Conclusion

Although the coarse estimates given here are not nearly as precise as the data supplied to the discussion by the atmospheric, oceanographic and geophysical sciences, they might well be relevant. The estimates for net releases of C from tropical vegetation and soils are, without exception, conservative, but still add up to several 10^{15} g/year. Even large errors in some of the estimates could hardly modify the overall conclusion that tropical land ecosystems are a net source of C for the atmosphere at present, their activity probably amounting to 30–80% of the annual release from fossil fuels. Likewise, it is probable that land ecosystems in other parts of the world (including fresh-water and estuarine ecosystems) are acting as net sinks. The amount removed from the atmosphere by these is even more difficult to estimate. From the evaluation of ecological data alone one is tempted to conclude that terrestrial sinks cannot fully compensate for the total quantity released by terrestrial sources so that, in accordance with the second hypothesis mentioned at the beginning, land ecosystems as a whole are a net source of C for the atmosphere. However, the possibility that releases and withdrawals are nearly balanced on a worldwide scale, as required by atmosphere-ocean models, cannot conclusively be ruled out. Although there are some open questions regarding the validity of atmosphere-ocean exchange models (Björkström, 1979b), these appear to be better substantiated than many other theories pertinent to the global CO_2 problem (Broecker et al., 1979; Oeschger et al., 1980). Therefore, the hypothesis that losses of CO_2 from and gains to the earth's land ecosystems are balanced on a global scale may be regarded as the hypothesis which, for the present, minimizes the amount of disagreement about all kinds of relevant knowledge on the global carbon cycle (Hampicke, 1979c, 1980).

It is doubtful that even the most careful evaluation of ecological data will by itself suffice to establish reliably the role of the land ecosystem in the global carbon cycle. Only a combined effort in all relevant research fields can solve this problem. A worldwide research programme should be initiated where evaluation of ecological field analyses and statistical data, satellite and aircraft remote sensing, analysis of stable isotopes of carbon (Stuiver, 1978; Freyer, 1979), and atmosphere-ocean models are integrated and carried out up to a point where the results of these different approaches converge.

Past and future emission of CO_2

by Ralph M. Rotty

Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge (Tennessee 37830, USA)

At present it appears that there are 2 major anthropogenic sources of CO_2: clearing of natural forests and fossil fuel burning. In his quest for agricultural land, man has removed large portions of the world's forests. During the 19th century, clearing of large areas of the temperature latitudes of the northern hemisphere occurred, and since then the process has gradually shifted southward. Tropical forests are undergoing the most rapid change now. As technology advances and the developed countries become more urbanized, there is, however, a trend toward increased reforestation. For example, since 1945 in the United States the total annual timber growth has exceeded the timber harvest (Clawson, 1979). Thus, from a combination of regrowth of forests on abandoned agricultural acreage and improved forest management procedures, the total C stored in the temperature forests of the world may be increasing. There is little doubt that some portions of the terrestrial biota provide a major source of CO_2 (as a result of the destruction of tropical forests), while other portions serve as sinks – at least on a time scale of several decades. Obtaining reliable quantitative information on either clearing or regrowth on a global scale is extremely difficult, if not impossible; extrapolating the USA case to all temperate areas obviously requires assumptions that are unfounded. Predicting future forest activity is very difficult beyond the qualitative assertion that forest management will become more extensive. When, and at what rate, destruction of natural forests will diminish is a societial unknown; obviously it must occur as the amount left uncut becomes less and less.

The second major source of CO_2 associated with man's activity is the combustion of fossil fuels. This source is easier to document, because the United Nations has developed data on each energy source for the period since 1860 (UN, 1955, 1976). Although other data sets now exist for certain fuels and/or certain portions of the world, it is customary to use these United Nations energy production data to calculate the CO_2 produced. In most cases the bases for the UN data and these other data sets are the same, and the discrepancies are minor. The UN data have the added advantage of being a consistent and continuous set so that year-to-year changes are in proper proportion.

Keeling (1973a) estimated the C released to the atmosphere for each unit of fossil fuel produced; e.g., for an average ton of coal mined, 0.693 t of C is oxidized to CO_2. Keeling then used these estimates to determine the annual CO_2 emissions since 1860. Rotty (1977a, 1977b) made refinements on the procedure, e.g., including flared natural gas, and recalculated annual emissions for the period 1950 through 1974. The discontinuity between Keeling's calculated values prior to 1950 and Rotty's for the more recent period are small enough to be negligible for most purposes, largely because gas flaring was such a small part of the total before 1950. When the UN issued a revised fuel data set for the years after 1950, Rotty (1979) recalculated the emissions and extended the series through 1978. Table 1 summarizes these calculations and is believed to contain the best estimates of CO_2 production now available for past fossil fuel combustion and cement production.

The CO_2 emissions from fossil fuel combustion have been growing at a rate of 4.3% per year since 1860 (with the exception of periods of world disaster – World Wars I and II and the economic depression of the 1930s) (Rotty, 1977a, 1977b). Therefore, in examining future possibilities, there is logic in assuming that the growth will continue at this rate for the next 50–100 years. On such a basis, the CO_2 from continued industrialization of the world could involve as

Table 1. Annual CO_2 releases from fossil fuel and cement. All data are million tons (10^{12} g) of C in the CO_2 released. (Data from 1869 to 1949 are from Keeling (1973a)). Values from 1950 to 1978 are from Rotty (1979) and are based on the most recent revisions of UN data available)

Year	Carbon	Year	Carbon	Year	Carbon	Year	Carbon
1860	93.3	1890	349.7	1920	958.9	1950	1665
1861	98.7	1891	365.4	1921	828.0	1951	1806
1862	98.4	1892	368.7	1922	890.6	1952	1839
1863	106.0	1893	361.6	1923	1005.3	1953	1886
1864	115.1	1894	377.1	1924	998.5	1954	1915
1865	121.9	1895	398.6	1925	1006.4	1955	2098
1866	128.7	1896	411.6	1926	1006.0	1956	2237
1867	137.9	1897	431.5	1927	1097.5	1957	2335
1868	136.7	1898	454.6	1928	1090.9	1958	2421
1869	141.8	1899	497.3	1929	1171.9	1959	2561
1870	145.0	1900	524.9	1930	1077.5	1960	2713
1871	161.9	1901	540.3	1931	968.2	1961	2673
1872	175.9	1902	552.9	1932	873.8	1962	2810
1873	188.4	1903	606.4	1933	918.8	1963	2974
1874	183.8	1904	613.4	1934	996.5	1964	3149
1875	189.2	1905	646.6	1935	1031.7	1965	3287
1876	191.6	1906	696.1	1936	1146.4	1966	3456
1877	196.0	1907	771.2	1937	1226.2	1967	3518
1878	196.5	1908	736.6	1938	1161.4	1968	3742
1879	207.6	1909	769.0	1939	1232.9	1969	3945
1880	227.1	1910	804.8	1940	1300.4	1970	4248
1881	244.4	1911	821.8	1941	1337.1	1971	4382
1882	262.5	1912	866.2	1942	1334.4	1972	4547
1883	280.0	1913	929.0	1943	1364.0	1973	4801
1884	282.1	1914	838.4	1944	1352.2	1974	4847
1885	276.4	1915	830.8	1945	1203.6	1975	4830
1886	278.7	1916	894.8	1946	1270.5	1976	5076
1887	297.7	1917	945.3	1947	1421.5	1977	5225
1888	321.9	1918	932.0	1948	1517.5	1978	5191*
1889	328.5	1919	828.9	1949	1469.6		

* 1978 estimated from data for 1st three quarters of the year less People's Republic of China.

Table 2. World energy patterns

	1975 Division Per capita energy (kW/cap)	Population (10^6)	Total energy (TW)	2025 Projected division Per capita energy (kW/cap)	Population (10^6)	Total energy (TW)
Northern America	10.13	237	2.40	10.6	315	3.34
Western Europe	3.74	365	1.37	7.8	447	3.49
USSR + CTP Europe	4.69	363	1.70	10.1	480	4.85
Japan, Australia	3.39	161	0.55	7.6	320	2.43
Developing America	0.93	323	0.30	5.2	797	4.14
Developing Africa	0.17	370	0.06	1.2	885	1.06
Developing Asia	0.21	1176	0.25	1.2	2665	3.20
Developing Middle East	0.97	116	0.11	5.2	353	1.84
CTP Asia	0.65	885	0.57	4.0	1714	6.86
World total (average)	1.83	3996	7.32	3.91	7976	31.2

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