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The Future Burden of Industrial CO_2 on the Atmosphere and the Oceans *

K. E. Zimen and F. K. Altenhein

Hahn-Meitner Institute for Nuclear Research, Berlin

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The cumulated input of industrial CO_2 into the atmosphere during the next 100 years or so will be about 10 times the natural CO_2 content if the present rate of increase is restricted only by the finiteness of fossil fuel resources. The resulting surplus of CO_2 in the atmosphere and the oceans as a function of time is calculated using the equations for the exchange kinetics between the reservoirs and the logistic function. The results indicate a transient maximum level of roughly 300% over pre-industrial figures in the atmosphere as well as in the mixed ocean surface. This level would be reached during the second half of the next century, if fossil fuels are not going to be replaced by other energy sources much faster than can be anticipated at the present time. Long before the maximum level is reached the increase will probably have serious consequences for the ecological systems in the sea.

What will be the long-term increase of CO_2 in the different reservoirs as a result of the combustion of fossil fuels?

Experimental studies by several authors [1, 2] revealed that up to 1970 the concentration of CO_2 increased from its pre-industrial value of 290 ppm to a seasonal and geographical average of 320 ppm, i. e. by approximately 10% in 100 years or so. From 1958 through the 1960s the increase was about 0.2%/a (0.7 ppm/a) [2] and more recently rates up to 0.5%/a (1.5 ppm/a) [3] were observed.

By comparing the measured increase with the calculated release of CO_2 due to combustion of fossil fuels it was concluded that about one third [4] up to one half [2] of the CO_2 input has remained in the atmosphere while the other part obviously was taken up into other reservoirs. Assuming that the fraction of CO_2 remaining in the atmosphere will be about the same in the future, and extrapolating the present trend of growth in fuel combustion several authors have calculated the atmospheric CO_2 content in 30 or 50 years from now (Table 1).

Most of the fossil fuels will be burned after the turn of the century, and the SCEP report [2] points out (p. 192): "monitoring the CO_2 problem therefore calls for the longest possible extrapolation of the average CO_2 concentration in the atmosphere". We, therefore, have considered the input of CO_2 over a longer period and tried to calculate the remaining surplus in the atmosphere and the uptake into the oceans.

The Model used

Figure 1 shows a box-model as used by other authors with the ocean reservoir divided into a rapidly mixed surface layer above the thermocline and the sea below this surface layer. Because of the relatively large size of the carbon reservoir in the deep ocean the input of industrial CO_2 into the atmosphere (n^i) will eventually be transfered into the deep ocean. What we want to know is the time function for the surplus of CO_2 in the other reservoirs during the transition period to a new steady state.

	A.D. 2000	2010	2020	2025
Revelle, Suess [5] (1957)	120—140	—	—	—
Bolin, Bischof [4] (1970)	128—136	—	—	—
Baxter, Walton [6] (1970)	123	—	—	150
Singer [7] (1970)	138	—	172—186	—
Machta [8] (1971)	126	—	—	—
Broecker et al. [9] (1971)	133—141	150—163	—	—
Fairhall [10] (1973)	128	—	—	—

Table 1. Expected increase of atmospheric CO_2 over pre-industrial level: N^a/N_0^a in %.

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* Short Communication: Naturwiss. **60**, 198 [1973]; the figures and results reported there have been revised somewhat here.

Reprint requests to Prof. K. E. Zimen, Hahn-Meitner-Institut für Kernforschung Berlin, *D-1000 Berlin 39.*

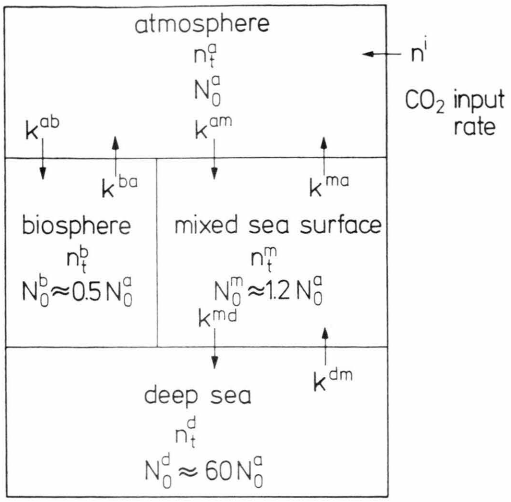

Fig. 1. Box-model for the transfer of CO_2 between reservoirs. (n^i input rate should read $\dot n^i$.)

Considering the time function $\dot n^i$ for more than the next decades the finiteness of the fuel reserves has to be taken into account. As proposed earlier [13] this can be done by using the logistic curve (Verhult, 1838):

$$\dot n^i = a[(n_\infty^i - n_t^i)/n_\infty^i]\, n_t^i = a_{\text{eff}}\, n_t^i \,. \tag{1}$$

According to this statement the rate of growth is proportional to the actual input n_t^i (exponential growth) *and* the momentary distance from the final limit n_∞^i. Integration leads to the so called logistic curve

$$n_t^i = n_\infty^i / \{1 + [(n_\infty^i / n_0^i) - 1] \exp(-a\,t)\} \,. \tag{1 a}$$

The cumulated input of CO_2 will thus follow a sigmoidal curve like all undisturbed processes of growth in a finite system.

Using the 4-box-model and symbols of Fig. 1 one can write down 4 differential equations for $\dot n^a$, $\dot n^m$, $\dot n^b$, and $\dot n^d$. To find the solutions for n_t^a, n_t^b, n_t^m, and n_t^d using these 4 equations and the logistic functions is rather difficult. To make the calculations simpler we have, like Baxter and Walton [6], combined the biosphere and the mixed sea layer into a "unisphere": $n_t^b + n_t^m = n_t^u$. Then we arrive at only 3 equations:

$$\dot n^a = \dot n_t^i + k^{ua}\, n_t^u - k^{au}\, n_t^a \,, \tag{2}$$

$$\dot n^u = k^{au}\, n_t^a + k^{dm}\, n_t^d - k^{ua}\, n_t^u - k^{md}\, n_t^m \,, \tag{3}$$

$$n_t^d = n_t^i - (n_t^a + n_t^u) \tag{4}$$

where the exchange coefficients follow from

$$k^{ab}\, n_t^a + k^{am}\, n_t^a = k^{au}\, n_t^a \quad \text{thus} \quad k^{ab} + k^{am} = k^{au} \,. \tag{5}$$

In order to also make n_t^m computable, we finally make the reasonable assumption that

$$n_t^m / n_t^u = N_0^m / N_0^u \,, \tag{6}$$

thus

$$k^{md} = k^{ud}\,(N_0^u / N_0^m) \,. \tag{7}$$

By integration one then arrives at the solutions given in the Appendix.

The Data used

The calculations were made from the following data. For the relative sizes of the reservoirs and the exchange coefficients we selected the figures used by Baxter and Walton [6]

$$N_0^a = 51.4 \times 10^{15}\ \text{mol}; \; N_0^m = 1.2 \times N_0^a;$$
$$N_0^u = 1.7 \times N_0^a; \; N_0^d = 60 \times N_0^a;$$
$$k^{au} = 1/5.3\ \text{a}\,, \; k^{ua} = k^{au}\,(N_0^a/N_0^u) = 1/9.0\ \text{a}\,,$$
$$k^{md} = 1/17.2\ \text{a}\,, \; k^{dm} = k^{md}\,(N_0^m/N_0^d) = 1/860\ \text{a}$$
$$(\tau = 1/k \text{ mean residence time in years}).$$

According to the careful recalculation of Baxter [6] the cumulated input of industrial CO_2 from around A.D. 1860 up to 1970 was

$$n_{1970}^i = 11.7 \times 10^{15}\ \text{mol}$$

and 1970 the input rate of CO_2

$$\dot n_{1970}^i = 0.425 \times 10^{15}\ \text{mol/a}\,.$$

We also need a figure for the final cumulated input of $CO_2\,(n_\infty^i)$ when all fossil fuels will be burned. We consider the figs. mentioned by McDonald [10a] (3.3×10^{18} g), and by Johnson [11] (11×10^{18} g) as being too low *. We therefore, have used

$$n_\infty^i = 26 \times 10^{18}\ \text{g}\ CO_2 \approx 600 \times 10^{15}\ \text{mol}$$

in accord with our recent compilation of the estimated ultimate recovery of coal, oil, and natural gas [12].

Finally we have to choose a figure for the growth coefficient a_{eff} in Equation (1). Using recent data

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* Baxter and Walton [6], on the other hand, mentioned (p. 227) a figure for the recoverable reserves of conventional fossil fuels which must be too high by orders of magnitude, viz. 3.45×10^{15} t h. c. e. corresponding to 1×10^{22} g of CO_2.

from the United Nations[24] the growth rate of energy consumption of fossil fuels between 1967 and 1970 was

$$\alpha = 6.5\%/\mathrm{a} \quad (1967-1970) .$$

Before A.D. 1967 one can, according to Baxter and Walton[6] roughly distinguish 3 periods with $\alpha_{\mathrm{eff}} = 4.1\%/\mathrm{a}$ (up to A.D. 1910), $\alpha_{\mathrm{eff}} = 1.6\%$ (1910 – 1945), and $\alpha_{\mathrm{eff}} = 4.5\%/\mathrm{a}$ (after 1945). Hence one cannot expect to satisfy the logistic function (1) exactly when combining the real cumulated input n^{i}_{1970} and the figures of $\dot{n}^{\mathrm{i}}$ and α_{eff} for 1970. Therefore an adjustment was made by instructing the computer not with Eq. (1), but rather with

$$\dot{n}_t{}^{\mathrm{i}} = \alpha_{\mathrm{eff}} (n_{t}{}^{\mathrm{i}} + \Delta n^{\mathrm{i}}) \ . \qquad (1\,\mathrm{b})$$

Because of the lower figure for α_{eff} between 1910 and 1945 the correction Δn^{i} must be a negative quantity. Using the above mentioned empirical figures for $\dot{n}^{\mathrm{i}}_{1970}$, α_{eff} (1967 – 1970), and n^{i}_{1970}, it follows from (1 b) $\Delta n^{\mathrm{i}} = -5.2 \times 10^{15}$ mol. Inasmuch as it is a constant, the correction to $\dot{n}^{\mathrm{i}}$ vanishes with growing $n_t{}^{\mathrm{i}}$.

We thus hope to have chosen a consistent set of the best available data. Our computer program is, of course, able to handle other sets of data as well in case new information makes one or more of the figures obsolete.

Results

Figure 2 shows the results for α_{eff} and $\dot{n}^{\mathrm{i}}$. During the next 100 years the effective growth factor will fall from its present value to below 1% per year. The input rate will rise steeply from its present value to a maximum of 10×10^{15} mol/a in A.D. 2040, and will decline towards the end of th 21st century.

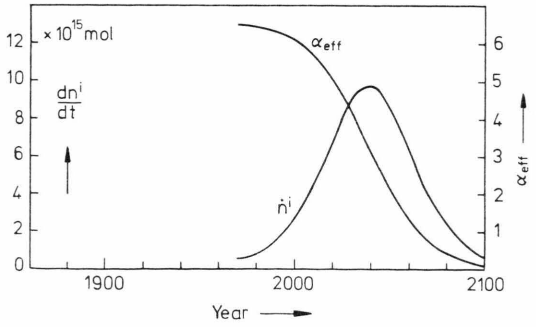

Fig. 2. The effective growth factor α_{eff} (%/a) of industrial CO_2 production and the resulting input rate dn^{i}/dt of CO_2 into the atmosphere.

Figure 3 presents the cumulated input (n^{i}), and the resulting surplus of CO_2 in the three reservoirs as a function of time. In a previous paper[13] the cumulated input of CO_2 into the atmosphere by

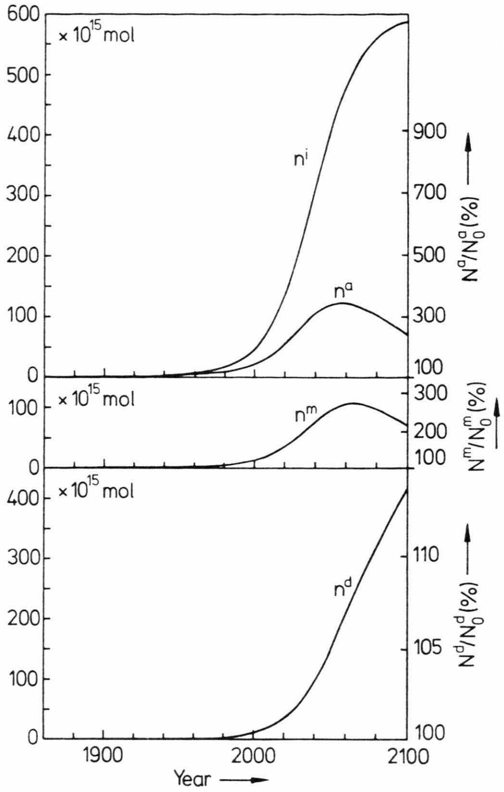

Fig. 3. Cumulated input of CO_2 into the atmosphere (n^{i}); resulting surplus in the atmosphere (n^{a}), the mixed surface sea (n^{m}) and the deep sea (n^{d}).

A.D. 2100 was calculated to lie between 400 and 640×10^{15} mol. Our refined computer calculation now gives $n^{\mathrm{i}}_{2100} = 590 \times 10^{15}$ mol i. e. nearly 12 times the pre-industrial figure. Such a tremendeous input of industrial CO_2 would raise the CO_2 content in the atmosphere to 139% of the pre-industrial level or to 408 ppm by the end of this century. The maximum increase to 344% or to 996 ppm, would be reached in the year 2055. By comparing n^{i} and n^{a} in Fig. 3 also the following becomes obvious: Predictions of n^{a} based on the assumption that 50% or so of the input will remain in the atmosphere (Tab. 2) are of rather limited value if longer periods are considered. This is, in fact, what was suspected in the MIT report[2] (p. 50).

The cumulated input of CO_2 into the mixed surface layer of the sea would be 13.4×10^{15} mol

(122%) in the year 2000. The maximum increase to 108×10^{15} mol (275%) would be reached in the year 2065.

Finally, it can be seen from Fig. 3 that the surplus of CO_2 in the deep ocean will steadily increase and will reach ca. 400×10^{15} mol at the end of the next century, corresponding to an increase from the pre-industrial level to 114%.

Validity of Results

The validity of our results rests, to begin with, on the data used. There is no general agreement on the four rate constants k^{au}, k^{ua}, k^{md}, k^{dm}, but no large (order of magnitude) discrepancies are encountered. The same is true for the relative sizes of the reservoirs N_0^a, N_0^m, N_0^d, for the cumulated input n^i_{1970}, and for the present input rate $\dot{n}_t^i$ of industrial CO_2. However, the figures used for the final input n^i_∞ differ considerably (see above) and for the justification of our choice we want to refer the reader to a previous publication[12].

Most obviously, our results also depend on assumptions concerning the growth coefficients a. We, therefore, want to emphasize, that we have made no special assumption but one: the applicability of the logistic curve. If one presupposes a reasonably steady development of the world (and only then extrapolations into the future make any sense) we can take for granted, from logic as well as from empirical ecological evidence[14], that all processes of exponential growth in a limited system will essentially and eventually follow the logistic curve. In other words, the application of the logistic curve implies that the results are valid if nothing else will limit the input rate of industrial CO_2 into the atmosphere than the restrictions imposed by the finiteness of resources. If only fossil fuels were available as energy sources the present growth factor in energy consumption of ca. 6%/a would really and necessarily have to decrease like a_{eff} in Figure 2. The increasing utilization of nuclear energy will delay the decrease of the growth factor for total energy consumption but most probably not considerably change the decrease of a_{eff} for the fossil fuels during the next decades. In the long run, however, fossil fuel reserves will probably be stretched out by deliberate actions of governments. In this case, of course, a_{eff} would be reduced more rapidly, the input of CO_2 into the atmosphere would be extended over a longer period of time and the resulting surplus n^a and n^m at any given time would be lower than in Figure 2. The conclusions to be drawn from the present paper may well turn out to become a strong incentive to such a deliberate action.

Besides the data used, one can also question the 3-box-model as being to simple to allow long-term predictions, and models with more "boxes" may give better approximations. The next step would be the 4-box-model with separate biosphere and mixed surface sea instead of the "unisphere" (Figure 1). Our 3-box-model, too, can make some assertions concerning the biosphere. Assuming

$$n_t^b / n_t^u = N_0^b / N_0^u \qquad (8)$$

in analogy to Eq. (6) we can expect a simular course for $n^b = f(t)$ as for $n^m = f(t)$ according to Figure 2. With a 4-box-model, however, one could allow for possible changes with time of the exchange coefficients between the biosphere and the other reservoirs (owing to a stimulation of photosynthesis for example) or of the size of the biospheric reservoir (as a result of large-scale deforesting in Brazil for example). A more detailed study including the biosphere, would, of course, have to bear in mind the fact that the biosphere itself is a multi-box-system[15]. Thus, our first approximation can surely be improved, but we feel that the principle course of $n^m = f(t)$ would not change considerably and the increase of N^m/N_0^m is so large, that a second approximation at the present time would not yield so much more information as to change the whole picture.

Implications of the Results

The impact of "man's unseen artifact" on climate due to the greenhouse effect has been widely discussed. Suffice it here to say that the greenhouse effect alone could bring about a considerable change in climate, but that the outcome of all processes triggered by the input of industrial CO_2 and other artifacts into the air is still controversial (cf. Broecker et al.[9], SMIC[16], Sawyer[17], Singer[18]).

The uptake of large quantities of CO_2 into the sea has not been a matter of concern up to now. However, the uptake of CO_2 will reduce the $CO_3^{=}$ concentration in the sea by the reaction

$$CO_2 + CO_3^{=} + H_2O \rightarrow 2\,HCO_3^{-}. \qquad (9)$$

In this way at some critical point in time the surface waters, which actually are oversaturated, could become undersaturated in $CO_3^=$ with respect to aragonite and, later on, calcite. This would, of course, create a very critical situation for all calcareous organisms living in the sea and for the food chains of which they are a part.

Broecker et al. [9] have calculated that such a critical undersaturation will not be reached soon. Fairhall [10], however, has recently come to the conclusion, that an additional input of 55 ppm of the volume of the atmosphere, i. e. of only 9.8×10^{15} mol, into the mixed surface sea would reduce the carbonate concentration to the critical point and that this point will be reached about A.D. 2010. If we take the figure of 9.8×10^{15} mol for granted we arrive from Fig. 3 at A.D. 1993 i. e. even somewhat earlier.

Of course, the sea is a very complicated chemical system and the presence of other ions may alter the picture considerably [9, 19, 20]. Möller et al. [21] in our Institute have shown e. g. that the solubility behaviour of $CaCO_3$ is very much dependant on the actual surface conditions (adsorption of Mg^{2+}) of the carbonates. Likewise, Jansen and Kitano [22] have demonstrated that the dissolution of actual carbonate sediments depends on crystal morphology, chemical composition and particle size. The actual supersaturation, therefore, also is a function of these factors and may vary widely. The organic components in sea water also may influence the uptake of CO_2 and its reactions [23]. Thus, the question as to the exact reaction of the chemical systems in the sea to the uptake of large amounts of CO_2 can probably not be answered easily, and we have to leave this question to the specialists in marine chemistry. However, as a glance at Fig. 3 makes clear, the increase of n^m will reach between 200 and 300%. Therefore, the most probable conclusion at the present time seems to be that there will be intolerable disturbances of the ecological systems in the sea with serious consequences for the human environment if the combustion of fossil fuels is not stretched out over a much longer period of time than can be anticipated at present.

Appendix

From the differential Eq. (1) to (3) and Eq. (4) on arrives at the following solutions for the surplus of CO_2 in the atmosphere, the mixed surface layer of the oceans, and the deep ocean respectively:

$$n_t^{\mathrm{a}} = n_t^{\mathrm{i}} + F_1 - F_2 ,$$

$$n_t^{\mathrm{m}} = N_0^{\mathrm{m}}/N_0^{\mathrm{u}} \{ [(c_1 + k^{\mathrm{au}}) / k^{\mathrm{ua}}] F_1 - [(c_2 + k^{\mathrm{au}}) k^{\mathrm{ua}}] F_2 \} ,$$

$$n_t^{\mathrm{d}} = - [(c_1 + k^{\mathrm{au}} + k^{\mathrm{ua}}) / k^{\mathrm{ua}}] F_1 + [(c_2 + k^{\mathrm{au}} + k^{\mathrm{ua}}) / k^{\mathrm{ua}}] F_2 ,$$

with the functions

$$F_1 = e^{c_1 t} [b_1 - a_1 \int_0^t n_t^{\mathrm{i}} e^{-c_1 t} \, \mathrm{d}t] ,$$

$$F_2 = e^{c_2 t} [b_2 - a_2 \int_0^t n_t^{\mathrm{i}} e^{-c_2 t} \, \mathrm{d}t] ,$$

and the constants

$$a_1 = [c_1 (c_2 + k^{\mathrm{au}}) - k^{\mathrm{ua}} k^{\mathrm{dm}}] / (c_1 - c_2) ,$$

$$a_2 = [c_2 (c_1 + k^{\mathrm{au}}) - k^{\mathrm{ua}} k^{\mathrm{dm}}] / (c_1 - c_2) ,$$

$$b_1 = [(c_2 + k^{\mathrm{au}}) (n_0^{\mathrm{i}} - n_0^{\mathrm{a}}) + k^{\mathrm{ua}} n_0^{\mathrm{u}}] / (c_1 - c_2) ,$$

$$b_2 = [(c_1 + k^{\mathrm{au}}) (n_0^{\mathrm{i}} - n_0^{\mathrm{a}}) + k^{\mathrm{ua}} n_0^{\mathrm{u}}] / (c_1 - c_2) ,$$

$$c_1 = - (\Sigma k/2) + (1/2) \, [(\Sigma k)^2 - 4 \, k^{\mathrm{au}} k^{\mathrm{ud}} - 4 \, k^{\mathrm{dm}} (k^{\mathrm{au}} + k^{\mathrm{ua}})]^{1/2} ,$$

$$c_2 = - (\Sigma k/2) - (1/2) \, [(\Sigma k)^2 - 4 \, k^{\mathrm{au}} k^{\mathrm{ud}} - 4 \, k^{\mathrm{dm}} (k^{\mathrm{au}} + k^{\mathrm{ua}})]^{1/2} ,$$

$$\Sigma k = k^{\mathrm{au}} + k^{\mathrm{ua}} + k^{\mathrm{ud}} + k^{\mathrm{dm}} .$$

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