model. I will call it the "fountain model", as it emulates a common type of fountain: a water well with basin and fountain, with an overflow to regulate the water level in the basin, and with a circulation pump feeding the fountain out of the basin. This pump always returns the same amount of water as it withdraws (closed loop). In other words, the circulation from the basin via the fountain back to the basin is balanced and has no influence on the water level in the basin. That level, for its part, is set in such a way that the outflow from the basin (through the overflow) is just as great as the inflow into the basin (except the inflow via the fountain). This regulation of the level has no influence on the circulation to the fountain.

As already said, this is the model [31] uses. It is the basis on which [31] carries out its considerations and reaches its conclusions. However, CO_2 in the atmosphere behaves decisively differently (see below). Therefore, all considerations and conclusions of [31] lack physical foundation. A model much closer to reality could, for example, be based on another type of fountain: with a hole in the bottom of the basin instead of the overflow, draining water into a lake to regulate the water level in the basin, and with a pump taking water out of that lake to feed the fountain. I will call this model the "fountain and lake model".

This model aligns much better with reality for two reasons: First, the circulation via the fountain is not a closed loop with always identical outflow and backflow; rather, these two flows are decoupled through the lake. Therefore, in this model the fountain's flowrate does influence the water level in the basin. Second, all outflow from the basin runs through the hole in its bottom, and it is the entirety of this outflow that scales with the water level, in contrast to the "fountain model", where this applies only to part of the outflow (the circulation to the fountain is independent of the water level!). Moreover, this scaling with the water level as such is also different: It refers to the entire water level in the basin in case of the "fountain and lake model", not only to the excess level above the level of the overflow, as in the "fountain model". These characteristics of the "fountain and lake model" fit well with reality, where interim storage in the ocean and biomass performs the function of the lake, decoupling the outflow from the atmosphere from the backflow into it, and where all outflow (through all sinks) depends on the entire concentration.

In the "fountain and lake model", there are not two separate processes, one for circulation, and the other for level adjustment; rather, both tasks are fulfilled by the same process: circulation. It is balanced in equilibrium, with a fixed correlation between the water level in the basin and the flowrate of the circulation, and it is imbalanced in transients, accomplishing the adjustment of the water level to the new equilibrium. The results differ drastically from those in the "fountain model".

And that's the crux of the matter: It is the underlying model that determines the results. Meaningful results can only be obtained with a model that is sufficiently clos to reality. The "fountain model" used in [31] does not meet this requirement, the "fountain and lake model" performs much better.

3. Open system

Ref. [31] claims that half of the anthropogenic emissions remain in the atmosphere and thereby bring about the increase in concentration. In order to review this view, two special features of the atmosphere must be taken into account: First, the atmosphere is an open system, and second, the outflow of CO_2 from the atmosphere increases with concentration. The open system simply follows from the fact that the CO_2 inventory in the atmosphere grows more slowly than humans emit, and the dependence of outflow on concentration follows inevitably from the fact that all

processes for removing CO_2 from the atmosphere are in principle based on diffusion, which always rises with concentration.

In such a system, two statements always apply:

- The concentration adjusts itself to that value, where outflow equals inflow.
- The concentration cannot rise more than the inflow.

The latter means that, for the concentration to have risen by 50 % (from 280 to 420 ppm), the inflow must have risen by at least 50 %. The 5 % anthropogenic emissions are far too small for this, the emissions from natural sources must have grown much stronger. Ref. [31] does not take into account the fundamental openness of the system.

4. The small and the large cycle

Much larger emissions from natural sources appear to be imperative (section 3). However, it is sometimes argued that emissions from natural sources have not grown as a whim of nature, but as a result of anthropogenic emissions. This is possible in principle, and to a certain extent it is even definitely true (see for example [19]). The direct reaction partners of the atmosphere - the near-surface ocean layer (about 50 to 100 m thick, well mixed, sunlit) and the short-lived terrestrial biomass (leaves, annual plants, etc.) - are relatively small reservoirs and they are in very intensive exchange with the atmosphere (see Fig. 1, from [28]). Therefore, these three reservoirs, which are collectively referred to as the "small cycle" in the following, strive very hard towards equilibrium. That means that, if the concentration in the atmosphere rises, for whatever reason, then the concentrations in the near-surface ocean layer and in the short-lived terrestrial biomass rise too, with only a short delay. And when these reservoirs have higher concentration, they also emit more CO_2 into the atmosphere.

This definitely is a part of the increased emissions from natural sources. But it is only a part of it, because at least warming has certainly increased the emissions from the ocean and biomass too (outgassing from ocean water and enhanced growing and rotting of biomass, see e. g. [10]). Other possible contributions may come, for example, from volcanic outgassing, or from changing sea currents with different CO_2 concentrations. We have very little knowledge of these processes, so we cannot say to what extent the emissions from them have changed.

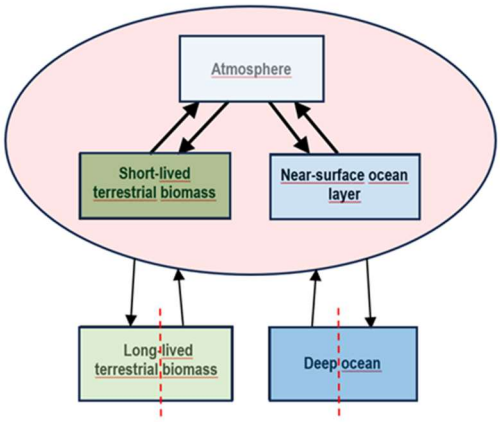

Figure 1: Schematic diagram of the CO_2 cycle which takes place in two stages: In the first, all CO_2 emitted into the atmosphere is rapidly distributed evenly in the "small cycle" (summarized in the ellipse). Then, in the second stage, carbon is more slowly removed from this "small cycle" into the "large cycle", which also encompasses the long-lived terrestrial biomass and the deep ocean. As a result of the long storage time in the last two reservoirs mentioned, absorption in them and return from them are decoupled for long periods of time (indicated by the dashed red lines).

However, it is not that important how much all these processes really contribute to the concentration in the atmosphere as an answer to anthropogenic emissions, because it only shifts the problem to another level: It now just is the "small cycle" that forms an open system with concentration-dependent outflow, whose concentration has increased by 50 %. The most important reaction partners of this new system, the deep ocean and the long-lived terrestrial biomass, are so large that a response to an increased concentration in the atmosphere is delayed so much that it does not have to be taken into account here. If emissions from these reservoirs have increased, then the cause can't be the anthropogenic emissions, it rather must be a whim of nature, even if we can't explain it.

In other words, within the time horizon relevant to the ongoing climate debate, we definitely have an open system in which the outflow increases with increasing concentration. Therefore, it remains the same: Nature must have contributed much more than humans to achieve an increase in atmospheric concentration by 50 %. Various possibilities to accomplish this have just been indicated. And it should be reminded that natural flowrates are very large and need to change relatively little to significantly affect the atmospheric concentration.

For clarification: This "small cycle" and "large cycle" is again only a model, and it even is a coarse one. Nature does not have a division into two parts, fast and slow, nature has a much finer gradation. But this division into two parts makes the principle clear: small reservoirs act fast on a disturbance, large reservoirs act much more slowly. The same fact in other words: Transients run the closer to equilibrium, the smaller the inventory in the affected reservoirs is. A cycle that includes the deep ocean, for example, takes thousands of years to reach equilibrium, and before that, the distance to equilibrium can be substantial. This is quite different with the "small cycle", as it is defined here, in which equilibrium will be reached already within a few years and the distance to equilibrium never can be large.

Supplement: In addition to the size of the reservoirs, the speed of adjustment, respectively the distance to equilibrium, naturally also depend on the exchange rate: The higher this rate, the faster the adjustment, respectively the smaller the distance.

5. Mass balance

A central argument in [31] is the mass balance of CO_2 in the atmosphere: This mass balance would "definitively prove that humans are the main cause of the increase of CO_2 in the atmosphere", [31] says. However, this view has already been rejected repeatedly in the cited literature, and this rejection stands on firm ground, as will be shown below.

The above statement in [31] regarding the mass balance seems to be the result of the authors of [31] falling victim to the heuristic trap of "inverse conclusion". This trap consists in the assumption that, if a statement is correct, its inverse is also correct. This is sometimes true, but not always. An example for the latter: CO_2 is a prerequisite of life. That is correct, without CO_2, there is no life. But the inverse is not correct: The presence of CO_2 does not guarantee the existence of life. We know this from Mars: Whether there is life on it is still uncertain, although there is undoubtedly CO_2 there.

In [31], it is not life on Mars, but the mass balance of CO_2 in the Earth's atmosphere: CO_2 in the atmosphere must fulfill that mass balance. That's correct, CO_2 in the atmosphere behaves like an inert gas, none is produced in it, and none vanishes, therefore, the mass balance must be observed. Furthermore, according to its "fountain model", [31] describes the CO_2 cycle on the basis of the assumption that natural flows into the atmosphere have not changed since the pre-industrial equilibrium (constant circulation). And on that basis, explaining the increase in concentration by retention of half of the anthropogenic emissions, actually fulfills the mass balance. That's correct, beyond doubt. But the inverse conclusion that, if the mass balance is fulfilled, then the said explanation of the increase in concentration is also correct, is inadmissible. That's exactly the heuristic trap mentioned above. Fulfilling the mass balance does not prove anything, because there are other possibilities that fulfill the mass balance too, even an infinite number of possibilities. Which one of these is the correct one can only be clarified by further considerations.

Let's take another look at the problem: The argumentation of [31] contains two crucial errors: First, in view of the capriciousness of nature, constant natural flows over 250 years are unlikely. And due to the warming, that has undoubtedly occurred, they definitely have changed. How much is debatable, but they have increased beyond doubt. Therefore, the assumption of constant natural flows is clearly invalid. And second, as already said, the fulfillment of the mass balance does not prove anything because it can be reached by an infinite number of pairings of inflow and outflow.

However, it's not just the lack of probative force of the mass balance, the very assumption that half of anthropogenic emissions remain in the atmosphere is untenable. For this assumption to be

correct, two different processes for CO_2 travelling through the atmosphere must exist: one for natural CO_2, and the other for anthropogenic CO_2. In the "fountain model", these two processes exist, but they do not exist in the real atmosphere. This follows inevitably from:

- All CO_2 molecules are the same and they follow the same laws.
- In the atmosphere, all molecules are well mixed, and all sinks take out CO_2 from the atmosphere only from this mixing.
- The sinks cannot realize the origin of the molecules and must therefore tread them all equally.
- Although there are different cycles outside the atmosphere (to the ocean and to the biomass, with any further subdivisions), inside the atmosphere they are all mixed together and all molecules remain in the atmosphere for the same length of time. One could even say that there are no cycles through the atmosphere at all, the atmosphere is rather something like a neutralized zone for all cycles, all cycles start renewed with the extraction of CO_2 from the (well mixed) atmosphere and they end with the (complete or only partial) return of that CO_2 to the atmosphere.

All of this speaks against the assumption in [31] that nothing has changed except for anthropogenic emissions, and that half of these emissions remain in the atmosphere and the other half is removed by natural sinks. Although this retention of 50 % fulfills the mass balance, it is not the correct pairing of inflow and outflow. Of course, the correct pairing must fulfill the mass balance as well, but this fulfillment as such is simply not enough, that's the error (one of the errors) in [31].

6. Natural or anthropogenic emissions?

As previously stated, due to the openness of the system, the concentration in the atmosphere can only have risen by 50 % if total emissions into it (the inflow) have increased by at least 50 %. A similar result can be obtained by examining the outflow instead of the inflow: The outflow is essentially governed by diffusion processes, meaning that the relationship between concentration and outflow must be proportionality (at least approximately, at least in the concentration range of interest here, i.e. from 280 to 420 ppm). Therefore, the outflow from the atmosphere must have risen by about 50 %. And, since the concentration in the atmosphere has increased, the inflow must have increased even more. Either way, an increase of approximately 50 % in total emissions appears necessary, and this large increase can only come about with a large contribution from naturel sources.

A few additional numbers: According to the IPCC, [1], Fig. 5.12, both inflow to and outflow from the atmosphere were approximately 81 ppm/y in the pre-industrial equilibrium (IPCC takes the year 1750 for that). But both have changed since then: On average over the years 2010 to 2019 the inflow from natural sources has been about 19.5 ppm/y higher than in 1750, and the outflow into natural sinks has been about 17.7 ppm/y higher. Combined with the anthropogenic emissions of 5.2 ppm/y, this gives an actual net outflow of 1.7 ppm/y. These values of IPCC clearly contradict the assumption of constant natural flows made in [31], according to IPCC they have increased three times more than the anthropogenic emissions!

7. 50 % and a hasty explanation

People tend to make hasty explanations. A well-known example: Every day, we see the sun rising and setting. For thousands of years, we had a plausible explanation: The sun orbiting around the earth. Today, we know this explanation was hasty, and we have a better one.

A similar situation applies to CO_2 in the atmosphere: The inventory has risen and still rises by an amount corresponding to half of the anthropogenic emissions. In line with the standard climate doctrine, [31] interprets this observation as the retention of half of the anthropogenic emissions. However, this assumption is similarly hasty as the belief that the sun orbits the earth.

The retention of 50 % simply does not hold, this has already been shown, see above. But the analysis can be continued: The problem begins with the process that should accomplish this retention. Regarding the sun, the ancient Greeks believed God Helios riding in a chariot across the sky every day, and returning underground during the night. For the ancient Greeks, this was a process actually possible for gods. And what does [31] say? It does not even try to describe the process of 50 % retention in physical terms. It simply relies on the fact that this is possible within the "fountain model", ignoring that this is just a model and not reality. Therefore, the question is: can such an effect (retention of 50 %) also occur in reality?

The answer is: theoretically yes, but only, if two prerequisites are fulfilled: First, the "small cycle" (section 4) must be a closed system (section 3); then all the CO_2 emitted into the atmosphere by human activities remains within this cycle. And second, the inventory in the rest of the "small cycle" must be exactly of the same size as that in the atmosphere; then all anthropogenic emissions distribute themselves equally between the atmosphere and the rest of the "small cycle", leaving 50 % in the atmosphere.

Let's check: Carbon inventories are not always well known, but the inventory in the rest of the "small cycle" is very likely much larger than that in the atmosphere. If true, much less than 50 % would remain in the atmosphere, even if the "small cycle" were a closed system. And that it is not, that is not only "very likely" the case, but it is definitely the case. Substantial amounts of carbon are transferred continuously out of the "small cycle" into the deep ocean and long-lived biomass. According to [1], Fig. 5.12, already the flow into the deep ocean is about one order of magnitude larger than the anthropogenic emissions! And due to its size, the deep ocean reacts to a disturbance only after a delay of around 1000 years. Therefore, the "small cycle" definitely is an open system, and it is out of balance in the relevant time frame.

Thus, the two prerequisites are not fulfilled in reality. No process is recognizable by which 50 % of the emissions systematically remain in the atmosphere. The increase in atmospheric CO_2 concentration must have another explanation.

Upon closer examination, the problem begins with the assumption that what we see is what happens with a particular emission (Ref. [31] views that the increase in concentration had come about by half of the anthropogenic emissions remaining in the atmosphere). Rather, what we see is just a change in the total inventory in the atmosphere. And this total inventory just changes due to the difference between total emissions and total removals, not due to any individual emission alone. The fact that this change corresponds to half of the anthropogenic emissions could be purely coincidental.

But failing to recognize the difference between the balance of the total inventory and the fate of an individual emission is the one thing, another is that [31] also incorrectly concludes that the constancy of the ratio between inventory growth and anthropogenic emissions (always 1:2) proves that the latter is the sole cause of the increase in concentration, with no other contributing factors.

This conclusion is definitely inadmissible, even if it might seem plausible at first glance, if emissions from natural sources had remained constant. In that case, anthropogenic emissions would be the only variable that drives change, making them necessarily the "sole cause" of all changes. However, as already shown, we know that natural emissions must have increased, and that increase must have had an effect. "Sole cause" cannot be true.

But regardless of this, the conclusion derived from the observation of a constant ratio is inadmissible in any case, because a constant ratio proves nothing: Whenever both sources, natural and anthropogenic, grow exponentially, the debated ratio remains constant. This is most likely the case here: The anthropogenic emissions have simply increased more or less exponentially, whatever the cause. And exponential growth is not unusual in natural processes, especially in their early stages. Thus, the observed constant ratio proves nothing, and certainly it does not confirm that anthropogenic emissions are the sole cause of the increase in concentration, as [31] suggests. The fact that this ratio is just 1:2 indeed seems to be pure chance.

This brings us back to models: Explanations, such as those for the movement of the sun or the increase in CO_2 concentration, are always based on models. Only if these models correspond

sufficiently well to reality, can their explanations be regarded as reliable. The "fountain model" used in [31] does not meet this requirement, the "fountain and lake model" seems to be much closer to reality. But it still is a model, not reality, we only ever can approach reality only through models.

8. A sink cannot be a source

Another central argument in [31] is that "a sink cannot be a source". Ref. [31] literally states: "nature is removing CO_2 from the atmosphere rather than adding … Since nature is removing … the rise in atmospheric CO_2 cannot be from natural causes". While this statement sounds logical, it is fundamentally flawed, as has already been shown many times in the cited literature, and as is confirmed below. Nature is always both a source and a sink, emitting and absorbing CO_2 simultaneously. Sometimes emissions exceed absorption, then nature is a net source, and sometimes the opposite occurs, then nature is a net sink.

The statement that "a sink cannot be a source" is based on the observation that the growth of the inventory in the atmosphere is smaller than the anthropogenic emissions of CO_2. This observation is correct beyond doubt, but is therefore the said statement drawn from it also correct? To find an answer, let's start with equilibrium and assume gradually increasing emissions from natural sources. The concentration in the atmosphere begins to rise, and, as a consequence, the outflow from the atmosphere rises too. However, the outflow always lags slightly behind the inflow. Thus, nature is a net source, albeit a small one. This holds for any realistic gradient of natural emissions.

Adding anthropogenic emissions to this scenario accelerates the rise in atmospheric CO_2 concentration, further increasing the outflow from the atmosphere (by the way: with all the outflow going into the same sinks as before, and all these sinks are natural sinks that all benefit in the same way from the increased concentration). If the anthropogenic emissions are small, this just means a smaller gap between the outflow from the atmosphere and the inflow into it from natural sources, meaning nature remains a net source, only a smaller one. However, with higher anthropogenic emissions, the outflow from the atmosphere can exceed the inflow into it from natural sources, making nature a net sink despite emitting increasing amounts.

This is the situation we actually have had over the last 60 or so years (based on measurements at Mauna Loa). Nature is the primary driver of increasing CO_2 concentration, but the additional anthropogenic emissions, although much smaller, are large enough to shift nature to be a net sink. Thus, nature is both the main contributor to rising CO_2 levels and a net sink at the same time. The claim in [31] that these two are mutually exclusive is not valid.

9. Decline of concentration

Based on the "fountain model" with two independent processes for CO_2 - one to exchanges CO_2 between the atmosphere and its partners, and another that removes CO_2 from the atmosphere - [31] concludes that, in the hypothetical case of a sudden stop to all anthropogenic emissions, the concentration of CO_2 in the atmosphere would decline with a time constant (e-folding time) of approximately 50 years. While this calculation is mathematically correct, the model it is based on is far away from reality. In reality, the decline would be much faster.

To better understand the process that removes CO_2 from the atmosphere, again a thought experiment: Imagine replacing one out of one thousand CO_2 molecules in the atmosphere with a red-colored molecule that is otherwise completely identical. The total number of CO_2 molecules in the atmosphere remains the same (no excess pressure!), but the red molecules do not stay in the atmosphere; instead, they are distributed throughout the whole cycle via exchange processes, until uniform concentration (color distribution) is achieved everywhere. In other words: The removal process from the atmosphere is just redistribution following the law of entropy increase (achieving maximum disorder, meaning equal concentration everywhere). The speed of this redistribution is determined by the exchange rate between the atmosphere and its reaction partners: If the exchange rate were twice as high, the process would also run twice as fast. This proportionality

follows from the fact already mentioned that the majority of the processes involved are based on diffusion. The overall result needs not to be perfect proportionality but it is certainly approximate, that's sufficient for the considerations here.

Next, instead of simply exchanging some CO_2 molecules for red ones, we introduce the same number of red molecules in addition to the existing inventory. The result will not be much different: mixing will occur at practically the same speed, governed by practically the same exchange rate, leading to practically the same final state.

This is how any excess CO_2 in the atmosphere behaves: It is not merely pushed out by excessive pressure (where "excessive" means above a given value, [31] takes the preindustrial equilibrium, or at least a value close to it), but rather, the dominant process is striving for equal distribution throughout the whole cycle, and this is accomplished by exchange processes. If only the pressure difference would act, a small excess pressure would result in a very slow decline in concentration. In contrast, the process of achieving uniform distribution throughout the cycle operates quickly (when the exchange rate is high), even if the quantity to be equally distributed is small.

Once again, any excess CO_2 is primarily reduced by exchange processes regulating distribution, and only to a much lesser extent by pressure effects regulating pressure equalization. However, both processes work simultaneously. Concentration therefore declines more quickly than if only one of these processes was working. Returning to the thought experiment with red molecules: this means that their concentration in the atmosphere decreases faster when they are introduced additionally than when they are introduced by exchange. This applies in general: The decline of any increased concentration is always faster when both effects are considered, equal distribution and pressure equalization.

Interim remark: To better reflect the true nature of the outflow process, it might be more appropriate to speak of "distribution within the cycle" rather than "decline of concentration", as the latter suggests that excess concentration is the primary driving force, while the former highlights the role of exchange rates. End of interim remark.

Another point to be considered regarding the decline of concentration is seasonal fluctuations in atmospheric CO_2 concentration: an increase of about 5 ppm in half a year, followed by a decrease of 5 ppm in the next half year (Mauna Loa measurements). Ref. [31] attributes these fluctuations primarily to temperature influences. Be that as it may, in any case, any CO_2 added seasonally to the atmosphere cannot decline faster than any other inflow of CO_2. In other words, the seasonal fluctuations indicate that any excess CO_2 in the atmosphere declines rapidly (for more details see e.g. [25]). Ref. [31] does not take this into account.

Final remark on the thought experiment with red molecules: It also provides a useful means of evaluating the two models discussed: The "fountain model" ignores the decline off excess concentration through mixing and assumes the excess pressure as the only driving force. This assumption brings about the long e-folding time of about 50 years. In contrast, the "fountain and lake model" considers both mixing and pressure-driven effects, leading to a much faster decline in concentration and aligning more closely with reality.

10. Different residence times

The residence time (or "atmospheric lifetime") is the average time CO_2 molecules stay in the atmosphere. It is the reciprocal of the relative outflow-rate. Ref. [31] assumes two different residence times: Approximately 4 years for circulation (corresponding to the annual exchange rate of 25 %), and approximately 50 years for removal (how these 50 years are calculated, see below). The residence time that characterizes circulation is sometimes also referred to as "turnover time", and that that characterizes removal is referred to as "adjustment time". Different residence times for CO_2 depending on its origin have been rejected clearly and repeatedly in the cited literature. This is confirmed below:

The two different residence times in [31] result from its assumption of separate processes for the circulation and for the removal of CO_2 from the atmosphere. However, different residence times

would only be possible

- if there were separate flow paths through the atmosphere, resulting in different flow-through times, or
- if the sinks treated CO_2 differently depending on its origin.

Neither of these conditions applies. There are no partition walls in the atmosphere to separate flows from specific sources to specific sinks, and the atmosphere cannot distinguish CO_2 molecules according to their origin. All CO_2 molecules are thoroughly mixed, behave identically, and all sinks operate similarly in response to concentration (for clarification: The strength of a sink can depend on various parameters like temperature etc., but whatever these dependencies are, a dependency on the concentration exists for all sinks). Consequently, there is only one process responsible for both tasks, and a single process can only have one residence time.

However, [31] claims two different residence times. The 50 years for removal are calculated from the net outflow of CO_2 from the atmosphere (approximately 2.5 ppm/y) and from the excess concentration in the atmosphere of about 140 ppm above equilibrium (420 versus 280 ppm) as the driving force. While this calculation of 50 years is mathematically correct, it lacks physical justification: The two numbers used in this calculation are not measured values but derived ones, which do not exist as tangible material quantities. There is no actual flow of 2.5 ppm/y; instead, there are two far larger counter-directional flows (around 40 times larger!) with a net difference of 2.5 ppm/y. Similarly, 140 ppm, taken as driving force, are just the calculated difference of the same parameter at two different points in time, not a physical quantity measurable in today's state. Thus, the calculated value of 50 years is only a theoretical value and has no physical relevance.

In section 9, it was shown that the outflow of CO_2 molecules from the atmosphere is driven by two forces (circulation and excess pressure) and thus occurs faster than if only one of the two would work. As a result, the actual residence time of the CO_2 molecules in the atmosphere is shorter than that resulting from the circulation alone, and it is much shorter than that resulting from the excess pressure alone.

Supplement: The old equilibrium from the pre-industrial era simply no longer exists and the atmosphere cannot "remember" it either. The atmosphere only knows its today's boundaries, and these yield an equilibrium significantly different from that 250 years ago. If anthropogenic releases were to stop (and natural emissions remained constant), the atmosphere would not return to the old equilibrium of 280 ppm concentration; rather, the new equilibrium would be relatively close to today's concentration.

11. $^{13}C/^{12}C$-ratio

Regarding carbon isotope ratios, [31] puts forward arguments that challenge the predominantly natural origin of the large amount of CO_2 in the atmosphere and appear to be plausible at first glance. Admittedly, I have not yet delved deeply into this issue. However, considering the virtually identical chemical behavior of different isotopes, the very small proportion of ^{13}C in all reservoirs, and the wide variation in possible carbon cycles, it seems to be more probable that the apparent contradiction could be resolved through reexamination of isotopic analyses and their conclusions, rather than through fundamental changes in the considerations and conclusions presented in this reply. This is also supported e.g. by [26]. Further scrutiny is urgently required to address this issue.

12. $^{14}CO_2$

Background: Over the last 250 years, CO_2 emissions only have increased constantly, except for two notable exceptions: Seasonal fluctuations, and the effects of the COVID-19 pandemic in 2020. The former are cyclic and minor, they can therefore make it difficult to recognize longer-term trends. What they nevertheless tell us, namely that CO_2 is rapidly removed from the atmosphere, has already been described in section 9. On the other hand, the drop due to the pandemic

was a single event, and it has led to a decrease in anthropogenic emissions of up to 17 % [32]. That should actually show some effect on the concentration curve (that also shows the seasonal fluctuations!), but nothing can be seen, no matter how closely you look. Rather, the concentration continued to rise unaffected. This strongly suggests that the total emissions have increased at about the same rate as before and that the anthropogenic emissions play only a minor role.

However, the pandemic-induced reduction of the emissions was short-lived, and therefore, at least theoretically, it could have been masked by other influences occurring simultaneously. What really happens when emissions decrease persistently remains uncertain. Without long-term observations we can only calculate it using models, with all the uncertainties models entail (especially, if we use inappropriate models).

However, $^{14}CO_2$ provides a remedy: $^{14}CO_2$ is an unstable variant of "normal" CO_2 (essentially $^{12}CO_2$, with about 1 % $^{13}CO_2$), which is produced naturally in the atmosphere by cosmic rays at a very low rate. With its half-live of about 5730 years, $^{14}CO_2$ reaches an equilibrium concentration in the atmosphere in the order of 10^{-10} %. Due to its radioactivity, it nonetheless can be measured precisely, and its concentration can be followed over time. In the late 1950s and early 1960s it was substantially generated by above-ground atomic bomb explosions, almost doubling its concentration. After the Test Ban Treaty 1963, the anthropogenic production stopped almost completely, and afterwards the concentration declined rapidly (Fig. 2). This gave us the unique opportunity to observe a major decline in CO_2 concentration.

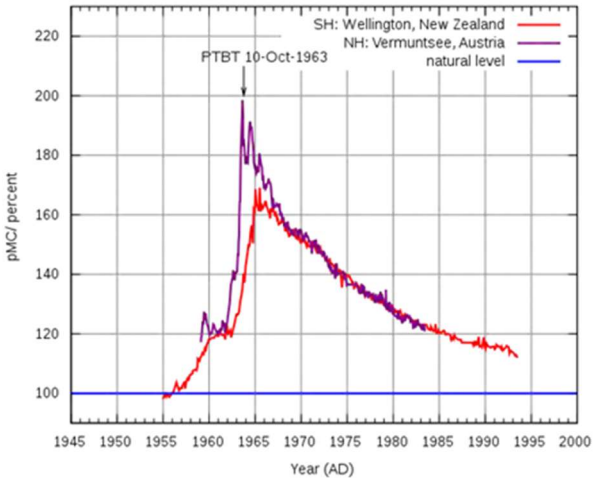

Fig. 2: Concentration of $^{14}CO_2$ over time. This is Fig. 1.3.1 of [31], the values are from Wikipedia 2008. The ordinate shows relative values in comparison to an internationally defined standard. After the first few years, the further decline occurred with a fixed time constant. The measured values here end in 1993, prolonged measurements show a further drop back to approximately the undisturbed value.

Ref. [31] puts a lot of effort into analyzing the $^{14}CO_2$ data and comes to the conclusion that "the decrease of the $^{14}C/C$ ratio in the atmosphere (after the Test Ban Treaty) supports the fact that fossil fuels are the cause of the CO_2 increase in the atmosphere". This is surprising because this connection is not easy to understand. Why does the decline in $^{14}CO_2$ show where "normal" CO_2 comes from? Do the two have anything to do with each other at all? But let's check it out.

In the first few years after the Test Ban Treaty, the concentration of $^{14}CO_2$ exhibited large fluctuations, likely due to delayed seasonal transfer from the stratosphere (where much of it was produced or transported immediately after production), into the troposphere (where all measurements were conducted). It is only after about 1970 that measurements showed the uninterrupted and continuous decline in concentration.

However, this decline is not due to the distribution of $^{14}CO_2$ within the "small cycle". Because of the high exchange rates in this cycle, this distribution has largely been completed within a few years. What is measured after 1970 is mainly the transfer of ^{14}C out of the "small cycle" into the deep ocean and long-lived terrestrial biomass. Ref. [31] gives the observed atmospheric lifetime of $^{14}CO_2$ as 16 years, respectively as 20 years with some amazingly high corrections due to the influence of burning fossil fuels. But even that is significantly shorter than the adjustment time of 50 years suggested in [31] for excess CO_2 in the atmosphere.

This is all the more important because, as already said, [31] claims that the rapid decline of $^{14}CO_2$

"supports the fact that fossil fuels are the cause of the CO_2 increase in the atmosphere". However, with an atmospheric lifetime of 16 or 20 years, the small anthropogenic emissions can never accomplish the strong rise in atmospheric concentration that has occurred. Ref. [31] itself has calculated that 50 years lifetime are required for this. Therefore, the rapid decline of $^{14}CO_2$ does not support fossil fuels as course, rather, it contradicts it. Ref. [31] attempts an explanation of this discrepancy via re-emissions from other reservoirs but this explanation is not convincing. Ref. [31] does not sufficiently take into account the specifics of how CO_2 is removed from the atmosphere, see section 9.

However, 20 or 50 years isn't everything anyway: Perhaps the most important insight that we can gain from the observations of $^{14}CO_2$ is that its fast decline did not stop at 50 % but persisted until the concentration has returned essentially to its pre-bomb-test baseline. This clearly contradicts the retention of 50 %. And when 50 % are not retained, then they cannot accumulate to a high concentration, as [31] assumes for anthropogenic emissions.

Summing up $^{14}CO_2$ data:

- They provide evidence of a rapid decline in concentration, and
- They disprove the claim that 50 % of CO_2 emitted remains in the atmosphere.

Assessment: What applies to $^{14}CO_2$ also applies to any other CO_2 emitted into the atmosphere, it cannot behave differently. Thus, $^{14}CO_2$ data directly contradict the central claim in [31] that the observed increase in atmospheric CO_2 concentration is man-made. And $^{14}CO_2$ data are real measured values, not calculated values with questionable models.

One last remark: $^{14}CO_2$ produced by nuclear explosions is not much different from the thought experiment with red molecules proposed in section 9. It's only that in this case the special recognizability of these molecules is not achieved by their color, but by their radioactivity. However, the distribution of the molecules is subject to exactly the same laws.

13. Oxygen

Ref. [31] claims that changes in oxygen-concentration prove the anthropogenic causation of the elevated CO_2-concentration. However, this argument does not hold either. Oxygen is consumed when fossil fuels are burned, and it is produced when plants grow (greening of the Earth). The oxygen mass balance merely reflects the accuracy of our estimates of these two processes; it says nothing about the source of the elevated CO_2 concentration. CO_2 emissions from natural sources do not affect atmospheric oxygen levels (except for emissions from wildfires).

14. Temperature influence

Ref. [31] extensively examines the relationship between temperature and increasing CO_2 concentration, with the result that warming should have had only a minor influence, maximum about 10 % or 13 ppm. Therefore, [31] concludes: "The main cause of the observed 130-ppmv increase is the 210 ppmv one-way human addition" (for clarification: ppmv is largely the same as ppm, 130 ppmv is the observed increase in atmospheric concentration, and 210 ppmv is the cumulated anthropogenic emission since the start of the Industrial Revolution).

Of course, the influence of temperature on emissions needs to be examined in detail. In contrast to [31], e.g. [30] shows a high influence, which may very well explain all the observed increase in concentration. But this is only of secondary importance, because the conclusion made in [31] is again some sort of a forbidden "inverse conclusion" (see section 5): The assumption, when the warming that has occurred indeed can explain the increase in concentration, then anthropogenic emissions are most probably irrelevant, is correct, but its inverse, if not the temperature is the cause, then anthropogenic emissions are, is not permitted. Temperature or humans that is simply too easy, there are also other possible sources of CO_2 (some are mentioned in section 4). A limited contribution of temperature - even if correct - proves nothing, at least not human causation.

15. Historical CO_2 levels

Ref. [31] undertakes an impressive effort to investigate whether ice core data, other proxy data, and historical chemical measurements show evidence of similar events in the past (rapid and large increases in CO_2 concentration). For the last 800,000 years - covered by ice core data - the answer appears to be no. Of course, all this has to be checked in detail, e.g. [33] tells the contrary, but again, that is secondary.

The real problem is that [31] seems to have fallen again into the heuristic trap "inverse conclusion" (see section 5): It is correct, if similar events occurred in the past, then there is a high probability that the current one is just a repetition, equally caused by natural factors. However, the inverse - that the current event must be caused by humans simply because nothing comparable has happened in the past 800,000 years - is not permissible. The true nature of nature is its capriciousness. Nature can very well do something now that it has not done in the last 800,000 years. We cannot dictate to nature what it should do; only physics can dictate to nature. And what physics dictates regarding open systems and the treatment of identical molecules from different origins is explained in this reply. Unless errors are found in these explanations, they remain valid. Anthropogenic releases have been much too small to increase the concentration by 50 %.

16. Summary and conclusions

The main result of [31] is the statement that the strong rise in atmospheric CO_2 concentration is manmade. And the main finding in this reply is that this cannot be correct. Anthropogenic emissions are far too small for an increase in concentration of 50 %, emissions from natural sources must have contributed the lion's share. The root cause for the incorrect result in [31] is the use of a model (the "fountain model") that does not correspond sufficiently well with reality. Statements made by such a model simply have no physical justification. If a model much closer to reality is used instead, the results are decisively different. In this reply, this is demonstrated by the "fountain and lake model".

The key shortcomings in the model used in [31] are its different treatment of identical molecules, its disregarding of the open character of the "system atmosphere", and its assumption of unchanged natural flows. And the key shortcomings in the analysis performed in [31] are conclusions that are not logically justified upon closer examination. Furthermore, the only measurements that really tell us something about the decline in CO_2 concentration, namely those of seasonal fluctuations and those of $^{14}CO_2$, are misinterpreted in [31], as is shown in this reply. The findings in this reply seem to be robust.

If they are, this has far-reaching consequences. There are only two possibilities left: If CO_2 drives climate change, then natural CO_2 sources are the primary drivers. And if other factors dominate, then CO_2 plays only a minor role, whatever its origin. In either case, reducing anthropogenic CO_2 emissions is unnecessary, at least for the sake of climate protection. We could enjoy the benefits of higher CO_2 concentrations, and we could deploy scarce resources more effectively for more pressing issues. A review of the arguments presented here is therefore imperative, not only due to the far-reaching consequences but also because of unresolved contradictions regarding the $^{13}C/^{12}C$ data. Of course, there may also be a decisive error elsewhere in this reply, but this also has to be demonstrated first.

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