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CO_2 from fossil fuel burning: global distribution of emissions

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ABSTRACT

The atmospheric concentration of carbon dioxide is increasing. An important source of this excess carbon dioxide is the burning of fossil fuels for energy uses. This paper describes an estimate of the areal distribution of CO_2 emissions from energy sources. CO_2 from fuel burned in international bunkers is not included nor is CO_2 from gas flaring or cement manufacture. Emissions are calculated on a 5° × 5° grid of latitude and longitude, based primarily on United Nations fuel use data. Fuel consumption data by country, by state within the US, and by province in Canada are used to calculate CO_2 emissions. Distribution of CO_2 emissions within these political entities is based on population distribution, using both discrete population data for subcountry units and population density maps. Aside from errors inherent in the UN fuel data and in our estimates for fuel composition and combustion efficiency, the major sources of error are (a) within-country regional variations in energy use per capita, (b) within-country regional variations in energy sources (e.g., hydroelectric versus coal electric), and (c) errors in our estimates of relative population density within political entities. While we believe regional patterns are accurately represented and that no CO_2 parcel is allocated very far from its correct source grid space, individual emission numbers by grid space are subject to large uncertainty. The final tabulation shows that 90% of total emissions are from the latitude band 20°–60° N, with the highest individual numbers from the grid spaces containing Frankfurt, London, and Tokyo.

1. Background

It has been long acknowledged that the burning of fossil fuels was adding carbon dioxide to the earth's atmosphere. In an early paper on the influence of CO_2 on global surface temperature, Arrhenius (1896) quoted an earlier calculation by Högbom that the annual emission of CO_2 to the atmosphere from coal burning amounted to "a thousandth part" of the CO_2 already there. Callendar (1938) estimated then current fossil fuel emissions at 1.2 billion tons carbon per year with about 40 billion tons emitted over the preceding half century. And, in their landmark paper, Revelle and Suess (1957) estimated CO_2 emissions at 17.4 billion tons C for the decade of the 1940s and 24.8 billion tons for the decade of the 1950s. By 1973 it was clear that atmospheric CO_2 was increasing and that fossil fuel burning was at least an important contributor, and Keeling (1973) produced carefully documented estimates of the annual industrial discharge of CO_2. Marland and Rotty (1984) have just updated those computations of global emissions using the best data available on fuel production and composition.

While it has been generally recognized that the bulk of these CO_2 emissions come from the mid-latitudes of the northern hemisphere, until quite recently these and other calculations have focused on global totals. It was assumed that CO_2 was rapidly dispersed and that the concentration was approximately uniform throughout the atmosphere. However, the distribution of CO_2 sources provides valuable information for estimating future emissions and Rotty (1979) calculated the distribution of emissions on a geopolitical basis.

With reliable atmospheric CO_2 measurements from a variety of locations, it is now apparent that there are regional and time dependent variations in the concentration of atmospheric CO_2 and that regional data on source strength would aid in understanding the geochemical cycling of carbon. It appears that there are hemispheric, and perhaps latitudinal, differences in the rate of growth of atmospheric CO_2; that the amplitude of the seasonal cycle of CO_2 concentration may be undergoing measurable change; and that the amplitude of the annual cycle is latitude dependent (Pearman, 1980; Fraser et al., 1983; Pearman et al., 1983). Fung et al. (1983) have introduced atmospheric trajectories obtained from climate models into analyses of the carbon cycle in an attempt to explain the seasonal variations. Recognizing the utility of knowing CO_2 emissions by geographic distribution, Rotty (1983) made the first cut at assembling such a data set, estimating CO_2 emissions by 10° latitude bands.

In this study we have relied on data compiled by the United Nations Department of International Economic and Social Affairs and the computational framework described by Marland and Rotty (1984) and have estimated global CO_2 emissions on a 5° × 5° grid of latitude and longitude for a representative, recent year, 1980.

2. Methods

To simultaneously demonstrate the approach taken in the computations, the quality of the data used, and the kinds of subjective judgments which have gone into the numbers, we illustrate by following the logic of the computation for a sample grid space, 0–5° S latitude and 75–80° W longitude. This is a grid space that contains parts of two countries, Peru and Ecuador. As a first step, we obtained data on total fossil fuel consumption for Peru and Ecuador from the United Nations Yearbook of World Energy Statistics and the accompanying data tape (UN, 1983). For each fuel type (solid, liquid, gas) consumption was taken as production plus imports minus the sum of exports, changes in stocks, supplies to international bunkers, and nonfuel uses of energy resources. The 1980 values for Peru and Ecuador are shown in Table 1.

Conversion factors adapted from Marland and Rotty (1984) were used to convert fuel consumption numbers to thousands of metric tons of carbon in the CO_2 produced during combustion of these fuels. The conversion factors used were 0.7326, 0.8373, and 0.01343 for solids, liquids, and gases respectively. The value for liquids is modified from that derived in Marland and Rotty (1984) because that paper was based on fuel production data while this one is based on fuel consumption data and the treatment of nonfuel uses of liquid petroleum products is different. Marland and Rotty (1984) included an estimate of CO_2 discharged by oxidation of nonfuel petroleum products whereas this paper does not include nonfuel products and presents only CO_2 emissions from energy uses. Total CO_2 emissions from fossil fuels burned in Peru and Ecuador during 1980 are thus 5769×10^3 and 3205×10^3 tons C respectively and we are left to allocate what fraction of each was discharged from each specific grid space.

Table 1. *Consumption of fossil fuels in 1980*

	Solids (thousand metric tons coal equivalent)	Liquids (thousand metric tons of oil equiv.)	Gases (terrajoules)
Peru	202.4	6239	29,550
Ecuador	0.0	3804	1,502

Geographic allocation of Peruvian and Ecuadorian CO_2 emissions was based on the product of 2 matrices for each country. In each case the first matrix was a set of values for the fraction of each grid space that was occupied by the country in question. For example, we isolated the grid space 0–5° S; 75–80° W on the appropriate map in the National Geographic World Atlas (NGS, 1981) and made the visual estimate that it was, by area, 55% Ecuador and 45% Peru. Proceeding similarly for each of the 12 grid spaces that contain parts of Peru and each of the 4 grid spaces that contain parts of Ecuador (2 are shared) produced the matrices shown in Fig. 1. In each case the numbers show the percentage of the area of the given grid space which is occupied by the country listed.

Although it has no impact on the Ecuador calculation (all within 5° of the equator), the general procedure needs to recognize that the absolute

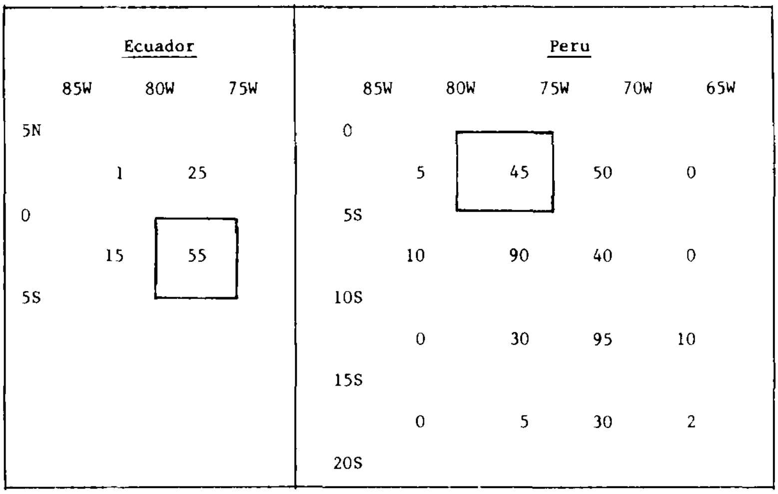

Fig. 1. The fraction of each 5° × 5° grid space occupied by Equador and Peru, respectively. A box accents the grid space used in the sample calculation in the text.

area of grid spaces decreases with increasing latitude. Because the area of each grid space is proportional to the cosine of its latitude, relative areas of a country were obtained by multiplying the fractional areas in each grid space, from this first matrix, by the cosine of the latitude of the center of the grid space.

For each country a second matrix was constructed in which each element of the matrix was intended to be a quantitative estimate of the relative density of fossil fuel consumption for the portion of the country in that matrix space as compared to that for the country as a whole. By and large this relative density number was based on population density with some consideration for major industrial areas. Relative values were assigned by the authors on a subjective basis and in most countries were simply integers from one to ten. Numbers were based on encyclopedia descriptions of population distribution, industrial activity, city and country population data, and regional population density maps when available (*Encyclopaedia Britannica*, 1982; Kurian, 1982; Rand McNally, 1983; UN, 1979). The second matrices for both Peru and Ecuador are shown in Fig. 2.

CO_2 emissions were then allocated to grid spaces within a country in proportion to the product of the two matrices. For example, for Ecuador the fraction of total CO_2 emissions discharged from the grid space 0–5° S; 75–80° W is taken to be

$$\frac{(55)(2)}{(1)(1) + (15)(2) + (25)(2) + (55)(2)} = \frac{110}{191};$$

i.e., 57.59% of the Ecuadorian total.

In essence relative area times the population density (i.e., population per unit area) would yield a value proportional to total population of the grid space. Similarly, relative area times relative energy consumption density produces a number proportional to energy consumption and to CO_2 emissions. The basic assumption is that, with secondary consideration of known industrial concentrations, within any political entity, CO_2 emissions are distributed in proportion to total population.

Taking, in the same manner, the product of the two matrices (and multiplying by the cosines of grid space midpoints) we find that 3.98% of Peruvian CO_2 emissions are to be attributed to the grid space 0–5° S; 75–80° W. Total CO_2 emissions from this grid space are thus 57.59% of Ecuador's 3205 × 10^3 tons of C plus 3.98% of Peru's 5769 × 10^3 tons; or 2076 × 10^3 tons of C in 1980.

All computations were performed on the Oak Ridge National Laboratory IBM 1094 with input data comprised of two matrices per country plus

Ecuador

	85W–80W	80W–75W
5N–0	1	2
0–5S	2	2

Peru

	85W–80W	80W–75W	75W–70W	70W–65W
0–5S	5	1	1	0
5S–10S	5	4	1	0
10S–15S	0	5	3	1
15S–20S	0	2	4	2

Fig. 2. Relative density of fossil-energy consumption, by country, for the portion of Ecuador and Peru in each 5° × 5° grid space.

UN data on consumption of solid, liquid, and gaseous fuels for 1980, by country.

It is important to recognize that while the second matrix contains a purely subjective attempt to describe the density of CO_2 sources within Peru: (a) the CO_2 total for Peru is based on UN data which is accurately known; and (b) the subjective assignment of relative densities within Peru involves only 12 grid spaces so that at very worst a parcel of CO_2 is displaced a linear distance of three grid spaces from its proper source. To give an idea of the sensitivity of the CO_2 source distribution to the subjective assignments in matrix 2, we show in Fig. 3 the % of Peruvian CO_2 emissions from each grid space for each of three models of CO_2 emission density distribution. In Fig. 3A all grid spaces were given a relative density of 1; that is, it was assumed that CO_2 emissions from all of Peru were uniform, e.g., emissions in tons C/km^2 were constant. Figure 3B uses the density values assigned in Fig. 2 assuming, for example, that CO_2 emissions in tons C/km^2 are 5 times greater from the densely populated areas of the north and west as from the more remote areas of the northeast. In Fig. 3C the density values were doubled for the two grid spaces with the largest emissions totals, but were left unchanged from Fig. 2 for all other grid spaces. The crucial point is that, especially in going from case B to case C, the basic pattern was preserved and the carbon total was unchanged.

While this method clearly produces only estimates of the CO_2 source distribution and too much credence should not be placed on the numerical values, we believe that regional patterns are accurately represented and that no parcel of CO_2 is displaced very far from its correct source. The scale of the UN (or other) fuel use data is an important consideration with regard to how far a parcel of emitted CO_2 might be displaced. That is, how well do the hard data allow us to distribute fossil fuel burning before we are obliged to rely on the much more subjective allocations typified by the Peru–Ecuador discussion.

The UN statistics on fuel consumption are based on 200 countries or other political subdivisions. Of these 200, 43 are contained in a single grid space so that no allocation had to be addressed. Another 30 fall into only 2 grid spaces. Only four countries (USSR, 213 spaces; Canada, 122; USA, 89; and China, 61) occupy more than 50 grid spaces and only 4 more (Pacific Islands Trust Territory, 42 spaces; Greenland, 44; Australia, 46; and Brazil, 47) occupy more than 30. Only 15 countries enter into more than 18 grid spaces. Of course the bulk of the CO_2 comes from a very small number of countries and the overall accuracy is very dependent on the treatment of

	85°W–80°W	80°W–75°W	75°W–70°W	70°W–65°W
0–5°S	1	11	12	
5°S–10°S	2	22	10	
10°S–15°S		7	22	2
15°S–20°S		1	7	0

Figure 3A

	85°W–80°W	80°W–75°W	75°W–70°W	70°W–65°W
0–5°S	2	4	4	
5°S–10°S	5	31	3	
10°S–15°S		13	24	1
15°S–20°S		1	10	0

Figure 3B

	85°W–80°W	80°W–75°W	75°W–70°W	70°W–65°W
0–5°S	1	3	3	
5°S–10°S	3	40	2	
10°S–15°S		8	32	1
15°S–20°S		1	6	0

Figure 3C

Fig. 3. Examples of the resulting matrix for CO_2 emissions from Peru, in % of the Peruvian total of 5769 tons C. The sensitivity of the CO_2 distribution to assumptions of the CO_2 emissions density factors in matrix 2 is illustrated with 3 different models of the density factors for Peru. In 3A the density factors (matrix 2) were all set equal to one. In 3B the density factors were as in Fig. 2. In 3C the density factors were as in Fig. 2 except that the values were doubled in the two boxes with highest CO_2 emissions.

these nations. Of the total 1980 emissions, 61% of the total is attributable to the USA, USSR, China, Japan, and West Germany. The key was to break the large countries into smaller subdivisions, i.e., states, provinces, islands, etc., over which energy consumption or total population could be accurately established. The subjective distribution function was then used only within each subdivision and not over the country as a whole.

For some of the major fuel consuming countries it is worth describing further how the relative CO_2 density numbers (matrix 2) were derived. It should be noted, however, that even for small countries the mean density of a grid space could be only crudely estimated. Grid spaces might include a major industrial center yet be largely low density, rural. The easiest spaces to characterize were often those that contained only a very small portion of a country and hence were likely to be relatively homogeneous. Some nations were simplified by clear settlement patterns where population (and presumably energy consumption) are concentrated along, for example, a coast line or river valley. For others, like Romania, it is not obvious that there is any inhomogeneity in population density and all blocks were assigned density values of 1 so that CO_2 distribution was taken to be the same as area distribution among the respective grid spaces. For grid spaces along a coast line, the CO_2 emissions number represents the total for the full grid space even though the off-shore portion contributed nothing.

This approach carries the additional assumption that the variety of energy types are distributed within each country in the same manner, e.g., that coal is not more important in one region and hydroelectric power in another. This is an implicit assumption that we were able to avoid only for the USA and Canada.

In southern Africa, the UN data set provides information on the South Africa Customs Union, a designation which includes Botswana, Lesotho, Namibia, South Africa, and Swaziland. The UN data set contains some information for the individual countries and some aggregated over the group. Because we were unable to allocate the collected data, the most straightforward approach was to sum everything over the five entities and then to treat the data as if there were a single country under the South African Customs Union heading (18 grid spaces). Allocation among grid spaces was by population with acknowledgement of the main industrial and mining centers in South Africa.

For the United Kingdom (8 spaces), Japan (14), Mexico (21), Argentina (23), Australia (46), Brazil (47), and others, the 1982 edition of the *Encyclopaedia Britannica* provides colored maps of population density and for the latter three of these there are strikingly clear distinctions between areas of high population density and industrial development as contrasted with remote, low density areas. For all of these, energy-consumption density was judged visually, based on population density, with a precision of 1 significant figure. Our suspicion is that the tendency in doing this was to be conservative in making distinctions. That is, there was a tendency to evaluate countries as being more uniform than is in fact the case, suppressing the high extremes and inflating the lows. This is especially likely in the larger countries with broad contrasts like China.

For the Federal Republic of Germany (5 spaces), Greenland (44), Argentina (23), Norway (22), and Indonesia (29), the Britannica gives population data by state or region and mean density data can be calculated. For the island groups of French Polynesia (27 spaces), Kiribati (29), and Pacific Islands Trust Territory, there is enough data by island to characterize the major energy consuming grid spaces. For a few countries (e.g., Fiji) we were able to assemble fairly accurate population data by grid space and thus estimated relative CO_2 emissions per grid space directly. Because CO_2 emissions were assumed to be proportional to population we did not have to proceed through the two matrix product.

In India (27 spaces), as in Indonesia, data on the population of major cities and on industrial concentrations were used to supplement the population density maps.

For Canada, we took data on energy consumption by Province (Friedenburg, 1979). We used the population density map for allocation within provinces, but essentially treated each province as though it were a separate nation. We were further able to distinguish primary nuclear and hydroelectric energy in Canada so that it was possible to allocate only fossil energy sources. Distribution within the Northwest Territories was aided by identifying nearly half of the population with specific communities. Similarly, state data for the USA (US DOE, 1983) allowed us to treat each state essentially as though it were a separate nation. Populations of discrete communities were used for allocation within Alaska. Hydro and nuclear electric energy were again excluded. Thus geographic misallocation for the USA and Canada is at the level of states or provinces and not nations. Aside from a very few grid spaces with particular need for discrimination, the USA is the only nation where we felt justified in using more than one significant figure in the second matrix.

Allocation within China relied largely on the Britannica population density map with a check on internal consistency available through tables of population by province.

With 213 grid spaces involved and less regional data available, the Soviet Union was the biggest challenge to subdivide. Total energy consumption (i.e., CO_2 emissions) was allocated to republics according to population, with the Ukraine and European Russia assumed to have 20% greater per capita energy consumption because of heavy industrialization. Allocation within republics was based on the Britannica population density map after additional subdivision of the immense area of Asian Russia. For the Russian Republic, some primary division was possible based on Britannica estimates of population in the European and Asian portions, the fraction east and west of the Yenisey River, and the fraction north of 60° latitude. For Eastern Siberia (east of the Yenisey River) we used population data by oblast and identified over one-third of the total population with 19 specific major cities. In summary, for the Soviet Union we did not go through the two matrix process but generated directly a single matrix based on total population. Soviet energy use was distributed among republics, oblasts, or other divisions based on total population and then further distributed within the subdivisions on the basis of population density maps with some bias for known industrial concentrations. Again, this incorporates the questionable presumption that the distribution of energy types, i.e., CO_2 emission per unit of energy consumption, is uniform across this vast and varied nation. Distribution errors within for example, the Soviet Union, can thus be associated with three principal sources which produce errors at different geographic scales: (1) non-uniform rates of CO_2 emissions per unit of energy consumption, (2) non-uniform values of energy consumption per capita, and (3) failure to accurately allocate population within republics or other subdivisions for which population data were available.

3. Results

The resulting values of CO_2 emissions from fossil fuel burning are shown in Table 2 and displayed graphically in Fig. 4. There are no qualitative surprises. The highest value is for the grid space which includes Frankfurt and the industrial center of Germany and this is followed closely by the London and Tokyo spaces. There is a run of high values through north central Europe from London to Moscow and another in the eastern USA. Peking, Korea, Japan, and southern California also stand out. Over 95% of the emissions are from the northern hemisphere.

Rotty (1983) made preliminary estimates of global CO_2 emissions by 10° latitude bands and a comparison shows that the basic features agree remarkably well despite the much coarser level of aggregation. Our results are summed over 5° latitude bands in Table 3.

The smallest value which shows as a non-zero value on the map (Fig. 4) is 0.1×10^3 metric tons of carbon. This value appears, for example, in grid space 5–10° S; 165–170° W where it represents 1.2% of the emissions from burning 7000 metric tons per year of liquid fuels in the Cook Islands. Smaller values were calculated but do not show in Table 2 or Fig. 4. Other small values are not represented in the data sets. Aside from failure to represent emissions from airplanes and ships in international commerce and flaring of natural gas; there are a very few small, stationary, occupied sites which are not accounted for (or are counted with the parent country) in the UN fuel use data and hence do not show here. Most prominent among these are the south pacific island nation of Tuvalu with a population of 7000 people and Wallis/Futuna Islands with some 17,000 inhabitants, also in the south pacific. The Galapagos Islands, Norfolk Island, Midway Island, Tokelau, Easter Island, and Ascension Island all contain over 1000 inhabitants but are not accounted for. Our estimate is that fewer than 40,000 people in small island nations, Antarctic research stations, etc. remain unaccounted for.

The data set also does not include CO_2 emissions from oxidation of non-energy petroleum liquids (e.g., solvents and lubricants) or from the manufacture of cement. Table 4 shows global total CO_2 emissions for 1980 and provides perspective on the magnitude of the omissions. We see that these add about 8.7% to what is included in our summary tables and map. The 3.9% attributable to cement manufacture and the oxidation of non-fuel liquids is probably distributed not too differently from the CO_2 attributable to fuel consumption but the 2.7% related to oxidation of fuels in international transport is widely distributed and quite unlike the inland fuel consumption pattern. Gas flaring should be related to crude oil production.

The confidence that can be placed in the values compiled here is a tenuous thing. The sums for individual countries are as good as the UN energy consumption data and our effort to characterize the composition and efficiency of oxidation of fuel (Marland and Rotty, 1984). The Marland and Rotty estimate for the global total was judged to be $\pm\sim 8\%$ but some individual country data are less certain than this. Division of countries by area was done visually and individual allocations are probably accurate within 10% in

Table 2. *Global CO_2 emissions from fossil fuel burning for fuel uses in 1980, by 5° × 5° grid spaces of latitude and longitude (in 10^3 metric tons of carbon) (T = 0·1–0·4) (there are no non-zero values south of 55° S)*

	180° W	175° W	170° W	165° W	160° W	155° W	150° W	145° W	140° W	135° W	130° W	125° W
90° N	0	0	0	0	0	0	0	0	0	0	0	0
85° N	0	0	0	0	0	0	0	0	0	0	0	0
80° N	0	0	0	0	0	0	0	0	0	0	0	0
75° N	0	0	0	T	2	38	22	T	0	0	T	0
70° N	8	8	2	12	3	30	61	25	4	8	6	2
65° N	T	1	37	31	4	140	2.100	88	38	13	5	5
60° N	0	0	0	4	4	43	0	0	7	180	59	89
55° N	0	T	T	2	0	0	0	0	0	27	250	670
50° N	0	0	0	0	0	0	0	0	0	0	190	15.000
45° N	0	0	0	0	0	0	0	0	0	0	0	6.300
40° N	0	0	0	0	0	0	0	0	0	0	0	34.000
35° N	0	0	0	0	0	0	0	0	0	0	0	580
30° N	0	0	0	0	0	0	0	0	0	0	0	0
25° N	0	0	0	15	4.100	0	0	0	0	0	0	0
20° N	0	0	0	0	1.100	0	0	0	0	0	0	0
15° N	0	0	0	0	0	0	0	0	0	0	0	0
10° N	0	0	0	0	0	0	0	0	0	0	0	0
5° N	0	0	0	0	1	0	0	0	0	0	0	0
0	0	1	0	0	0	T	0	0	0	0	0	0
5° S	0	0	T	T	0	1	0	0	3	0	0	0
10° S	2	140	26	T	0	1	T	0	0	0	0	0
15° S	7	2	1	T	1	1	49	2	2	0	0	0
20° S	8	1	0	T	4	T	1	1	2	0	0	0
25° S	0	0	0	0	0	0	T	T	0	0	0	0
30° S	0	0	0	0	0	0	0	0	0	0	0	0
35° S	0	0	0	0	0	0	0	0	0	0	0	0
40° S	0	0	0	0	0	0	0	0	0	0	0	0
45° S	0	0	0	0	0	0	0	0	0	0	0	0
50° S	0	0	0	0	0	0	0	0	0	0	0	0
55° S	0	0	0	0	0	0	0	0	0	0	0	0
60° S												

	120° W	115° W	110° W	105° W	100° W	95° W	90° W	85° W	80° W	75° W	70° W	65° W
90° N												
	0	0	0	0	0	0	0	0	0	0	0	0
85° N												
	0	0	0	0	0	0	0	0	0	0	0	0
80° N												
	0	0	0	0	0	0	0	0	0	0	6	9
75° N												
	1	0	0	0	0	0	0	1	1	0	T	0
70° N												
	5	0	2	2	2	2	1	1	0	0	1	T
65° N												
	15	25	3	3	3	2	0	1	1	1	6	T
60° N												
	150	440	30	30	30	19	1	0	2	0	2	2
55° N												
	1,300	16,000	3,000	1,700	170	67	67	23	14	34	170	150
50° N												
	3,700	3,000	1,700	2,600	7,300	9,000	4,100	8,900	11,000	21,000	4,200	4,200
45° N												
	2,400	8,900	6,800	6,700	11,000	31,000	81,000	91,000	85,000	99,000	1,900	2,400
40° N												
	9,700	6,100	8,400	17,000	29,000	37,000	59,000	55,000	71,000	3,600	0	0
35° N												
	70,000	11,000	9,600	27,000	56,000	53,000	41,000	54,000	11,000	0	0	120
30° N												
	16	1,600	4,700	14,000	52,000	38,000	7,700	36,000	420	0	0	0
25° N												
	0	340	1,800	6,800	5,600	140	1,000	3,800	3,900	290	0	0
20° N												
	0	0	71	3,700	25,000	6,600	1,000	41	3,200	850	5,400	3,800
15° N												
	0	0	0	0	0	520	1,500	250	310	1,800	9,000	4,500
10° N												
	0	0	0	0	0	0	5	970	1,600	6,700	4,600	4,500
5° N												
	0	0	0	0	0	0	0	17	2,100	3,200	1,300	890
0												
	0	0	0	0	0	0	0	630	2,100	550	150	120
5° S												
	0	0	0	0	0	0	0	250	1,800	270	120	120
10° S												
	0	0	0	0	0	0	0	0	750	1,400	280	130
15° S												
	0	0	0	0	0	0	0	0	49	690	520	260
20° S												
	0	0	0	0	0	0	0	0	0	190	810	220
25° S												
	0	0	0	0	0	0	0	0	0	370	2,400	1,500
30° S												
	0	0	0	0	0	0	0	0	0	4,500	1,400	4,300
35° S												
	0	0	0	0	0	0	0	0	0	990	2,000	3,600
40° S												
	0	0	0	0	0	0	0	0	0	190	500	190
45° S												
	0	0	0	0	0	0	0	0	0	120	340	0
50° S												
	0	0	0	0	0	0	0	0	0	150	180	1
55° S												
	0	0	0	0	0	0	0	0	0	0	0	0
60° S												

Table 2—(*cont.*)

	60° W	55° W	50° W	45° W	40° W	35° W	30° W	25° W	20° W	15° W	10° W	5° W
90° N												
	0	0	0	0	0	0	0	0	0	0	0	0
85° N												
	0	0	0	0	0	0	0	0	1	0	0	0
80° N												
	0	0	0	0	0	0	0	0	2	0	0	0
75° N												
	2	25	0	0	0	0	0	12	T	0	0	0
70° N												
	0	28	0	0	15	0	0	21	63	11	0	0
65° N												
	0	17	18	17	0	0	0	250	76	13	110	540
60° N												
	T	0	0	0	0	0	0	0	0	0	3,200	13,000
55° N												
	170	0	0	0	0	0	0	0	0	43	11,000	120,000
50° N												
	1,100	1,100	0	0	0	0	0	0	0	0	450	22,000
45° N												
	0	0	0	0	0	0	0	0	0	0	8,200	31,000
40° N												
	0	0	0	0	0	9	94	0	0	0	6,700	13,000
35° N												
	0	0	0	0	0	0	0	0	100	0	2,100	1,400
30° N												
	0	0	0	0	0	0	0	0	1,300	850	300	150
25° N												
	0	0	0	0	0	0	0	0	9	26	16	9
20° N												
	0	0	0	0	0	0	0	26	220	130	37	13
15° N												
	170	0	0	0	0	0	0	0	270	300	100	140
10° N												
	630	140	0	0	0	0	0	0	0	350	820	990
5° N												
	230	210	2	0	0	0	0	0	0	0	21	5
0												
	120	240	510	600	720	60	0	0	0	0	0	0
5° S												
	120	240	600	1,200	4,500	120	0	0	0	0	0	0
10° S												
	120	240	1,200	1,200	2,400	0	0	0	0	0	0	0
15° S												
	280	460	1,200	2,300	230	0	0	0	0	0	0	0
20° S												
	760	5,300	10,000	5,000	0	0	0	0	0	0	0	0
25° S												
	1,800	2,700	1,100	0	0	0	0	0	0	0	0	0
30° S												
	6,900	900	0	0	0	0	0	0	0	0	0	0
35° S												
	2,100	0	0	0	0	0	0	0	0	0	0	0
40° S												
	0	0	0	0	0	0	0	0	0	0	0	0
45° S												
	0	0	0	0	0	0	0	0	0	0	0	0
50° S												
	3	0	0	0	0	0	0	0	0	0	0	0
55° S												
	0	0	0	0	0	0	0	0	0	0	0	0
60° S												

	0	5° E	10° E	15° E	20° E	25° E	30° E	35° E	40° E	45° E	50° E	55° E
90° N												
	0	0	0	0	0	0	0	0	0	0	0	0
85° N												
	0	0	0	0	0	0	0	0	0	0	0	0
80° N												
	0	0	0	0	0	0	0	0	0	0	0	0
75° N												
	0	0	0	2	22	39	4	0	0	0	4	4
70° N												
	0	0	150	1,200	1,100	1,600	2,000	73	51	73	110	120
65° N												
	33	2,200	2,400	3,300	9,600	4,500	1,400	1,300	3,600	2,200	730	1,400
60° N												
	0	6,000	21,000	8,400	9,800	10,000	5,600	73,000	44,000	29,000	15,000	5,800
55° N												
	60,000	150,000	110,000	84,000	53,000	29,000	39,000	49,000	36,000	20,000	16,000	4,100
50° N												
	53,000	84,000	53,000	67,000	52,000	62,000	31,000	54,000	16,000	4,100	890	1,300
45° N												
	21,000	35,000	21,000	15,000	36,000	25,000	5,800	7,600	22,000	31,000	2,200	6,700
40° N												
	6,500	6,400	7,100	3,300	10,000	3,700	5,700	3,900	4,200	15,000	5,600	3,300
35° N												
	1,400	1,400	1,900	340	750	390	11,000	6,000	3,100	4,900	5,500	2,200
30° N												
	150	160	590	590	590	480	3,700	580	350	5,800	7,300	2,600
25° N												
	140	120	88	150	260	320	660	4,200	1,600	5,000	3,900	1,600
20° N												
	13	33	17	8	12	4	410	61	1,900	240	220	96
15° N												
	230	1,100	460	47	30	85	170	170	280	210	110	0
10° N												
	1,400	2,800	580	40	27	77	85	190	130	42	3	0
5° N												
	0	320	630	42	45	54	220	220	140	62	0	0
0												
	0	130	230	290	94	130	280	1,100	43	0	0	32
5° S												
	0	0	120	140	93	110	130	150	0	T	1	0
10° S												
	0	0	110	270	120	520	210	180	70	66	7	T
15° S												
	0	0	180	240	240	1,200	1,000	200	22	210	5	1
20° S												
	0	0	200	760	570	6,400	1,400	28	23	94	0	340
25° S												
	0	0	4	620	1,500	22,000	6,800	0	2	4	0	0
30° S												
	0	0	0	2,800	2,900	15,000	1,400	0	0	0	0	0
35° S												
	0	0	0	0	0	0	0	0	0	0	0	0
40° S												
	0	0	0	0	0	0	0	0	0	0	0	0
45° S												
	0	0	0	0	0	0	0	0	0	0	0	0
50° S												
	0	0	0	0	0	0	0	0	0	0	0	0
55° S												
	0	0	0	0	0	0	0	0	0	0	0	0
60° S												

Table 2-(*cont*).

	60° E	65° E	70° E	75° E	80° E	85° E	90° E	95° E	100° E	105° E	110° E	115° E
90° N												
	0	0	0	0	0	0	0	0	0	0	0	0
85° N												
	0	0	0	0	0	0	0	0	0	0	0	0
80° N												
	0	0	0	0	0	0	0	0	0	0	0	0
75° N												
	0	3	8	4	240	11	14	14	27	13	22	5
70° N												
	670	220	220	130	33	540	7	7	7	7	14	7
65° N												
	660	400	260	260	130	250	13	14	14	31	54	20
60° N												
	13,000	4,000	5,300	1,300	11,000	7,900	3,600	1,900	1,500	190	160	83
55° N												
	2,100	1,800	2,200	1,900	8,100	11,000	3,700	570	4,900	2,000	1,900	1,400
50° N												
	890	440	2,200	890	2,600	3,300	320	170	330	540	200	880
45° N												
	6,300	27,000	21,000	17,000	1,700	3,300	1,300	1,100	700	970	6,000	10,000
40° N												
	2,300	16,000	1,400	3,200	720	1,100	1,100	2,200	11,000	11,000	18,000	29,000
35° N												
	430	1,200	3,500	4,500	400	1,500	1,500	1,900	19,000	23,000	27,000	38,000
30° N												
	870	2,800	2,600	14,000	9,300	5,200	1,700	4,100	20,000	20,000	28,000	16,000
25° N												
	0	900	7,300	4,900	4,900	11,000	1,400	1,600	6,000	11,000	23,000	5,200
20° N												
	0	0	5,100	5,100	3,800	150	140	2,800	2,100	1,000	860	82
15° N												
	0	0	780	9,900	780	0	16	1,000	3,100	2,200	0	84
10° N												
	0	0	1	3,200	760	0	8	770	1,900	300	0	300
5° N												
	0	0	2	0	0	0	0	990	12,000	34	2,000	550
0												
	0	0	T	0	0	0	0	13	2,000	170	200	530
5° S												
	0	0	0	0	0	0	0	0	66	6,600	6,600	260
10° S												
	0	0	0	0	0	0	0	0	0	27	0	0
15° S												
	5	0	0	0	0	0	0	0	0	0	0	10
20° S												
	0	0	0	0	0	0	0	0	0	0	200	890
25° S												
	0	0	0	0	0	0	0	0	0	0	570	1,900
30° S												
	0	0	0	0	0	0	0	0	0	0	54	5,800
35° S												
	0	0	0	0	0	0	0	0	0	0	0	130
40° S												
	0	0	0	0	0	0	0	0	0	0	0	0
45° S												
	0	0	0	0	0	0	0	0	0	0	0	0
50° S												
	0	0	0	0	0	0	0	0	0	0	0	0
55° S												
	0	0	0	0	0	0	0	0	0	0	0	0
60° S												

	120° E	125° E	130° E	135° E	140° E	145° E	150° E	155° E	160° E	165° E	170° E	175° E
90° N												
	0	0	0	0	0	0	0	0	0	0	0	0
85° N												
	0	0	0	0	0	0	0	0	0	0	0	0
80° N												
	0	0	0	0	0	0	0	0	0	0	0	0
75° N												
	8	16	4	11	8	7	3	2	0	0	T	0
70° N												
	27	14	14	14	27	41	68	68	61	25	13	12
65° N												
	27	540	160	15	140	140	130	25	44	T	T	4
60° N												
	77	4	48	87	36	7	360	110	160	4	0	0
55° N												
	1,600	2,200	510	1,300	850	0	0	650	T	T	T	0
50° N												
	6,100	8,400	2,500	2,300	2,100	2	1	0	0	0	0	0
45° N												
	13,000	14,000	5,900	1,400	16,000	790	0	0	0	0	0	0
40° N												
	7,400	43,000	5,800	120,000	26,000	0	0	0	0	0	0	0
35° S												
	11,000	27,000	33,000	10,000	0	0	0	0	0	0	0	0
30° N												
	6,500	5,700	0	0	0	0	0	0	0	0	0	0
25° N												
	17,000	800	0	0	0	T	0	0	0	0	0	0
20° N												
	1,700	0	0	0	0	4	0	0	0	22	0	0
15° N												
	5,300	500	0	0	560	1	0	0	T	T	T	0
10° N												
	1,000	1,000	6	5	T	2	7	7	T	3	3	0
5° N												
	66	13	3	0	0	0	T	T	0	0	4	0
0												
	200	20	53	86	94	8	32	0	0	34	T	T
5° S												
	120	36	9	33	92	240	32	24	12	1	0	0
10° S												
	21	210	1,000	160	470	68	16	1	2	8	T	4
15° S												
	250	510	510	410	860	310	0	0	7	8	0	190
20° S												
	0	99	980	980	980	1,800	590	0	110	410	0	0
25° S												
	950	0	95	470	950	1,900	4,900	0	0	0	0	0
30° S												
	1,400	270	540	2,200	1,800	4,500	3,600	0	0	0	58	0
35° S												
	0	0	0	380	5,500	3,000	210	0	0	0	1,600	760
40° S												
	0	0	0	0	120	1,600	0	0	0	150	1,500	200
45° S												
	0	0	0	0	0	0	0	0	0	190	93	0
50° S												
	0	0	0	0	0	0	0	0	0	0	0	0
55° S												
	0	0	0	0	0	0	0	0	0	0	0	0
60° S												

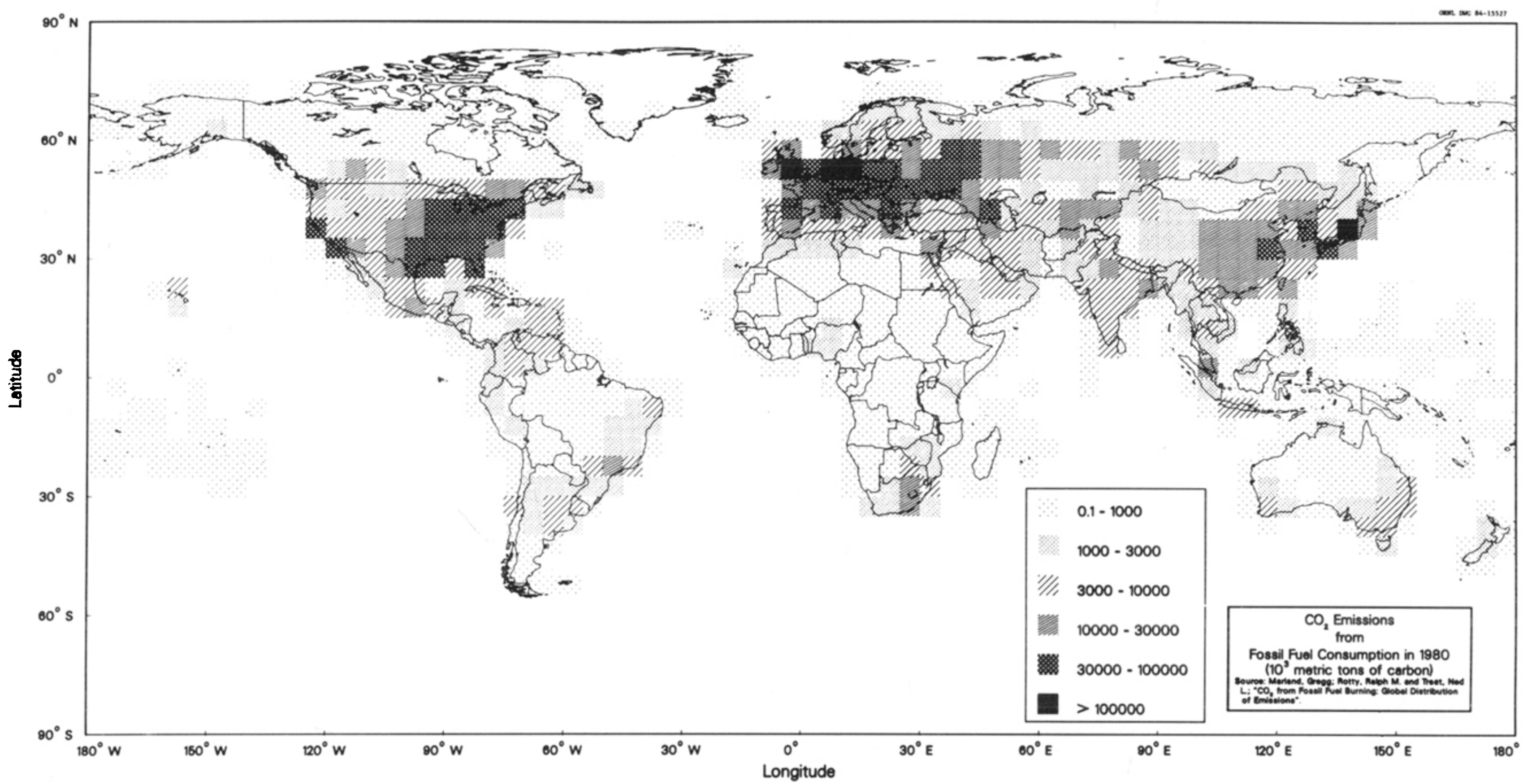

Fig. 4. Global CO_2 emissions from fossil fuel burning in 1980.

Table 3. *CO_2 emissions during fossil fuel burning for energy uses by 5° bands of latitude, 1980**

Northern hemisphere latitude band	CO_2 emissions (thousand tons C)	Southern hemisphere latitude band	CO_2 emissions (thousand tons C)
85–90	0	0–5	11,544
80–85	1	5–10	24,190
75–80	17	10–15	11,365
70–75	601	15–20	12,387
65–70	9,141	20–25	39,291
60–65	39,539	25–30	52,387
55–60	294,268	30–35	60,469
50–55	854,434	35–40	20,463
45–50	634,248	40–45	4,434
40–45	846,680	45–50	742
35–40	726,033	50–55	336
30–35	578,493	55–60	0
25–30	316,692	60–65	0
20–25	140,728	65–70	0
15–20	76,712	70–75	0
10–15	45,891	75–80	0
5–10	36,094	80–85	0
0–5	25,744	85–90	0

* Computer-generated totals are shown to permit summing but significance beyond the second figure is not implied.

Table 4. *Global total CO_2 emissions from industrial activities in 1980*

Source	CO_2 (million tons C)	Fraction of CO_2 from inland fuel consumption
Solid fuel consumption*	1,933	39.8
Liquid fuel consumption*	2,210	45.5
Gas fuel consumption*	720	14.8
Total, this text	4,863	100.1
Gas flaring†	102	2.1
International bunkers‡	130	2.7
Cement manufacture†	121	2.5
Nonfuel petroleum liquids oxidized‡	69	1.4
Total	5,285	108.8
1980 total calculation from fuel production data†	5,284	

* Sum of values used in this text (based on fuel consumption).

† From Marland and Rotty (1984).

‡ Estimates of quantities not otherwise included in this text.

most cases. Errors in this category are partially self-compensating because the demands of internal consistency require that each grid space be allocated 100% to either adjoining countries or to open water. Numbers for the density of fuel consumption are perhaps best described as qualitatively accurate. Whereas regional patterns are likely to be well-represented, individual values should be treated with skepticism. This is especially true for values at the extremes of the distribution in countries which have a wide range in distribution of fuel-consumption density.

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