much as 14×10^9 metric tons of C by the year 2000 and 48.5×10^9 metric tons by 2025. The total known fossil fuel resources are more than enough to provide the C for this scenario. However, there is the problem of availability of the fuel at the location (or country) where it is needed. Most of the fossil resources are in the form of coal, and most of the coal is located in the USA and the USSR. The extent to which these vast amounts will be available to some of the most rapidly growing nations will determine how closely the world is able to follow the historical 4.3% growth in the future. The rate of growth of energy use is far greater in most developing nations than in the developed ones, and the growth in most cases is closely coupled with oil availability. As presently known oil resources become exhausted, the importance of new oil discoveries in the poorer parts of the world will become even more important. The availability of fossil fuels to these nations could influence the CO_2 emissions in the years 2000–2025 by a factor of 2 or more. The assumption of continued 4.3% per year growth in CO_2 is probably an upper limit case.

Projecting CO_2 emissions into the future is really dependent on the development of a world energy scenario. For the purpose of constructing a plausible energy scenario, I suggest dividing the world into the 9, more or less uniform, socioeconomic sectors indicated in table 2. Based on assumptions about the energy growth rate within each sector, it is possible to imagine that the world will require perhaps 4 times as much energy in 2025 as at present. This scenario is predicated on strong, conscious efforts to eliminate extreme poverty in the world. Over the next 50 years the developing world as a whole is envisioned to raise the per capita energy use to a level that is slightly greater than the present world average. Even then, in Africa and non-communist Asia the projected population of over 3500 million people will still have a less than average per capita energy use than the present world average. In fact, the total number of people living in extreme poverty (for this purpose, having energy use less than 1 kW/capita) will probably exceed the number of such people today. On the assumption that most of the energy in this scenario will come from fossil fuel sources – because most of the increase is in the developing world – the CO_2 emissions will grow in proportion to energy growth. The total fuel requirements for this scenario would be less than in the 4.3% per year growth case, and the growth in CO_2 emissions would likely approximate the energy growth rate of 2.9% per year. In this scenario, in the year 2000 the CO_2 emission would involve 10×10^9 metric tons of C and in the year 2025, 20.6×10^9. These can probably be considered mid-range estimates.

As a low CO_2 emission case for the future, consider a scenario in which much more non-fossil (e.g., solar and nuclear) energy is used in the world. Achieving production of as much as 8 TW of the year 2025 requirements (about 25%) from solar and solar-derived sources, i.e. hydro, wind, biomass, etc., is a formidable target for the next 50 years. Adding a possible 4 TW from nuclear reactors still leaves almost 20 TW to be derived from fossil fuels. This would require a 2% per year increase in fossil fuel use and would give CO_2 emissions involving 8×10^9 metric tons of C in the year 2000 and 13.1 metric tons by 2025.

The 3 cases presented here for future CO_2 emissions from fossil fuels can be regarded as high, medium, and low cases. Confidence should be high that the eventual amount of C involved will fall within these brackets, i.e. $8 < C < 14$ (in 10^9 metric tons C) for the year 2000, and $13.1 < C < 48.5$ for the year 2025. Where within these wide limits the actual amount will fall is subject to anyone's guess, but the intermediate scenario presented here has some logic and can serve as a basis for future refinements.

Prediction of future CO_2 concentrations in the atmosphere

by U. Siegenthaler and H. Oeschger

Physics Institute, University of Bern, CH-3012 Bern (Switzerland)

Introduction

Future atmospheric CO_2 concentrations depend on 2 factors: a) past and future CO_2 inputs by burning of fossil fuel and by deforestation, b) the fraction of the produced CO_2 that remains in the atmosphere.

We concentrate here on the 2nd subject and discuss the global C cycle with respect to the processes that determine the partitioning of CO_2 between atmosphere, ocean and biosphere. Then we give the results of CO_2 predictions obtained from model calculations. The 1st aspect, scenarios for future energy use, is discussed in the contributions by Niehaus and by Rotty in this volume.

Observations carried out by Keeling and his coworkers at Mauna Loa (Hawaii) and the South Pole show that the average atmospheric CO_2 concentration increased from 315 ppm in 1958 to 329 ppm in 1973, which corresponds to an airborne fraction of 56% of the total fossil CO_2 emissions in the same period (Keeling and Bacastow, 1977). Inclusion of data for later years yields a slightly lower percentage. The observed CO_2 increase is not quite constant from year to year, but varies slightly with a periodicity of about 4 years. These oscillations appear to be caused by a natural phenomenon called Southern Oscillation which includes large-scale deviations of atmospheric and oceanic conditions from their average state (Bacastow, 1976; Newell et al., 1978). The value for the airborne fraction is probably affected by these fluctuations as well as by possible errors of the order of 10% in the data for fossil fuel consumption. The non-airborne fraction of the fossil CO_2 must have been taken up by the oceans or the biosphere. The CO_2 fluxes into these reservoirs, and therefore the partitioning of the excess CO_2 amongst atmosphere, ocean and biosphere, depend on the characteristic time of the CO_2 increase. Under the assumption that the rate of increase of fossil energy use remains at its present value of about 4% per year, the airborne fraction will probably remain near 50% during the next 10-20 years. When the input rate deviates significantly from the past exponential increase, a time-dependent model for the CO_2 cycle is necessary for calculating the airborne fraction. This is also the case for longer-term predictions, even if the exponential growth continues, since the increased partial pressure of CO_2 will influence the carbonate chemistry of seawater and therefore the oceans' capacity for taking up excess CO_2.

The ocean as a sink for anthropogenic CO_2

The amount of C dissolved in the ocean is about 60 times the atmospheric C mass. Only about 1% of it is, however, dissolved CO_2 gas, the major part is in the form of bicarbonate and carbonate ions. The equilibrium capacity of seawater for uptake of excess CO_2 depends, therefore, on the chemical equilibria between these 3 species, and is not 60 but only 6 times the atmospheric excess. In other words, if the atmospheric CO_2 concentration increases by 10%, the total CO_2 concentration of seawater (including CO_2 gas, bicarbonate and carbonate ions) increases, at equilibrium, by 1% only; the ratio, which happens to be approximately 10, is the so-called buffer factor. Its value can be calculated from chemical equilibrium constants, and it has also been verified directly by CO_2-seawater equilibration experiments (Keeling and Guenther, 1980; Takahashi et al., 1980).

If chemical equilibrium between the atmosphere and the entire world ocean were established instantaneously, any amount of excess CO_2 would be partitioned in a ratio of 1:6 between atmosphere and ocean, and the airborne fraction (neglecting any biospheric effect) would be 14%. The rate of uptake by the ocean is, however, limited by 2 factors. Firstly, the CO_2 exchange rate between air and sea is limited, and secondly, the downwards mixing of surface water laden with excess CO_2 is not infinitely fast. The global mean CO_2 exchange rate between air and sea has been determined by means of different methods as 18 moles per m^2 of ocean surface per year (for a pre-industrial CO_2 level of about 290 ppm). The results of the different methods agree to within better than ±20% (Peng et al., 1979). This corresponds to a mean residence time of 8 years for CO_2 in the atmosphere, defined as the ratio of atmospheric CO_2 to the air-sea exchange flux.

The average age of deep waters in the ocean, relative to the surface, is of the order of 1000 years, as determined by ^{14}C measurements. The consumption of fossil fuel has increased roughly exponentially, with a growth rate of 4.3% per year after World War II (Rotty, this volume). This corresponds to an e-folding time of 23 years, and in view of the ^{14}C ages of deep-sea water it is obvious that the industrial CO_2 can not yet have penetrated to large volumes of the deep sea.

Air-sea exchange of CO_2 and vertical transport within the ocean have been simulated by relatively simple models, either pure box models (e.g. Bacastow and Keeling, 1973; Björkström, 1979), or by a box diffusion model (Oeschger et al., 1975) in which oceanic mixing is described by vertical eddy diffusion, assuming a constant diffusion coefficient. According to a typical model calculation (Oeschger et al., 1975, p. 185) for the CO_2 increase until 1970, the excess CO_2 concentration in surface water is 85% of its equilibrium value; i.e., compared to downward mixing, gas exchange through the air-sea interface is rapid enough for chemical equilibrium to be nearly established. The step which limits the oceanic CO_2 uptake is, therefore, the vertical transport of water in the ocean.

In restricted areas of the cold ocean surface, vertical exchange with intermediate and deep waters is much faster than for the rest of the sea surface. One-dimensional models cannot take into account this feature explicitly, which may lead to an underestimate of the total CO_2 uptake. Broecker et al. (1979) estimated that this rapid deep water formation corresponds, for the fossil CO_2, to the uptake capacity of a layer with a depth of 75 m (if averaged over the whole

Airborne fraction, defined as ratio of atmospheric CO_2 excess above natural level to cumulative CO_2 input into the atmosphere, as predicted by the box diffusion model for the 2 scenarios discussed in the text. $\varepsilon = 0.2$: plant growth is assumed to increase due to CO_2 fertilization; $\varepsilon = 0$: constant biomass

Scenario		Airborne fraction (%) 2020	2070	2170
Upper limit:	$\varepsilon = 0.2$	65	69	54
	$\varepsilon = 0$	71	80	75
+50% maximum:	$\varepsilon = 0.2$	53	45	35
	$\varepsilon = 0$	59	52	42

ocean surface) in addition to a mean penetration depth of about 350 m predicted by vertical diffusion alone. This yields an increase of 20% of the amount of CO_2 taken up by the ocean, which would then be about 44% of the total fossil input instead of 40% as predicted by the box diffusion model for an exponential increase with an e-folding time of 35 years (no biospheric interaction).

The validity of the box diffusion model has been checked by considering the penetration of bomb-produced ^{14}C and tritium into the ocean (Oeschger et al., 1975; Broecker et al., 1979). The result is that the model is essentially consistent with the available data. While 2- or 3-dimensional ocean models will be necessary for adequately modelling the detailed transports within the ocean, they will probably not yield essentially different results for the CO_2 uptake.

The biosphere – source or sink for CO_2?

So far, our discussion has been restricted to the excess CO_2 produced by the combustion of fossil fuels. According to existing models of the global C cycle, the biosphere should be a net sink for fossil CO_2. Typically the biosphere would take up 12% of the fossil CO_2 (Oeschger et al., 1975, p. 188); at best a net biospheric source corresponding to perhaps 10% of the fossil fuel source is compatible with these models (Oeschger et al., 1980).

The argument for assuming that the biosphere may be a CO_2 sink is that greenhouse experience shows that plant productivity may be stimulated by increasing the CO_2 concentration in air. It is extremely difficult to assess the importance of such a CO_2 fertilization effect in nature where plant productivity may be limited by other factors. For further discussion see Lemon (1977); Loomis (1979), van Keulen et al. and Hampicke (both this volume).

However, the global biomass may be decreasing because of human influences. Bolin (1977) evaluated FAO data on world forest resources and concluded that the net annual input of C into the atmosphere due to the human influence on the land biosphere is 1.0±0.6 Gt per year, compared to 5 Gt of C per year of fossil input. Woodwell et al. (1978) even estimated that the annual release of C from the biota may be between 4 and 8 Gt, and possibly as high as 18 Gt. Their estimates are, however, apparently biased towards high values. An important argument of Woodwell et al. is a study by Veillon, which indicates a rate of forest clearing of about 1.3% per year in a region of Venezuela. Woodwell et al. apparently simply extrapolated from this and other studies on restricted areas to a worldwide rate of clearing of 1–2% per year. Loomis (1979) presents evidence that the actual global rate of deforestation is probably significantly less, and that forest regrowth may in general be underestimated.

Obviously, it is hardly possible at this moment to determine the magnitude of the present (and past) net CO_2 input from the biosphere; it is not even certain if the biosphere actually is a net source or a net sink for CO_2. The reason is, of course, that the biosphere is a very inhomogeneous reservoir, so that a large number of careful regional studies are necessary to obtain reasonably accurate estimates of global biomass and fluxes. This situation is much more complex than in the case of the oceans, since the concentrations of many salts, including total CO_2, measured in any one liter of seawater, are representative for the whole

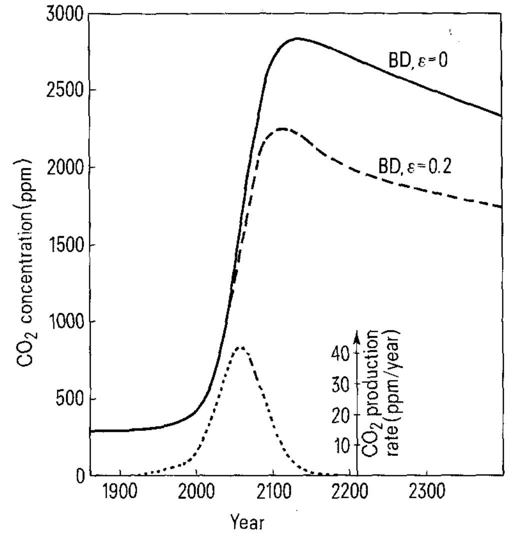

Fig. 1. Atmospheric CO_2 concentration as predicted by the box diffusion model for an upper-limit scenario (see text). Thin dashed curve: assumed CO_2 production rate.

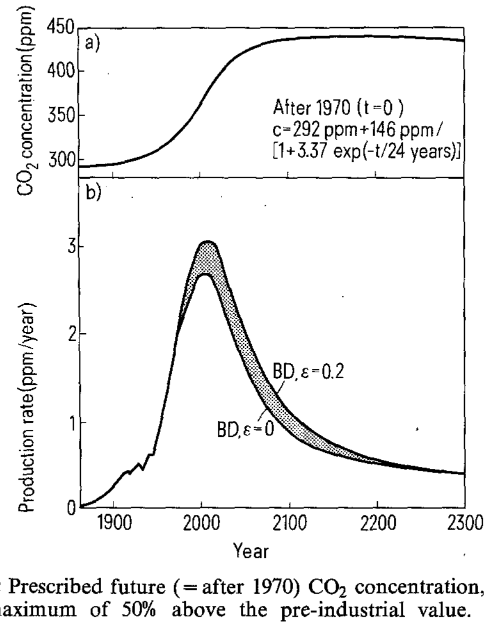

Fig. 2. *a* Prescribed future (= after 1970) CO_2 concentration, going to a maximum of 50% above the pre-industrial value. *b* CO_2 production rate in ppm/year (1 ppm = 2.1 Gt of C). Before 1970: actually observed; after 1970: calculated to reach the prescribed concentration.

ocean within 10–20%. Similarly, the state of modelling of the biosphere is at an initial stage only compared to the reasonably advanced – although still far from perfect – modelling of the ocean.

In the near future, the safest way to estimate the net biospheric CO_2 flux will still be the calculation of the difference between fossil CO_2 production and ocean uptake using atmosphere-ocean models. The result is that in the recent past, the biosphere has behaved almost neutrally on a global average. It may have acted as a modest net CO_2 sink, or contributed modestly, perhaps 10%, to the fossil source.

Model predictions

Predictions of future atmospheric CO_2 levels have been presented and discussed by Keeling and Bacastow (1977), Siegenthaler and Oeschger (1978); see also Niehaus (this volume). Here we give a summary of results obtained by means of the box diffusion model. Two scenarios are discussed:

An upper-limit scenario assumes that all economically exploitable fossil fuels (11.5 times the pre-industrial CO_2 mass in the atmosphere) will be burned in the next 200 years. The cumulative fuel consumption is assumed to grow as a logistic function of time; the maximum burning rate would be nearly 20 times the present annual output and occur around the year 2060. The results for 2 different assumptions on the biospheric flux are shown in figure 1. The solid curve is valid for a constant biomass (biota growth factor $\varepsilon = 0$), the dashed curve for a biomass increasing with increasing CO_2 concentration ($\varepsilon = 0.2$). The maximum atmospheric level would be 7–10 times higher than the natural level. According to current climate models, which predict a mean global warming of 1.5–3 K for each doubling of the CO_2 concentration (Schneider, 1975), the corresponding temperature increase would be between about 4.5 and 9 K. The model results show that even after the CO_2 input would essentially have stopped, the atmospheric levels would decrease only very slowly. The reason is that, after the near-surface ocean layers have been saturated, the transportation to deep layers occurs very sluggishly.

This upper-limit scenario is not very realistic since fossil fuel consumption would probably be reduced when serious climatic consequences became apparent or other limits to growth became effective. Another scenario, near the lower limit, is to assume that energy production could be handled in such a way that the CO_2 level would not exceed a prescribed limit. This limit is arbitrarily set at a 50% increase above the natural level, corresponding to a global warming of about 1 °K. Figure 2a shows the prescribed atmospheric CO_2 level, figure 2b the corresponding permitted CO_2 production rate in ppm/year (1 ppm = 2.12 Gt C). It is seen that the fossil energy production could increase only little above the present rate and would have to decrease rapidly after the beginning of the next century. It seems probable that the actual CO_2 input rates during the next several decades will exceed those of this scenario, because the growing energy demand cannot be sufficiently satisfied by other resources, so that the atmospheric CO_2 excess will be more than 50% in the early 21st century.

It is not possible nor would it make sense to present predictions for every conceivable energy scenario. Instead, we can get a feeling for future CO_2 burdens by considering the predicted airborne fractions of the cumulative CO_2 emissions for different times (table). The airborne fractions given for the next 50–100 years are for both scenarios and both model versions ($\varepsilon = 0.2$ and $\varepsilon = 0$) between 45 and 80% of the cumulative CO_2 input. These are, therefore, the limits we can give for the airborne fraction for any energy scenario between the two extreme cases.

Physiological aspects of increased CO_2 concentration

by H. van Keulen, H. H. van Laar, W. Louwerse and J. Goudriaan

Centre for Agrobiological Research, Wageningen (The Netherlands), and Theoretical Production Ecology, Agricultural University, Wageningen (The Netherlands)

Introduction

The massive use of fossil fuels, to satisfy the energy demands of the industrialized world, leads to the emission of a large amount of C compounds into the atmosphere. Recent estimates place the amount at about 5×10^9 t of C per year. The release of C from soil organic material, following the conversion of forest lands to either grassland or arable land by deforestation in large scale reclamation activities and by shifting cultivation, could be equally important, but there is a continual debate on the magnitude of this source.

Estimates based on soil properties, climatic conditions and changes in land use, lead some authors to figures as high as 5×10^9 t of C released anually from the soil (Buringh, 1979), whereas others claim losses around 1×10^9 t (Loomis, 1979).

Most of the C is released in the form of CO_2. Part of