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On the Increase of CO_2 in the Atmosphere

And the CO_2 Residence Time Confusion

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Abstract

There is a lot of discussion between Climate Realists about the origin of the CO_2 increase in the atmosphere. Some think that it is mostly natural and others that it is mostly human caused. The carbon mass balance, supported by all available observations, shows that humans are the primary sources of the increase.

Related discussions are driven by confusion about the interpretations of the term "residence time" for CO_2 in the atmosphere: turnover time (for a single molecule), adjustment time (for an extra mass of CO_2 above equilibrium), or long-tail lifetime (for the last remaining extra CO_2).

In this work we will try to show the difference between the three definitions.

Keywords: Carbon mass balance; residence time; turnover time; adjustment time; lifetime.

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1. Introduction

In the period 2000-2010, there were several discussions with climate realists in several countries about the cause of the increase of CO_2 in the atmosphere, including the Norwegians Segalstad and Goldberg, in the Netherlands a group around the late Arthur Rörsch, in the UK Richard Courtney, and others. That was the motivation for creation of a comprehensive website [Engelbeen, 2007], where the evidence of a human cause of the CO_2 increase was catalogued. In 2024 a more elaborated overview [Engelbeen et al, 2024] was published for the CO_2 Coalition.

Based on my knowledge of chemical processes, in my opinion the carbon mass balance was already sufficient proof that the human emissions of fossil fuel burning were the cause of the CO_2 increase in the atmosphere.

A closely related issue is the speed at which the human releases of CO_2 are removed from the atmosphere by natural processes, which is what determines the effect of current CO_2 emissions on future atmospheric CO_2 levels.

From these discussions, it was clear that there was a lot of confusion about the term "residence time," as that was used for quite different definitions for the fate of human emissions as individual molecules (turnover time), as extra carbon mass (adjustment time), or as theoretical residence time based on models (lifetime). That was discussed in a workshop, organized by Clintel in Athens, September 2024 [Engelbeen, September 2024].

The combination of these two discussions was highlighted at the end of the recent Scandinavian Climate Realists Conference in Oslo, August 31, 2025 as a discussion piece between Hermann Harde and me. Here follows the main points of my point of view.

2. The carbon mass balance, the $\delta^{13}C$ changes and the oxygen balance

2.1 The carbon mass balance.

The human use of fossil fuels each year causes a certain amount of CO_2 emissions. These amounts are rather well known, based on sales (taxes!) and burning efficiency of the different fuels. They might be somewhat underestimated, due to the human nature to avoid taxes and for political reasons for some countries, but certainly not overestimated.

100% of human CO_2 emissions go directly into the atmosphere, and are reflected in both its total mass and its isotopic composition. The rate at which the amount of CO_2 in the atmosphere is increasing averages only about half the rate of human emissions, which means that "nature" (defined as the net sum of all natural CO_2 sources and sinks) is removing half as much CO_2 as humans are adding. Since nature is removing CO_2, rather than adding it, nature cannot be causing the ongoing increase in the amount of CO_2 in the atmosphere.

Most of the carbon emitted by humans is "fossil" carbon. However, that doesn't mean most of the extra carbon (in CO_2) in the air is fossil carbon. Based on isotopic analyses, we know that about 2/3 of the original fossil CO_2 molecules in the air have been replaced through exchanges of carbon between the atmosphere and other "carbon reservoirs," such as the oceans and the terrestrial biosphere.

Figure 1 shows the CO_2 increase in the atmosphere and the summed human emissions from fossil fuels only, not including the more uncertain emissions of land use changes. That shows that fossil fuel emissions are about twice the increase in the atmosphere. While one must be aware that upgoing variables in many cases cause spurious correlations, in this case, cause and effect are quite certain. The influence of rising sea surface temperatures on CO_2 levels is quite small, as can be calculated with the formula of Takahashi, based on near one million seawater samples.

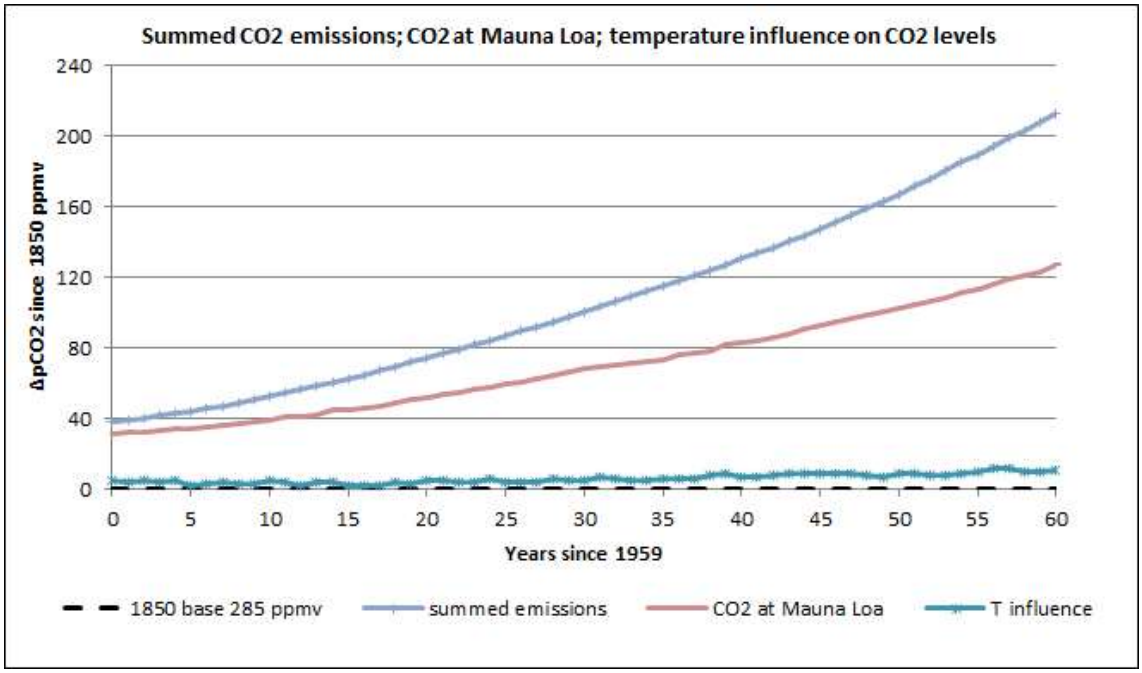

Figure 1: Increase of CO_2 in the atmosphere compared to fossil fuel emissions without land use change and theoretical influence of sea surface temperatures since 1850.

All the available observations point to fossil fuel emissions as the main cause of the CO_2 increase in the atmosphere. That is reflected in a comprehensive report of the CO_2 Coalition (Engelbeen et al, 2024). The carbon mass balance calculations are the main proof that human emissions are the main cause of the ongoing increase in atmospheric CO_2, and the isotopic evidence corroborates that proof.

2.2 The $^{13}C/^{12}C$ balance

Fossil fuels emissions have low ^{13}C content, compared to the atmosphere. Inorganic carbon on earth has a $^{13}C/^{12}C$ ratio, expressed as $\delta^{13}C$, of around zero ‰ (which is defined as a $^{13}C/^{12}C$ molar ratio of 0.0112372). Organic material has slightly less ^{13}C relative to ^{12}C (i.e., negative $\delta^{13}C$), due to the discrimination between ^{12}C and ^{13}C during the incorporation of CO_2 in living material by photosynthesis and other biological processes. Fossil fuels, being of ancient organic origin, likewise have a negative $\delta^{13}C$.

Over the past 170 years there is a direct correlation between CO_2 level and $\delta^{13}C$ in ice cores, firn, and direct measurements of ambient air and fossil fuel emissions (Rubino et al, 2013):

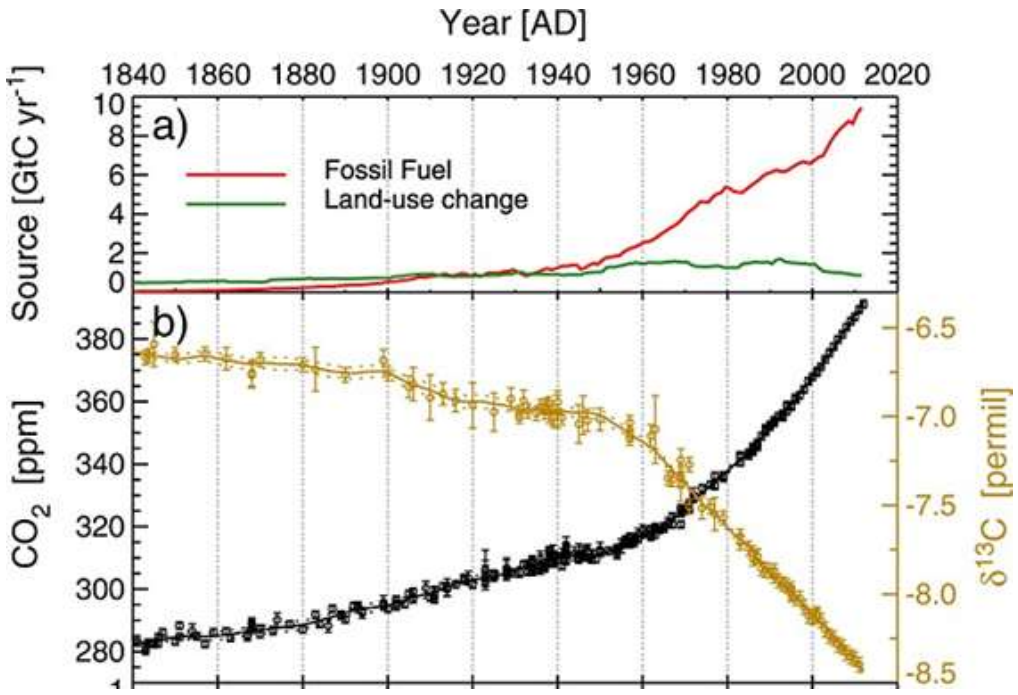

Figure 2: CO_2 and $\delta^{13}C$ in ice cores, firn and air compared to fossil fuel emissions.

2.3 The oxygen balance

Each type of fuel uses specific quantities of oxygen when burned, and the total oxygen use can be calculated from the sales and burning efficiencies. Sufficiently accurate measurements of oxygen are only recently available to measure the drop in oxygen over time. The oxygen balance shows that less net oxygen was used than calculated from fossil fuel burning. That implies that the biosphere is a net producer of oxygen and thus a net absorber of CO_2. The remainder of the oxygen and CO_2 balance then is what the oceans absorbed as CO_2:

The O_2 balance shows the partitioning of the CO_2 absorption between the biosphere and the oceans and is a clear indication of the increase of biomass in the world: The earth is greening...

3. The differences in the definitions of residence time

3.1 The turnover time.

There is a lot of confusion on this topic: the main definition of residence time is the time that a single particle or molecule resides in a reservoir. That is also called the turnover time. For CO_2 in

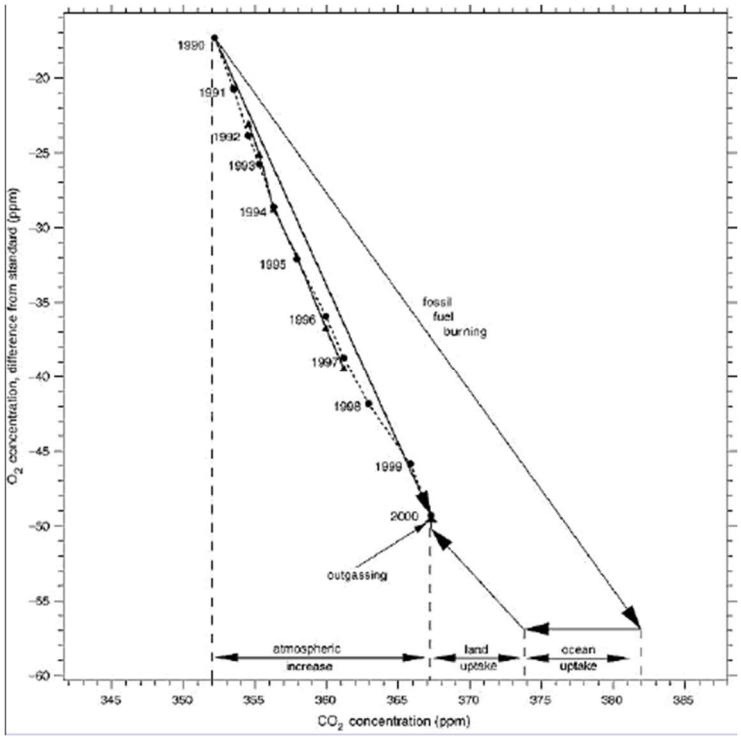

Figure 3. O_2 and CO_2 balances from fossil fuel use.

the atmosphere, the residence time for a single molecule is about 4 years:

$$RT = Mass / Output$$

Or:

$$RT = 890\ PgC / 215\ PgC/year = 4.14\ years$$

The residence time or turnover time refers to how long (on average) a single molecule of CO_2 (of whatever origin) remains in the atmosphere, before it is either removed from the air, or replaced by a CO_2 molecule from another reservoir (oceans or biosphere). One-way removal, temporary removal (cycling back and forth), and exchanges of carbon with carbon from other reservoirs all "reset" the residence time.

About 95% of all CO_2 that leaves the atmosphere is recycled in the same year, mostly independent of the total amount of CO_2 in the atmosphere, as these are caused by processes that depend on temperature, sunlight and pressure difference processes, not the absolute CO_2 pressure in the atmosphere.

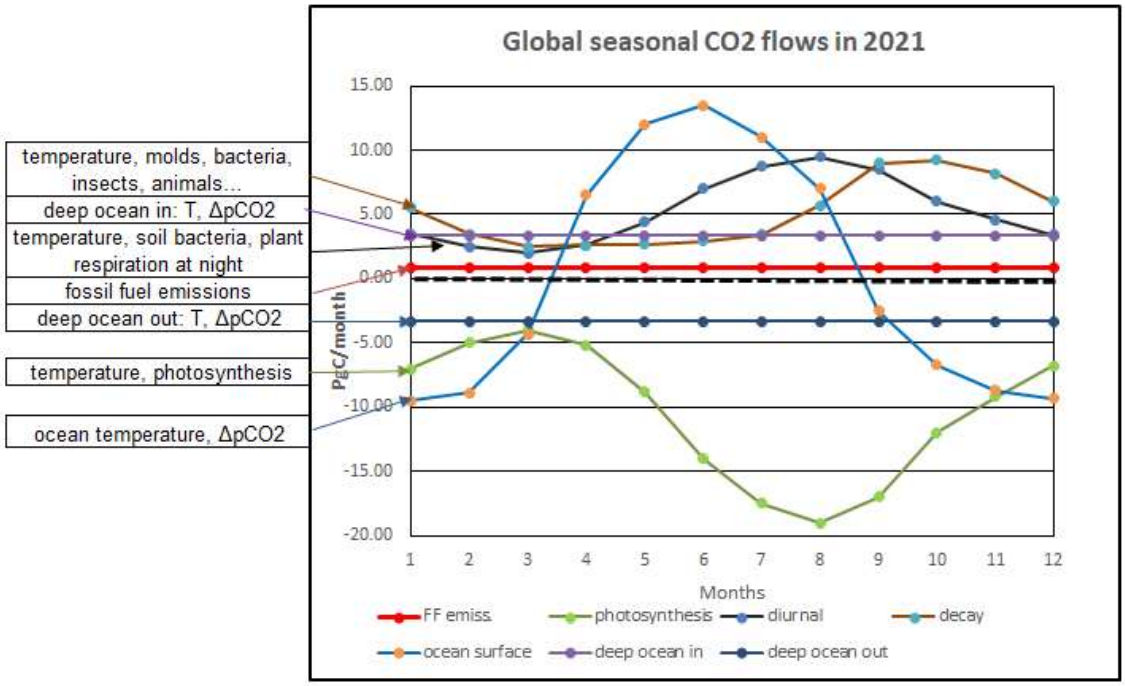

Figure 4. Seasonal and continuous CO_2 flows in and out of the atmosphere.

The residence time only shows how much CO_2 over a year is cycling in and out of the atmosphere and doesn't give any indication on how fast an extra injection of CO_2 into the atmosphere above equilibrium is removed out of the atmosphere.

3.2 The adjustment time

The adjustment time is the time needed to reduce a disturbance in one of the inputs to a reaction of mass or volume or concentration back to 1/e (~37%) of the initial disturbance. For a linear reaction the formula is quite simple:

$$\tau = Disturbance / Effect$$

Or (using 2020 figures):

$$\tau = (415\ \mu atm - 295\ \mu atm) / 2.35\ \mu atm/year = 51\ yrs$$

Where 295 μatm (ppmv) was the 2020 equilibrium between ocean surface partial CO_2 pressure (pCO_2) for the average sea surface temperature and the atmosphere, according to the formula of Takahashi. 415 μatm was near the observed year 2020 CO_2 level in the atmosphere and 2.35 μatm/year was the observed net removal rate of CO_2 out of the atmosphere, based on the polynomial through the net removal rates per year, which is quite variable.

That means that the higher the CO_2 level in the atmosphere goes, the faster nature removes CO_2 from the atmosphere. Quantitatively, for each 50 μatm rise in the CO_2 concentration, the rate of natural CO_2 removals accelerates by about 1 μatm/year. That makes the effective lifetime of CO_2 added to the air (the "adjustment time") about 50 years, and the half-life of added CO_2 is 50×ln(2) ≅ 35 years.

That fact was mentioned in the IPCC's Second Assessment Report (SAR 1995), but it is omitted from subsequent IPCC Reports. The SAR [WGI TS, B.1, p.16] notes that, "Within 30 years about 40-60% of the CO2 currently released to the atmosphere is removed." That implies an adjustment time of 33-59 years, and a half-life of 23-41 years.

3.3 The long-tail lifetime

The lifetime of CO_2 in the atmosphere, according to the IPCC, occurs quickly in the first about 31.6% into the ocean surface layer, but slower and slower for other reservoirs. Moreover,

according to the Bern and similar models, each reservoir has its own restrictions in maximum uptake, meaning that the last remaining extra CO_2 will stay in the atmosphere for hundreds to thousands of years:

$$\frac{1}{\tau} = \frac{0.316}{\tau_1} + \frac{0.270}{\tau_2} + \frac{0.253}{\tau_3} + 0.152$$

Where τ_1 is 2.57 years, τ_2 is 18.0 years and τ_3 is 171.0 years according to the IPCC (2001) description of the Bern model coefficients for the different sinks and 0.152 is the remaining fraction "forever" in the atmosphere…

The saturation of the different reservoirs is only true for the ocean surface, as chemical reactions indeed restrict the uptake of CO_2 in the ocean surface layer, but there is no restriction up to 1,000 ppmv for the CO_2 uptake by the biosphere for most (C3-cycle) plants and no restriction at all, up to the far future, for the deep oceans. That gives, based on observations, roughly following overall coefficients for the different reservoirs:

$$\frac{1}{\tau} = \frac{0.1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3}$$

Where τ_1 is less than a year for the ocean surface but restricted to about 10% of the increase in the atmosphere. That is called the Revelle/buffer factor.τ2 for the biosphere is about 100 years and τ_3 for the deep oceans is about 125 years and there is no remaining fraction.

This formula is not the mathematical calculation for the real adjustment time, but illustrates that three independent processes are at work, each with their own adjustment times, based on observed or calculated uptakes.

The rate of carbon uptake by the ocean and biosphere are chiefly governed by the elevation of atmospheric CO_2 concentration above its equilibrium level (Knorr 2009). The higher the CO_2 level rises, the faster natural processes remove CO_2 from the air.

Conversely, if CO_2 levels were falling, those natural removal processes would slow, and eventually reverse. Just as rising CO_2 levels have caused "global greening" (Zhu 2016), falling CO_2 levels would eventually cause "global browning" (Burton 2024), and the terrestrial biosphere would become a source of CO_2 rather than a sink. But the deep oceans are so far from saturation that they will continue to remove CO_2 from the atmosphere, albeit at a slower pace, even if atmospheric CO_2 falls to the levels of the early 20th century.

The combined processes removing CO_2 from the atmosphere together make the observed adjustment time about 50 years, but in a hypothetical future in which CO_2 levels are falling rather than rising the projected "long tail" lifetime is much longer.

3.4 Bern model problems

The main problem of the Bern model is that it completely isolates the deep oceans from the atmosphere and any extra CO_2 that is absorbed by the deep oceans must pass the chemical and physical restrictions of the ocean surface.

The Bern model sees the pCO_2 difference between atmosphere and ocean surface as one average over the whole surface, while in the real world, there are large differences between the equator where upwelling deep waters emit a lot of CO_2 and the poles where a lot of CO_2 and O_2 sinks directly into the deep oceans.

Next picture shows the difference between the Bern model and the observations at two stations: one near the equator and one in the North Atlantic (Bates et al, 2014):

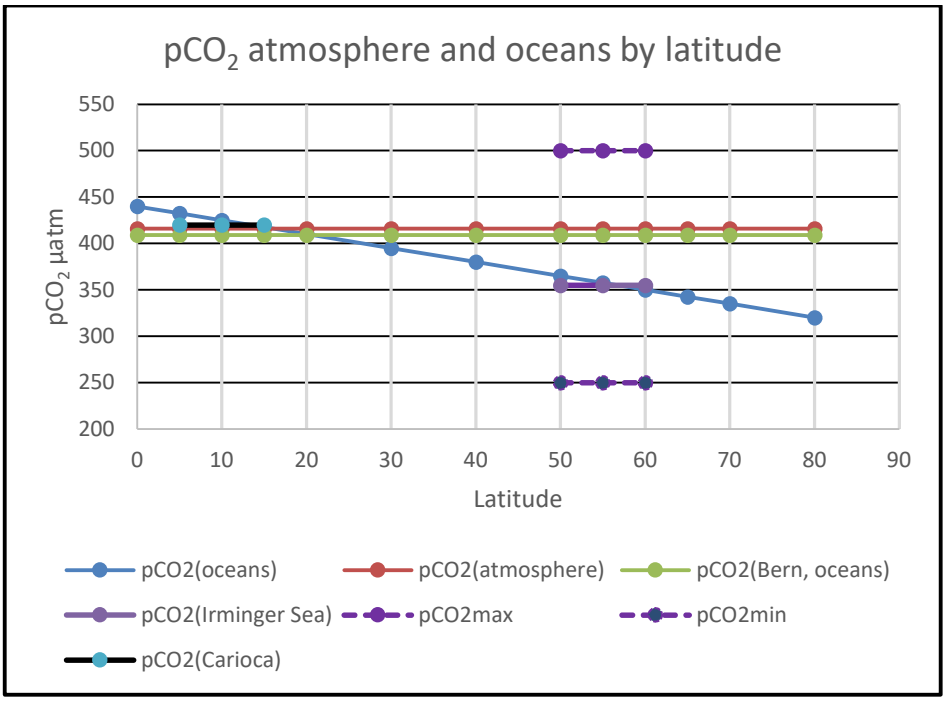

Figure 5. Observed vs. Bern model pCO_2 difference between atmosphere and ocean surface.

Based on several investigations (Yashayaev et al, 2007), lots of oxygen are sinking directly into the deep oceans. The solubility of CO_2 in seawater is a lot higher that of O_2, that deserves far more investigation than is currently done…

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References

Bates et al (2014): *A Time-Series View of changing Surface Ocean Chemistry Due to Ocean Uptake of Anthropogenic CO2 and Ocean Acidification*

https://tos.org/oceanography/assets/docs/27-1_bates.pdf

Burton, D. (2024). *Comment on Stallinga, P. (2023), Residence Time vs. Adjustment Time of Carbon Dioxide in the Atmosphere.* OSF Preprints. https://doi.org/10.31219/osf.io/brdq9

Engelbeen, F. (2007): Web page about the origin of the CO2 increase in the atmosphere.

https://www.ferdinand-engelbeen.be/klimaat/co2_origin.html https://www.ferdinand-engelbeen.be/klimaat/co2_origin.html

Engelbeen, F. (2025): *On the increase of CO_2 in the atmosphere*, discussion piece for the Nordic Climate Conference, Oslo, August 2025.

https://www.ferdinand-engelbeen.be/klimaat/klim_pdf/On_the_increase_of_co2.pdf

Engelbeen, F. (2024): *On the CO_2 residence time and other confusions*, discussion piece for the Clintel workshop, Athens, September 2024..

https://www.ferdinand-engelbeen.be/klimaat/klim_pdf/On_the_CO2_Residence_Time.pdf

Engelbeen, F., Hannon, R., Burton, D. (2024): *The Human Contribution to Atmospheric Carbon Dioxide*, published by the CO_2 Coalition, December 2024.

https://co2coalition.org/wp-content/uploads/2024/12/Human-Contribution-to-Atmospheric-CO2-digital-compressed.pdf

IPCC (2001): coefficients of the Bern model by Siegenthaler and Joos (1992):

https://unfccc.int/resource/brazil/carbon.html

Knorr, W. (2009). *Is the airborne fraction of anthropogenic CO2 emissions increasing?* Geophys. Res. Lett., 36, L21710. https://doi.org/10.1029/2009GL040613 (Excerpt: "From what we understand about the underlying processes, uptake of atmospheric CO2 should react not to a change in emissions, but to a change in concentrations.")

Rubino et al (2013): *A revised 1000 year atmospheric δ13C-CO2 record from Law Dome and South Pole, Antarctica*

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/jgrd.50668

SAR 1995. IPCC Second Assessment Report: Climate Change 1995, Working Group I, Sec. B.1.

https://archive.ipcc.ch/ipccreports/sar/wg_I/ipcc_sar_wg_I_full_report.pdf#page=29

Yashayaev, I et al (2007): *Spreading of the Labrador Sea Water to the Irminger and Iceland basins*

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2006GL028999

Zhu, Z. et al (2016). *Greening of the Earth and its drivers.* Nature Climate Change, 6(8), 791–795. https://doi.org/10.1038/nclimate3004