Anthropogenic contributions to the atmospheric content of carbon dioxide during the industrial era

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Empirically supported relationships for the relaxation of airborn carbon dioxide have been used to calculate how much reported anthropogenic emissions of carbon dioxide have contributed to the atmospheric level of carbon dioxide over the time period 1750–2010. The results show that about 20% of the anthropogenic emissions of carbon dioxide on the average have remained airborn. This means that anthropogenic emissions on the average have contributed about 50% to the concomitant increase of the atmospheric concentration of carbon dioxide. The remaining half of the increase must derive from non-anthropogenic sources. Model projections based on the presumption that non-anthropogenic sources are of insignificant magnitude can be anticipated to overestimate man-made contributions to future carbon dioxide levels and global temperatures by factors of the order of 3–14 for projections extending to year 2100 or longer.

The United Nation's Intergovernmental Panel on Climate Change (IPCC) has evaluated evidence leading them to conclude that the atmospheric content of carbon dioxide has increased since the start of the industrial era [1]. On basis of prescriptions of the Bern carbon cycle model [2], the IPCC judges that the increasing carbon dioxide level is attributable almost exclusively to human activities such as land-use changes and combustion of fossil fuels.

The kinetic analysis presented in the preceding paper led to the conclusion that the Bern model fails to provide reliable information on the relaxation of carbon dioxide emissions. In this paper, empirically determined kinetic characteristics of the relaxation process have been used to calculate how fast and to what extent anthropogenic carbon dioxide emissions have been removed from the atmosphere during industrial times.

Theory

The atmospheric relaxation of reported anthropogenic emissions of carbon dioxide was evaluated by the kinetic approach described by Joos *et al.* [3], according to which the decay of each infinitesimally small emission pulse is assumed to follow a specific impulse response function. The amount of anthropogenic carbon dioxide that has remained airborn at a certain later time *t* may then be determined as the convolution integral of the emission history with the atmospheric impulse response.

The emission history was described as a function *Em(t)* expressing the time dependence of the emission rate. Explicite polynomial expressions for *Em(t)* were obtained by regression analysis of data reported by the Carbon Dioxide Information Analysis Center (CDIAC) for anthropogenic emissions of fossil carbon dioxide 1751–2009 [4] and of emissions due to land-use changes 1850–2005 [5]. A fifth-degree polynomial was used for data prior to 1900 and a sixth-degree polynomial for subsequent data. Emissions occurring prior to the time periods for which estimates are available were assumed to be of negligible magnitude. Emissions due to land-use changes over the period 2006–2010 were put equal to 1.48 Giga ton carbon (GtC) per year, the mean value for the period 2001–2005 according to the CDIAC.

In accordance with the kinetic results presented in the preceding paper, the impulse response function was assumed to be given by the empirically supported single-exponential relaxation function

$$\textit{Remaining fraction} = (\mathbf{Exp}[-t/\tau] + Keq)/(1+Keq) \qquad (1)$$

with $Keq = 0.015$, where τ denotes the relaxation time. This means that the emission amount remaining airborn at any time t after year 1750 was determined by evaluation of the integral

$$\textit{Remaining airborn}(t) = \int_{-\infty}^{t} Em(t')\left(0.985\ \mathbf{Exp}[(t' - t)/\tau] + 0.015\right) \mathrm{d}t' \qquad (2)$$

Unless otherwise stated, the empirically supported value $\tau = 14$ years (see preceding paper) was used in all calculations. In some calculations made for comparative purposes, Eqn. (1) was replaced by the triphasic pulse response function reported by the IPCC to characterise predictions of the Bern model (Eqn. 5 in the preceding paper).

Results

Emissions of fossil carbon dioxide

The blue curve in Fig. 1 shows how the cumulative total amount of fossil carbon dioxide emissions has increased since 1750 according to data reported by the CDIAC [4]. The red curve indicates the amount of these emissions that has remained airborn, as calculated from Eqn. (2) with the assumption that the relaxation time of airborn carbon dioxide is 14 years. The results indicate that the larger part (68–73% after 1930) of the total amount of fossil carbon dioxide emitted since 1750 continuously has been removed from the air.

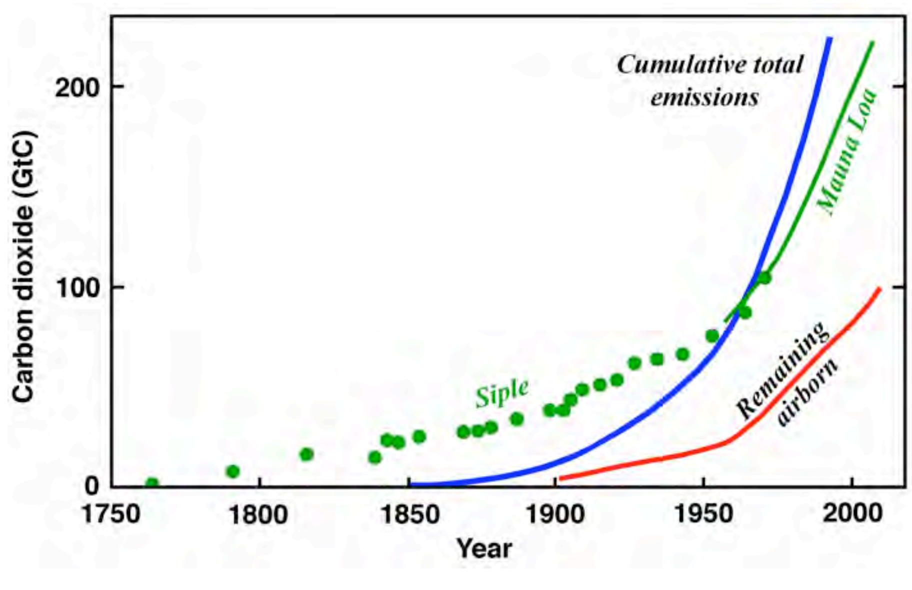

Figure 1. *Cumulative total emissions of fossil carbon dioxide (blue) and the amount that has remained airborn (red). Green data indicate how the atmospheric concentration of carbon dioxide has increased according to results obtained at the Siple and Mauna Loa stations*

Green data in Fig. 1 indicate how the atmospheric concentration of carbon dioxide has increased since 1750 according to analyses of an ice core from the Siple station (green points) [6] combined with the Keeling curve describing direct measurements made at Mauna Loa (green curve) [7]. The data refer to the increase of the concentration of airborn carbon dioxide relatively to a pre-industrial value assumed to be given by 276 ppm, and have been converted to GtC using the standard relationship 1 ppm = 2.12 GtC.

Inspection of Fig. 1 provides the immediate inference that anthropogenic emissions of fossil carbon dioxide only have provided minor contributions (red curve) to the increasing atmospheric level of carbon dioxide (green data). Before 1960, the increased air content of carbon dioxide even exceeds the cumulative total amount of fossil emissions (blue curve).

Total emissions of anthropogenic carbon dioxide

The CDIAC keeps records also of yearly anthropogenic carbon dioxide emissions attributable to land-use changes [5]. Adding these data to those for the emissions of fossil carbon dioxide, one gets a data series covering what is known about the history of total anthropogenic emissions during the industrial era. A new emission rate function *Em(t)* was determined by polynomial regression analysis of the combined data. Eqn. (2) with τ = 14 years was then applied to calculate the progress curve for the total amount of anthropogenic carbon dioxide that has remained airborn since 1750.

The results are given by the black curve in Fig. 2, where the red curve and green data are identical to those in Fig. 1. Consequently, the red curve indicates the fossil part of the total anthropogenic contributions (black curve) to the increased atmospheric content of carbon dioxide, as described by the Siple/Mauna Loa results (green data). Table 1 specifies the results numerically for selected periods of time. Anthropogenic contributions were calculated as the difference between the amount of emissions remaining airborn at, respectively, the end and start of the time period.

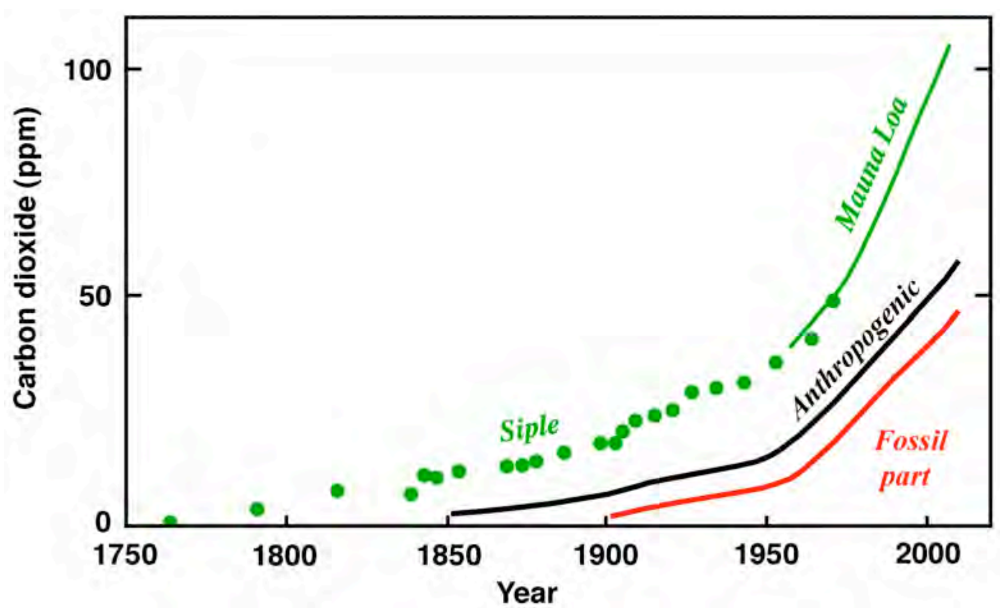

Figure 2. *The black curve shows the contributions of anthropogenic emissions to the increasing atmospheric concentration of carbon dioxide (green data). The red curve shows the part of the anthropogenic contributions that is attributable to the combustion of fossil fuels.*

Table 1. Contributions of anthropogenic carbon dioxide emissions to the increased atmospheric carbon dioxide content over different periods of time				
Time period	*Increased content of carbon dioxide in the air (GtC)*	*Anthropogenic contribution (GtC)*		*Total amount emitted (GtC)*
1750–2009	236	123	(52%)	531
1990–1999	32	15	(46%)	80
2000–2009	40	19	(48%)	99

Assuming that the Siple/Mauna Loa results provide a correct picture of the increasing atmospheric concentration of carbon dioxide during the industrial era, the results in Table 1 indicate that on the average only half of this increase has been caused by anthropogenic emissions. The anthropogenic contributions to the atmospheric content of carbon dioxide on the average have corresponded to about 20% of the total amount of anthropogenic carbon dioxide emitted (19% during the the last two decades of the examined time period).

Predictions of future atmospheric carbon dioxide concentrations

The impulse response function for the relaxation of atmospheric carbon dioxide is of great interest to climate modellers, because it may be used to calculate the expected contributions of anthropogenic emissions to future atmospheric carbon dioxide levels for postulated emission scenarios. Using Eqn. (2) with τ = 14 years, such calculations were performed for a scenario where the anthropogenic emission rate was assumed to remain constant at 10 GtC/year (the approximate emission rate at the end of 2009) from 2010 onwards. In a second scenario, the emission rate was assumed to be given by 10 GtC/year at the start of 2010 and to increase by 0.14 GtC/year (the average rate increase over the period 1980–2009 according to data reported by the CDIAC). This means that Eqn. (2) was evaluated by extension of the calculations accounted for in Fig. 2, shifting *Em(t')* to 10 (or to 10 + 0.25*t'*) GtC/year from 2010 onwards.

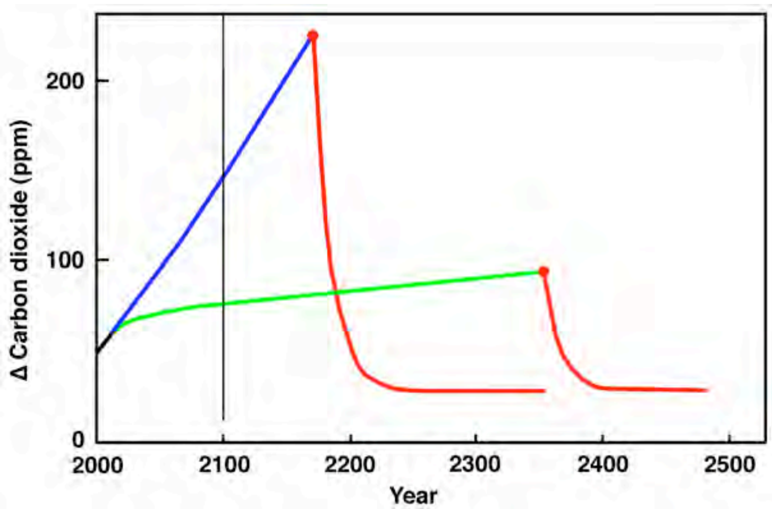

Figure 3. *Future contributions of anthropogenic emissions to the atmospheric concentration of carbon dioxide in the case that emission rates continue to increase (blue curve) or are fixed at their present values (green curve). Red parts of the curves indicate how the concentration of airborn anthropogenic carbon dioxide will decrease when the known reservoirs of fossil fuels have been depleted.*

The results of these calculations are given in Fig. 3, where the anthropogenic contribution to the atmospheric carbon dioxide concentration since 1850 is expressed in ppm. The blue curve corresponds to the scenario where emissions rates are assumed to continue to increase at a linear rate. Under such conditions, anthropogenic emissions will continue to provide most significant contributions of the order of 1 ppm/year to the atmospheric carbon dioxide level.

The green curve in Fig. 3 refers to the scenario where the emission rate is assumed to remain constant from 2010 onwards. Under such conditions, a steady-state will be approached where the anthropogenic contribution to the atmospheric carbon dioxide level equals 0.07 ppm/year, which corresponds to 1.5% of the yearly amount of carbon dioxide emitted.

Future anthropogenic carbon dioxide emissions are usually discussed with the assumption that they derive exclusively from the combustion of fossil fuels. Applying that restriction to the scenarios in Fig. 3, emissions will come to an end when the reservoirs of fossil fuel have been depleted. According to the IPCC [1], the known reservoirs of fossil carbon contained 3700 GtC in pre-industrial times. The industrial consumption of fossil carbon up to 2010 has been 365 GtC [4], which has left 3335 GtC in the fossil reservoirs. The scenarios from 2010 onwards, therefore, should be terminated when about 3400 GtC have been converted into anthropogenic emissions. This will occur after about 160 years in the scenario with increasing emission rates, and after approximately 340 years in the scenario with constant emission rates.

The corresponding termination points are marked by red points in Fig. 3. Once the emissions have been terminated due to depletion of the pools of fossil carbon, the excess of anthropogenic carbon dioxide still remaining airborn will decrease according to the relaxation function in Eqn. (1), as indicated by the red curves in Fig. 3. When all relaxation processes eventually have been completed, the final persisting contribution of anthropogenic emissions to the air level of carbon dioxide will be about 26 ppm. This represents the 1.5% equilibrium level corresponding to the assumed total amount of fossil carbon available for conversion into anthropogenic carbon dioxide emissions (3700 GtC).

Comparison with predictions of the Bern model

Climate modellers often use the end of this century as a reference point to illustrate their predictions of future carbon dioxide levels and consequent climate changes. The results in Fig. 3 show that anthropogenic emissions over the period 2010–2099 will add 90 ppm to the level of airborn carbon dioxide in the examined scenario of increasing future emission rates, and 17 ppm in the scenario of constant emission rates. Basing the calculations on the impulse response function prescribed by the Bern model, the corresponding figures become 281 and 133 ppm, respectively.

This means that the Bern model in the examined two scenarios overestimates the amount of anthropogenic carbon dioxide reamining airborn in 2100 by a factor of approximately 3 and 8, respectively , as compared to the amounts calculated using empirically determined data for the relaxation of atmospheric carbon dioxide. At the termination points, the corresponding overestimation factors have grown to about 4 and 14, respectively. The latter datum is close to the factor (0.22/.015 = 14.7) by which the Bern model overestimates the empirically estimated equilibrium constant for the relaxation process. This thermodynamic inadequacy of the model becomes a predominant source of error when the predictions concern scenarios covering several centennia.

Discussion

Atmospheric accumulation of anthropogenic carbon dioxide

According to the Keeling curve (the Mauna Loa data depicted in Figs. 1–2), the concentration of atmospheric carbon dioxide has increased about 80 ppm since 1958. The Bern carbon cycle model was designed and tuned with the presumption that this long term increase of the level of airborn carbon dioxide derives exclusively from anthropogenic emissions.

No evidence has been presented to support that presumption. On the contrary, reports are available which indicate that non-anthropogenic factors such as volcanism [8] and thermal degassing of the hydrosphere [9] may have contributed significantly to the increased level of airborn carbon dioxide. Under such circumstances, one had better replace presumptions about the magnitude of anthropogenic contributions by empirically based attempts to estimate the contributions.

In the preceding paper, evidence was presented to show that Eqn. (1) gives a theoretically adequate and experimentally supported description of the relaxation of atmospheric carbon dioxide. Results described in this paper have been calculated from Eqn. (1) by standard kinetic methods, using empirically supported values of the equilibrium constant *Keq* and the relaxation time τ. The calculations are based only on descriptive characteristics of the relaxation process, and include no assumptions as to their mechanistic background. Data now reported, therefore, illustrate the kinetic implications of presently available empirical knowledge about the relaxation process by which anthropogenic carbon dioxide emissions are removed from the atmosphere.

In particular, the present study provides empirically based estimates of the extent to which anthropogenic carbon dioxide emissions have remained airborn during the industrial era. The results in Table 1 indicate that this part on the average equals about 20% of the total amount emitted. This is considerably more than the equilibrium part (1.5%) that eventually will remain airborn when the relaxation process has been completed. There is no reason to question that anthropogenic emissions have had a most significant effect on the atmospheric level of carbon dioxide.

The effect is much too weak, however, to account for the atmospheric carbon dioxide concentration increase indicated by the Siple/Mauna Loa data. According to the empirically based estimates in Table 1 and Fig. 2, anthropogenic emissions contribute only to about one half of the increase. This means that the other half must derive from non-athropogenic sources.

Implications of the results

The Bern carbon cycle model predicts that anthropogenic emissions of carbon dioxide remain airborn to such a large extent that they fully account for the increasing carbon dioxide levels observed at Mauna Loa. This prediction reflects that the model has been designed to provide such an outcome due to the presumption that the rising carbon dioxide levels derive exclusively from anthropogenic emissions. As was shown in the preceding paper, this presumption has forced the designers to give the model such extreme properties that it fails to account for fundamental experimentally observed characteristics of the relaxation of airborn carbon dioxide. The model gravely underestimates both the relaxation rate and the water solubility of atmospheric carbon dioxide, which leads to a drastic overestimation of the emission amounts that remain airborn.

The descriptive inadequacy of the Bern model obviously must extend also to the model predictions regarding the contribution of anthropogenic emissions to future atmospheric carbon dioxide levels. This is born out by the results in Fig. 3, which indicate that empirically based estimates of such contributions are much lower than those predicted by the Bern model in the two representative emission scenarios now considered.

All climate model projections assessed by the IPCC are based on input data representing future carbon dioxide levels, as calculated for postulated emission scenarios by application of the Bern model or similar carbon cycle models that have been tuned to fit the Keeling curve. This means that the model projections can be anticipated to be gravely erroneous already at the input level. The precise magnitude of the errors will depend on the emission scenarios and time periods considered.

Typical emission scenarios discussed by the IPCC fall within the limits set by the two scenarios considered in Fig. 3, and projections of the future climate usually extend to the year 2100. In such cases, input data for the climate models can be anticipated to overestimate the anthropogenic contributions to future atmospheric carbon dioxide levels by factors of the order of 3–8. Projected temperature changes due to the assumed greenhouse effect of anthropogenic carbon dioxide will be correspondingly overstimated.

The future consumption of fossil fuels may continue to rise for a few decades, but the emission rates can be anticipated to flatten out and start to decrease long before the fuel reservoirs become depleted. The scenario with increasing emission rates in Fig. 3 (blue curve), therefore, is likely to set an upper limit for the total future amounts of anthropogenic carbon dioxide that may accumulate in the air. This means that future contributions of anthropogenic emissions to the atmospheric levels of carbon dioxide are unlikely to ever exceed 160 ppm and probably will not even exceed 100 ppm. Such relatively small contributions are not likely to have any unacceptable effects on the climate according to assessments of the IPCC [10]. Climate model projections indicating that emissions of fossil carbon dioxide may increase the global temperature up to 4 ˚C during the present century are unrealistic and inconsistent with present empirical knowledge regarding the relaxation kinetics of airborn carbon dioxide.

The carbon cycle budget presented by the IPCC [1] is based in critical respects on the predictions of the Bern model. The results in Table 1 indicate that the budget will have to be drastically modified to become consistent with the empirically supported data now described. Such implications of the present results will be considered in the following paper, which deals with temperature effects on the atmospheric concentration of carbon dioxide.

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