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Effective CO_2 lifetime and future CO_2 levels based on fit function

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Abstract. The estimated global CO_2 emission rates and the measured atmospheric CO_2 concentrations show that only a certain share of the emitted CO_2 accumulates in the atmosphere. For given atmospheric emissions of CO_2, the effective lifetime determines its accumulation in the atmosphere and, consequently, its impact on the future global warming. We found that on average the inferred effective lifetime of CO_2 decreases as its atmospheric concentration increases, reducing the rate of its accumulation in the atmosphere. We derived a power function that fits the varying lifetimes. Based on this fitting function, we calculated the increase of CO_2 for different scenarios of future global emission rates.

1   Introduction

The lifetime (residence time) of CO_2 in the atmosphere plays a rather important role in the climate debate. Correctly quantifying of future CO_2 increase in the atmosphere is important for the assessment of expected global warming and for the construction of climate change scenarios. Even if the increase of the emission will be stopped at a certain level, the CO_2 mixing ratio will continue to grow until the corresponding equilibrium is reached. In the literature one finds a large scatter of values for its lifetime, ranging between a decennial and a millennial timescale. For instance, Solomon (2008) and Kikuchi et al. (2009) estimated a lifetime of 5 to 10 yr. In contrast to these very small values, Archer and Brovkin (2008) and Archer et al. (2009) inferred a millennial timescale. The IPCC-report (Intergovernmental Panel on Climate Change) published a more realistic centennial timescale with a value of about 200 yr (IPCC, 2007). In 2001, the IPCC Technical Report still stated that the lifetime ranges between 5 and 200 yr. Jacobson (2005) published lifetimes of 30–95 yr, and Dietze (1995) derived a value of 55 yr. In other words, there is great ambiguity about this "lifetime" term, and such scatter indicates fundamental differences in the definition of the term "lifetime" and therefore the consequential methods of its estimation. Hence, it is absolutely necessary to define the term "lifetime" before one states a certain calculated lifetime is wrong and another value has to be the only one correct. The other side of the problem is the lack of knowledge about sinks and sources and the nonlinear interaction between them.

Characteristic time, timescale, response time, lifetime, residence time, time constant, relaxation time, and turnover time are all expressions related to the same or a similar subject. The characteristic times provide a feeling for the velocity (or persistence) of processes taking place in physical-chemical systems. They help to estimate which processes are important compared to other processes, which processes are fast and come quickly into an equilibrium state so that, for instance, transport can be neglected, or opposite, which processes are slow, so that the state will be exclusively determined by transports. However, there is still a great ambiguity and thus misinterpretation of results concerning the time behavior of complex systems such as atmospheric chemistry.

Körner and Sonnemann (2001) defined the so-called effective characteristic time of water vapor if including both the loss but also the chemical production processes returning hydrogen radicals formed by the decomposition of water vapor, back to water vapor. Such cycles in which a constituent is destroyed in the first step but after that is formed back were called "zero cycles". Analogously to the definition of the effective lifetime in photochemical systems, we define an effective lifetime of CO_2 in the atmosphere as the lifetime which excludes all zero cycles.

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Atmospheric CO_2 is in permanent exchange with the biosphere and the oceans. For instance, in the process of plant growth CO_2 is consumed, but the same quantity is released into the atmosphere when the plant rots. Globally averaged over a certain period, both processes form nearly a zero cycle, meaning the balance is settled under the equilibrium condition of constant global biomass. The same assertion is true in global mean under equilibrium conditions for the process of CO_2 exchange between the atmosphere and the oceans. However, the exchange is more intricate as cold water and ice contain more CO_2 than warm water. The global streams of the oceans transport water poor in CO_2 from lower to higher latitudes, and other streams enriched with CO_2 convey water from higher latitudes backward to lower ones, releasing its excess CO_2 when the water becomes warmer. When the water becomes cooler in connection with La Niña events or volcano eruptions, it takes up more CO_2, which decreases the atmospheric content. We call these system-internal exchange processes. The system consists of the atmosphere, biosphere, lithosphere, and surface water of the oceans. Moreover, there is a permanent exchange between the surface water and the deep water of the oceans induced by the thermohaline circulation (ocean conveyor belt).

It is not important for the global balance of atmospheric CO_2 whether an individual CO_2 molecule passes through such a zero cycle with a certain characteristic time on the order of some years – the decennial timescale. This time does not determine the velocity at which the anthropogenic emitted CO_2 will be removed from the atmosphere.

The main sink for atmospheric CO_2 is the ocean (following the idea of the paper, we exclude zero cycles related to the biosphere, etc.). The huge mass of water could take up large quantities of atmospheric CO_2; without that, its concentration in the atmosphere would noticeably rise. However, this process is marked by a certain timescale, so if the emission of CO_2 takes place faster than the oceans are able to take it up, CO_2 becomes congested in the atmosphere. This is currently the main problem: the anthropogenic exhaust of CO_2 is essentially faster than the velocity of accumulation by the oceans. If no external emission occurs (zero anthropogenic emission), the system (total: ocean–atmosphere–lithosphere–biosphere) will run into a quasi-equilibrium state. "Quasi" here means that there are still small internal variations induced by climatic variations, for example. Under the condition of a steady state, the system-internal exchange processes run further, but the atmospheric CO_2 concentration is on average nearly constant and wavers only around the steady state value.

It is an intricate process to derive the lifetime of CO_2 in the atmosphere directly as this time does not mainly depend on simple decay processes like chemical decomposition (e.g., methane) or chemical transformation. As mentioned above, it includes exchange processes between the atmosphere on the one hand and ocean, biosphere, or soil on the other hand. Since the industrial revolution CO_2 has not been in a quasi-equilibrium state; thus, the emission rates and therefore the atmospheric concentrations have been continuously rising. The CO_2 lifetime is certainly not a constant quantity if the environmental conditions change. It is difficult to give a prognosis about the future evolution of the CO_2 emission rate because the forecast also depends on social and political developments, which are highly changeable and almost unpredictable. In order to assess the genesis of the atmospheric CO_2 concentration we are neither interested in the fate of an individual molecule nor in estimated individual sources and sinks. However, based on measurements of CO_2 mixing ratio, growth rate, and anthropogenic emission, we can derive a fit function for the effective lifetime. For some scenarios, we calculate the future increase of CO_2 under the assumption that the fit function coefficients for the effective CO_2 lifetime derived from past CO_2 data are valid for the nearest future.

2   Data and method

Our current database combines CO_2 mixing ratios measured at Mauna Loa for the period 1959 to 1979 (Keeling et al., 1976; Thoning et al., 1989; Tans and Keeling, 2011) and globally averaged annual mean CO_2 for the period 1980 to 2010 (Conway et al., 1994; Masarie and Tans, 1995; Dlugokencky and Tans, 2011). The same combination of the periods is taken for the growth rates (the data sources are the same). We use global total carbon emission data from fossil-fuel burning and cement production according to the Carbon Dioxide Information Analysis Center (Boden et al., 2011; Friedlingstein et al., 2010) because these data are consistent in time and not composed from the individual series of non-consistent growth rates published by different authors. We assume that CO_2 is completely mixed in the whole atmosphere after its emission. In other words, we neglect the time lag between emission at the different pollution centers and adequate global mixing of the emitted CO_2. Such an approach is permissible because the timescale for mixing in the atmosphere is essentially smaller (a few years) than the residence time of carbon dioxide. The current (2010) global annual emission of CO_2 amounts to $33.51\,\mathrm{Gt\,yr}^{-1}$, as derived from carbon emission data, and about $30.6\,\mathrm{Gt\,yr}^{-1}$ according to the update by the International Energy Agency (IEA), which is somewhat lower than the data used in our calculations. Various reliable estimations of the CO_2 emission rate differ by a maximum of 12 % but mirror the gradient of changes fairly well. Figure 1 shows the input data employed for the analysis, together with the error bars for the emission rate and growth rate according to the specifications of the respective references. The error bars of the CO_2 concentration are very small and range within the thickness of the black curve. The uncertainty for global annual emission is ± 5 % (IPCC "likely" range).
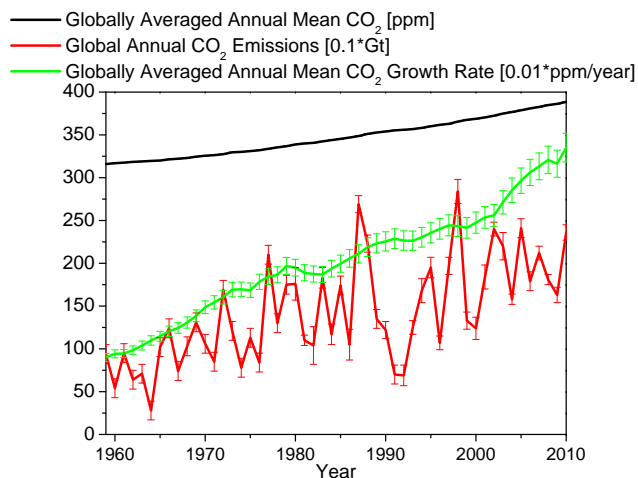
Fig. 1. Globally averaged annual mean of the CO_2 mixing ratio (ppm) in the atmosphere (black line), global annual emission rate of CO_2 per year in billions of tons (green line), and globally averaged annual mean growth rate of CO_2 ($ppm\,yr^{-1}$) (red line). The vertical bars indicate the error according to specification of the references. The scale of the emission rate and growth rate has been enlarged by factors 10 and 100, respectively.

The balance of the atmospheric carbon dioxide can be written as follows:

$$\frac{dq_{CO_2}}{dt} = E_{CO_2} - L_{CO_2} \cdot q_{CO_2}, \qquad (1)$$

where q_{CO_2} stands for the CO_2 mixing ratio [ppm], E_{CO_2} is the annual emission rate related to the increase of the mixing ratio [$ppm\,yr^{-1}$], and L_{CO_2} means the so-called reduced loss term [yr^{-1}], which is the total loss term divided by the concentration of the considered constituent CO_2. Note that the loss term considers only the effective loss and not the loss in a so-called zero cycle, where the loss of a molecule is formed back by reverse process. All quantities depend on time. The global emission of CO_2 has been distributed over the whole atmosphere. If we assume Eq. (1) as the evolution equation for CO_2 in the atmosphere, the effective lifetime of CO_2 is the inverse loss term:

$$\tau_{CO_2} = L_{CO_2}^{-1}. \qquad (2)$$

In order to reduce the scatter of the data, particularly of those of the growth rate, we smooth all data by using a 5 yr running mean. The effective lifetime is unknown, but it can be determined by Eq. (1) because all other terms are known in the equation. The details of the conversions from global annual emission [$Gt\,yr^{-1}$] to annual emission rates into mixing ratio [$ppm\,yr^{-1}$] can be found in Appendix A.

3   Results and discussion

Figure 2 displays the effective CO_2-lifetime (short lifetime) calculated from Eqs. (1) and (2) (black line). The lifetime
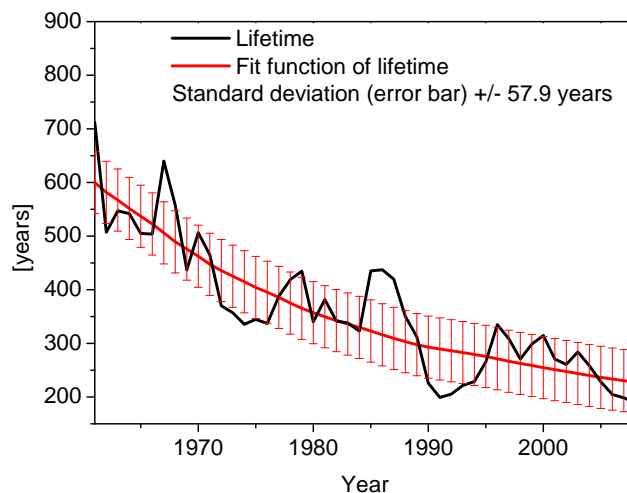

Fig. 2. Effective CO_2 lifetime in years derived (Eqs. 1 and 2) from the CO_2 records (black line) and the fitted curve of lifetime according to Eq. (3) (red line). The error bar represents the standard deviation of the lifetime from the fitted function of lifetime.

decreased from 1960 to the present roughly by a half to a third. Events such as El Niño (e.g., in 1997/98), La Niña (e.g., in 2000/01), the mega eruption of the volcano Mt. Pinatubo (1991), and strong eruptions of the volcanos Mt. Agung (1963), Mt. St. Helens (1980), El Chichón (1982), and other impacts influence the lifetime considerably. Obviously, the decrease of the lifetime slows significantly with an increasing CO_2 mixing ratio. Hence, the lifetime is a nonlinear function of the CO_2 concentration itself. The main loss process of CO_2 is connected with its absorption into cold water. Oceanic vortexes convey CO_2 into deep water. It was supposed that the sedimentation of plankton (Eppley and Peterson, 1979) and other processes (Woodwell and Houghton, 1977; Woodwell, 1978) might contribute to an additional downward transport of carbon. The so-called CO_2 fertilization should intensify the growth of plankton. On Earth, the paramount majority of CO_2 is bound in limestone, and the atmospheric share is small compared with the share found in limestone. The formation of limestone after the weathering of minerals removes CO_2 from the atmosphere. It is not the subject of this paper to estimate the share of the processes removing CO_2 from the atmosphere. Evidently, the larger the discrepancy to a saturation concentration of CO_2 in water is, the faster atmospheric CO_2 is removed. Under quasi-equilibrium conditions, such as those assumed in the preindustrial era, the effective lifetime becomes infinity for zero emission because no effective CO_2 loss occurs.

As an approximation inferred from the visualization of the lifetime in double-logarithmic coordinates, we assume the following relation:

$$\tau_{CO_2} = A \left(q_{CO_2} - C \right)^{\beta}. \qquad (3)$$
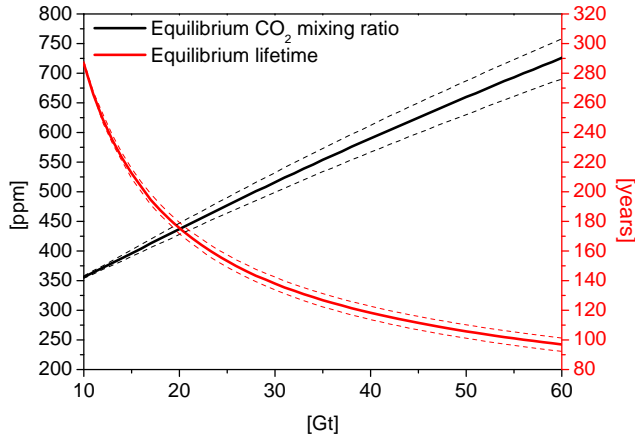
Fig. 3. Equilibrium mixing ratio in ppm of CO_2 for constant emission rates between 10 and $60\,\mathrm{Gt\,yr^{-1}}$ (black line) and the corresponding equilibrium lifetime (red line). The corresponding dashed lines represent upper and lower limits calculated from input data according to the upper and lower limits of their uncertainties (Fig. 1).
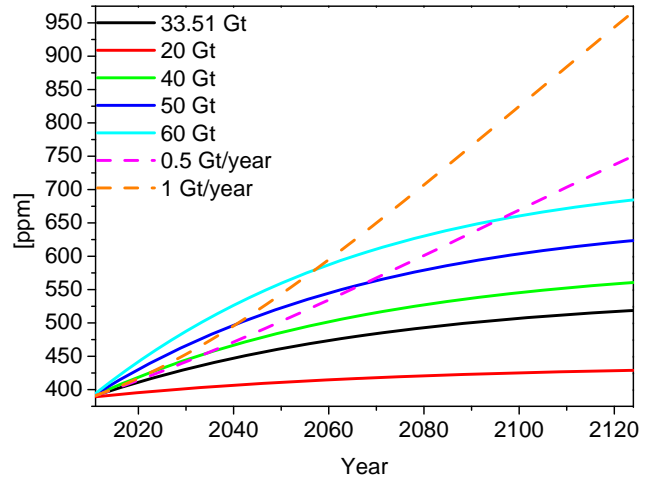

Fig. 4. CO_2 increase for constant emission rates (solid curves), starting from the present atmospheric CO_2 level of 388.56 ppm for the parameters of the lifetime formula derived above. The dashed curves represent the increase of CO_2 if the emission rates continuously increase at a rate of $0.5\,\mathrm{Gt\,yr^{-1}}$ and $1\,\mathrm{Gt\,yr^{-1}}$, starting from the present value of $33.51\,\mathrm{Gt\,yr^{-1}}$.

The parameters A, C, β of the power function can be inferred from a best-fitting procedure. Under this assumption, the differential Eq. (1) becomes the following:

$$\frac{dq_{CO_2}(t)}{dt} = E_{CO_2}(t) - \frac{q_{CO_2}(t)}{A\left(q_{CO_2}(t) - C\right)^{\beta}}. \tag{4}$$

Equation (4) is a nonlinear differential equation that could possibly possess more than one solution. However, we integrate the differential equation starting with defined initial values that result in unequivocal physically real solutions. The numerical analysis reaches the following results: $A = 7.655$, $C = 305.8$ [ppm], and $\beta = -0.51$. Note that the parameters C, A and β derived for a given time period are valid for this period only, but, as an assumption, they can be used for calculation into the nearest future. We employ for the analysis the largest available period of consistent data. The negative β value indicates a decrease of the lifetime with increasing CO_2. The red line in Fig. 2 shows the fitted curve. The correlation coefficient for this analysis amounts to $r = 0.8639$. The standard deviation of the lifetime from the fitted curve amounts to 57.9 yr and is shown by the error bars. Most of the calculated lifetimes lie within the range of the standard deviation. A linear regression indicates that the absolute difference of the lifetime from the fitted curve of lifetime decreases with time (not shown).

For a constant emission rate E_{CO_2}, a particular integral of the differential equation is $q_{CO_2} = \mathrm{const}$ and, consequently, $dq_{CO_2}(t)/dt = 0$. The mixing ratio $q_{CO_2}(t)$ approaches this constant value, which can be numerically calculated from the non-algebraic equation:

$$E_{CO_2} - \frac{q_{CO_2}}{A\left(q_{CO_2} - C\right)^{\beta}} = 0. \tag{5}$$

Figure 3 depicts the equilibrium mixing ratio of CO_2 for constant emission rates between 10 and $60\,\mathrm{Gt\,yr^{-1}}$ (black solid line). The red solid line (right-hand scale) exhibits the calculated equilibrium lifetime. The corresponding dashed lines indicate upper and lower limits calculated from upper and lower limits due to the uncertainties in the input data (Fig. 1). The parameters for the upper and lower fit functions are $A^u = 7.667$, $C^u = 302.1$, $\beta^u = -0.498$ and $A^l = 7.708$, $C^l = 308.0$, $\beta^l = -0.5353$, respectively. The equilibrium lifetime for the present day CO_2 emission amounts to 130 yr with a corresponding mixing ratio of 542.5 ppm. The equilibrium at the present value of 388.56 ppm corresponds to an emission rate of $14\,\mathrm{Gt\,yr^{-1}}$. This value agrees with the CO_2 emission in 1969–1970. In order to stay below 700 ppm, the CO_2 emission rate should not exceed $56\,\mathrm{Gt\,yr^{-1}}$. However, the mixing ratio does not exceed 750 ppm even for a very large emission rate of $60\,\mathrm{Gt\,yr^{-1}}$. The main reason is the decreasing lifetime of CO_2 to about 100 yr. The primary question arising in this context is whether it is justified to extrapolate Eq. (3) to larger CO_2 mixing ratios. There is no indication that the decrease of the lifetime will be stopped in the future, but this does not mean that the parameters derived from a limited interval are also valid for extrapolated CO_2 concentrations. An error in the lifetime by certain percentages results in an error of the same order in the CO_2 concentration. That the derived parameters are not constant makes clear, for example, an extrapolation into the past. The effective lifetime (Eq. 3) becomes infinity for $q_{CO_2}(t) = 305.8$ ppm. Therefore, at least the parameter C depends on $q_{CO_2}(t)$ and period of calculations and must

decrease to the value of the preindustrial CO$_2$ mixing ratio for zero emission.

The preindustrial CO$_2$ mixing ratio amounts to about 278 ppm (Etheridge et al., 1996; MacFarling Meure et al., 2006). On the other hand, the parameter C should slightly increase for an extrapolation to greater values, meaning that the lifetime becomes longer so that the calculated curves for CO$_2$ increase can be considered as a lower limit of the growth. An upper limit is certainly given if using the present lifetime for calculation of the future increase of CO$_2$ under the specific assumption of the development of the emission rate. This would, of course, overestimate the increase of CO$_2$.

Figure 4 depicts the time behavior of the CO$_2$ increase for constant emission rates (solid curves), starting from the present atmospheric CO$_2$ level of 388.56 ppm for the parameters of the lifetime formula derived above. The dashed curves represent the increase of CO$_2$ if the emission rates continuously increase at a rate of 0.5 Gt yr^{-1} and 1 Gt yr^{-1}, respectively, starting from the present value of 33.51 Gt yr^{-1}. The year 2100 is frequently used as a time marker to which anthropogenic changes are related. For the case of the linear increase of the annual emission rate, the emissions will amount to 78.5 Gt yr^{-1} and 123.5 Gt yr^{-1} in 2100, respectively. If the emission retains the increase of the last decade, between 0.5 and 1 Gt yr^{-1}, the mixing ratio will reach values between 670 and 825 ppm in 2100, respectively.

The figure makes clear that equilibrium will be approached with a timescale determined by the effective lifetime of CO$_2$, which depends on the CO$_2$ mixing ratio. If the emission rate does not increase beyond the present rate of 33.51 Gt yr^{-1}, the CO$_2$ mixing ratio still attains a value of 506.9 ppm in 2100 and reaches 95 % of its equilibrium value only in 2124. Even for a reduction of the emission rate from 33.51 to 20 Gt yr^{-1}, the CO$_2$ mixing ratio will increase slightly further up to 437 ppm.

4 Conclusions

The main point of this paper is the innovation to use a fit function and extrapolation to the future. The effective lifetime of atmospheric carbon dioxide decreases with increasing CO$_2$ concentration according to a power function. The analysis of calculations based on the derived fit function shows that, at the present emission rate, the equilibrium lifetime is equal to 130 yr and the corresponding equilibrium mixing ratio amounts to 542.5 ppm. To keep the values of the CO$_2$ mixing ratio at present day values (388.56 ppm), the emission should be reduced to 14 Gt yr^{-1}. In order to hold CO$_2$ below 700 ppm (sometimes used in the CO$_2$-doubling scenarios), the emission rate should not exceed 56 Gt yr^{-1}. If the growth of emission continues at the present rate (0.5– 1 Gt yr^{-1}), then the mixing ratio of CO$_2$ will reach 670– 825 ppm till the end of this century.

It is not the goal of this contribution to discuss the consequences of an enhanced carbon dioxide concentration in the atmosphere. However, the impact on the global temperature also depends on the expected level of CO$_2$. Thus, a further decrease of the lifetime of CO$_2$ should be taken into consideration in all scenarios of CO$_2$ accumulation in the atmosphere. Finally, we have to note that such an approach can be applied to the time behavior of other species such as methane.

Appendix A

The emission per square centimeter Earth surface for the present value amounts to $33.51 \times 10^{15}/5.1 \times 10^{18}$ g cm^{-2} = 6.5706×10^{-3} g cm^{-2}, distributed over the whole column between surface and infinity if CO$_2$ is completely mixed (5.1×10^{18} cm^2 is the surface of Earth). The mean scale height at the surface is approximately 8 km = 8×10^5 cm (mol volume divided by the mean molecular weight of dry air 28.95 and multiplied by 1.033 kg air weight in a beam of 1 cm^{-2}), and the contribution per 1 cm^3 at sea level is consequently 6.5706×10^{-3} g cm^{-2}/8×10^5 cm = 8.213×10^{-9} g cm^{-3}. In 1 cm^3 are $44/22\,400 = 1.964 \times 10^{-3}$ g cm^{-3} of CO$_2$. The increase related to the present emission rate is then $8.213 \times 10^{-9}/1.964 \times 10^{-3} = 4.1819 \times 10^{-6} = 4.1819$ ppm. Thus, a global emission of 1 Gt CO$_2$ distributed over the whole atmosphere corresponds to a mixing ratio of 0.1248 ppm.

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