



# Estimation of e -Time for CO<sub>2</sub> and Revelle Factor

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## Abstract

This study develops a very simple climate model, based on the standard lagging formula. The mathematical function is derived in detail. The main purpose is to estimate the e-time of carbon dioxide in the atmosphere. Many models evaluate the inflow to the atmospheric CO<sub>2</sub> reservoir by rate equations describing the flow from e.g. sea to atmosphere with the weakness that not all parameters describing that flow are well known.

This paper calculates the inflow and outflow to the atmosphere from the best data material that could be obtained. The conclusions are based on data rather than estimated flow parameters. I obtain as a result for each individual year an e-time. The average over 270 years is 3.96 years and it is fairly constant over this time period.

A challenge in the compilation of the annual mass balance of CO<sub>2</sub> in the atmosphere is the unknown amount of additional natural CO<sub>2</sub> emission beyond the 1750 level. I used the amount determined by Skrable, and I add the increased emissions of the oceans due to temperature increase and the massive increase in wood burning to obtain a diagram that corresponds to the measured values of the CO<sub>2</sub> increase.

The conclusion is, that the anthropogenic contribution to atmospheric carbon dioxide in 2020 is only 28.9 ppmv. Including the anthropogenic burning of wood gives a total of 50.5 ppmv. I have estimated the Revelle factor (*R*) per year over 120 years. With an average value of 1.44, it is significantly lower than the value assumed by the IPCC. Thus, the absorptive capacity of the ocean is significantly higher than assumed in most IPCC models, where they use a Revelle factor (*R*) greater than 10. Also, the extent of biomass growth can be verified. All necessary data to falsify this are available in extensive databases.

**Keywords:** e-time  $\tau$ ; Global Carbon Cycle; Biomass respiration; Revelle Factor; Absorption  $S_{LAND}$  and  $S_{OCEAN}$ .

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## 1. Introducti

Status quo from the perspective of IPCC AR5 [5] Chapter 6.1.1.1 (p.470fp) Carbon Dioxide and the Global Carbon Cycle:

“The removal of all the human-emitted CO<sub>2</sub> from the atmosphere by natural processes will take a few hundred to thousand years (high confidence). Based on the amount of CO<sub>2</sub> remaining in the atmosphere after a pulse of emissions (data from Joos et al. 2013 and on the magnitude of the historical and future emissions for each RCP scenario, we assessed that about 15% to 40% of CO<sub>2</sub> emitted until 2100 will remain in the atmosphere longer than 1000 years (Archer and Broukin 2008).”

AR5 Chapter 6.1.1.1 addresses the process of CO<sub>2</sub> accumulation in biochemical cycles:

“The Human-Caused Perturbation in the Industrial Era CO<sub>2</sub> increased by 40% from 278 ppmv about 1750 to 390.5 ppmv in 2011. Anthropogenic CO<sub>2</sub> emissions to the

atmosphere between 1750 and 2011 were  $555 \pm 85$  PgC (IPCC). Of these,  $375 \pm 30$  PgC were from fossil fuel combustion and cement production, and  $180 \pm 80$  PgC were from land use change (including deforestation, afforestation, and reforestation). {6.3.1, Table 6.1 p. 486} It is very likely that increases in CO<sub>2</sub> emissions from fossil fuel combustion and those from land use change are the main drivers of the observed increase in atmospheric CO<sub>2</sub> concentration. The deep sea stored  $155 \pm 30$  PgC. Vegetation biomass and soils that were not affected by land-use change stored  $160 \pm 90$  PgC”.

According to IPCC AR Chapter 6 Fig 6.1 it is presented that natural emissions have increased significantly since 1750. However, Chapter 6.1.1.1 does not explain that natural respiration has increased by 10.7%, photosynthesis by 13%, ocean absorption by 33% and ocean emissions by 29% between 1750 and 2009. But these very values lead to the interpretation that the anthropogenic share of the increase is only 24% - as noted by Berry[1] and Skrable et al.[3]

The IPCC says in Box 6.1:

"It is very certain that emissions from fossil fuels and land use change are the main cause of the observed increase in CO<sub>2</sub>."

This is a contradiction. I disagree with these assumptions. In particular, the idea that 15% - 40% of anthropogenic CO<sub>2</sub> will remain in the atmosphere for more than 1000 to 10,000 years.

The Bern model does not discriminate between anthropogenic CO<sub>2</sub> or natural CO<sub>2</sub>, but the strong buffering described in the Bern model would mean, that all emissions (or increased absorptions) would have a timescale around 1000 to 10,000 years. This is contradicted by the rather rapid variations observed. Especially the rather fast decreases that has occurred in history. The anthropogenic emissions are blamed for the rise in temperature during the industrial age. (IPCC AR6 WGI TS Technical Summary p. 39). These predictions are based on the assumption that there is a strong “buffering” effect in surface sea, where the high value of the Revelle factor significantly blocks absorption of excess CO<sub>2</sub> in the atmosphere. IPCC use Revelle factors  $R > 10$ . This analysis shows that the Revell factor  $R$  is about 1.44 based on IPCC data. However, good agreement between calculations and observations is only a necessary but not a sufficient condition for reliable simulations.

The conflict in the current knowledge: The IPCC uses values of land use change  $E_{LUC}$  and fossil fuel emissions  $E_{FF}$ , while natural effects  $E_{NF}$  are supposed to have remained constant during the last 7000 years. This leads to a new time scale, the adaptation time or response time, which is quite different from the e-time, in which CO<sub>2</sub> molecules are the same - according to the equivalence principle - regardless of whether they result from natural emissions or fossil fuel emissions. It is assumed by IPCC that the climate is static over a period of over 170 years. Therefore, the Bern model is not adequate to describe the carbon cycle. Harde[2] has demonstrated this very well, so there is no need to discuss this further.

Skrable et al. also prove that on the basis of the <sup>14</sup>C measurements the anthropogenic share can only be very small. The same applies to the statements of Berry.

Our goal is to determine the e-time and the Revelle factor ( $R$ ) based on physical principles and exclusively using the available measurement data since 1750. The determination of the correct e-time is a prerequisite for further research on the future development of the CO<sub>2</sub> content of the atmosphere. The Revell factor enhance the outflow of excess carbon from ocean.

This paper assumes, human carbon transferred to the carbon cycle stays in this cycle forever and caused by principle of equivalence we do have only one e-time. Likewise, the atmospheric e-time determined on an annual basis is shown do be almost constant over 270 years and thus provided evidence that no saturation phenomena occurred in the ocean and in the biomass.

This paper uses the following definitions:

- Natural Carbon is carbon from natural processes with  $E_{NF}$  emissions before 1750 and  $E_{DCNF}$  additional annual emissions since 1750
- Human Carbon is from burning carbon fuels and producing cement  $E_{FF}$
- Land Carbon is from human-caused land-use change  $E_{LUC}$
- Burned Biomass  $E_{BMV}$  caused by human activity not included in  $E_{LUC}$
- Ocean emissions caused by temperature rise  $E_{OT}$

## 2. Our proposed model

I consider the total volume of CO<sub>2</sub> in the atmosphere with sources and sinks. I do not distinguish between natural and anthropogenic CO<sub>2</sub> emissions. I calculate with a single e-time. Even though there are different absorption processes with different reaction times, there is a single e-time.

Use of a tank model (Fig. 1):

If a tank has 3 valves at the bottom, each with different mass flow rates, then when all valves are open, the time to empty the tank is essentially determined by the largest valve. The CO<sub>2</sub> molecule will not wait for the turn of the smallest valve, which has the longest residence time. The individual molecules do not have different priorities; the equivalence principle applies. This approach must be based on the total CO<sub>2</sub> mass in the atmosphere. Restricting it to the anthropogenic fraction of the CO<sub>2</sub> content is not reasonable. If one follows this approach, one arrives at significantly different results than the IPCC. The basic assumption of why the IPCC model with biochemically driven time scales up to several 1000 years is not proven, can be explained by a tank model. With a Revelle factor ( $R$ ) of 10, IPCC obviously is closing valve  $S_{OCEAN}$ . The reason that IPCC ends up with a model where the smallest valve determines the time, is their Impulse Response Function (IRF). Their IRF comes from curve fitting of exponential functions to a curve that is not exponential. The exponentials are only curve fitting functions without physical meaning.

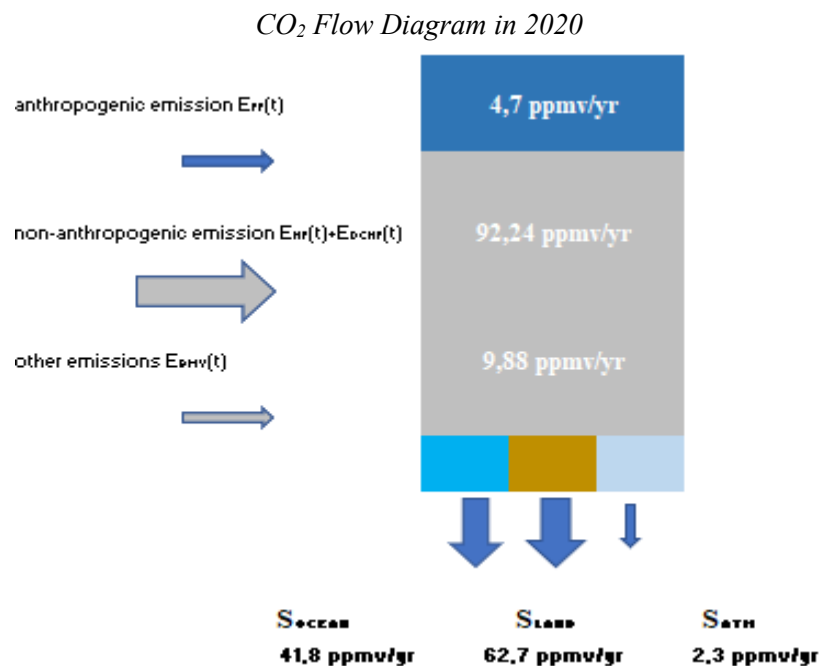


Fig. 1: Explanation of the tank model (Definitions see page 332)

In Fig. 1 emissions are inflow to the atmosphere and the outflow goes to different sources ( $S$ ). It is the size of the valve that determines the total outflow of the reservoir atmosphere. The largest valve essentially determines (has the main influence on) the time until the reservoir is empty, not the smallest. The e-time  $\tau$  is an essential measure for the future development of the CO<sub>2</sub> content of the atmosphere.

Therefore, I follow the approach:

- The historical CO<sub>2</sub> content based on natural CO<sub>2</sub> emissions/uptake follows the same physical exchange principle as anthropogenic emissions.
- There is no justification for assuming that pre-industrial emissions are constant.
- There is no justification for assuming that Airborne Fraction is constant.
- Increased CO<sub>2</sub> levels from 280 ppmv to 411 ppmv have been shown to increase biomass by up to 30%, see Huntingford et al.[6] and Tayler et al.[7] This also enhances the seasonal biomass cycle in the northern hemisphere.
- The increased biomass and increased CO<sub>2</sub> partial pressure cause an additional increase in absorption and emission.
- The results of the <sup>14</sup>C study (Skrable et al. [3]) were included in the work.
- The residence time  $\tau$  can be composed of different components.
- Since there was an equilibrium between  $E_{LAND} + E_{OCEAN}$  and  $S_{LAND} + S_{OCEAN}$  before 1750, I assume that the ocean has increased absorption due to increased CO<sub>2</sub> partial pressure, as assumed by the IPCC in Fig. 6.1.
- The increase in  $E_{DCNF}$  (=Emissions additional non fossil, see table 1) was tabulated from Skrable et al.[3].
- The partial pressure of 1 hPas results in a C uptake of 3.3t/km<sup>2</sup>yr on land and 0.9 t/km<sup>2</sup>yr in the ocean. Takahashi et al.[8]. although there are large uncertainties here (Nsikak et al. [9])
- Biomass burning, which has increased sharply, especially since the 1970s, must be accounted for in the overall CO<sub>2</sub> budget. These are not included in  $E_{LUC}$  and  $E_{NF}$  (bp statistics[10]).

### 3. Physical concept to estimate the e-time

#### 3.1 General comment:

There are many definitions of lifetime. The way we define time constants is according to Edwin X. Berry [1]

In our model I use the e-time.

e-time = the average time for the level to move (1 - 1/e) of the distance to its balance level. These principles are contained in an equation, the general conservation law (Harde [2]).

#### 3.2 Our model with e-time

Mathematical model is the standard lagging formula, Tahvonen et al.'s equation [21] (which also can be derived from the Bern model formalism) is:

$$\frac{dC}{dt} = \frac{-C}{\tau} + \frac{dEa}{dt} \quad (1)$$

where

$C$  = atmospheric concentration of CO<sub>2</sub>, unit: ppmv

$\tau$  = e-time, unit: year

$Ea$  = total emission into the atmosphere since starting year (in this paper we have 1750 as starting year), unit: ppmv

$dEa/dt$  is the change in total emission with time.

$dC/dt$  is the change in atmospheric concentrations.

$C/\tau$  is the outflow from the atmosphere and

$dEa/dt$  in this equation is the total influx into the atmosphere – from sea, from land and

from human emissions.

Equation(1) can be derived from basic equations used in the Bern model (Oeschger et.al[14]). The general solution to equation (1) is

$$C(t) = e^{-t/\tau} * \int_0^t e^{u/\tau} * \frac{dEa}{du} du + C(0) * e^{-t/\tau} \tag{2}$$

Where t=0 in our analysis corresponds to year 1750.

The integral on the right side cannot be solved in a general way. It is thus not possible to write down a closed analytical expression for C(t).

I can obtain the following equation from the general solution (2).

$$C(t) = e^{-\frac{t}{\tau}} * \int_{t-1}^t e^{u/\tau} * \frac{dEa}{du} du + e^{-1/\tau} * C(t - 1) \tag{3}$$

The equation for tau can be derived from the equation above.

If the emission during year t is uniform an equal to  $\emptyset(t)$ , then  $\frac{dEa}{dt} = \emptyset(t)$

Eq. (3) becomes,

$$C(t) = \tau * \emptyset(t) * (1 - e^{-1/\tau}) + e^{-1/\tau} * C(t - 1) \tag{3.5}$$

Since we have an approximate knowledge of  $\tau$ , as the average time a CO<sub>2</sub> molecule stays in the atmosphere is about 4 years (can be estimated from IPCC data), we can approximate

$$\tau * (1 - e^{-1/\tau}) \approx 0.88$$

With  $\emptyset(t)$  as the emission during year t we get the following equation.

$$C(t) = C(t - 1) * e^{-\frac{1}{\tau}} + 0.88 * \emptyset(t) \tag{4}$$

Equation (4) is derived from equation (2) and is consequently general.

$$e^{-1/\tau} = (C(t) - 0.88 * \emptyset(t)) / C(t - 1)$$

$$\tau = 1 / \ln (C(t - 1) / (C(t) - 0.88 * \emptyset(t))) \tag{5}$$

Equation (5) is slightly approximative (since we assumed that

$$\tau * (1 - e^{-1/\tau}) \approx 0.88.$$

The important feature is to use the same approximation for all year.

E(t) is the emission of CO<sub>2</sub> per Year. With different sources of emissions, we define:

$$E(t) = EFF(t) + ENF(t) + EDCNF(t) + ELUC(t) + EOT(t,T) + EBMV(t)$$

$$S(t) = SN(t) + SLAND(t) + SCEMENT(t) + SDCN(t) + SOCEAN(t) + BIM$$

In equilibrium there must be E(t) = S(t)

In a simple model further changes in these fluxes are simply disregarded in the total balance.

In the IPCC report in 1750 the CO<sub>2</sub> concentration has been 589 GtC ~ 276.5 ppmV. We use the same starting point.

Table 1: Compilation of used symbols

Symbol	Quantity
$E_{FF}$	Emission fossil fuel
$E_{NF}$	Emission non fossil year 1750
$E_{DCNF}$	Emissions additional non fossil (Skraable)
$E_{LUC}$	Land use change, Forestry, deforestation, Dynamic global vegetation model (DGVM)
$E_{OT}$	Emissions by ocean temperature increase
$E_{BMV}$	Emissions by antropogen burning of biomass
$S_N$	Absorption by gross photosynthesis
$S_{LAND}$	Absorption by Land
$S_{CEMENT}$	Cement + process absorptions
$S_{DCN}$	Absorption by additional biomass
$S_{OCEAN}$	Absorption by ocean
$BIM$	Budget imbalance

#### 4. Evaluation of the e-time $\tau$ of CO<sub>2</sub> in the atmosphere and $\tau$ per year.

The target value for  $C(t)$  was calculated for each year in an Excel spreadsheet using the known emission data from Global Carbon Budget with the variable Tau. To get the measured  $C(t)$  line to coincide with the calculated  $C(t)$  line in the spreadsheet there were two preconditions:

1. the total emission amount must be correct
2. the chosen value of Tau could be adjusted until there was a clear match.

I calculate the e-time by sum of emissions (Example for 2020):

$$\Sigma E_i = 226.53 \text{ GtC/yr} \sim 106.3 \text{ ppmv/yr} ; C(2020) = 414.70 \text{ ppmv} ; C(2019) = 411.43 \text{ ppmv}.$$

$$C(t) = C(t - 1) * e^{-\frac{1}{\tau}} + 0.88 * \Sigma E_i(t) \tag{6}$$

follows  $\tau = 4.0$  years.

When we calculate  $C(t)$  using equation (6) for any single year since 1750 the new  $\tau$  value, by using data from Global Carbon Budget [4], Mauna Loa Observatory MLO[13], pb[10], Skraable at al.[3] and EDGAR[16], I get a perfect match of these data and the calculated CO<sub>2</sub> concentrations between 1750 and 2020, as shown in Fig 2. Using these data (Table 2) in formula (6) for each individual year, we have only one variable in each case, namely  $\tau$ . The result is shown in Fig. 2 and Table 2. We simulate the increase of CO<sub>2</sub> since 1750.

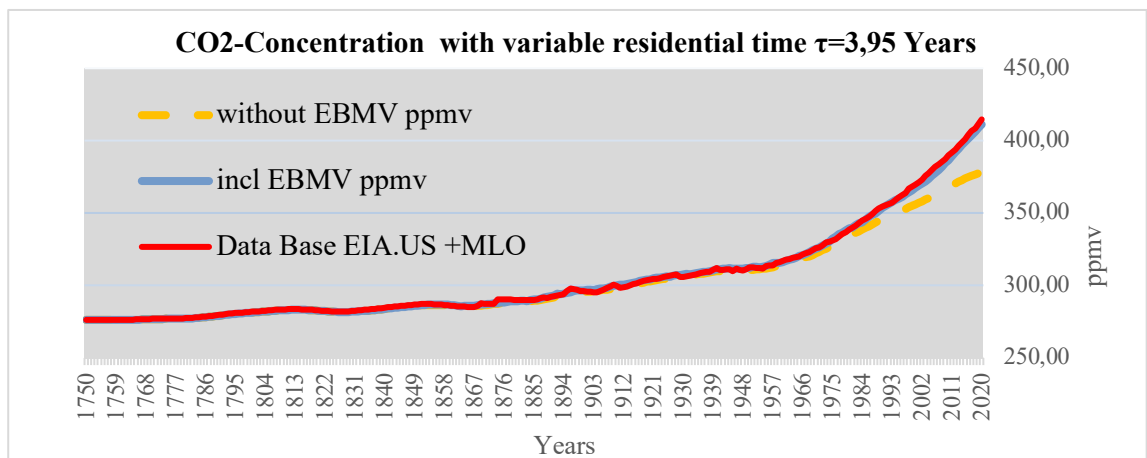


Fig 2: Measured and simulated  $C(t)$  The red line represents the database from Mauna Loa[34], EIA[15], Science of Climate Change <https://scienceofclimatechange.org>

and Skrable[3], the blue one our calculation. The yellow one if we do not consider the biomass burning  $E_{BMV}$ . Additionally, the temperature increase is incorporated.

In the same way, it is possible to determine the tau value by means of the same data with formula (5) each year. The result is Fig 3. Analysis of the trend in  $\tau$ -value on an annual basis shows a decrease since 1970 Fig.3. Further investigation of the causes is needed here. It is expected that the e-time should be constant, and despite the decrease in the data after 1970 the value is fairly constant. The fact that we obtain a rather constant value strongly support that the data used in our analysis are consistent. If the biomass increases the likelihood for being absorbed increase, thus the e-time in the atmosphere decrease if the biomass increase. We obtained with standard deviation the value of 3.92 +/-0.03.

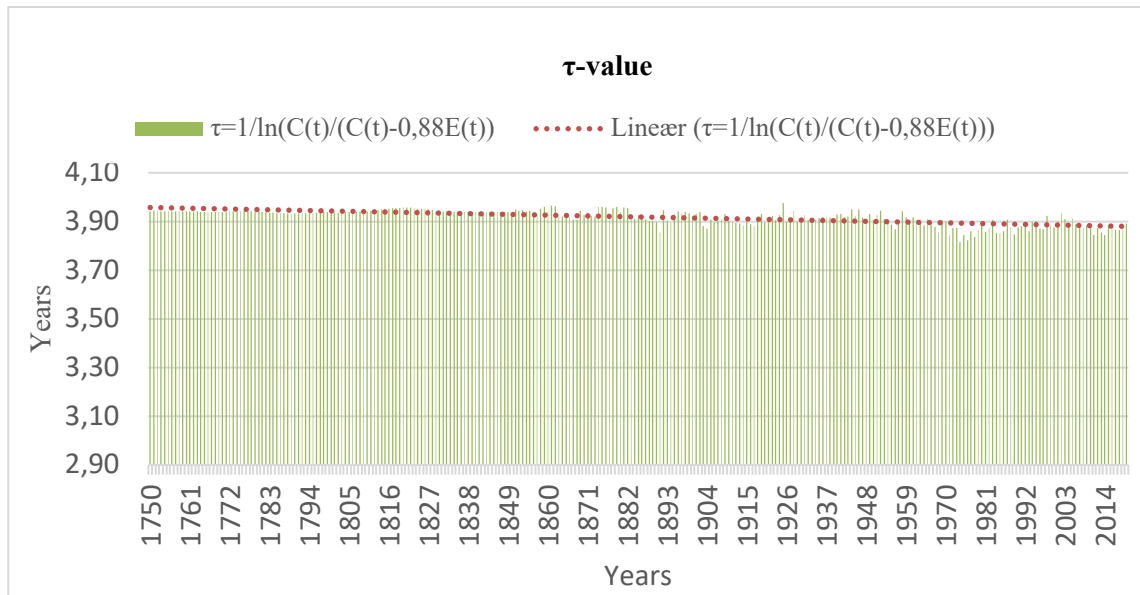


Fig 3: Calculation of  $\tau$ -value

According to Skrable at al.[3]:

In 1750 was the end of the little ice age. From 1750  $C(t)$  increased from 276.44 ppmv to 287.06 ppmv in 1850 due to natural warming. This process did not stop, but increased according to the magnitude of the relation  $R$  of  $^{14}C/^{12}C$  to 359.0 ppmv (without  $E_{FF}$ ,  $E_{LUC}$ ,  $E_{BMV}$ ,  $S_{OT}$  see page 341 our Discussions) in 2018. The observed exponential decay of  $^{14}C$  in the atmosphere after the dropping of the atomic bomb gives an e-time of about 9.5 years (calculated by data Table 2a from Skrable). The impact of  $E_{FF}$ ,  $E_{LUC}$ ,  $E_{BMV}$ ,  $S_{OT}$  is only 47 ppmv in 2018. This has to be added, Skrable did not implement  $E_{BMV}$  and  $S_{OT}$ . But in his revision of May 11, 2022 [22], he enlarged  $E_{DCNF}$  from 82 to 88. His result is 405.4 ppmv. See Table 2a page 300 in Skrable et al.[3]. This is close to our results, but using a different method.

Table. 2: This is shown in the excerpt from the Excel spreadsheet.

Year	antropogen	Skrable	C(1750)=	Temp.cor.	C(t)	C(t)		
	Eff kum.	E <sub>DCNF</sub> kum.	E <sub>FF</sub> kum				E <sub>LUC</sub> kum	S <sub>OT</sub>
	ppmv	ppmv	ppmv	ppmv	2.4ppmv/K	ppmv	ppmv	EIA.US +SPD+MLO
1750	0	0	276,48	0	0	0	276,48	276,44
2010	15,0677	76,4758	276,48	4,99	2,30	11,20	386,51	389,9
2011	15,4637	77,2816	276,48	5,16	2,51	12,09	388,98	391,65
2012	15,8981	78,0940	276,48	5,63	2,73	13,05	391,89	393,85
2013	16,2926	78,8961	276,48	5,36	2,97	14,11	394,11	396,52
2014	16,6338	79,7057	276,48	5,51	3,24	15,21	396,78	398,65
2015	16,9273	80,4968	276,48	5,77	3,53	16,17	399,37	400,83
2016	17,1510	81,2692	276,48	5,37	3,84	17,18	401,29	404,24
2017	17,3198	82,0223	276,48	5,33	4,18	18,26	403,59	406,55
2018	17,5042	82,7120	276,48	5,59	4,55	19,34	406,18	408,52

**5. Calculation of the total balance  $E(t) = E_{NF} + E_{DCNF} + E_{FF} + E_{LUC} + E_{BMV} + E_{OT}$**

Here I explain the evaluation of the data in the Excel table. Determination of the values using the example of the year 2020. All data were obtained from the sources according to the reference annexes. The determination of these values in sections 5.1a to 5.1d is the prerequisite for the successful determination of tau and the Revelle factor (R).

The finding for year 2020:

Natural emissions  $E_{NF}$  released about 150 GtC (1750).  $E_{NF}$  was assumed to be constant over 270 years. The additional natural emissions are referred to as  $E_{DCNF}$  (Skrable Table 2[3]).

*5.1a. Additional non-fossil fuel emissions  $E_{DCNF}$  growth according to Skrable et al.[3]*

$E_{DCNF}$  is the sum of additional emissions caused by partial pressure increase on ocean surface and biomass respirations due to growth of biomass. I consider here the growth of biomass as shown in Figure 4. Another method would be to use the annual variation of the Mauna Loa Observatory measurements. I explain this in a separate chapter 6.

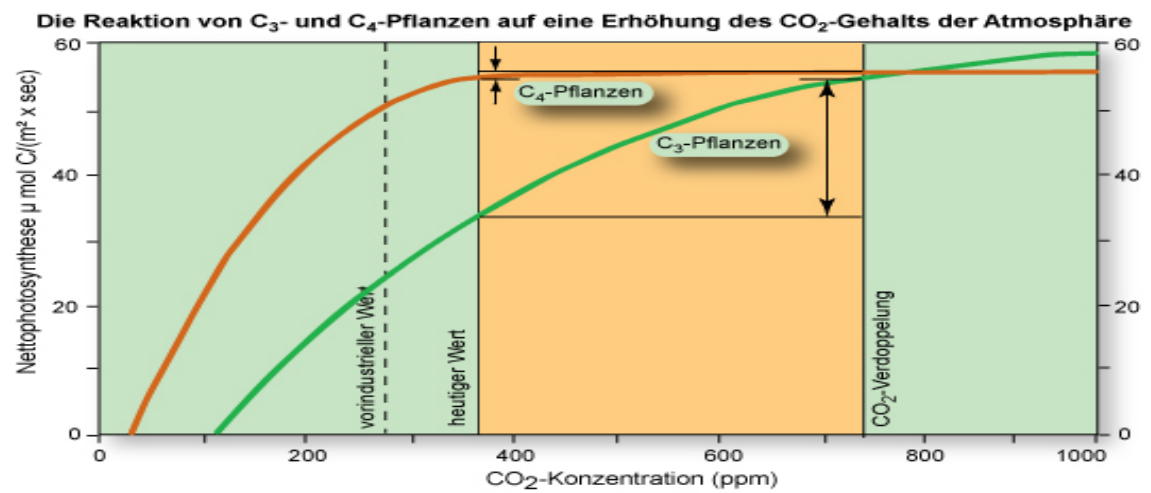


Fig 4: Hamburger Bildungsserver[12]: photosynthesis at higher CO<sub>2</sub> concentrations

According to Fig 4 the increase of C3-plants for 280 ppmv to 400 ppmv is up to 30% , proofed by Taylor et al.[7]

The total increase in 2020 is  $E_{DCNF} = 47.13$  GtC

*5.1b  $E_{FF}$  in 2020 is 9.5 GtC and  $E_{LUC}$  is 2.92 GtC according Global Carbon Budget*

*5.1c Emission by temperature increase of ocean  $E_{OT}$*

The CO<sub>2</sub> emission of the ocean was stable until 1975. With the temperature increase until 2020 there is an increase in CO<sub>2</sub> emission, but we do not get Becks estimations. Increase in sea temperature by 0.8°C see Fig 5:

According to Takahashi [8], the Ocean balance:

$$P(CO_2)_{sw} = (pCO_2)_{sw} * (T_0) * exp(0.0433 * (T - T_0))$$

for 1°C Results 18μatm, for 0.8°C 14.4 μatm

With 1 μatm = 0.9 g/m<sup>2</sup>yr that is 2.4 ppmv/yr at 1°C For 0.8°C follows

$S_{OT} = E_{OT}(t, T) = 1.905$  ppmv/yr equal to 4 GtC/yr.

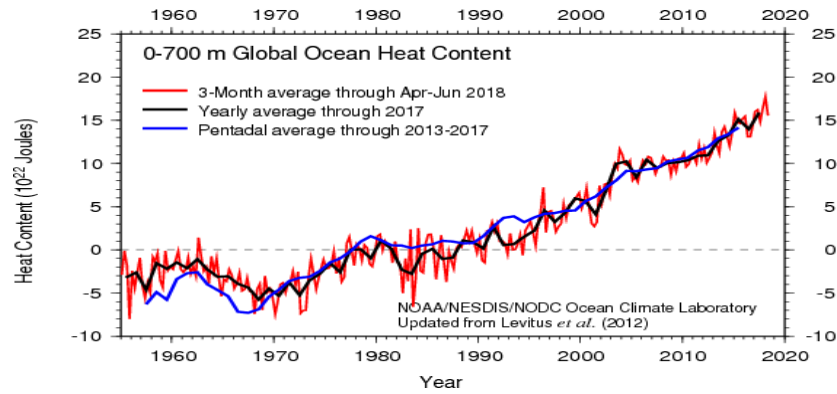


Fig 5: Increase of global ocean heat content [24]

5.1d Emissions from biomass combustion  $E_{BMV}$  are 13.9 GtC/yr

CO<sub>2</sub> emissions from biomass burning have increased dramatically, especially since 1970. The data was provided by the bp study [10]. See Fig 6. Until 2000, there is a good agreement without  $E_{BMV}$ . Since 2000, the measured CO<sub>2</sub> levels have increased much more. If I add the CO<sub>2</sub> from annual biomass production, from geothermal and biomass according to the bp study [10], we get over 700 TWh in 2019, especially due to the strong increase since 1970 with 27.9 TWh. The calorific value when burning biomass can be converted directly. 1 TWh ~ 0.069 MtCO<sub>2</sub>. If we do not take this into account in our overall balance, the CO<sub>2</sub> balance does not fit the theory and the measurement. Geothermal and other values can be neglected. They are very small.

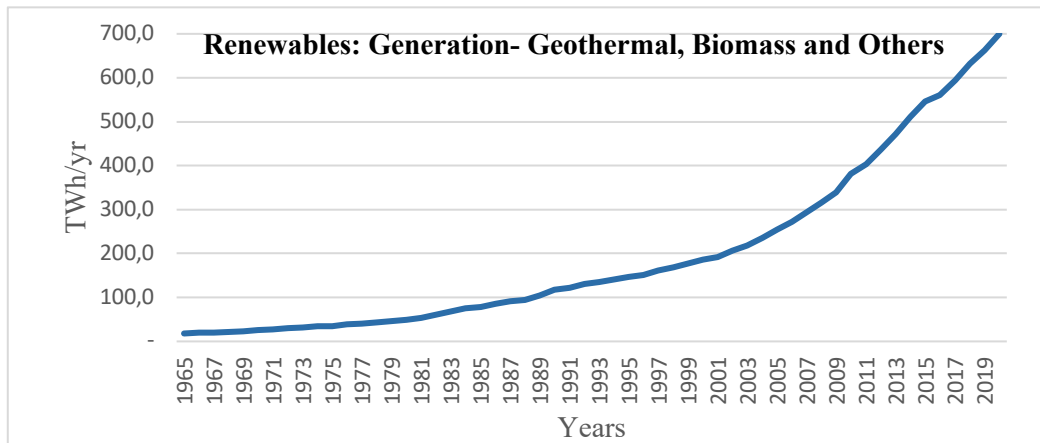


Fig 6: Energy production by Geothermal and Biomass according bp study[10]

Recently, Yatang Cheng et al. [23] from MPIC published a study looking at biomass burning leading to an increase in aerosol particles that enhance cloud cover at low altitudes, causing a decrease in temperature in Asia.

5.2 Summary of individual emissions

We have a total emission of 227.53 GtC/yr in 2020. We can split the absorption of this emission with 39.7% =90 GtC to the ocean and 133 GtC remain for the land+cement. 4.2 GtC =1.98 ppmv remain in the atmosphere. With Formula (5) we receive  $\tau = 3.95$  years.

In the calculation, I used the Global Carbon Budget 2021 data[4] for  $E_{FF}$  and  $E_{LUC}$ . The data for  $E_{NF}$  and  $E_{DCNF}$  were used from Skrable et al. [3]. The Data for  $E_{BMV}$  from bp [10]. Using these data, we obtained an increase in 2020 of  $E_{DCNF} = 47.13$  GtC/yr ~ 21.8 ppmv/yr.  $E_{FF}+E_{LUC}$  in 2020 is 12.4 GtC/yr.

Thus, the anthropogenic increase in CO<sub>2</sub> emissions in 2020 is only 5.5% +/- 0.5% of 227 GtC/yr. Summed up since 1750, the anthropogenic share is 23.3ppmv +/- 1.14 ppmv Using the best available data for emissions since 1750, we thus calculate an anthropogenic influence of the increased *Science of Climate Change*

CO<sub>2</sub> content of only 17.4% (23.3 ppmv of 135 ppmv). If  $E_{BMV}$  should be defined as part of anthropogenic emissions we have different values: 50.5 ppmv +/- 6.4 ppmv.

There is no evidence of constant AF, no evidence that out of the mass flow the emitted, absorbed and remaining amounts are from the same source. The air born fraction makes no sense.

### 6. The monthly mean CO<sub>2</sub> at Mauna Loa Observatory

Rough estimate:

The annual variations caused by absorption and emission from plants depend on the northern and southern global land area. In the Northern Hemisphere we have 66% of the land mass and of that 25% is desert and ice. This is 70% of the total biologically active land area on Earth. In 2020, a total of 226.8 GtC will be emitted. In the Northern Hemisphere it was 158.8 GtC, an estimated 58% was in winter = 92.1 GtC.

In the Southern Hemisphere it was 68 GtC with 42% in October through March. Total emissions were thus 120.7 GtC in winter and 106.1 GtC in summer. The difference between winter and summer is 14.6 GtC, which is about 6.9 ppmv and corresponds to the measurement at Mauna Loa.

As can be verified in Fig 7 the amplitude in 1958 to 1960 was a 3-year average of 6.0 ppmv. In 2019 to 2021, it averaged 7.1 ppmv, a 19% increase. This is equivalent to the increase in the entire biomass cycle of CO<sub>2</sub> emissions. In the calculation, we had total emissions of 81.3 ppm in 1960 and 106.6ppm in 2020, an increase of 31.1%. 40% of this was emitted from the ocean. So, for the CO<sub>2</sub> biomass cycle, the increase is 18.6%. This fits our rough approximation.

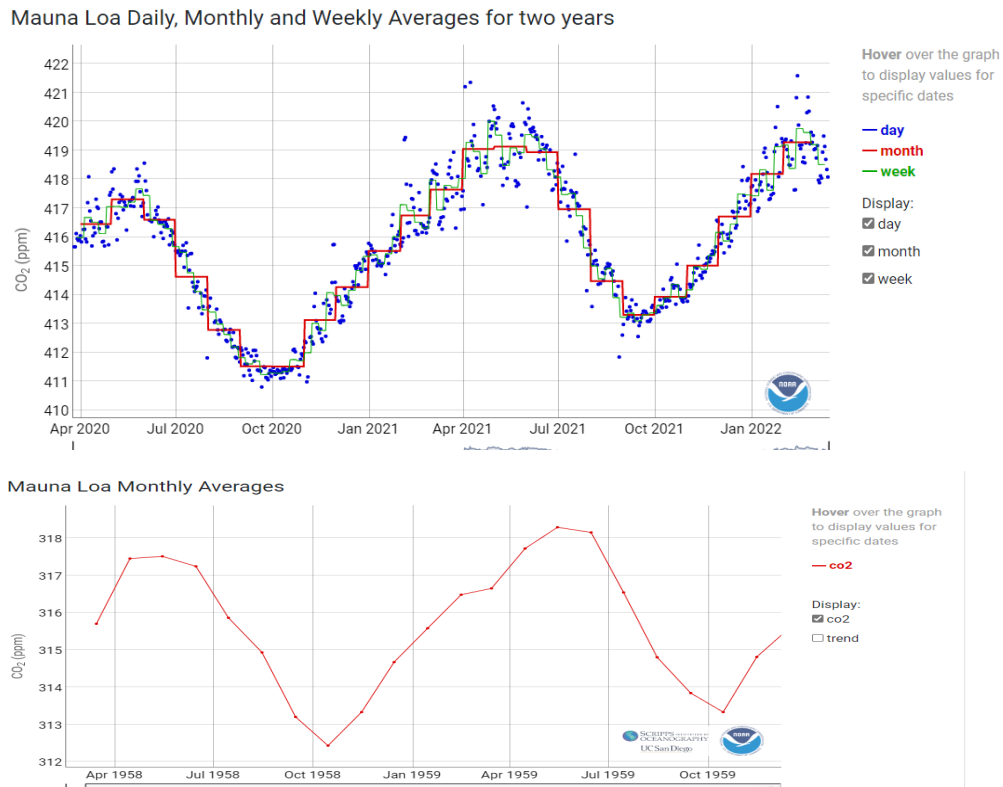


Fig 7: CO<sub>2</sub> values from Mauna Loa in 2021 and 1958[13]

Massen [18] and Beck [17] just showed the difference during the year in the northern latitudes. According to Beck in start of the Year SOY and mid of the Year MOY by sea stations is about 7  
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ppm and on land stations about 10 ppm during 1985 until 2005. This confirms the influence of biomass. The magnitude of negative MOY gradients of the sea stations remains more or less constant with time (Table 5 in [18]), whereas the latitudinal gradients of land stations change remarkably (trend is - 0.0032 per year) and suggest a rising summertime CO<sub>2</sub> uptake in the more northern regions, possibly due to an ongoing greening of the NH land-masses (Fig. 5 in [18]).

### 7. The absorption process and the constancy of *S<sub>LAND</sub>* and *S<sub>OCEAN</sub>*

Henry’s Law states:

$C_i$  = concentration in liquid mol/dm<sup>3</sup>;  $P$  = partial pressure of gas in atm = 102325Pa, and  $H_{cp}$  in mol/m<sup>3</sup>Pa

According to Wikipedia:

“Atmospheric chemists often define the Henry solubility as  $H_{cp} = c_a/P$ .  $c_a$  is the concentration of a species in the aqueous phase, and  $P$  is the partial pressure of that species in the gas phase under equilibrium conditions. The Henry solubility can also be expressed as the dimensionless ratio between the aqueous-phase concentrations of a species and its gas-phase concentration  $c_g$ :  $H_{cc} = c_a/c_g$ . For an ideal gas, the conversion is:  $H_{cc} = H_{cp} * R * T$  with  $H_{cc}$  constant of solubility and  $R$  the gas constant.  $C_i$  is proportional to  $P$  and revers proportional to  $T$ .”

So, we find:

$$C_i = P * H_{cc} / (R * T) = P/T * H_{cc} / R$$

and  $H_{cc}/R$  is constant. As colder the ocean as larger  $C_i$  at constant partial pressure.

1750 we had

$$C_i = 27,6 \text{ Pa} / 287.5 \text{ K} * H_{cc} / R = 0.0960 * H_{cc} / R$$

2020 we had

$$C_i = 42 \text{ Pa} / 289.1 \text{ K} * H_{cc} / R = 0.1453 * H_{cc} / R$$

$C_i$  increased about 51%. ((Relation 0.1453 to 0.0960).

#### 7.1 *S<sub>LAND</sub>* and *S<sub>OCEAN</sub>* in relation to $C(t)$ :

The annual absorption of *S<sub>OCEAN</sub>* and *S<sub>LAND</sub>* seems to be constant in the last 270 years in relation to  $C(t)$ . Table 3 and Fig 8 confirms there is no saturation in *S<sub>OCEAN</sub>* and *S<sub>LAND</sub>*.

Table 3: This is shown in the excerpt from the Excel spreadsheet for each single year. The ratio of  $E(t)$  - divided into shares of land (61.5%) and Ocean (36.59%) in relation to  $C(t)$ .  $E(t) = E_{NF} + E_{DCNF} + E_{FF} + E_{LUC} + E_{OT} + E_{BMV}$

Year	Sum E(t) in ppmv ENF+EDCNF+EFF+ELUC+EOT+EIA.US+SPO+MLO	C(t) Measurement	61,50% SLAND/c(t) in %	36,65% SOCEAN/c(t) in %
1750	70,4	276,44	15,37%	9,16%
2012	101,9	393,85	15,61%	9,30%
2013	103,0	396,52	15,67%	9,34%
2014	103,7	398,65	15,71%	9,36%
2015	103,5	400,83	15,58%	9,28%
2016	104,3	404,24	15,58%	9,28%
2017	105,3	406,55	15,64%	9,32%
2018	105,8	408,52	15,64%	9,32%
2019	106,2	411,43	15,59%	9,29%

From Table 3, we obtain the diagram Fig 8 for all years.

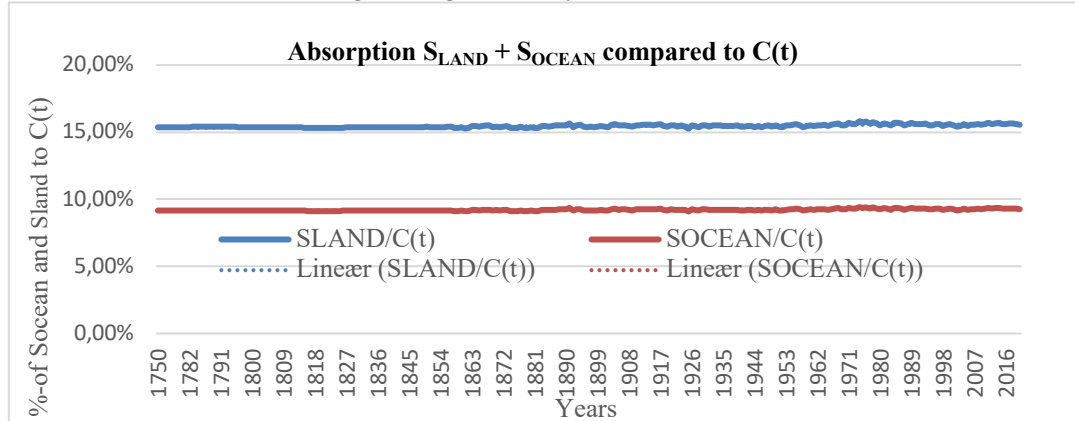


Fig 8: The relative total absorption on ocean and on land stays constant over 270 Years

Absorption by ocean  $S_{OT}+S_{Ap}$  :

In contrast, Nsirik et al. [9] give measured values of 1.84 to 2.96 mol/ m<sup>2</sup> CO<sub>2</sub>/yr. That would be 105.6 t/km<sup>2</sup>yr!

The North Atlantic does have a very strong CO<sub>2</sub> sink capacity. Measurements from 2005 with CO<sub>2</sub> = 380ppmv shows a very high fluctuation depending on weather conditions and temperature. With high standard deviation there is a significant and consistent undersaturation of the process of absorption.

Our focus: The absorption of CO<sub>2</sub> by Ocean is linear to partial pressure. Between 2011 and 2020 we have 411.7ppmv-391.65ppmv=20.05ppmv. This gives a higher CO<sub>2</sub> emission of 4 GtC/yr (Henry’s Law).

$S_{OT} = E_{OT} =$  see list 5c above = 4 GtC/yr.

The total absorption by Ocean in 2020 is 80.0 GtC +4 GtC +4 GtC = 88.0 GtC/yr = 41.3 ppmv/yr or 39.5% of all absorptions.

### 8. Estimation of the Revelle factor (R) with the Bern Model

In this section I will estimate the Revelle factor based on the Global Carbon Budget data[4]. and values from IPCC AR5 Chapter 6 Fig. 6.1. The analysis will be based on the Box-Diffusion model (BDM) developed by Oeschger[14]. The BDM is also called the Bern Model. Following Oeschger we have a three-box model – the atmosphere, the mixed layer and land. In addition there is the “Deep Sea”. The mixed layer is the surface layer of the oceans, and it is assumed that the carbon concentration is uniform within the mixed layer. It is also assumed that the depth of the mixed layer is 75 meters. Carbon is flowing from the atmosphere into the mixed layer. Carbon is transported away from the mixed layer in two ways:

- direct flow from the mixed layer into the atmosphere
- by eddy diffusion from the mixed layer into the Deep Sea

Using the same notations and values as Oeschger et al.[14] (but without division by area which is irrelevant).

$$N_i + n_i(t) = \text{total amount of } C \text{ in reservoir } i$$

$$i = a \text{ (atmosphere), } m \text{ (mixed layer), } d \text{ (deep sea)}$$

$$N_i \text{ is the preindustrial equilibrium value (constant) and}$$

$$n_i \text{ is the deviation from the preindustrial equilibrium}$$

$$h_m = \text{depth of mixed layer} = 75 \text{ meters}$$

$h_d$  = depth of deep sea = 3725 meters

$$k_{am} = \text{exchange rate atmosphere – mixed layer} = \frac{1}{7.53 \text{ years}} = 1/\tau_{am}$$

$$k_{ma} = \text{exchange rate mixed layer – atmosphere} = \frac{1}{9.73 \text{ years}} = 1/\tau_{ma}$$

The effect of the Revelle factor (as defined by Suess and Revelle) is that the outflow from the surface sea to the atmosphere is given by:

$$\Phi = k_{ma}(N_m + R * n_m) \quad (7)$$

Where

$N_m$  is the preindustrial level of carbon in surface sea

$n_m$  is excess carbon in surface sea

$k_{ma}$  is a rate constant (inverse of the preindustrial residence time)

The Revelle factor enhance the outflow of excess carbon. The background to the Revelle factor is that the effective solubility of CO<sub>2</sub> in sea water is pH dependent. The solubility decreases when the pH decrease. Atmospheric CO<sub>2</sub> increases -> carbon in surface sea increases -> pH decreases -> solubility decreases

$$R = \text{Revelle factor} \approx 10$$

$$\text{at pre – industrial equilibrium: } k_{am} * N_a = k_{ma} * N_m \quad (8)$$

Comment:  $1/k_{am}$  is equivalent to  $\tau$  between atmosphere and mixed layer. Oeschger et al. used the value 7.53 years. The outflow from the mixed layer into the atmosphere is given by the expression:

$$k_{ma}(N_m + R * n_m) \quad (9)$$

Where  $N_m + n_m$  is the total carbon content in the mixed layer. The outflow from the atmosphere into the mixed layer is:

$$k_{am}(N_a + n_a) \quad (10)$$

As can be seen from the above equations, the Revelle factor  $R$  increases the outflow from the mixed layer faster than the content increases. If for example the carbon content in the mixed layer increases with 10% above equilibrium,  $n_m = 0.1 * N_m$ , the outflow increases from the equilibrium  $k_{ma} * N_m$  to  $k_{ma} * (N_m + R * 0.1 * N_m) = 2 * k_{ma} * N_m$  (using the BDM value  $R=10$ ), which is an 100% increases (doubling).

The outflow is strongly dependent on the concentration (Revelle effect). How much carbon that can be absorbed by the surface sea, without significantly changing pH (and consequently the outflow) is dependent on the absorption volume.

I do not see any significant increase from surface sea to atmosphere in data. At the same time, we know that surface sea has absorbed certain amount of carbon. If the surface sea is only 45 meters it means that it has a rather high additional carbon concentration, but a rather moderate increase in outflow. That leads to a lower  $R$  value in the data analysis. If surface sea is 90 meters, the concentration increase is only half and there is still room for an amplification.

The Revelle factor can be calculated from the following equations:

If we know the equilibrium flux,  $\Phi_{eq}[ppmv/a] = k_{ma} * N_m$ , and we know the additional flux,

$$\Phi_{add} = k_{ma} * R * n_m,$$

then we can calculate the  $R$ -value from data.

$$R = \frac{\phi_{add}}{\phi_{eq}} * \frac{N_m}{n_m} = \text{relative flux increase/relative carbon increase in mixed layer}$$

With

$$N_m = 900 \text{ and } \phi_{eq} = 60.7 \text{ we get } R = 14.8 * \frac{\phi_{add}}{n_m} \quad (11)$$

Unfortunately, the values given in the literature and IPCC that are needed to determine the Revelle factor with certainty are all inconsistent or not available. I will therefore estimate the values of the Revelle factor using different parameters from the literature. The percentage of land and ocean in emission and absorption together with the IPCC data are crucial for the value of  $R$ . Small changes affect large swings.

I assume that the following data from IPCC (Fig 6.1) are correct:

$$\begin{aligned} \phi_{am} &= 60 \text{ GtC}; \phi_{ma} = 60.7 \text{ GtC}; \\ N_m &= 900 \text{ GtC}; N_a = 589 \text{ GtC}; \\ n_a &= 240 \text{ GtC}; n_d = 155 \text{ GtC}; \end{aligned}$$

The data for  $k_{ma}$  and  $k_{ma}$  from Oeschger cannot be correct.

In the calculation I assume:

1.  $k_{ma}$ =14.49 and not 9.73 as given by Oeschger
2. absorption fraction Ocean 1750-2020: 37.6% up to 38.7%
3. emission fraction Ocean 1750-2020: 36.7% up to 40.0%
4. deep sea  $\phi_{md}$  is proportional to  $\phi_{am}$

Brief procedural description of our considerations for determining  $\phi_{add}$  and  $n_m$ :

$$\phi_{add} = \phi_{ma} - \phi_{eq} \quad (12)$$

$\phi_{ma}$  can be determined from the sum of emissions according to Global Carbon Budget GCB [4] for each year. The proportion of CO<sub>2</sub> emitted by the Ocean is known. It is between 36.7% and 40%. According to IPCC the share in 1750 is  $60.7/169 = 35.9\%$  in 2006 it is 39.6%. With this data we do have  $\phi_{add}$ .

To obtain  $n_m$ , we need the  $C$  uptake of the Ocean. The total absorption  $\phi_{am}$  is the sum of all emissions per year  $\phi_{ma}$  minus the fraction that remained in the atmosphere. According to IPCC 1750, the fraction of the ocean is:  $60/169.2 = 35.46\%$ , in 2006 39.4%.

Now the values of the CO<sub>2</sub> absorbed in Deep Sea are missing. With a residence time of 2000 years and a content of 37100 GtC, the following is obtained:

$$\phi_{md} = 37100 (1 - EXP(-1/\tau)) = 18.45 \text{ GtC} \quad (13)$$

An annual exchange of 18.45 GtC at equilibrium. This can only be an estimate, since we would actually have to use the diffusion equation. On the other hand, with the method we reach the IPCC value of 155 GtC in 2008, which justifies the estimate. I assume that the value  $\phi_{md}(t)$  is proportional to the value  $\phi_{am}(t)$ . From this, equation (4) can again be used to determine the  $C_{deepsea}(t)$ . In 2006 we obtain in this way the value of 37255 GtC and are thus in agreement with IPCC Fig 6.1. It follows, there will be about 30% of the absorbed  $C$  from  $\phi_{am}$  diffusing into Deep sea.

If we now determine  $C_{ocean}(t)$  with equation (4) and annually subtract the fraction diffused into Deep sea:

$$C_{OCEAN}(t) = C_{OCEAN}(t-1)/EXP(1/\tau_m) + \phi_{am} + \phi_{md}(1750) - \phi_{md}(t) \quad (14)$$

we obtain a reasonably correct value for  $C_{ocean}(t)$ . This procedure then yields

$$nm(t) = C_{ocean}(t) - Nm \quad (15)$$

the annual values. From this follows  $n_m(t)$  with which we calculate the Revelle factor  $R$ .

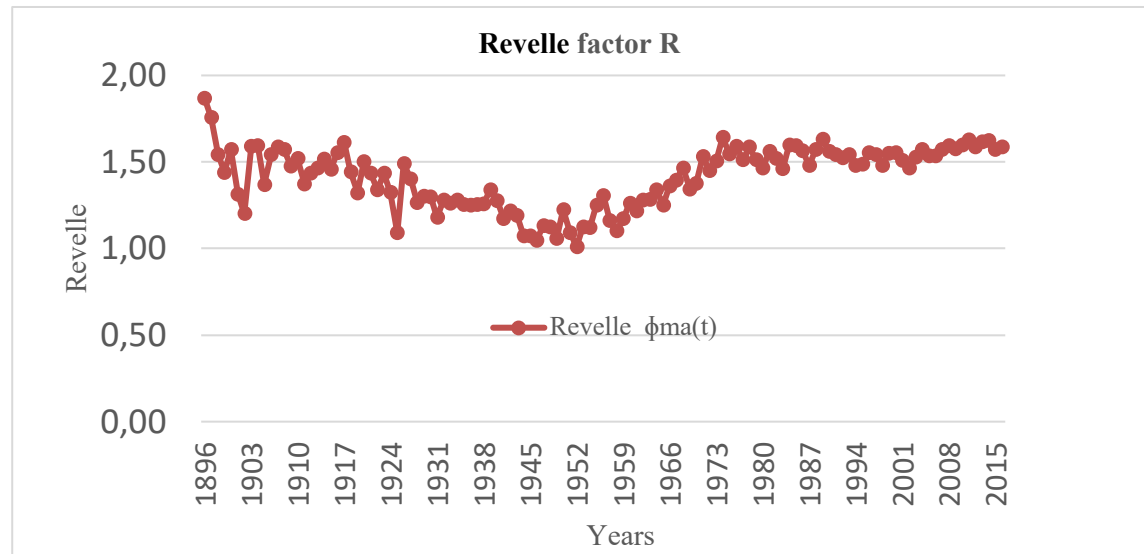


Fig 9: Revelle factor R

The average value with standard deviation is 1.44 +/- 0.2 which proves the high absorption capacity of the ocean.

## 9. Discussion:

The results can only be as good as the data used, since I did not use freely selectable parameters or make other corrections. I have tried to get the best possible data. In the calculation, I used the Global Carbon Budget 2021 data[4] for  $E_{FF}$  and  $E_{LUC}$ . The data for  $E_{NF}$  and  $E_{DCNF}$  were used from Skrable et al. [3]. The Data for  $E_{BMV}$  from bp [10].

An essential question is the determination of the biomass. In the reports of IPCC\_AR6\_WGII as well as IPCC\_AR5\_WGII, biomass is given as 450 PgC and 450 to 550 PgC, respectively, as constant values since 1750. In contrast, Erb et al. [19] assumes an increase of 100 GtC since 1750, as does Zaichun Thu et al. [20]. He observed a widespread increase of growing season integrated leaf area index (LAI) (greening) over 25% to 50% of the global vegetated area, since 1982 using NASA data. The importance of this question lies in the short e-time. If this is constant, then a 30% increase in photosynthesis means an equal 30% increase in CO<sub>2</sub>. At 450 GtC biomass, 30% is 135 GtC. This would correspond to an increase from 280 ppmv to 364 ppmv.

The increase of  $C_i$  of 51% must have consequences in the carbon content of the surface ocean. With a stable residence time we have equilibrium between CO<sub>2</sub> content in the atmosphere and the carbon reservoir biomass and ocean. If the carbon content of the atmosphere changes, the carbon content of the biomass and the oceans must change in the same proportion.

My view (today) is that the absolute best way to estimate the effective Revelle factor  $R$  is the way I did it. All parameters are in the data (even the ones that we do not know of).

I believe that the calculation of the residence time is simple, straightforward and completely understandable. There is no significant increase in residence time. My understanding is that scientists have observed rather fast increases AND decreases over the last 100's of years (e.g. Beck). Fast decreases strongly contradict the IPCC model.

What I have newly introduced are the values of Skrable  $E_{DCNF}$  for additional natural CO<sub>2</sub> emissions as well as the values of bp-study about the extent of wood burning, which are not included in the  $E_{LUC}$ ! Without these, at least since 1970, the reconciliation would be difficult. An important

criterion is the data used by Skrable. From the <sup>14</sup>C method, it should be expected to obtain a correct additional natural CO<sub>2</sub> emission. However, I had to supplement this via  $E_{OT}$  and  $E_{BMV}$ . Here, a review of the linearized interpolated data used by Skrable from the very small volume of measured data would be beneficial. The variation of specific activity of <sup>14</sup>C  $S(0)$  in year 1750 in Skrable's paper is 16.33 +/- 2.7 dpm (gC)<sup>-1</sup>. This is +/-16,3%. By using the value of  $S(0) = 14.9$ , which is only 9% less, it would not be necessary to implement  $E_{BMV}$  and  $E_{OT}$ . They would be part of  $E_{DCNF}$ .

In contrast to this, I have calculated the equation for the CO<sub>2</sub> content of the atmosphere from the data of Global Carbon Budget 2021 using the e-time formula for every single year since 1750 with only one parameter, namely the tau value. This was presented in Fig 3 and compared with the measured CO<sub>2</sub> values contained therein. By iterative procedure the Tau value could be determined in such a way that the graph agrees with the calculated one. The result from this is the tau value of 3.92, while Berry obtains the value 3.5. I was also able to determine the tau value per year since 1750 by means of the measured values and thus confirm its constancy, which Berry assumed as an assumption. With Berry's work it can be confirmed retrospectively that the premises of IPCC Fig 6.1 are correct.

Of course, it would be interesting to obtain the tau values for the individual reservoirs. There is also a need for more research here. Also, the effects of the temperature increase of 3.5K and the calculated increase of the CO<sub>2</sub> content by 100 ppmv (Harde) is very exciting.

If the fixed tau value is a proof that the concentration is proportional to the outflow, then, if  $C(t)$  of the atmosphere increases the  $C$  fraction of the biomass must increase in the same measure. In the case of the ocean, the temperature dependence is added. For residence time the direction of the flux does not matter, but for relaxation time, the direction is essential. Moreover, since most natural fluxes are temperature dependent, the absorption of some additional CO<sub>2</sub> above the dynamic equilibrium acts as a pressure dependent process that is essentially temperature independent. So far there is no assumptions on relation between outflow and pressure. If the outflow is proportional to the pressure - then tau will be a constant. The fact that tau is rather constant (using equation 1) is a very strong indication that the outflow in fact is proportional to the pressure.

I do NOT assume that the outflow is proportional to the pressure. It is the other way around. Analysis of the data leads to the conclusion that the outflow is nearly proportional to the pressure (since tau is nearly constant). I show that the outflow is almost proportional to the pressure - I do not assume that.

Indeed, a decreasing tau value shows that the outflow is increasing faster than the pressure. In the Bern model - which is used by the IPCC - emissions in addition to natural emissions are predicted to remain in the atmosphere for a long time. This is because the natural sinks are saturated (due to ocean acidification and limited biomass increase).

In addition, I could confirm that the sinks  $S_{OCEAN}$  and  $S_{LAND}$  remained constant in relation to  $C(t)$  over 270 years, i.e. no saturation can have occurred.

### 9.1 A future task

It is difficult to do a  $C$  mass balance. The carbon balance in 1750 differs significantly from that in 2020. This should be investigated further, considering the carbon content of soil (1500 GtC) and permafrost (1200 GtC). According to Schrumpp et al. (2011) [25] the carbon emissions from the soil should be 10 times the anthropogenic emissions! This is not included in any carbon balance so far.

Emission and absorption from biomass and ocean are currently about 210 GtC/yr and about 100 ppmv/a, respectively. According to Mauna Loa data, CO<sub>2</sub> concentration varies by 9 ppmv between northern summer and winter. This is equivalent to 9% of total natural emissions. Thus, absorption and emission occur simultaneously across the planet with a variation of 9%.

Anthropogenic emissions are smaller than the natural fluctuation between summer and winter with about 5 ppm. So it makes no sense to consider them as separate superpositions with their own residence time as suggested by the Bern model.

Within the last 10 years we had a certain stagnation with  $E_{FF}$  but not with  $E_{BMV}$ :

In 2010 the emissions of  $E_{FF}+E_{LUC}$  has been 12.21 GtC. included  $E_{BMV}$ : 19.78 GtC\*

In 2020 the emissions of  $E_{FF}+E_{LUC}$  has been 12.42 GtC included  $E_{BMV}$ : 26.31 GtC\*

In 2010 the absorption of  $S_{LAND}+S_{OCEAN}+S_{CEMENT}$  has been 5.71 GtC.

In 2020 the absorption of  $S_{LAND}+S_{OCEAN}+S_{CEMENT}$  has been 6.14 GtC, an increase of almost 0.7%/a. \* Data from [4], [10]

Although the emissions  $E_{FF}$  stalled, the sinks grew further. The partial atmospheric pressure increased an average of 2 ppmv/yr from 2000-2010, and an average of 2.4 ppmv/yr in 2010-2020. We conclude that any reduction of emissions from 12 GtC/yr to 6 GtC/yr would not change the rate of absorption, the force of absorption caused by partial pressure of CO<sub>2</sub> keeps it constant. There is a constant relation between partial pressure of CO<sub>2</sub> and absorption. Hence there will be no further increase of  $C(t)$ . At 6 GtC/yr of emissions and 6 GtC/yr of absorption we reach a new equilibrium. Even if  $E_{FF}$  emissions remained constant in the last decade, this does not lead to a stagnation of the increase in CO<sub>2</sub> concentration. This is not due to saturation of the sinks. On the contrary, their absorption capacity is steadily increasing. The cause is the very strong increase in emissions of  $E_{BMV}$ . This has not been sufficiently considered so far. See Fig 6.

A look into the future: The tau value of 3.92 years makes the CO<sub>2</sub> level hardly exceed the Scenario SSP2-4,5 even if the remaining reserves of 918 GtC of  $E_{FF}$  available according to IPCC are burned.

## Summary

I was able to determine the e-time, based on Global Carbon Budget [4] and bp [10] data, annually from 1750 to 2020. The result of 3.92 +/- 0.03 years (standard deviation) is relatively constant over 270 years. This is also a requirement for a stable Revelle factor  $R$  determined using the Oeschger Box Diffusion Model. It is 1.44 +/- 0.2, which proves the high absorption capacity of the ocean. This also shows the constancy of  $S_{OCEAN}$  and  $S_{LAND}$  in relation to  $C(t)$ . Thus, no saturation phenomenon can be detected.

In the context of the CO<sub>2</sub> balance, it was checked how the absorption capacity of the oceans changes due to the increased CO<sub>2</sub> content. The concentration  $C_i$  in liquid mol/dm<sup>3</sup> from Henry Law increased by 50%. Likewise, the Mauna Loa data and the photosynthesis of the biomass [6], [7], [12] showed that the biomass grew in the same order of magnitude and thus its absorption and emission capacity increased in the same proportion as the CO<sub>2</sub> content of the atmosphere. The value for  $E_{DCNF}$  given by Skrable had to be supplemented with the values of  $E_{BMV}$  and  $E_{OT}$ . Only in this way was it possible to compare the measured  $C(t)$  values with those determined on the available data basis. Finally, from these results the conclusion can be drawn that the anthropogenic fraction of the CO<sub>2</sub> content of the atmosphere is 28.9 ppmv (as for Berry), with the inclusion of  $E_{BMV}$  it is 50.5 ppmv +/- 6.4 ppmv (as for Skrable).

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