PREPRINT

Comment on Stallinga, P. (2023), Residence Time vs. Adjustment Time of Carbon Dioxide in the Atmosphere.

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The goal of Stallinga (2023), to address confusion about CO_2 "residence time" and "adjustment time," is laudable. Unfortunately, the author, himself, has confused them.

Dr. Stallinga made two key errors, the second following from the first. His first and most important mistake was his claim that, "the adjustment time is never larger than the residence time."

That is backward. It is easily shown that the adjustment time is much longer than the residence time, because some of the processes which reduce the residence time do not reduce the adjustment time.

He also wrote that neither the residence time nor the adjustment time is "longer than about 5 years."

That is correct only for the residence time. It is wrong by a full order of magnitude for the adjustment time. The adjustment time can be determined from measurements, and it is approximately fifty years.

There are four different commonly mentioned atmospheric lifetimes for CO_2 emissions:

1. Many climate scientists cite a theoretical "long tail" atmospheric lifetime, often claimed to be hundreds or even thousands of years, based on various inconsistent and unverifiable computer models. It is of little practical consequence, except as a talking point for activism. [Archer 2008]

2. The measurement-derived adjustment time, of about 50 years. This is the lifetime which determines the duration of effect for contemporary CO_2 emissions. [Spencer 2023, Engelbeen 2022]

3. The ^{14}C radiocarbon "bomb spike" atmospheric lifetime, of about 20 years (but sometimes mistakenly reported as 15-16 years). This has important ramifications for carbon dating, but not for climate.

4. The short "residence time," of 3 to 5 years. The IPCC's AR6 report calls this "turnover time." [IPCC AR6 WG1, Annex VII Glossary, p.2237] Like the long tail lifetime, it is of little practical consequence.

1. The theoretical "long tail" lifetime

If CO_2 levels were falling, "browning" would replace "greening,"[Zhu 2016] and the terrestrial biosphere would presumably become a source of CO_2, rather than a sink. So models of the theoretical decay curve for atmospheric CO_2 in the hypothetical event that emissions suddenly cease typically show a "long tail."[Archer 2008] That is, the decay curve would gradually diverge from a simple exponential decline, in that the second CO_2 half-life would be longer than the first, the third would be longer than the second, etc.

That is uncontroversial. However, nature provides few clues for modeling the shape of decay curve's long tail. So the models are based on little more than guesses, and they are untestable.

Models like MAGICC [Meinshausen 2011] or the Bern Model [Strassmann 2018], are widely used, probably because they're readily available, but their long term projections are not reliable, as estimates for the "fatness" and "length" of the "long tail" vary wildly.[Wang 2016] So integrating the modeled long tail yields greatly varying (and often very exaggerated) estimates of climate impact, which special interests can use to calculate even more exaggerated "social cost of carbon" figures.

Some especially unrealistic estimates claim that as much as 40% of a theoretical pulse of anthropogenic CO_2 will remain for more than 1000 years, or even that, "the mean lifetime of fossil fuel CO_2 is about 30–35kyr." [Archer, 2005]

However, second and subsequent CO_2 half-lives are largely irrelevant while CO_2 emissions exceed natural CO_2 removals and atmospheric CO_2 concentrations are rising, as is currently the case.

Moreover, if CO_2 levels were to fall so low that second and subsequent half-lives become relevant (i.e., if at least half of the anthropogenic CO_2 increase were gone from the atmosphere), it would be painfully obvious to everyone left alive that slowing the CO_2 decline is desirable, rather than harmful. So using the theoretical "long tail" as a multiplier for supposed harms from carbon emissions is clearly a mistake, but it is a common one.

The theoretical "long tail lifetime" is of little practical consequence, except as a talking point for activism.

2. The measurement-derived adjustment time

You can think of the adjustment time as the "effective residence time." It's the duration of the effect on CO_2 levels from adding CO_2 to the atmosphere.

The measurement-derived adjustment time is about 50 years. It's determined from observations, from the rate at which net natural sinks (mostly ocean, terrestrial biosphere & soil) remove CO_2 from the atmosphere.

We have pretty good data for the rate at which fossil CO_2 is added to the atmosphere (currently about 4.6 ppmv/year) [GCB 2023], and since 1958 we have excellent data for the rate at which the atmospheric CO_2 level is rising (currently about 2.5 ppmv/year at Mauna Loa, averaged over a decade). The difference between those two rates is the net natural CO_2 removal rate: 4.6 – 2.5 = 2.1 ppmv/year [NOAA GML, n.d.].

(Aside: Alternatively, a similar calculation can be done including estimated "land use change emissions," i.e., CO_2 from clearing forests, draining swamps, etc. Doing so increases emissions and calculated removal rate by exactly the same amount. However, estimates of land use change emissions are very rough, so I've chosen not to include them. That effectively treats them as reductions of natural CO_2 removals.)

Figure 1 shows the net natural CO_2 removal rate is plotted vs. the atmospheric CO_2 concentration. It is obvious that the CO_2 removal rate is an approximately linear function of the atmospheric CO_2 level. (The spreadsheet is included in the supplemental data.)

https://sealevel.info/Global_Carbon_Budget_2023v1.1_with_removal_rate_plot2.png

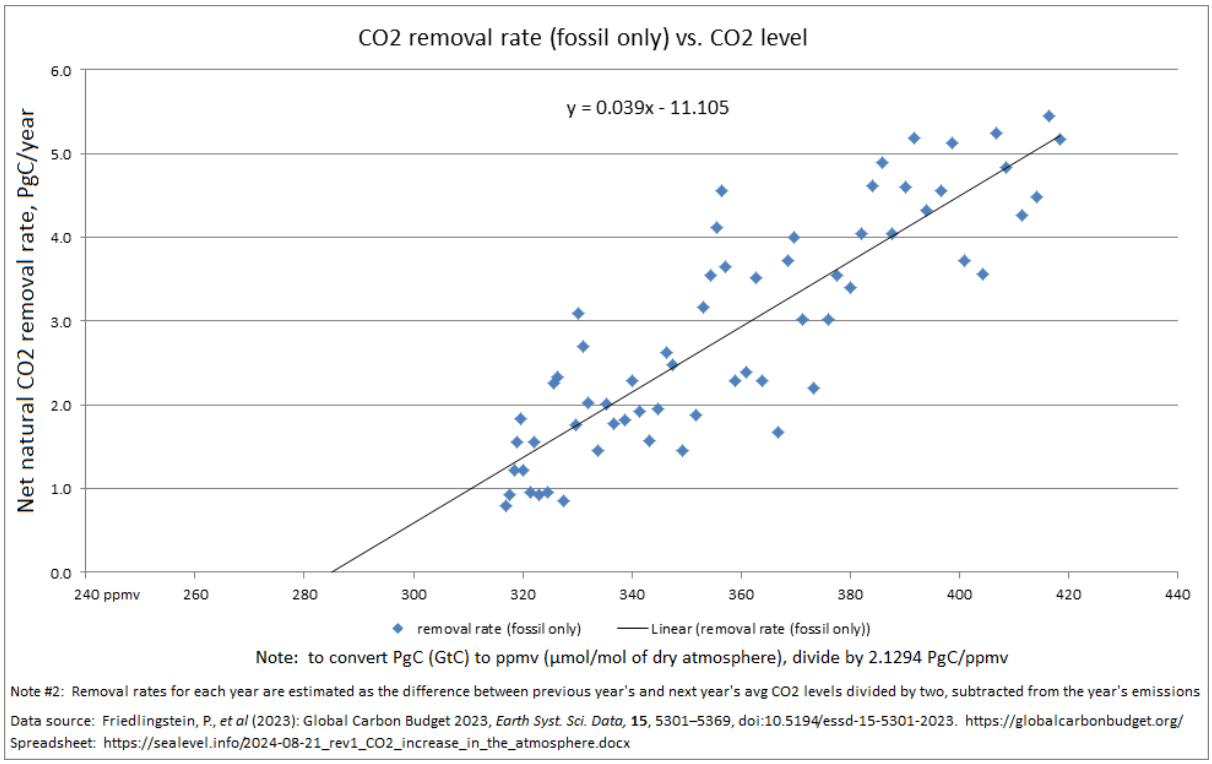

Fig. 1. *Net natural CO_2 removal rate (fossil only) vs. Mauna Loa CO_2 level. Removal rates for each year are estimated as the difference between the previous year's and next year's average CO_2 levels divided by two, subtracted from the year's emissions. Removal rates are shown as PgC/year; to convert to ppmv/year divide by 2.1294 PgC/ppmv.*

The x-intercept gives an estimate of the equilibrium level, which is 285 ppmv. (An alternative calculation including land use change emissions yields a slightly lower value.)

The slope is 0.039 PgC/ppmv. Converting it to common units by dividing by 2.1294 PgC/ppmv yields a net natural CO_2 removal rate of 1.83% per year. In other words, about 1.83% of the "excess" CO_2 above the 285 ppmv equilibrium level is removed each year by natural sinks.

The linearity of the relation is unsurprising, since the two major contributors, ocean uptake and terrestrial greening (trees!), are both approximately linear functions of atmospheric CO_2 level. That's probably obvious for ocean uptake, but it might be less so for greening. However, agronomists have extensively studied the responses of a wide variety of plants to elevated CO_2, and the studies show that average response of C3 plants (which include all trees) to elevated CO_2 is highly linear, until CO_2 levels exceed about 1000 ppmv, which is far higher than burning recoverable fossil fuels could ever raise outdoor CO_2 levels.[Wang 2016]

https://sealevel.info/C3_and_C4_Pflanze_vs_CO2_Konzentration_en_1750_2023_linearity_highlighted3.png

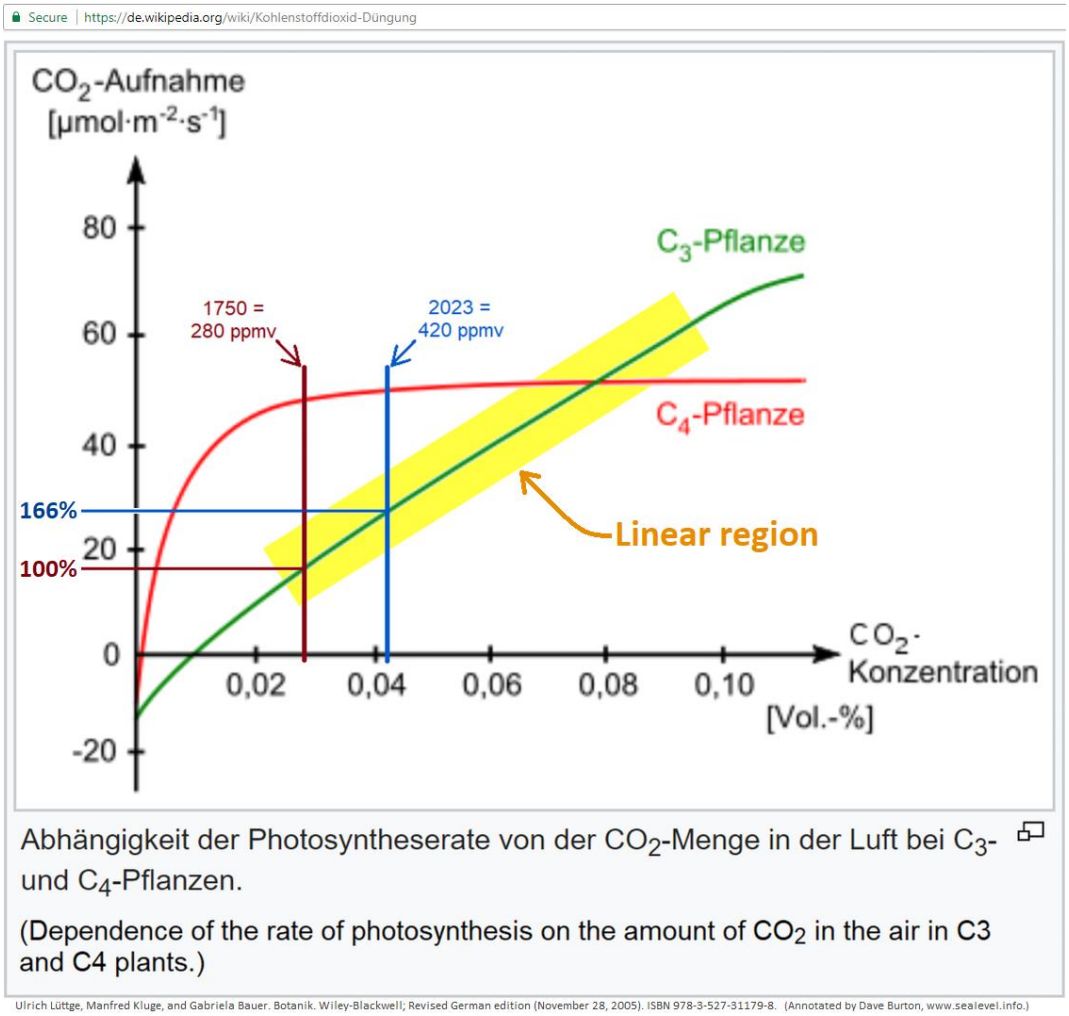

Fig. 2. *Dependence of the rate of photosynthesis on the amount of CO_2 in the air in C3 and C4 plants. Adapted from Wikipedia reproduction of an illustration from Lüttge 2005, p.473; https://commons.wikimedia.org/wiki/File:Photosynthese_CO2-Konzentration.svg, CC BY-SA 3.0.*

Figure 2 is adapted from Lüttge 2005, by way of Wikipedia. It shows that the average rate of CO_2 uptake by C3 plants is highly linear until CO_2 levels exceed about 1000 ppmv. Note that trees and sphagnum moss, which sequester large amounts of carbon for relatively long periods of time, are both C3 plants.

Spencer (2023) did a more refined analysis of the relation between atmospheric CO_2 level and the rate of natural CO_2 removal, taking into account ENSO. He reported an equilibrium level (x-intercept) of 294 ppmv, and a net natural CO_2 removal rate of 2.02% per year (above that equilibrium level).[Spencer 2023]

A removal rate of 2% per year means the adjustment time is 1 / 0.02 = 50 years. A 50 year adjustment time makes the half-life of added CO_2 50×ln(2) = 35 years.

In other words, if humans suddenly stopped emitting CO_2, then the CO_2 level in the atmosphere would drop by almost 65 ppmv (i.e., half of 423-294) in just 35 years. (A simple simulation program is included in the supplemental material.)

The 50 year, measurement-derived adjustment time is the only time constant which matters for analyses of the cause of rising CO_2 levels, and projections of CO_2 levels in the atmosphere.

3. The ^{14}C radiocarbon "bomb spike" atmospheric lifetime

The atmospheric lifetime of “bomb spike” ^{14}C radiocarbon in the atmosphere is about 20 years.

(It is sometimes erroneously estimated as about 15-16 years. Incidentally, one of the papers making that mistake was Stallinga (2023), which reported it as 14.0 years.)

^{14}C is usually reported as “Δ14C,” which is defined as the fraction of atmospheric carbon which is (or was) in the form of the ^{14}C isotope, divided by a standard "Modern" value for that fraction (either $^{14}C/C$ = 1.170e-12 or $^{14}C/C$ = 1.176e-12), and reported as ‰ (parts-per-thousand) relative to that standard (either positive or negative).

The amount of ^{14}C radiocarbon in the atmosphere was nearly doubled by atmospheric testing of hydrogen bombs in the 1950s and early 1960s (i.e., Δ14C briefly approached +1000‰ in the northern hemisphere). When the Limited Test Ban Treaty went into effect in 1963, the USA, USSR & UK ceased atmospheric tests of H-bombs, and the “bomb spike” began falling, as exchanges with the oceans and other carbon reservoirs replaced atmospheric CO_2 containing elevated radiocarbon.

Additionally, by the late 1960s the atmospheric CO_2 level was rising by about 1 ppmv/year, due to human emissions, mostly from fossil fuels. That so-called “fossil carbon” is depleted of ^{14}C, because ^{14}C decays to ^{14}N with a half-life of 5700 ±30 years, so adding fossil carbon to the atmosphere lowers the percentage of ^{14}C in CO_2 in the air. That is called the “Suess Effect.”[Keeling 1979] Suess Effect dilution accounts for about one-fourth of the total observed decline in Δ14C since the bomb spike.

As a result of the combined effects of those two processes, the Δ14C bomb spike declined with an observed half-life of about 11 years.

At first blush, that would appear to make the atmospheric lifetime 11/ln(2) = about 16 years. However, increasing the amount of CO_2 in the atmosphere (by burning fossil fuels) reduces Δ14C without actually removing ^{14}C from the air, it only reduces the fraction of carbon which is in the form of ^{14}C.

To calculate the actual average atmospheric lifetime of ^{14}C added to the atmosphere by the bomb spike, we need to consider, instead, what the Δ14C decay rate would have been, were it not for Suess Effect dilution from fossil fuel use.

Graven (2020) conducted simulations with a simple carbon cycle model, and plotted the calculated $^{14}CO_2$ decay with and without fossil fuel CO_2 supply, as shown in their Figure 4:

https://sealevel.info/Graven2020_Fig4_250pct_cropped3.png

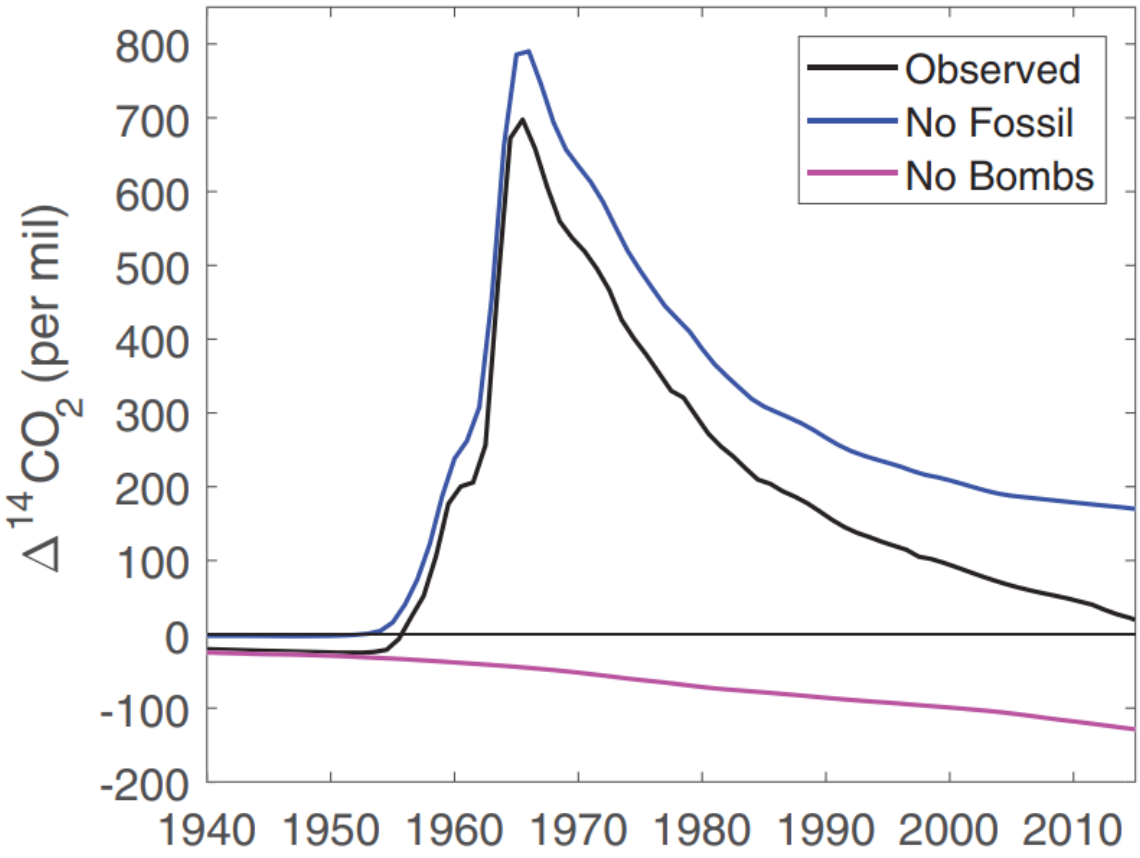

Figure 4. Observed $\Delta^{14}CO_2$ and simulated $\Delta^{14}CO_2$ for scenarios without nuclear weapons tests ("No Bombs") or without fossil fuel burning ("No Fossil").

Graven, H. *et al* (2020). Changes to carbon isotopes in atmospheric CO2 over the industrial era and into the future. *Global Biogeochemical Cycles,* 34(10), e2019GB006170. doi:10.1029/2019GB006170

Fig. 3. *^{14}C radiocarbon bomb spike: observed levels vs. two simulations. From Graven (2020).*

Dr. Graven graciously sent me their data, from which I constructed a log-linear plot, and found an atmospheric lifetime of about 20 years, as shown in Figure 4.

https://sealevel.info/Graven2020_nofossil_logscale_1970-1995_annot6.png

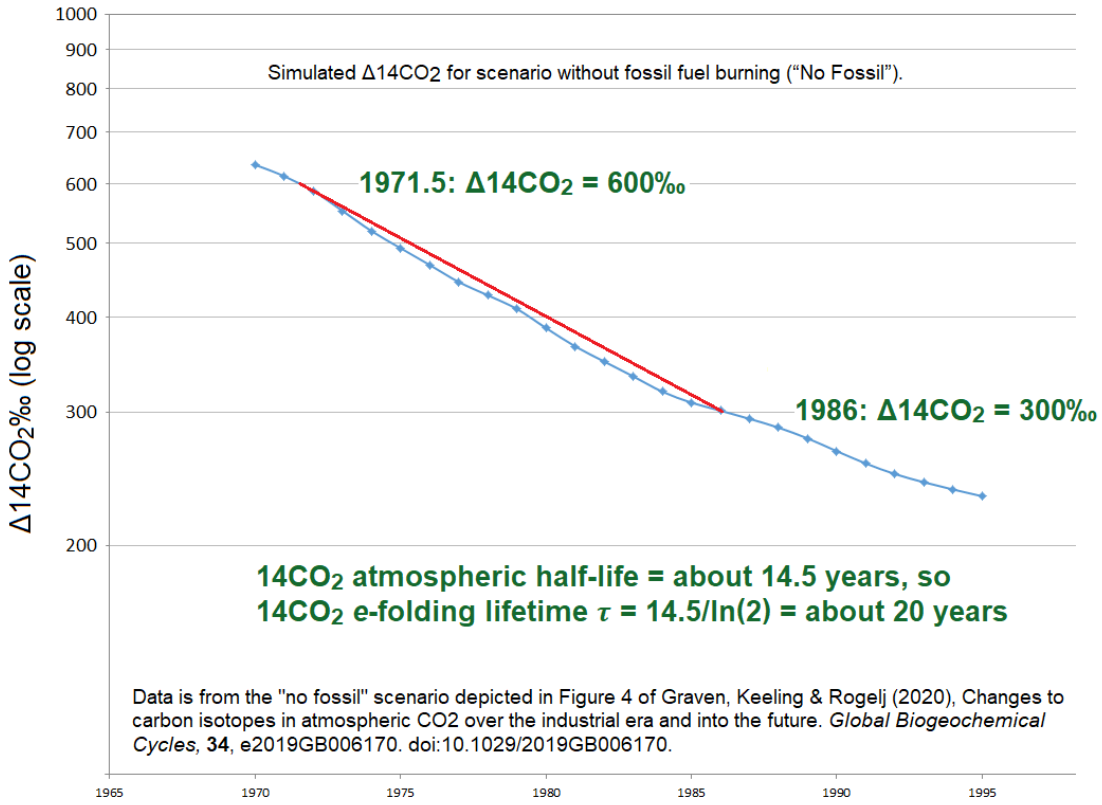

Fig. 4. *Log-linear plot of "bomb spike" Δ14C, showing the approximately 20 year lifetime.*

(Note: the reason for using the left part of the graph for this determination is that it's the part of the graph for which the greatest portion of the observed trend is due to ^{14}C removals, which is what we're interested in, and for which the smallest portion of the observed trend is due to Suess Effect dilution and the carbon cycle model.)

The reason that the bomb spike radiocarbon atmospheric lifetime (20 years) is shorter than the measurement-derived CO_2 adjustment time (50 years) is that some of the processes which reduce the amount of ^{14}C in the atmosphere do so by exchanging it for other carbon, from other carbon reservoirs (mostly oceans and terrestrial biosphere & soils). That reduces Δ14C without reducing the total amount of carbon in the atmosphere.

Those "exchange" processes contribute to the relatively short 20 year atmospheric lifetime of "bomb spike" radiocarbon, without contributing to the net removal of CO_2 from the atmosphere. So the 20-year ^{14}C bomb spike lifetime is too short for use analyzing the causes of CO_2 level changes, or projecting trajectories of CO_2 levels in the atmosphere.

4. The short "residence time" or "turnover time"

The short residence time, which AR6 calls the "turnover time," is the average amount of time which molecules of CO_2 added to the atmosphere remain there. This is commonly estimated to be only 3-5 years.[IPCC AR6 WG1, Annex VII Glossary, p.2237]

The reason it's so short is that, in addition to the "removal processes" which result in the 50-year measurement-derived adjustment time, and the "exchange processes" which shorten the ^{14}C radiocarbon atmospheric lifetime to about 20 years, the residence time is further shortened by processes which only temporarily remove carbon from the atmosphere.

When a CO_2 molecule is absorbed by a puddle or raindrop, that's the end of its residence time in the air. When that puddle or raindrop evaporates, releasing the dissolved CO_2 molecule back into the air, that's the start of a new residence time, but it does not affect the amount of CO_2 in the air.

Similarly, if a carbon atom is exchanged between the air and the terrestrial biosphere or ocean, either immediately or perhaps after a growing season, that exchange "resets the timer" if you're counting "residence times" of carbon atoms, but it does so without affecting the amount of CO_2 in the air.

Because they don't affect the amount of CO_2 in the air, those processes are not relevant when analyzing atmospheric CO_2 trends. So the 3-5 year short residence time is irrelevant to analysis of the cause of rising CO_2 levels and for projecting trajectories of CO_2 levels in the atmosphere.

Supplemental data

Supplemental data can be found on the author's website:

https://sealevel.info/Comment-on-Stallinga2023

Conflicts of interest

The author declares no conflicts of interest.

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