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# Analysis of the Simulation Results of Three Carbon Dioxide ($CO_2$) Cycle Models

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***Author's contribution***

*The sole author designed, analysed, interpreted and prepared the manuscript.*

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## ABSTRACT

The $CO_2$ (carbon dioxide) circulation models referred by the IPCC (Intergovernmental Panel on Climate Change) show that the increase of atmospheric $CO_2$ by 240 GtC (Gigatonnes of carbon) from 1750 to 2011 is totally anthropogenic in nature, which corresponds to the permille value of about -12.5‰, but the observed value is only -8.3‰. The author's improved 1DAOBM-3 $CO_2$ circulation model shows that the anthropogenic $CO_2$ amount in 2011 is only 73 GtC, satisfying the observed atmospheric permille values from 1750 to 2017. The $CO_2$ circulation between the ocean and the atmosphere has increased the amount of atmospheric $CO_2$ by natural $CO_2$ 197 GtC from the ocean, and this explains why the net uptake rate is only 1.9 GtC $yr^{-1}$. Together with the anthropogenic amount of 73 GtC, the total increase is 270 GtC by 2017, corresponding to the observed atmospheric $CO_2$ concentration. The simulations for 1000 GtC emissions by 2100 have been carried out by three models, including 1DAOBM-3, Bern2.5CC, and the mean model of 15 circulation models (called Joos 2013). The residence time of 1DAOBM-3 is 16 years for anthropogenic $CO_2$ impulse, the same as for the radiocarbon decay time. The decay time of 1DAOBM-3 for the impulse function is about 600 years meaning the residence time of about 150 years only. These values are much shorter than the residence times of two other models, which show that 25±9‰ of any anthropogenic $CO_2$ is still found in the atmosphere after 1,000 years. The

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reasons have been analyzed. The advantage of 1DAOBM-3 over the other models is that its results are in line with the oceanic and atmospheric observations from 1750 to 2017 but the future simulations include uncertainties due to ocean and biosphere uptake rate models.

*Keywords: Climate change; lifetime of atmospheric $CO_2$; $CO_2$ cycle models; climate models.*

## 1. INTRODUCTION

$CO_2$ cycle models are applied to calculate and evaluate the lifetime of atmospheric $CO_2$ caused by the anthropogenic emissions into the atmosphere. The IPCC has selected the Bern Carbon cycle model (Bern 2.5 CC) in the Assessment Report 4 (AR4) to describe the dynamic responses of the anthropogenic $CO_2$ perturbations [1,2]. In the AR5 report, the IPCC [3] has stated that "*the removal of human-emitted $CO_2$ from the atmosphere by natural processes will take a few hundred thousand years [high confidence".* Depending on the RCP scenario considered, about 15 to 40% of emitted $CO_2$ will remain in the atmosphere longer than 1,000 years." These lifetime values are based on the $CO_2$ cycle model by Joos et al. [4]. Ollila [5] has introduced an enhanced semi-empirical atmosphere-ocean-biosphere model by the name 1DAOBM-2, which gives much shorter lifetimes: the residence time (T) of the anthropogenic $CO_2$ is 16 years and the residence time of the total $CO_2$ is 55 years. It should be noted that the term "lifetime" is the same quantity as "relaxation time" or "adjustment time," which is about four times longer than the residence time.

One objective of this study is to introduce the enhanced version of 1DAOBM-3 and the simulation results of the model. Another objective is to analyze and compare the simulation results of these three $CO_2$ cycle models, 1DAOBM-3, BernCC2.5, and Joos2013 [4]. A very decisive feature of the 1DAOBM-3 in comparison to the other two models is its distinct difference between anthropogenic $CO_2$, natural $CO_2$, and the mixture of these two $CO_2$ types, named "total $CO_2$." This feature turns out to be an important factor in the validation of results.

In the research studies [2,4], there is a serious deficiency or error concerning anthropogenic $CO_2$. Joos et al. [2] state that "*Currently, only about half of the anthropogenic CO2 emission stays airborne*." In Joos et al. [4], there is a reference to the Impulse Response Function (IRF): "*The IRF is thus a firs t-order approximation how excess anthropogenic carbon is removed from the atmosphere by a particular model."* The researchers use the terms "anthropogenic $CO_2$" and "atmospheric $CO_2$" as if they were the same concepts, which they are not, because atmospheric $CO_2$ is a mixture of anthropogenic and natural $CO_2$. In AR5, the IPCC [3] (p. 467) refers to the study of Joos et al. [4] in pointing to the atmospheric $CO_2$ increase: "*About half of the emissions remained in the atmosphere 240 PgC±10 PgC since 1750.*"

According to Joos et al. [4] the whole increase of the atmospheric $CO_2$ since 1750 is anthropogenic. Huge dissolving rate 80±20% GtC $yr^{-1}$ flushes $CO_2$ from the atmosphere into the ocean and at the same time about the same size absolving rate releases $CO_2$ from the ocean into the atmosphere. The anthropogenic $CO_2$ amount was zero in the surface layer of the ocean in 1750 and still, its proportional content is still much lower than in the atmosphere. It means that the natural $CO_2$ flux from the ocean compensates the anthropogenic $CO_2$ loss into the ocean. It looks like that this natural $CO_2$ has not been considered in the model of [4].

1DAOBM-3 applies the same equation as 1DAOBM-2 for calculating the accurate permille value of the atmospheric $CO_2$ composition and it is calculated using the actual atmospheric $CO_2$ amounts (GtC)

$$\delta^{13}C = (CIA_{ant} * (-28) + (CIA_{tot} - CIA_{1750} - CIA_{ant}) * (-8) + CIA_{1750} * (-6.35))/CIA_{tot} \quad (1)$$

where $CIA_{ant}$ is anthropogenic $CO_2$, $CIA_{tot}$ is the total $CO_2$, and $CIA_{1750}$ is the total $CO_2$ in 1750. The measurement unit of $^{13}C$ proportion is $\delta^{13}C$ and it is a fraction of carbon isotope 13 expressed as (‰) (written also in forms per mil, per mill, permil, permill or permille). Equation (1) shows that the contemporary atmosphere is the mixture of three $CO_2$ fractions: the anthropogenic amount, the fraction originating from the ocean, and the atmospheric mass in 1750. The permille values of these fractions are: the fossil fuel $CO_2$ -28 ‰, the ocean -8 ‰, and the atmosphere in 1750 -6.35 ‰ [6,7]. The $^{13}C/^{12}C$ in equation (1) is 0.011162 for natural $CO_2$ and 0.010922 for anthropogenic $CO_2$. There is a light fractionation, when $CO_2$ passes through the air/sea interface.

Inoue et al. [8] have estimated that air to sea value is about -10‰ and the sea to air value is -8‰, and therefore the latter value is used in equation (1) for the $CO_2$ flux originating from the ocean. The calculated value of 1DAOBM-2 using equation (1) is -8.35‰ for 2011, which is the same as the observed permille value in 2011 [9].

The Joos2013 model found that the amount of anthropogenic $CO_2$ is 240 GtC when the total atmospheric $CO_2$ amount of 835 GtC in 2011 would mean the portion is 28.8% for the anthropogenic $CO_2$. Applying these values in equation (1) gives the permille value -12.45‰. This enormous error of Joos2013 model can be also illustrated with a graphical presentation.

A calculation formula for permille value is

$$\delta^{13}C = (({}^{13}C/{}^{12}C)_{sample} / ({}^{13}C/{}^{12}C)_{standard} - 1) * 1000 \quad (2)$$

where $({}^{13}C/{}^{12}C)_{sample}$ is the actual isotope relationship of a $CO_2$ fraction in question. The value of $({}^{13}C/{}^{12}C)_{standard}$ is 0.0112372. It means that permille value depends linearly on the ${}^{13}C/{}^{12}C$ and they are depicted in Fig. 1 according to equation (2).

The hypothetical permille value of Joos2013 is the same as the observed permille value but this value is not according to the linear dependency of ${}^{13}C/{}^{12}C$ as it should be. An analysis for 1DAOBM-2 and Joos2013 was carried using these values and the results are depicted in Table 1.

This analysis gives permille value of -12.84‰ for the atmosphere according to Joos2013 composition and the difference is insignificant with respect to the -12.45‰. The atmosphere according to Joos2013 could reach the observed permille value of -8.35‰ only if the permille value of the natural $CO_2$ fraction would be -0.29‰. There is no such a $CO_2$ phase on the Earth.

The simplest way to calculate the atmospheric permille value is by adding together the anthropogenic $CO_2$ and the natural $CO_2$ according to their proportions in the atmosphere in 2011: $\delta^{13}C = 0.29*(-28) + 0.71*(-6.35) = -12.57$‰. One could criticize the permille value -6.35‰ of the natural $CO_2$ in this calculation. It might have increased during the centuries but in that case, the permille value difference of the Joos2013 to the observed permille value would be even greater.

The gap between these calculated and observed permille values of Joos2013 is huge and shows that Bern2.5CC and Joos2013 have a prominent error in their model constructions. This great error creates a justified concern about whether the overall results of these models are based on

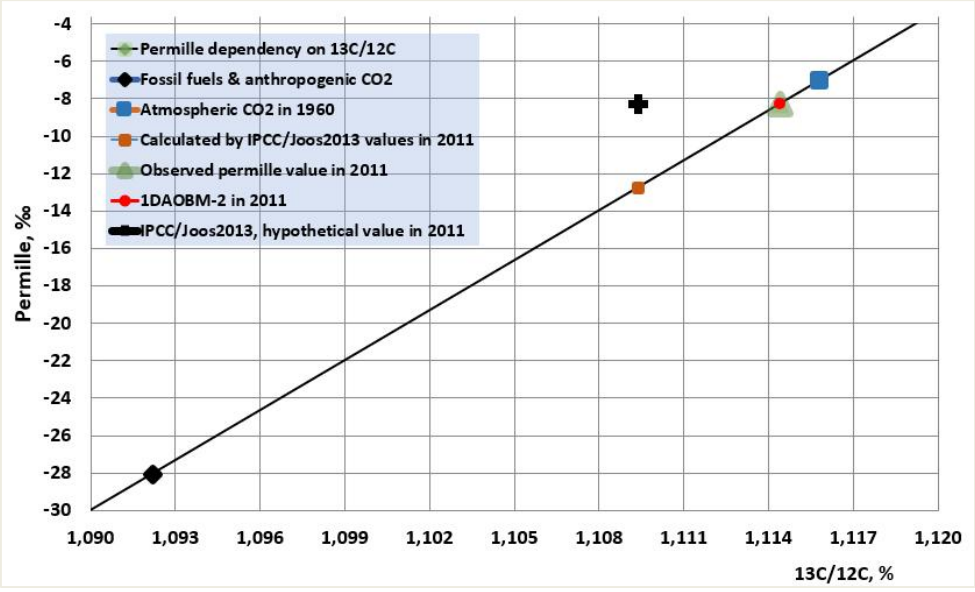


**Fig. 1. The permille values of different $CO_2$ compounds as a function of ${}^{13}C/{}^{12}C$**

**Table 1. Permille values for 1DAOBM-2 and Joos2012 results in 2011**

| Atmosphere 2011 | | | 1DAOBM-3 | | |
|---|---|---|---|---|---|
| | GtC | 13C/12C | 12C, GtC | 13C, GtC | Permille, ‰ |
| Natural $CO_2$ | 771 | 0,011162 | 762,489 | 8,510 | -6,35 |
| Anthropogenic $CO_2$ | 63 | 0,010922 | 62,3193 | 0,680 | -28 |
| Total $CO_2$ | 834 | 0,011144 | 824,808 | 9,191 | -8,31 |
| | | Joos2013 and the IPCC | | | |
| Natural $CO_2$ | 594 | 0,011162 | 587,443 | 6,557 | -6,35 |
| Anthropogenic $CO_2$ | 240 | 0,010922 | 237,407 | 2,592 | -28 |
| Total CO2 | 834 | 0,011093 | 824,850 | 9,149 | -12,84 |

real grounds. The deficiency of these two models may be one reason the researchers of these studies do not refer to the atmospheric permille value or why they do not use it for the calibration or the validation.

There are two schools of thought about the ocean's capacity to dissolve the atmospheric $CO_2$ and at which rate this dissolution can happen. The most common approach could be called the "buffer factor"–based estimation, or the buffering of the $CO_2$ exchange from air to seawater, also known as the "Revelle factor" [10]. The Revelle factor value is about 14 in the high latitude waters and about 10 in equatorial waters. Buffer factor 10 means that a 10% increase of partial $CO_2$ pressure can increase only 1% of the total carbon amount in the ocean. This approach has led to the maximum net dissolving rate of 2.2 $GtCyr^{-1}$ by [11], 2.3 GtC $yr^{-1}$ by [12], and 2.3±0.6 GtC $yr^{-1}$ by [13], which will not increase despite an increased atmospheric $CO_2$ concentration. The Bern2.5CC and Joos2013 models apply the buffer capacity approach.

There are studies that do not accept the almost constant buffer capacity of the ocean. The increased atmospheric $CO_2$ concentration can increase the buffer capacity by 2.5 to 6 times [14]. Other minerals like borate, kaolinite, and clay minerals can essentially increase the storage capacity of $CO_2$ [15,16], and in the latter study, the researchers have concluded that these buffers together mean an infinite buffer capacity. In 1DAOBM, the dissolution rate is not restricted by the buffer factor estimate.

## 2. METHODS

### 2.1 The Carbon Cycle Model 1DAOBM and Its Improvements

Ollila [17] introduced the 1DAOBM-1 model in 2015 and an improved version, 1DAOBM-2, a year later [5]. The 1DAOBM is a four-box model in which the ocean is divided into surface ocean and the intermediate and deep ocean. 1DAOBM contains two ideal mixing components (the atmosphere and the ocean), one plug flow component with four parallel residence times (the biosphere), and the outlet (the intermediate & deep ocean). The oceans have been assumed to have the capacity to dissolve the anthropogenic $CO_2$ emissions of the present century. The surface ocean part is based on the known dissolution chemical equations. The net flux rate from the surface ocean into the deep ocean is based on the empirical data. The removal of the anthropogenic $CO_2$ from the atmosphere is based on the huge carbon cycle flux rates of the dissolution pump and the biosphere carbon cycle, which remove 20–25% of $CO_2$ yearly from the atmosphere to other reservoirs and, at the same time, recycle natural and anthropogenic carbon.

An important feature of 1DAOBM is its capability to keep separated anthropogenic $CO_2$, natural $CO_2$, and their mixture, total $CO_2$. This feature cannot be found in the other two models used in the simulation studies.

### 2.2 Improvements in the Carbon Cycle Model 1DAOBM-3

The improvements of the 1DAOBM-3 model have been explained in Appendix. The calibrations of 1DAOBM-3 are now based on the measurements in the atmosphere because they are much more accurate in comparison to the oceanic $CO_{2,ant}$ measurements. The permille values from the Scripps data set [9], the $CO_2$ emission data are provided by CDIAC [18], and the ocean temperature data originate from NOAA [19].

### 2.3 Simulations Results by 1DAOBM-3

The simulation results of the $CO_2$ fluxes and amounts in the reservoirs by 1DAOBM-2 have been repeated by 1DAOBM-3. The dissolving rate by the surface ocean depends strongly on

the temperature according to Henry's law. In simulations up to 2013, the coefficient of determination is $r^2$ = 0.83 when the Pinatubo anomaly was removed. The decay rate simulation applying 1DAOBM-3 for 1964–2017 gives a similar residence time of 16 years for anthropogenic $CO_2$, as in the earlier simulation for 1960–2013. This simulation is almost exactly in line with the radiocarbon $^{14}C$ decay rate starting in 1964 when the nuclear tests in the atmosphere were suspended [5]. The radiocarbon is a perfect tracer to analyze the dynamic behavior of anthropogenic $CO_2$ because both $CO_2$ isotope $^{13}C$ and $^{14}C$ fluxes start from zero in the $CO_2$ circulation system. Because the radiocarbon has been in the descending mode for decades, it is not applicable for showing the actual dynamic behavior of $CO_2$ concentration in the ocean, but it is an excellent tracer in the atmosphere. Fig. 2 depicts the results of simulation using the real emission values, the observed sea temperatures, the calculated $CO_2$ fluxes, and the calculated/observed $CO_2$ concentrations.

Although the emissions increase, the calculated net anthropogenic $CO_2$ flux rate into the atmosphere remains relatively low; on the other hand, the natural $CO_2$ flux from the ocean into the atmosphere increases continuously. The reasons for these values are analyzed in the validation section. It might look odd that the yearly net anthropogenic flux $FB_{ant,dn}$ into the biosphere can be even higher than a yearly emission value, as it is shown during 1900–1970. This is because the $FB_{ant,dn}$ depends on the actual $CO_2$ amount in the atmosphere and not on the yearly emission flux values.

The cumulative $CO_2$ flux changes and reservoir change values from 1750 to 2017 are depicted in Fig. 3.

The major observation of this model simulation is that the amount of anthropogenic $CO_2$ in the atmosphere is only 73 GtC in 2017, but the natural $CO_2$ originating from the ocean is 197 GtC. This means that the total $CO_2$ increase in the ocean is only 36 GtC from 1750 to 2017. The $CO_2$ land sink in 2017 is 2.8 GtC $yr^{-1}$ being close to the estimate 2.5±1.3 of the IPCC [3] (p. 486) for 2002-2011. The sequestration capacity of the ocean has almost not been utilized. The division of the anthropogenic $CO_2$ between the biosphere (127 GtC) and the ocean (234 GtC) is 35% versus 65% by 2017. Sabine et al. [20] have estimated that the anthropogenic $CO_2$ sink value of 120 GtC in 1994 is about 30% the maximum sink capacity of the ocean, thus giving a maximum sink capacity value of 400 GtC.

## 2.4 Validation of Simulation Results

The validation of 1DAOBM-3 can be tested in four different ways. Firstly, Sabine et al. [20] have found that the global oceanic anthropogenic $CO_2$ sink from the period of 1800 to 1994 is 118±19 GtC, the estimate of Waugh et al. [21] is 134 GtC for the same period, and Khatiwala et al. [13] value for the inventory is 140±25 GtC. Sabine and Tanhua [22] summarized that the most common estimate of the oceanic anthropogenic $CO_2$ inventory in the mid-1990s is about 120 GtC. The model-calculated value for 1994 is 123 GtC, which is well inside the research study values.

Secondly, many research studies in recent years have shown the greening of the Earth during the few last decades. Zhu et al. [23] have found a widespread increase of growing season integrated Leaf Area Index (LAI) (greening) over 25–50% of the global vegetated area, whereas less than 4% of the globe shows decreasing LAI (browning). Based on recent inventory data and long-term field observations, Pan et al. [24] have estimated that the global carbon sink between 1990 and 2007 has been 2.4±0.4 GtC $yr^{-1}$ in the terrestrial sink, meaning about 40.8 GtC from 1990 to 2017. Cheng et al. [25] have calculated that Earth's global terrestrial uptake has increased by 0.83±0.26 GtC per year, or a total of 24.9 GtC over the past three decades. Furthermore, they determined that a 10% increase in atmospheric $CO_2$ induces an approximate 8% increase in global gross primary production (GPP). Bastin et al. [26] have estimated that the global forest cover has increased about 9%, which is 40–47% more than previous estimates. They have increased the estimates of global forest carbon stocks by 15 to 158.3 GtC in comparison to that of Pan et al. [24]. Keenan et al. [27] have estimated that the residual carbon sink has steadily increased over recent decades from 1–2 GtC $yr^{-1}$ in the 1950s to 2–4 GtC $yr^{-1}$ in the 2000s. The latter figure is greater than the sink value of 2.5 GtC $yr^{-1}$ in 2017 per IDAOBM-3 simulation.

Estimates of the terrestrial sink show an essential growth, but the values still vary a lot. The calculated terrestrial sink value of 127 GtC since 1750 is on the high end of these estimates. The research studies show that the increase in

atmospheric $CO_2$ will also increase the global GPP production in the future.

Thirdly, the residence time of the anthropogenic $CO_2$ in the atmosphere is 16 years, the same as that of the radiocarbon $^{14}C$ value, observed since the nuclear bomb tests in 1964. The model-calculated total atmospheric $CO_2$ concentration correlates very well with the observed $CO_2$ concentration: the coefficient of determination is 0.999, and the standard error of estimate is 0.79 ppm during the period from 1960 to 2017.

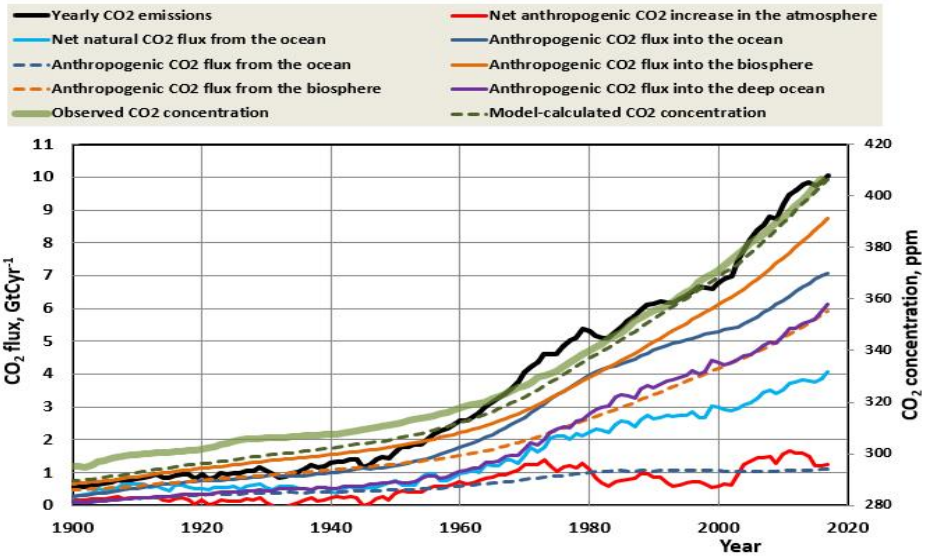


**Fig. 2. Yearly $CO_2$ emissions and fluxes between the reservoirs by 1DAOBM-3 using the data as defined in section 2.1**

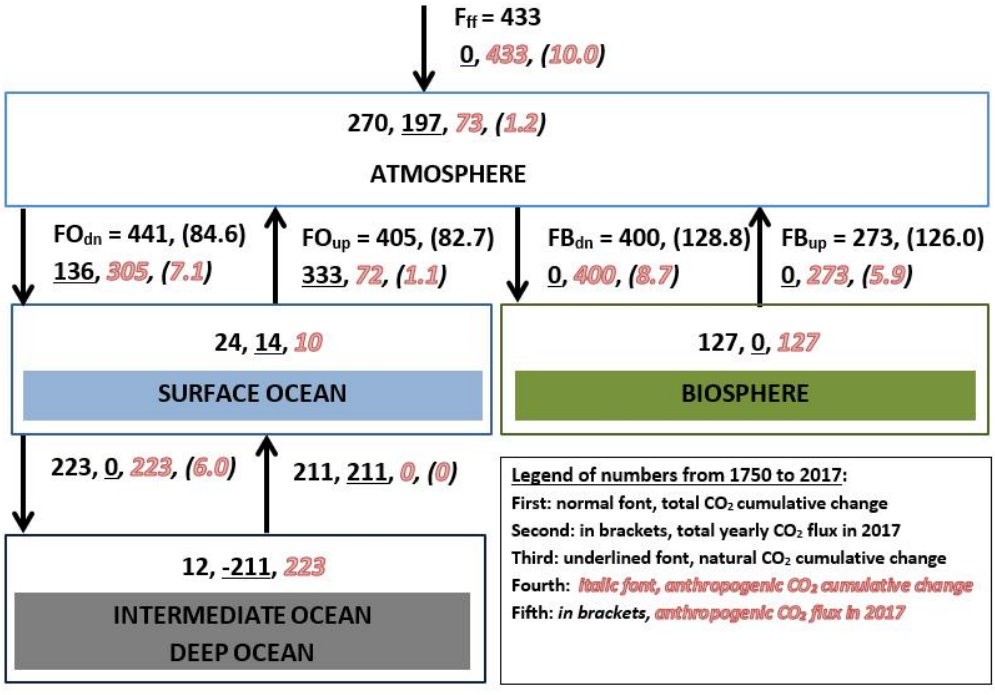


**Fig. 3. The cumulative $CO_2$ flux changes and reservoir change values from 1750 to 2017**

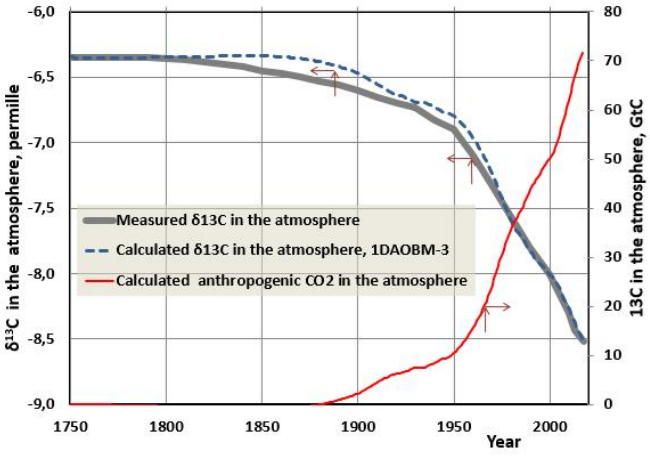


**Fig. 4. Observed and 1DAOBM-3–calculated permille values in the atmosphere and the cumulative anthropogenic $CO_2$ value in the atmosphere from 1750 to 2017**

Fourthly, the flux rate of anthropogenic $CO_2$ into the deep ocean has been calibrated according to the observed permille values of -8.56 for $\delta^{13}C$ in 2017. The model-calculated permille trend value from 1750 to 2017 shows a very good fit with the observed value [7,9] as indicated in Fig. 4.

## 3. RESULTS

### 3.1 The Basic Features of the Bern2.5CC and Joos2013 Models

The carbon cycle model of Bern2.5CC [2] is a combination of a well-mixed atmosphere, the HILDA ocean model [28], and the Lund-Potsdam-Jena (LPJ) dynamic global vegetation model [29]. The HILDA model consists of two well-mixed surface boxes for low and high latitudes, a well-mixed deep-water box for high latitudes, a well-mixed atmosphere, and a vertically diffusive-advective ocean interior in low latitudes. The LPJ model combines process-based, large-scale representations of terrestrial vegetation dynamics and land-atmosphere carbon and water exchanges in a modular framework. The atmospheric $CO_2$ decay response C of a $CO_2$ pulse (In) according to time t can be fitted into a combination of three different residence times [1]

$$C = In * (0.217 + 0.186*\exp(t/1.189) + 0.338*\exp(t/18.51) + 0.259*\exp(t/172.9)) \quad (3)$$

The Joos2013 model is a mean result of 15 different $CO_2$ circulation models [4]. The mean of the results was calculated for a 100 GtC pulse in 2010 when the atmospheric $CO_2$ concentration was 389 ppm. The atmospheric $CO_2$ decay response C of this $CO_2$ pulse according to time t is fitted into a combination of three different residence times [4].

$$C = In * (0.2173 + 0.2763*\exp(t/4.304) + 0.2824*\exp(t/36.54) + 0.224*\exp(t/394.4)) \quad (4)$$

Both equations (3) and (4) include a constant, which means that a relatively large portion of about 21.7% of any anthropogenic $CO_2$ emission will stay in the atmosphere forever. This means that, according to these models, the balance of $CO_2$ between the atmosphere and the ocean and terrestrial sink will never come near the preindustrial state. The simulations of the Joos2013 model include the warming effects of $CO_2$ according to the climate sensitivity of 3.0ºC.

Both Bern2.5CC and Joos2013 have the same feature as a majority of $CO_2$ circulation models: for a 1000–2000 GtC pulse, the $CO_2$ fraction remaining in the atmosphere is 20–25% [30]. It should be noted that even though the models calculate the atmospheric $CO_2$ concentration, the research studies [2,4] use the expression "anthropogenic $CO_2$" remaining in the atmosphere.

### 3.2 Simulation Results of 1000 GtC Emission

BP [31] has estimated that oil reserves will be exhausted by 2066 and gas reserves by 2068 if the production and consumption continue at the present rates. Humanity has used fossil fuels totaling 433 GtC by 2017. The total amount of

1000 GtC for a future scenario is thus a pessimistic value for future total emissions. The author has composed a 1000 GtC scenario by keeping the yearly emissions at 10.2 GtC until 2048 and thereafter by decreasing yearly emissions linearly to zero by 2100.

A simulation of the 1000 GtC emission amount was carried out by1DAOBM-3. In Fig. 5, flux rates are yearly values, and in Fig. 6, the flux rate values are cumulative. The temperature remains in the value of 2017 onward.

The maximum values of different variables are the following: the amount of total atmospheric $CO_2$ is 1027 GtC in 2089; the $CO_2$ concentration is 482 ppm in 2067; anthropogenic $CO_2$ in the atmosphere is 82.4 GtC in 2041; the natural $CO_2$ amount in the atmosphere is 379 GtC in 2089; and the anthropogenic $CO_2$ in the biosphere is 367 GtC in 2110. The latter value starts to decrease gradually, being 250 GtC in 2300, because 10% of a yearly anthropogenic $CO_2$ flux from the biosphere has a delay time of 80 years to return into the atmosphere.

It is rather difficult to estimate the net $CO_2$ rate change in the biosphere in Fig. 5. Therefore, this important variable has been depicted as a function of the atmospheric $CO_2$ concentration in Fig. 7.

Even though the $CO_2$ flux rate into the biosphere depends linearly on the $CO_2$ concentration, it turns out that the net rate change becomes nonlinear after 2023 when the $CO_2$ concentration exceeds 420 ppm, and in 2050 the net rate change does not increase anymore. The nonlinearity develops from 2023 to 2046 when the yearly emission rates are still at the constant values of 10.2 GtC. This nonlinearity has been caused by the $CO_2$ flux from the biosphere, when the delay times of 5, 20, 60 and 80 years from the root respiration develop into full effect according to Eq. (A23). Because after 2100 there are no $CO_2$ emissions anymore, the biosphere becomes a net source of $CO_2$ into the atmosphere after 2110.

The dynamic models of Bern2.55CC and Joos2013 are combinations of first-order dynamic processes. A dynamic first-order process can be simulated in the discrete form, enabling continuously changing input variables:

$$dT(n) = \Delta t/(T+\Delta t))/((T/\Delta t) * (Out(n-1) + In(n) \quad (5)$$

where Out(n) is the output of the process in step n, In(n) is the input of the process of step n, T is the time constant, Δt is the simulation step interval (1 month), and n-1 is the previous step value. Fig. 8 depicts the $CO_2$ concentration of three $CO_2$ models according to the actual emissions.

All models overreact for the input change during the first 25-30 years. Therafter the longest residence times of Bern2.5CC and Joos2013 control the output of these models, and the error in comparison to the observed $CO_2$ increases rapidly, being 432.5 ppm for Bern2.5CC and 441.5 ppm for Joos2013 in 2017, when the actual measured value is 406.5 ppm. The output of 1DAOBM-3 follows very well the observed $CO_2$ value being 407.3 ppm in 2017.

Fig. 9 depicts the $CO_2$ concentration curves of the Bern2.5CC and Joos2013 circulation models, and the fitted curve of the 1DAOBM-3 model. The fitting is according two a first-order dynamic process

$$C = 0.35*In*(exp(t/12))+0.65*In*(exp(t/150)) \quad (6)$$

where C is $CO_2$ concentration, In is the $CO_2$ emission input, and the time constants are 12 and 150 years.

The fitting curve for 1DAOBM-3 is not perfect, but it is simple and describes in an illustrative way how the sequestration rate decreases as the amount of $CO_2$ increases in the ocean and the terrestrial sink. In the simulation of Fig. 9, the outputs of the three models have been forced to the observed $CO_2$ value in 2010, even though the simulations start from 1950. This explains why the $CO_2$ concentration curves of Bern2.5CC and Joos2013 do not have the overreaction after 1950. Joos et al. [2] have used this kind of forcing in Bern2.5CC by starting the simulations from the observed $CO_2$ values in 1800 or 2000.

According to the 1DAOBM-3 simulation, the maximum $CO_2$ concentration will be 482 ppm in 2067, and it has decreased to 375 ppm in 2210. The decreasing rate of the atmospheric $CO_2$ in 143 years has been from 1027 GtC to 799 GtC corresponding to 0.75 ppm decrease per year, which means the average uptake rate of 1.6 GtC per year by the sinks. As Fig. 5 illustrates the deep ocean uptake rate is in the maximum value of 3.1 $GtCy^{-1}$ in 2067. The maximum $CO_2$ concentration of Joos2013 is 567 ppm in 2087, and the value in 2210 is 518 ppm. The differences between 1DAOBM-3 and the other two models are significant.

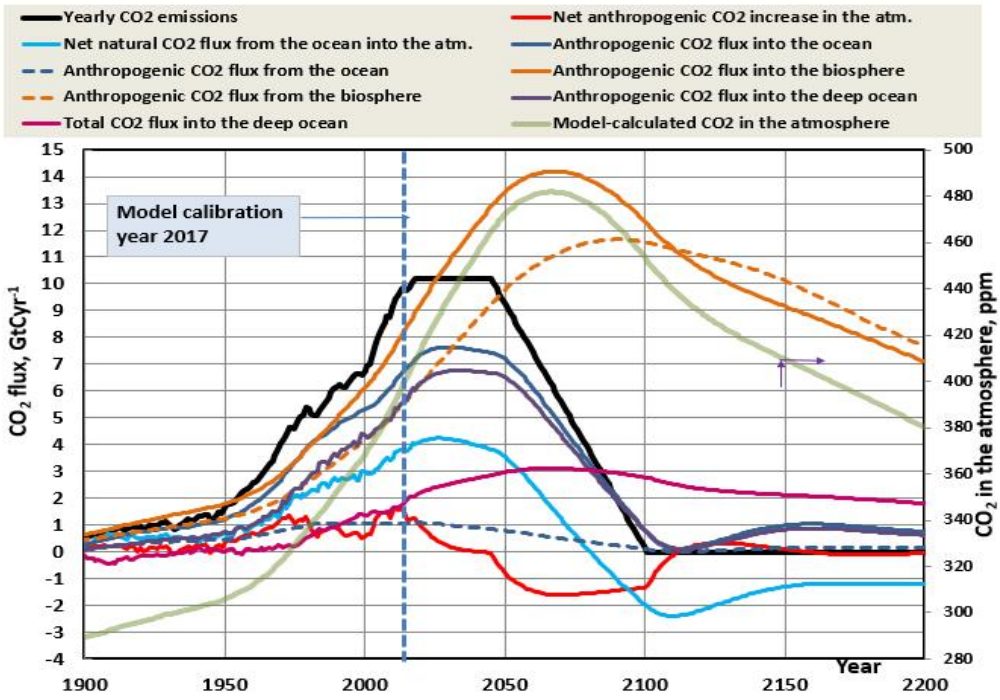


**Fig. 5. Simulation result for a 1000 GtC emission by 1DAOBM-3 showing the yearly flux rates**

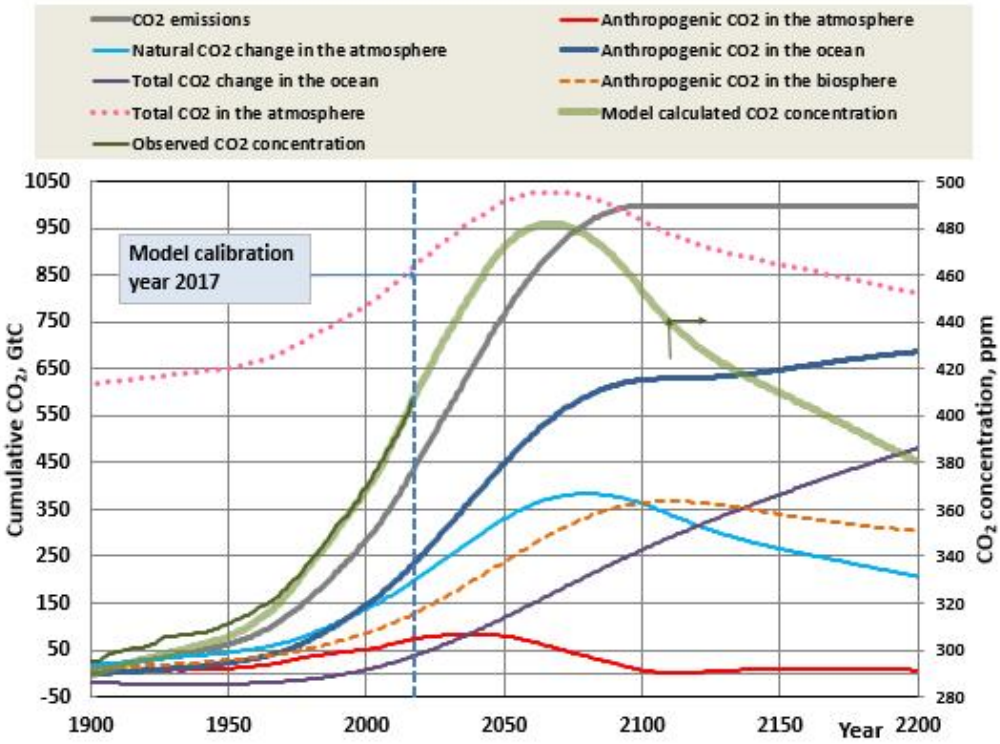


**Fig. 6. Simulation result for a 1000 GtC emission amount by 1DAOBM-3 showing the cumulative flux rates**

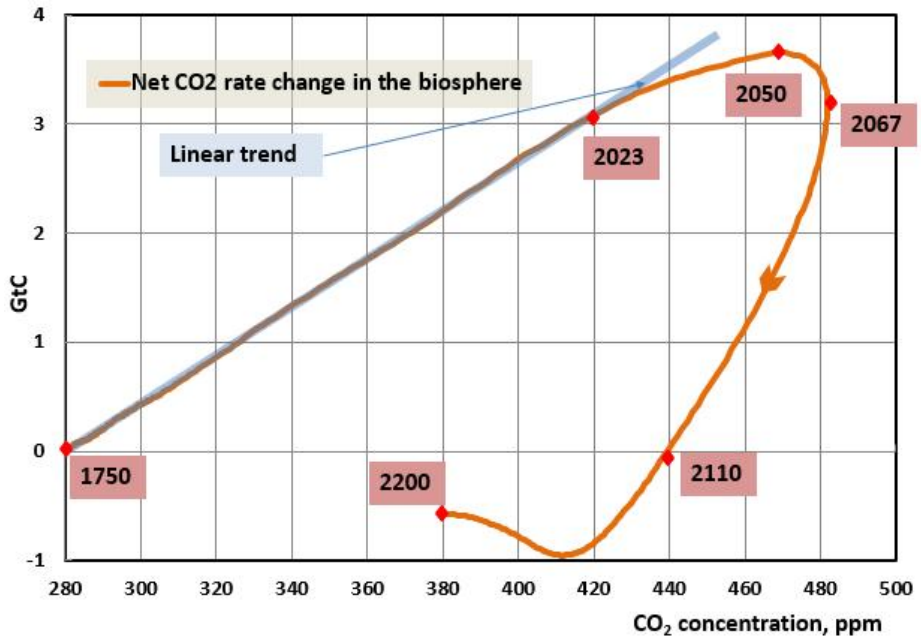


**Fig. 7. Simulation result for a 1000 GtC emission amount by 1DAOBM-3 showing net $CO_2$ rate changes in the biosphere. The red dots show years**

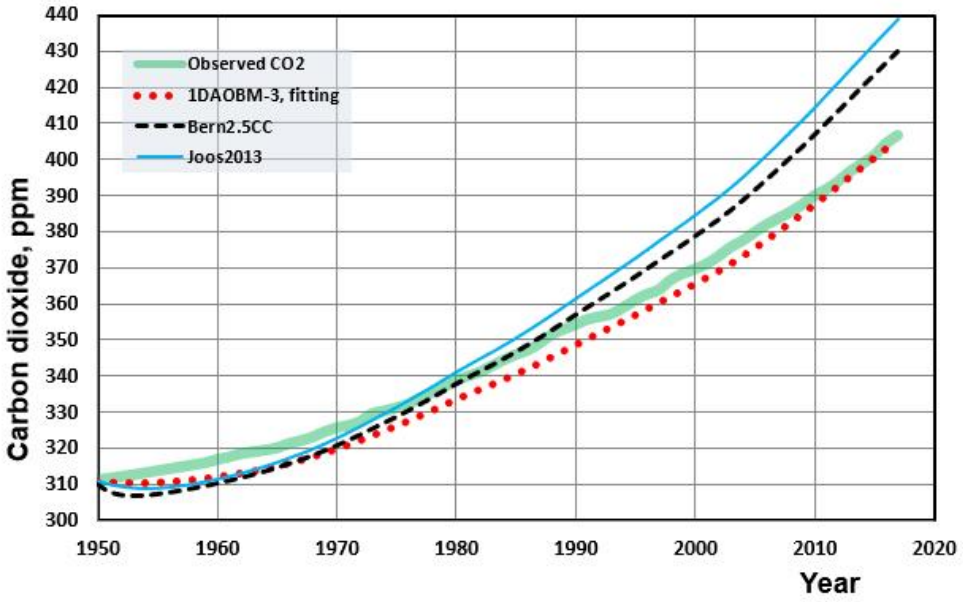


**Fig. 8. The $CO_2$ concentration curves of three $CO_2$ circulation models according to actual $CO_2$ emissions from 1950 to 2017**

Because the $CO_2$ concentration of Bern2.5CC and Joos2013 does not return close to the preindustrial value of 280 ppm after 1000 GtC emissions, the comparison based on the "end point" is not useful. A more realistic comparison point can be selected to be the conditions of the year 2020 in Fig. 8, when the $CO_2$ concentration will be about 410 ppm. The statistical and scientific facts show that today's climate conditions are better than in 1750, and therefore it is a proper reference point.

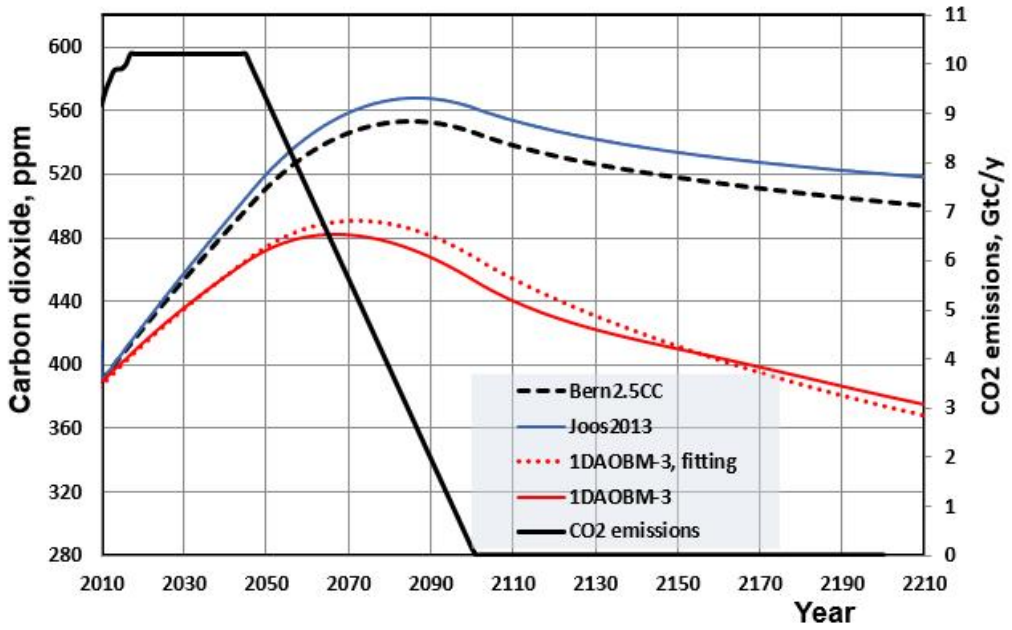


**Fig. 9. The $CO_2$ concentration change of three $CO_2$ circulation models for the total 1000 GtC emissions from 1730 to 2100. The start year of simulations is 1950 but the model-calculated $CO_2$ concentrations are forced to the observed $CO_2$ concentration in 2010**

The major concerns of the increased global temperature have been the increased amount of hazardous climate events and decreased crop amounts. The annual tornado account since 1954 shows that violent tornado frequency has been decreasing [32]. The landfall metric of Atlantic hurricanes reveals a statistically significant downward trend since 1950 [33]. A significant decrease in tropical and global cyclone frequencies has been observed since the late 1990s [34,35]. The world's wheat production has increased steadily, even in the warmest countries like India and Brazil [36]. India's government reports that food grain production was estimated to be at an all-time high in 2016–2017 [37] during the highest temperature peak during the present warm period.

The proxy temperature analyses reveal two warm periods [38], namely the Roman warm period from 250 BC to AD 450 and the Middle Age warm period from AD 950 to 1250. The retreating Mendenhall glacier in Alaska has exposed forest remnants older than 1,000 years based on their radiocarbon ages according to a statement by professor Connor [39]. Evidence shows that these warm periods, which have been called climate optimum periods, have been long and at least as warm as the present one. According to the evidence, we are living again in climate optimum conditions.

### 3.4 Simulation Results of Decay Times

The easiest way to compare these three models is to depict the decay rates. Fig. 10 depicts the decay rates according to the fitting equations (3), (4), (6), and (7) starting from 2010.

The fourth curve in Fig. 10 is for 1DAOBM-3 by using 70 years' residence time. It is represented as a reference to illustrate the effective residence time would be about 70 years after 70 years and then it increases gradually to 150 years. The major difference of 1DAOBM-3 model is that the $CO_2$ impulse rate decreases to almost zero after 300 years but the other two models show that about 22-30% of the impulse size is still in the atmosphere.

## 4. DISCUSSION

The grounds of the $CO_2$ circulation models are different. Bern2.5CC and Joos2013 are principally built on the assumptions that the buffer factor phenomenon restricts the maximum uptake of the ocean to 2.2–2.3 GtC per year. In

1DAOBM-3, there is no this kind of restriction but despite this, the net maximum uptake rate is only 3.1 GtC $yr^{-1}$ in a 1000 GtC emission simulation.

Because all three models utilize the measured anthropogenic values in the oceans in 1990–1994, this flux value into the deep ocean is about the same in 1990–1994 but not necessarily the same thereafter due to the maximum uptake rate of 2.3 GtC $yr^{-1}$ of Bern2.5CC and Joos2013. In 1DAOBM-3, the net anthropogenic $CO_2$ rate into the ocean is 6.1 GtC $yr^{-1}$, and the net natural $CO_2$ rate from the ocean into the atmosphere is 4.2 GtC $yr^{-1}$ in 2017. This means that the net $CO_2$ flux into the ocean is still only 1.9 GtC $yr^{-1}$, which is smaller than the buffer-restricted rate. It looks like other two models do not consider the natural $CO_2$ from the ocean into the atmosphere. The major consequence is that the anthropogenic $CO_2$ amount in the atmosphere of these models is far too great.

During the first 30 years, the calculated $CO_2$ concentrations by the Bern2.5CC and the Joos2010 models from 1950 to 2017 show too low values and relatively great error for the year 2017: 432.5 ppm and 441.5 ppm versus the observed 406.6 ppm. The output of 1DAOBM-3 closely follows the observed $CO_2$ value, being 406.5 ppm in 2017. The Bern2.5CC simulation in Fig. 2 of Joos et al. [2] closely follows the actual $CO_2$ concentration from 1800 to 2000 [40]. The simulation starting from 1950 in Fig. 8 shows that the Bern2.5CC model calculated values start to deviate from the observed values after 30 years. The author cannot explain these different results, but it seems logical that Bern2.5CC and Joos2013 give higher atmospheric $CO_2$ concentration values in the long run due to the longer residence times, as seen in the decay curves in Fig. 8.

The situation in 2149 corresponds to the $CO_2$ concentration of 410 ppm in 2020 according to 1DAOBM-3. The carbon budget shows that the ocean has sequestrated the total anthropogenic $CO_2$ of 647 GtC by 2167; the terrestrial sink value is 341 GtC, and the atmosphere has 11 GtC of the anthropogenic $CO_2$. The division between the oceanic and terrestrial sinks is thus 66% / 34% in 2167.

The buffer-restricted uptake of the ocean has a commonly accepted theory basis. In research studies before 2010, this led to the so-called “missing carbon” problem because the increased terrestrial sink was not generally accepted. This problem can be found in the missing sink by Bern2.5CC [2], in which the terrestrial sink is accepted as the missing sink surrogate before 2000, which then turns into the $CO_2$ source. In research studies after 2000, the terrestrial sink has been accepted as reality. For example, according to Canadell [41], 5 GtC of 9 GtC emissions in 2006 have been taken up naturally, half by the ocean and half by the terrestrial biosphere.

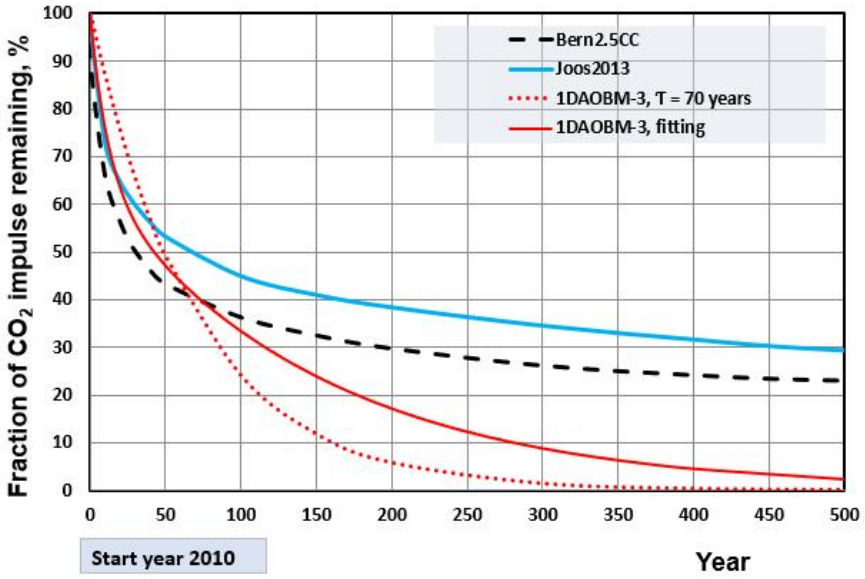


**Fig. 10. Decay rates of atmospheric $CO_2$ concentration using different carbon cycle models**

But there could be another mechanism that could explain a 35% greater maximum uptake rate of 3.1 GtC $yr^{-1}$ per 1DAOBM-3 versus 2.3 GtC $yr^{-1}$. The $CO_2$ sequestration by the ocean in 1DAOBM-3 is based on the ocean circulation fluxes between the atmosphere and the ocean. The dissolving flux varies between 75-90.7 GtC $yr^{-1}$, and the absolving flux from the ocean varies between 75-87.7 GtC $yr^{-1}$. These flux rates have been calibrated according to the measured atmospheric anthropogenic and total $CO_2$ amounts in 2017. The actual cold ocean circulation currents, which transfer the $CO_2$-rich seawater from the high latitudes (mainly the North Atlantic) into the Southern Ocean, are not very well known concerning their rates and interactions with the deep ocean. It is generally accepted that the cold ocean waters dissolve $CO_2$ from the atmosphere, and thereafter, these cold ocean currents flow toward the Southern Ocean, where the warmer sea water absolves $CO_2$ back into the atmosphere.

Archer and Brovkin [30] have stated that the dissolved $CO_2$ must wait for the overturning circulation of the ocean, which takes centuries or a millennium. These time scales are not well known. It could be assessed on the basis of the speeds of warm surface currents like the Gulf current. Its speed is estimated to be about 4 km per hour, so it would take about 3 months for the Gulf current to flow from Key West to the Arctic Ocean. This huge water mass flow cannot disappear, but it must continue flowing below the surface, and it does so as a Labrador current and an East Greenland Current. These cold currents flow at depths of 2000–4000 thousand meters, and they flow to the south as the Canaries Current up to the Equator. If the water mass of these currents is close to the Gulf current, the time from the Arctic Ocean to the Equator should be months, not centuries. One example of time scales is that the atmospheric $CO_2$ concentration reacts with an 11-month delay to the Ocean temperature change [42].

The uptake process of $CO_2$ by the ocean is complicated and there might be doubts that the oceanic anthropogenic $CO_2$ could be different by nature in comparison to the same in the atmosphere. All the researchers who have carried out the estimation studies of the anthropogenic oceanic $CO_2$ amounts or fluxes have not identified this problem but they inform that the oceanic anthropogenic $CO_2$ can be summarized into the total mass of fossil fuel emissions distributed in atmospheric, oceanic and terrestrial sinks as noticed in the review article [22].

Keeling et al. [43] have found that land photosynthesis increases the discrimination of $^{13}C$ isotopes when the atmospheric $CO_2$ concentration increases. They propose a correction term of +0.014‰ $ppm^{-1}$ ± 0.007‰ $ppm^{-1}$ for the model-calculated atmospheric permille values if these values are based on the land photosynthesis model. When this correction term is applied for the results of Joos2013 model, the calculated permille value of -12.9‰ in section 1 would increase to -11.2‰. 1DAOBM-3 was calibrated using the observed atmospheric permille value in 2017 and therefore the possible increased $^{13}C$ discrimination of land photosynthesis has been included in the model. It should be noticed that the carbon residence time in terrestrial vegetation is one of the major uncertainties in the future climate responses [44].

Major uncertainties of 1DAOBM-3 are the deep-sea sequestration rate and the terrestrial uptake rate of carbon. Both models are linear depending on the $CO_2$ concentration of surface ocean or the atmospheric $CO_2$ concentration, but it turns out the net rate change in the biosphere becomes highly nonlinear after the $CO_2$ concentration of 420 ppm. The calibration of model parameters depends on atmospheric permille value. In this way 1DAOBM-3 model is in line with the observed values in 2017, when cumulative $CO_2$ emissions have been 433 GtC. The future uptake rate of the biosphere includes uncertainties because the model equations are simple and possible saturation or nonlinear effects of higher $CO_2$ concentrations are not included.

A pessimistic estimate for the total $CO_2$ of humanity is 1000 GtC. If a model is in line with the observations at the point of 43% of the possible scale, it is a good possibility that the model works well during the rest of the scale. The net uptake of the ocean has been only 36 GtC of total $CO_2$ by 2017, and the sequestration capacity of the ocean has not been utilized almost at all. The photosynthesis rate dependency on the $CO_2$ concentration for C3 plants is close to linear in the concentration from 280 to 600 ppm. Increasing biomass also increases humidity and rain conditions regionally and these factors are positive indicators that also terrestrial uptake rate could continue to increase in a linear way in the future.

## 5. CONCLUSION

As analyzed in section 1, the Bern2.5CC and Joos2013 models include a serious problem with the amount of anthropogenic $CO_2$ in the atmosphere: Joos2013 shows the anthropogenic $CO_2$ to be 240 GtC in 2011, when the direct permille measurement shows that the value is 67 GtC. This "wrong carbon" error in the atmospheric composition of Bern2.5 and Joos2103 models leads to another significant error. The mechanism of $CO_2$ circulation flows does not recognize that there is a great net natural $CO_2$ flux from the ocean into the atmosphere since 1750.

1DAOBM-3 calculates that the anthropogenic $CO_2$ in the atmosphere in 2017 is only 73 GtC. This $CO_2$ amount produces a calculated permille value of -8.52‰, practically the same as what was observed. Also, the historical permille values are close to the observed values. Because the total amount of atmospheric $CO_2$ in the same year was 867 GtC, the missing portion is natural $CO_2$, which must originate from the ocean, and its amount is 198 GtC, as shown in Fig. 2.

The big difference in 1DAOBM-3 in comparison to the other two models is that there are much greater anthropogenic and natural fluxes between the atmosphere and the ocean, as in the buffer-limited approach, but the net flux is not much greater. The result is that the 1DAOBM-3 approach can explain how the natural $CO_2$ enters the atmosphere, and it satisfies all the observed values of the atmospheric measurements, but the buffer-restricted approach cannot do it.

The cumulative values of 1DAOBM-3 from 1750 to 2017 show that the total (anthropogenic + natural) $CO_2$ in the ocean since 1750 has hardly started to increase because its amount as depicted is only 36 GtC. The ocean sink amount means only a 1.9% increase in the total oceanic $CO_2$, which is a very small increase considering the terrestrial sink increase in recent decades. This means that the uptake capacity of the oceans has not been practically utilized at all by 2017.

## COMPETING INTERESTS

Author has declared that no competing interests exist.

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## APPENDIX

**Table A-1. The calculation bases for variables and coefficients of the 1DAOBM-3. The amounts are in GtC and fluxes are in GtC $yr^{-1}$**

| Variable Acronym | Variable name | Calculation formula |
|---|---|---|
| $FO_{tot,dn}$ | Total dissolution carbon pump flux from the atmosphere into the ocean | $80.5 + K_{dn}*(CIA - CIA_{1750})$; $K_{dn} = 0.0366$; CIA is the total atmospheric carbon (1) |
| $FLUSH_{AO}$-% | Flush-% of the dissolution pump from the atmosphere into the ocean | $100 * FO_{tot,dn} / CIA_{tot,n}$ (2) |
| $FO_{ant,dn}$ | Anthropogenic dissolution carbon pump flux from the atmosphere into the ocean | $FLUSH_{AO}$-% * $CIA_{ant,n-1}$ / 100 (3) |
| $FO_{nat,dn}$ | Natural dissolution carbon pump flux from the atmosphere into the ocean | $FO_{tot,dn} - FO_{ant,dn}$ (4) |
| $FO_{tot,up}$ | Total dissolution carbon pump flux from the ocean into the atmosphere | $80.5 + K_{up} * (CSO_{tot} - CSO_{1750})$; $K_{up}$=0.32 (5) |
| $FLUSH_{OA}$-% | Flush-% of the dissolution pump from the ocean into the atmosphere | $100 * FO_{tot,up} / CSO_{tot,n}$ (6) |
| $FO_{ant,up}$ | Anthropogenic dissolution carbon pump flux from the ocean into the atmosphere | $FLUSH_{OA}$-% *$CSO_{ant,n-1}$ / 100 (7) |
| $FO_{nat,up}$ | Natural dissolution carbon pump flux from the ocean into the atmosphere | $FO_{tot,up} - FO_{ant,up}$ (8) |
| $\Delta CIA_{nat}$ | Natural net $CO_2$ flux change from the ocean into the atmosphere | $FO_{nat,up} - FO_{nat,dn}$ (9) |
| $CSO_{tot}$ | Dissolved organic carbon in the ocean in the range of 280 ppm – 430 ppm | $2.2 - 5.5774*10^{-3}*T - 8.631*10^{-5}*T^2 + 6*10^{-4}*$ (C-350); T is ocean temperature ($^0$C), C is $CO_{2,tot}$ concentration in CSO (10) |
| $CSO_{tot}$ | Dissolved organic carbon in the ocean in the range of 430 ppm – 600 ppm | $2.255 - 5.114*10^{-3}*T - 6.84*10^{-5}*T^2 + 3*10^{-4}$ * (C-500); T is ocean temperature ($^0$C), C is $CO_{2,tot}$ concentration in (11) |
| $FN_{ant,deep}$ | Anthropogenic net $CO_2$ flux from the surface ocean into the intermediate & deep ocean | $K_{ant} * (CSO_{tot,n} - CSO_{tot,1750}) * (CSO_{ant,n-1} / CSO_{tot,n})$; $K_{ant}$ = 16.0 (12) |
| $\Delta CSO_{tot}$ | Total $CO_2$ change in the surface ocean | $CSO_{tot} - CSO_{tot,1750}$ (13) |
| $\Delta CSO_{ant}$ | Anthropogenic $CO_2$ change in the surface ocean | $FO_{ant,down} - FO_{ant,up} - FN_{ant,deep}$ (14) |
| $\Delta CSO_{nat}$ | Natural $CO_2$ change in the surface ocean | $\Delta CSO_{tot} - \Delta CSO_{ant}$ (15) |
| $FN_{ant,ocean}$ | Anthropogenic $CO_2$ flux into the ocean | $FN_{ant,deep} + \Delta CSO_{ant}$ (16) |
| $FN_{nat,deep}$ | Net natural $CO_2$ flux from the deep ocean | $FO_{nat,atm} - \Delta CSO_{nat}$ (17) |
| $FN_{tot,deep}$ | Total net $CO_2$ flux into the deep ocean | $FN_{ant,deep} + FN_{nat,deep}$ (18) |
| $\Delta CDO_{ant}$ | Anthrop. $CO_2$ change in the deep ocean | $F_{deep,n} - F_{deep,n-1}$ (19) |
| $FB_{tot,dn}$ | Total biosphere carbon cycle flux from the atmosphere into the | $120 + KB_{dn} *(CIA - CIA_{1750})$; $KB_{dn}$ = 0.017 (20) |

| Variable Acronym | Variable name | Calculation formula | |
|---|---|---|---|
| | biosphere | | |
| $FLUSH_{AB}$-% | Flush-% of the biosphere carbon cycle from the atmosphere into the biosphere | $100 * FB_{tot,dn} / CIA_{tot,n}$ | (21) |
| $FB_{ant,dn}$ | Anthropogenic biosphere carbon cycle flux from the atmosphere into the biosphere | $KA_{dn} * CIA_{tot,n-1}$<br>$KA_{dn} = 0.03305$ | (22) |
| $FB_{ant,up}$ | Anthropogenic biosphere carbon cycle flux from the biosphere into the atmosphere | $0.5*CIA_{tot,n-1} + 0.1*CIA_{tot,n-5} +0.05*CIA_{tot,n-20} +0.2*CIA_{tot,n-60} +0.1*CIA_{tot,n-80}$ | (23) |
| $\Delta CIB_{ant}$ | Anthrop. $CO_2$ change in the biosphere | $FB_{ant,down} – FB_{ant,up}$ | (24) |
| $\Delta CIA_{ant}$ | Anthrop. $CO_2$ change in the atmosphere | $F_{ff} – \Delta CSO_{ant} – \Delta CDO_{ant} – \Delta CIB_{ant}$;<br>$F_{ff}$ is $CO_2$ emission flux | (25) |
| $\Delta CIA_{tot}$ | Total $CO_2$ change in the atmosphere | $\Delta CIA_{nat} + \Delta CIA_{ant}$ | (26) |
| $F_{ff}$ | Anthropogenic $CO_2$ emission flux from fossil fuel combustion | | |

Total dissolution carbon pump flux from the atmosphere into the ocean $FO_{tot,dn}$ depends linearly on the difference of the atmospheric $CO_2$ amount minus the same in 1750 per eq. (A1). As a consequence, $FO_{tot,dn}$ increases from 75.0 $GtCyr^{-1}$ in 1750 to 84.62 $GtCyr^{-1}$ in 2017. Total dissolution carbon pump flux from the ocean into the atmosphere $FO_{tot,up}$ depends linearly on the difference of the surface ocean total $CO_2$ concentration minus the same in 1750 per eq. (A5). As a consequence, $FO_{tot,up}$ increases from 75.0 $GtCyr^{-1}$ in 1750 to 82.72 $GtCyr^{-1}$ in 2017. The linear dependencies of eq. (1A) and eq. (5A) means that both fluxes increase as the total atmospheric $CO_2$ increases, and both fluxes diminish into the 1750 value if the actual $CO_2$ concentration values in the atmosphere or in the surface ocean approach the values of the year 1750. The IPCC (2011) has used the values of Sarmiento and Gruber [45], which are 60 $GtCyr^{-1}$ in 1750 and 80.0 $GtCyr^{-1}$ in 2011. The dependency on the atmospheric $CO_2$ concentration is thus smaller in this study.

The coefficient $K_{ant}$ is 16.0 in eq. (A12) and is calibrated so that the amount of atmospheric anthropogenic $CO_2$ gives permille values of -8.56 for $\delta^{13}C$ in 2017. Coefficients $K_{dn}$ and $K_{up}$ have been calibrated so that the natural cumulative $CO_2$ amount in the atmosphere is 197 GtC from 1750 to 2017 closing the total $CO_2$ amount in the atmosphere in 2017. The total $CO_2$ change in the ocean is only 36 GtC from 1750 to 2017. A major change is that that the total biosphere carbon flux $FB_{tot,dn}$ from the atmosphere into the biosphere depends linearly on the atmospheric $CO_2$ per eq. (A20).

The $CO_2$ flux into the biosphere $FB_{ant,dn}$ increases linearly on the increasing total atmospheric $CO_2$ concentration (Eq. A22). This is an approximation of the photosynthesis rate for C4 plants which represent 82% vegetated land surface [46]. The actual rate is slightly nonlinear for C4 plants [47] and for C3 plants it is about constant after 350 ppm. Because the $CO_2$ concentration exceeded 350 ppm in 1987, the error not including C3 plants in the model is rather small. The increase in biomass increases also other important growing conditions like humidity and rains in regional scale. In the earlier model version, it depended on the anthropogenic $CO_2$ amount. The coefficients $KB_{dn}$ and $KA_{dn}$ have been calibrated so that the $CO_{2,ant}$ of the biosphere in 2017 is 127 GtC, thus closing the $CO_{2,ant}$ budget in different reservoirs.

The respiration of plants happens in leaves and roots in relationship roughly 50%/50%. The research studies of the respiration rate of plants in elevated $CO_2$ concentrations show contradicting results. For example Drake [48] found that $CO_2$ respiration decreased about 10% in high higher $CO_2$ concentrations, and Leakey et al. [49] found that respiration increased 37% in 550 ppm concentration. Gonzalez-Meler et al. [50] have concluded that respiration rate stays about at constant value in the elevated $CO_2$ conditions. Decreasing respiration means greater take up rate. There is no

generally accepted research result concerning respiration dependency on $CO_2$ concentration. It should be noticed that respiration studies have been short term studies related to respiration process in leaves. The long term respiration models are almost non-existing. Therefore, the $CO_2$ flux from the biosphere into the atmosphere (Eq. 20)) has not been revised, because there is no reliable new research studies about the respiration rate.



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