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A 1° x 1° distribution of carbon dioxide emissions from fossil fuel consumption and cement manufacture, 1950-1990

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Abstract. One degree latitude by one degree longitude (1° x 1°) data sets of carbon dioxide emissions from fossil fuel consumption and cement manufacture were produced for 1950, 1960, 1970, 1980, and 1990. National estimates of carbon emissions were combined with 1° x 1° data sets of political units and human population density to create the new 1° x 1° carbon emissions data sets. The human population density data set has an effective resolution of the country/state level. This resolution translates to the 1° x 1° carbon emissions data set. Latitudinal distribution of emissions have also been calculated. The data show continual growth with time over most of the world, with increased growth rates in major urban areas. A slow southerly shift in the bulk of the emissions is apparent as Asian countries increase their energy consumption to support their growing economies and populations. The digital data sets are available by anonymous ftp.

Introduction

The most important anthropogenic activity driving the increasing concentration of greenhouse gases in the Earth's atmosphere is the discharge of carbon dioxide (CO_2) from combustion of fossil fuels. A series of papers published since 1973 has attempted to estimate the global total of CO_2 emissions from fossil fuels, and some of these papers describe efforts to estimate national emissions for all countries [*Keeling*, 1973; *Marland and Rotty*, 1984; *Marland et al.*, 1985; *Marland and Boden*, 1993; *Andres et al.*, 1996; *Marland et al.*, 1994; *Boden et al.*, 1995]. To model the flows of carbon through the global geochemical cycle and to understand and anticipate the pattern of increasing CO_2 in the atmosphere [e.g., *Tans et al.*, 1990; *Enting and Mansbridge*, 1991; *Ciais et al.*, 1995; *Conway et al.*, 1994; *Taguchi*, 1996], a systematic description of the geographic and temporal pattern of emissions is needed. In response to this need, *Marland et al.* [1985] estimated global emissions for 1980 at 5° latitude by 5° longitude (5° x 5°) resolution. In this paper, the estimate is extended to a finer resolution, 1° latitude by 1° longitude (1° x 1°), and represents decadal distributions of emissions from 1950 to 1990.

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This analysis is a contribution to the Global Emissions Inventory Activity (GEIA). GEIA began in 1990 as an activity of the International Global Atmospheric Chemistry project, a joint project of the Scientific Committee of the International Council of Scientific Unions *International Geosphere-Biosphere Programme* [1994] and the International Association of Meteorology and Atmospheric Physics Commission on Atmospheric Chemistry and Global Pollution. The stated goal of GEIA is to establish and maintain reliable, global inventories of emissions to the atmosphere from natural and anthropogenic sources. The initial objective has been to produce and maintain emission inventories at a 1° resolution. The data sets presented in this paper are available in digital form from the GEIA data archive (ftp ncardata.ucar.edu, cd pub/GEIA) or from the Carbon Dioxide Information Analysis Center (ftp cdiac.esd.ornl.gov).

Data and Methodology

Data Sets

The 1° x 1° data sets of anthropogenic CO_2 emissions were constructed from three data sets: estimates of CO_2 emissions by country, a 1° x 1° data set of human population density and a 1° x 1° data set of political units. CO_2 emissions were calculated at the country level, and population density was used as a surrogate for the within-country distribution of CO_2 emissions. In this presentation, CO_2 emissions were calculated from country-level energy consumption data, but the data management system has been designed in a modular fashion so that state, regional, and

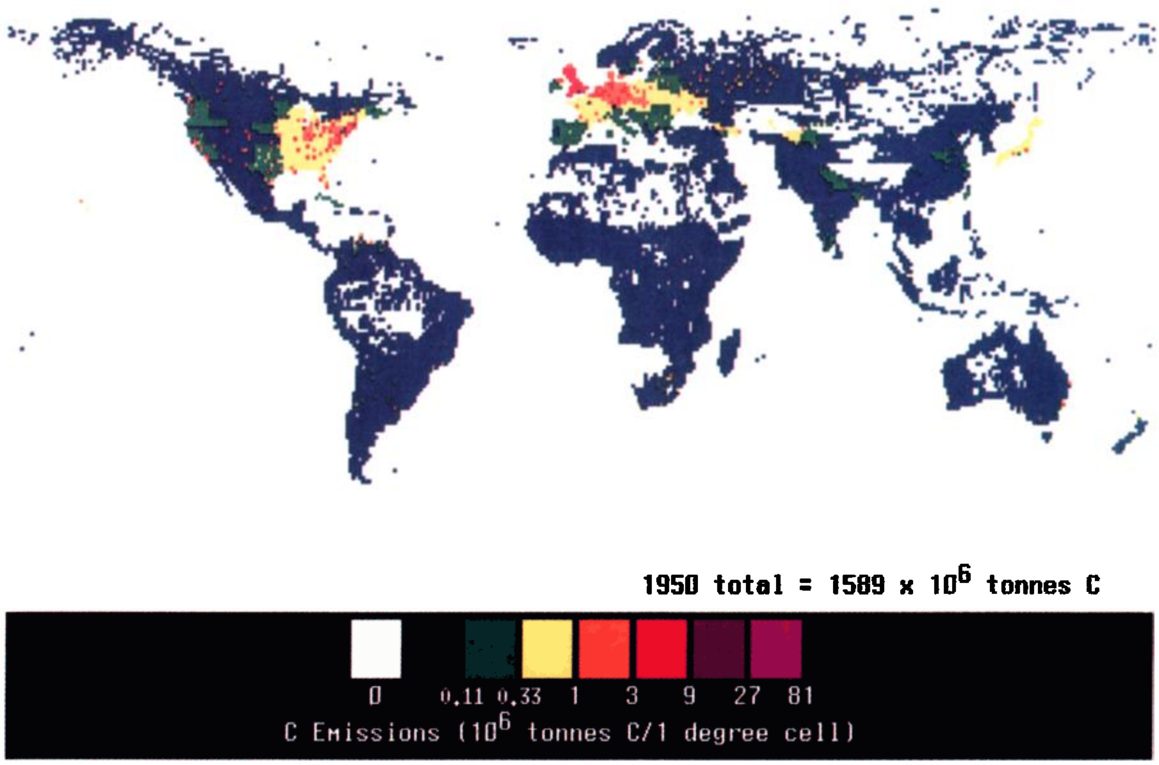

Plate 1a. Distribution of carbon emissions from fossil fuel combustion and cement manufacture for 1950. The map has a 1° resolution and scale.

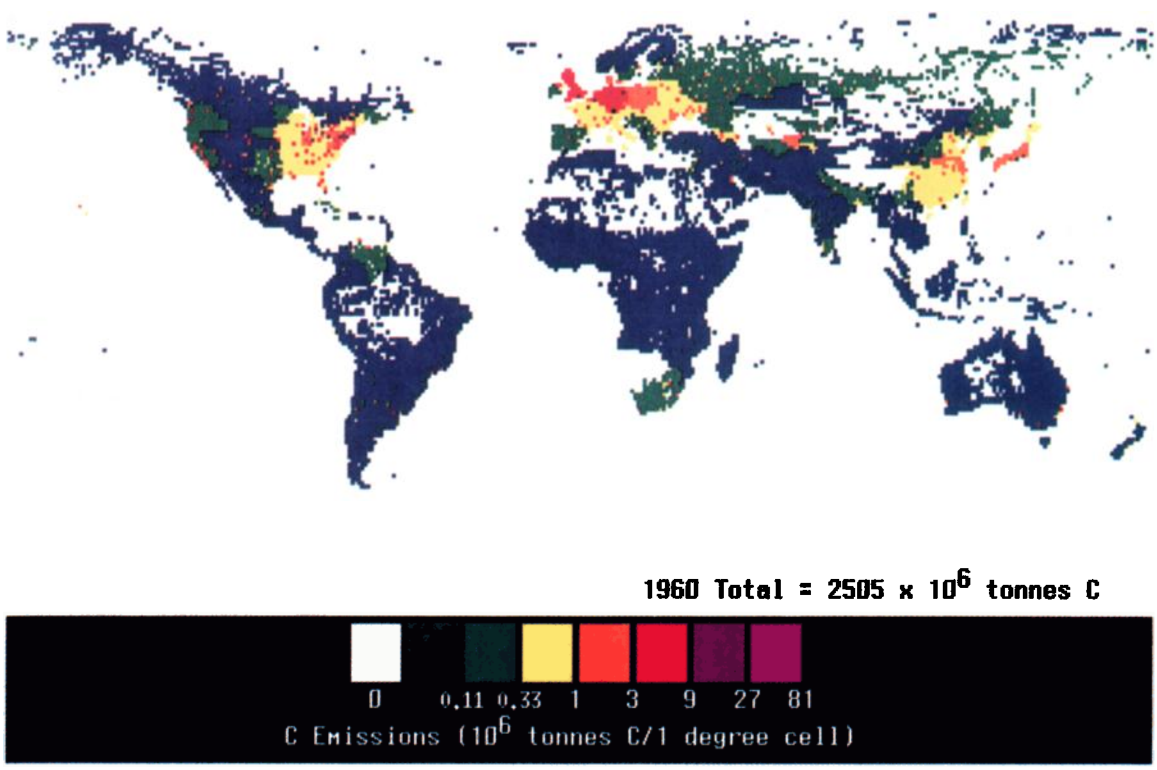

Plate 1b. Same as for Plate 1a, except for 1960.

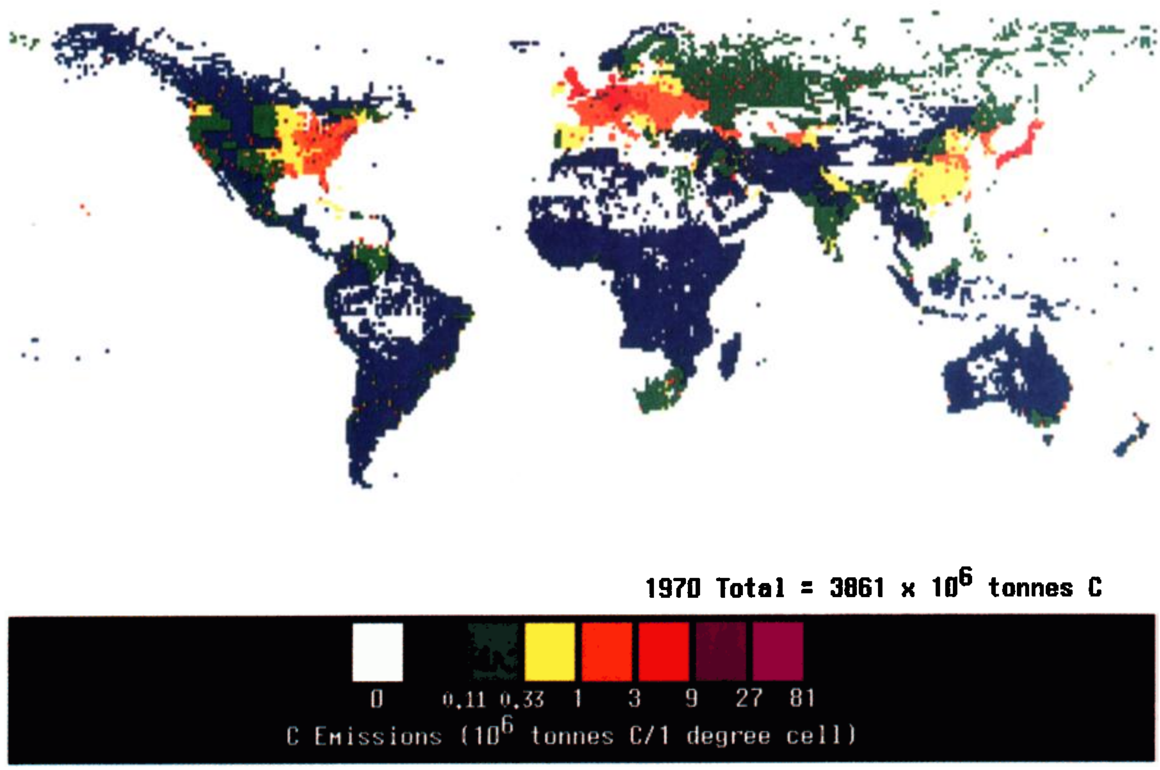

Plate 1c. Same as for Plate 1a, except for 1970.

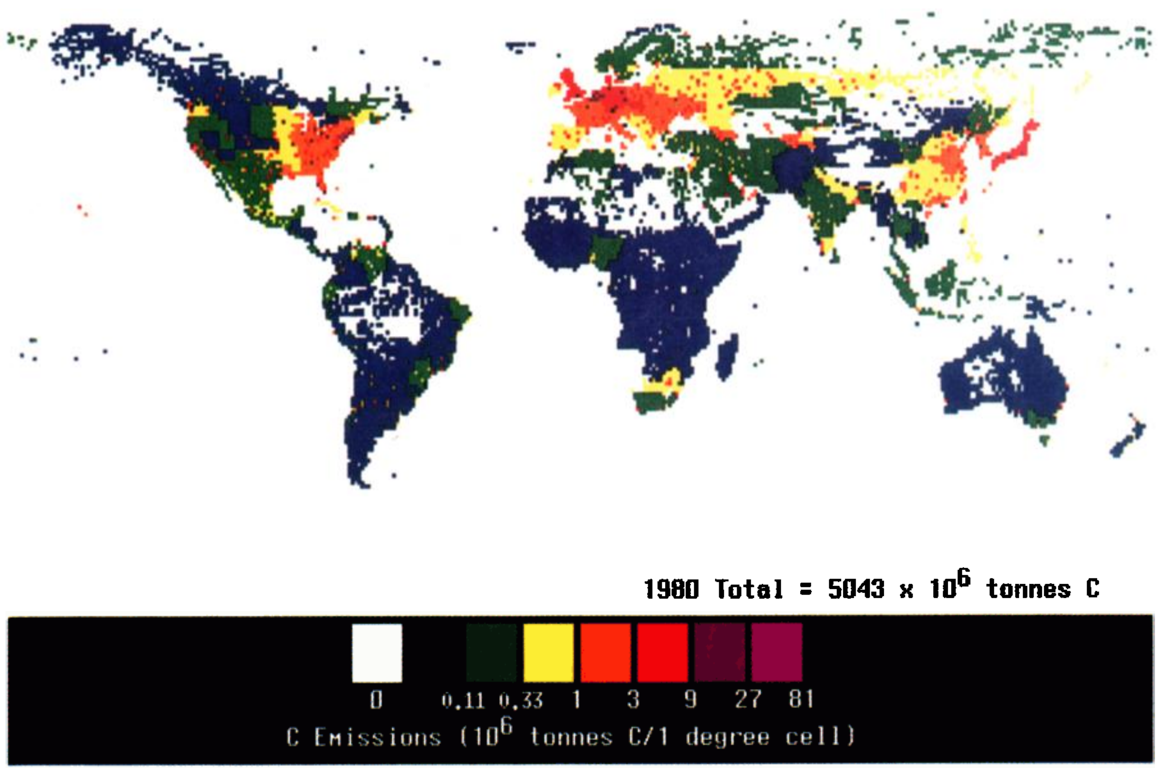

Plate 1d. Same as for Plate 1a, except for 1980.

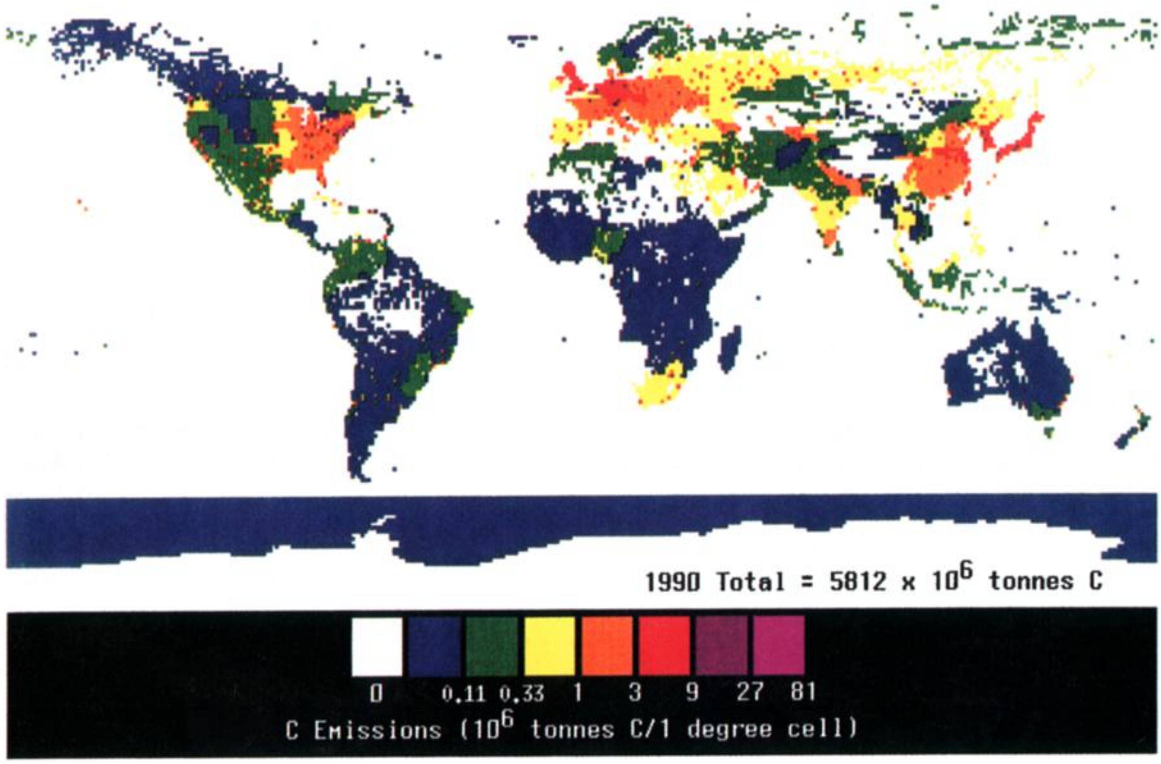

Plate 1e. Same as for Plate 1a, except for 1990. In 1990, the Antarctic Fisheries appear around Antarctica. It represents the liquid fuels consumed by the Southern Ocean, maritime harvesting industry. Because these emissions occur in ever changing ship tracks, they have been spread evenly over maritime areas south of 59°S. While areally large, these emissions only represent 0.003 x 10^6 metric tons C.

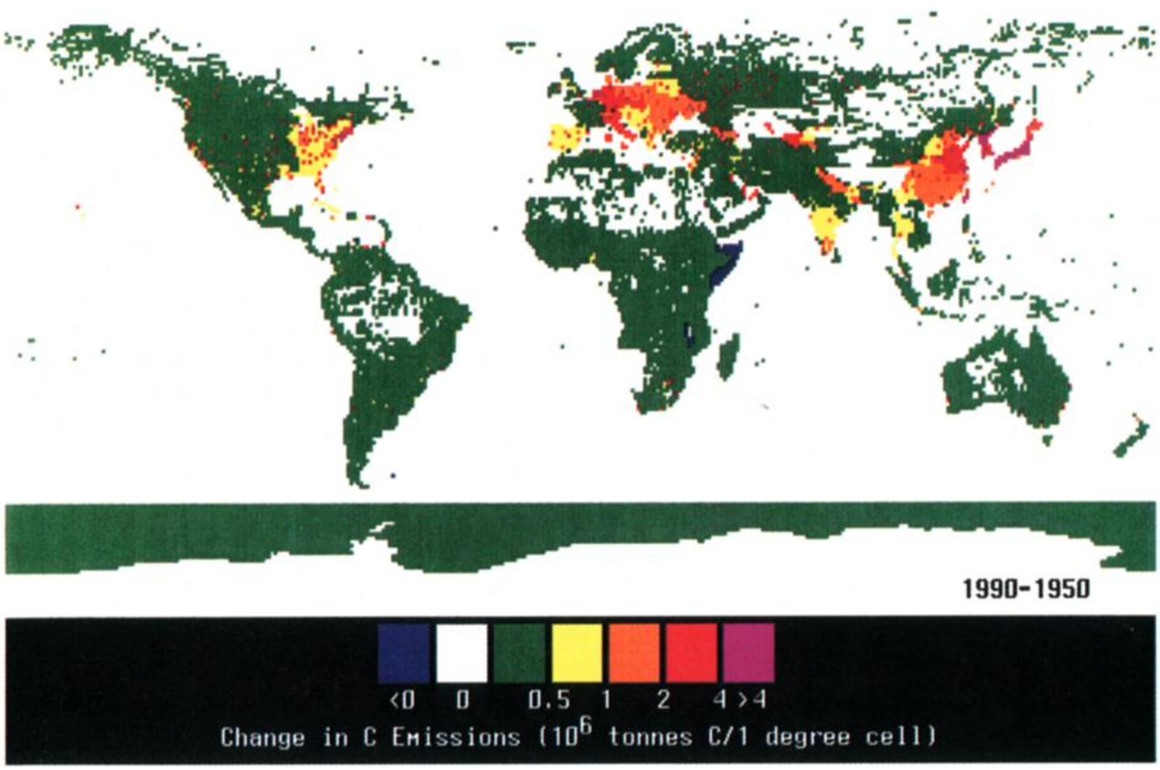

Plate 2. Changes in carbon emissions from 1950 to 1990.

provincial level data can be inserted to provide finer resolution in subsequent versions.

National estimates of CO_2 emissions were calculated with the methods described by *Marland and Rotty* [1984] and *Boden et al.* [1995] using 1994 United Nations (U.N.) energy statistics (The United Nations Energy Statistics Database, United Nations Statistical Division, New York, 1994.). National estimates of CO_2 emissions include emissions from the calcining of $CaCO_3$ to produce cement and rely on U.S. Bureau of Mines statistics for data on cement production [*Solomon*, 1993]. For fossil fuels, emissions were based on apparent consumption at the national level and thus emissions from burning of bunker fuels, that is, fuels used in international commerce, and fuels used to produce nonfuel products (e.g., plastics) are not included. Because of these exclusions, annual totals of CO_2 emissions are 3.1-5.5% less than the global totals reported by *Andres et al.* [1996]. Detailed summaries of the national and global CO_2 emissions from fossil fuels can be found in the work by *Boden et al.* [1995]. This source contains data for years 1950 to 1992, bunker fuel data, and a discussion of the methods and limitations to the national CO_2 data sets.

The initial 1° x 1° political unit data set was completed at the Goddard Institute for Space Studies (GISS) and is available via anonymous file transfer protocol (ftp nasagiss.giss.nasa.gov). It describes the 1993 distribution of political units. The GISS political unit data set contains 186 countries, with 9 of these further subdivided into 168 provinces, states, or regions. Unlike the *Marland et al.* [1985] 5° x 5° methodology in which each grid cell was allocated in proportion to the relative areas of the countries embraced, 1° x 1° cells were assigned to a single political unit. Each cell was assigned to the spatially dominant political unit (or ocean), except that secondary consideration was given to the preservation of small countries that might otherwise not appear in the data set and to ensuring best possible representation of the total surface area of each country. *Lerner et al.* [1988] provide further details on the GISS political unit data set.

The initial 1° x 1° data set of human population density was completed at GISS and is also available via their ftp. It describes the 1984 distribution of human population density. Populated cells were defined as those identified with some human use, according to *Matthews* [1983]. Additionally, population was added into cells with large urban areas despite not having a specific agricultural land use, as indicated by *Matthews* [1983]. However, population was not placed into cells associated only with lumbering. This procedure is identical to that used for domestic animal populations described by *Lerner et al.* [1988].

For each political unit, the populations of all urban areas with population greater than 100,000 were assigned to the proper geographic cells. A total of 1076 urban populations were thus set. Rural population was then calculated from the difference between the total population for the political unit and the sum of the urban populations located in the political unit. This remaining rural population was then distributed with uniform density among all populated cells within the political unit. The population of a cell is thus the sum of any collocated urban area population and the uniformly distributed rural population. This distribution strategy creates a 1° x 1° human population density data set with a variable spatial resolution dependent upon the country/state level from which population statistics were derived [*United Nations*, 1984; *Europa Yearbook 1985*, 1985; *1986 Information Please Almanac*, 1986].

Because the GISS political unit data set used areal dominance to assign a cell to a political unit or to the ocean and because urban populations were placed by geographic coordinates, the populations of 95 coastal urban areas were assigned to cells designated as ocean in the GISS political unit data set. Similarly, the populations of 43 urban areas near political borders were assigned to cells in the neighboring political unit (e.g., the population of Lille, France, was placed in a cell identified as spatially dominant Belgium). The GISS political unit data set was modified to recode the 95 cells designated as "ocean" to appropriate political units because they had urban populations. The GISS population density data set was modified to relocate the 43 border urban area populations into the nearest cell identified with the correct political unit (e.g., the population of Lille was displaced by one cell geographically into a cell identified as being France). These population relocations were done after the cell populations were converted from population density (people per square kilometer) to absolute population (people per cell) by multiplying by the area of the cell, as determined by a simple cosine function of latitude.

In addition, the GISS political unit data set was modified for this study to add 15 political units and 10 subdivisions that occur in the U.N. energy statistics but not in the original GISS data set. The GISS population density data set was then modified to populate these 15 additional political units.

Finally, the GISS political unit data set was modified to account for political units which have changed names (e.g., Cambodia and Kampuchea) and political units which have aggregated or disaggregated (e.g., the union of North and South Vietnam) over the time period of interest (1950-1990). These changes are in name only and did not include minor changes in national borders.

It is important to note that the appropriate distribution of population in this application depends on the level of aggregation of the emissions data. If emission coefficients were available on a per capita or per area basis, the GISS focus on preserving total land area and assigning population to the correct cell would be appropriate. When emissions data are available at the national level, as in the energy statistics used here, population must be associated with the proper political unit. Adjustments to the initial political and population data sets ensure that summing emissions over all cells identified as country X will give the emissions total for country X and that emissions from a major city are allocated within 1 cell of the correct location of the city. Of course, this does not address the issue of how well the distribution of population within a country represents the distribution of CO_2 emissions.

Integration Methodology

The three data sets were combined to provide a representation of decadal distributions of CO_2 emissions from

1950 to 1990. CO_2 emissions from any cell are the product of the total emissions from the country and the ratio of the population of the cell to the total country population. The U.N. energy data set allows estimation of CO_2 emissions for each country for 1950, 1960, 1970, 1980, and 1990, but does not help with the within-country geographic distribution. The use of the one population data set as a proxy for within-country emission distributions assumes that the within-country distribution has not changed temporally. Despite this approximation, relative growth rates in CO_2 consumption among countries are sufficiently different that gross trends in the regional source term are preserved. These are particularly apparent when sums over latitudinal bands are produced. Changes with time were estimated by differencing the data sets for two time periods.

Results and Discussion

Plate 1 contains maps of CO_2 emissions from fossil fuel consumption and cement manufacture at decadal intervals from 1950 to 1990. Emissions are defined to be zero over the oceans and in remote areas where land-use maps show no human occupation, for example, the far northern parts of North America and Asia, central portions of Asia and Africa, and Antarctica. Namibia, Lesotho, Tuvalu, and Kerguelen Island have zero emissions in the data sets because they are not represented in the U.N. energy statistics. Emissions from Iran were set to zero in 1950 because of problems with the U.N. statistics. It is clear that cells set to zero have emissions of very small magnitude.

Cells with the highest emissions are densely populated cells in countries with high national emissions (Table 1). Los Angeles tops this list because its cell has the highest population in the country with the highest annual CO_2 emission. Note that from 1980 to 1990, Moscow and Toronto switched their relative positions in the list. Because the within-country distributions do not change, this switch is solely a function of fossil fuel usage in the respective countries; that is, increasing in the former USSR while decreasing in Canada. For the same reason, the relative position of cities within the United States remains unchanged.

Table 1. Highest Emitting Cells Per Data Set

Year	City	Emissions
1950	Los Angeles	31
1960	Los Angeles	36
	New York	28
	Chicago	28
1970	Los Angeles	52
	New York	41
	Chicago	40
	Tokyo	30
	Philadelphia	30
	Newark	28
	San Francisco	27
1980	Los Angeles	56
	New York	45
	Chicago	43
	Tokyo	37
	Philadelphia	32
	Newark	30
	San Francisco	30
	Toronto	29
	Moscow	29
1990	Los Angeles	60
	New York	48
	Chicago	46
	Tokyo	43
	Philadelphia	34
	Newark	32
	San Francisco	32
	Moscow	31
	Toronto	28
	Detroit	27

All cells with emissions greater than or equal to 27 x 10^6 metric tons C are identified by the major city occupying them.

The 1980 1° x 1° data set was aggregated into a 5° x 5° data set for comparison with the *Marland et al.* [1985] 5° x 5° map. The aggregated 5° x 5° data set smooths the emissions distribution. The two maps appear very similar. The highest emitting cell in the work by *Marland et al.* [1985] is in the German industrial heartland, followed by the cell containing New York City, Philadelphia, and Newark. The aggregated data set exchanges the places of these top two cells.

The 1° x 1° data sets indicate where emissions are growing over time. In 1950, emissions were concentrated in eastern North America, central Europe, and the United Kingdom (U.K.) (Plate 1a). These centers grew by 1960 and new centers appeared in Venezuela, South Africa, Asian USSR, China, Japan, and India (Plate 1b). Emissions growth continued in many of these areas in 1970, while emissions in Southeast Asia and Australia also increased (Plate 1c). Areas with significant growth by 1980 included Mexico, Ecuador, Brazil, Nigeria, Algeria, the Middle East, and Asian USSR (Plate 1d). The 1990 data set indicates emissions increased rapidly in Colombia, South Africa, the Middle East, India, and China (Plate 1e).

While emissions increased in some parts of the world, they temporarily decreased in others. Compared to the decade before, emissions decreased in sub-Saharan Africa, the Middle East, Peninsular Malaysia, and Laos in 1960; China, Yemen, Malawi, Burundi, and Rwanda in 1970; Southeast Asia, Sri Lanka, Yemen, Sweden, the U.K., and many parts of Africa in 1980; Canada, parts of Central and South America, Africa, and most of Europe in 1990. Plate 2 shows the changes that occurred from 1950 to 1990 and only a few areas show 1990 emissions less than in 1950: Cape Verde Islands, Falkland Islands, Gibraltar, Malawi, Netherland Antilles, and Somalia.

The changing geographic distribution of emissions is particularly evident when latitudinal bands are summed (Table 2). Plate 3 shows continuous growth in most latitudes but with proportionally greater growth in the latitudes of the major Asian urban areas during recent decades. At 1° resolution, the latitudinal distribution is rather noisy with discrete peaks at the locations of major urban centers. Table 3 provides a synopsis of the principal

Table 2. Latitudinal Sums of CO_2 Emissions in Five Degree Bands

Latitude	1950	1960	1970	1980 This Study	1980 *Marland et al.* [1985]	1990
90°-85°N	0	0	0	0	0	0
85°-80°N	0	0	0	0	0	0
80°-75°N	0	0	0	0	0	0
75°-70°N	1	2	3	5	1	6
70°-65°N	9	19	32	45	9	48
65°-60°N	17	33	58	80	40	84
60°-55°N	101	166	246	310	294	324
55°-50°N	320	486	650	784	854	746
50°-45°N	221	360	561	703	634	686
45°-40°N	345	476	765	942	847	1042
40°-35°N	231	345	575	745	726	922
35°-30°N	161	267	405	534	578	684
30°-25°N	64	129	183	289	317	415
25°-20°N	18	52	82	165	141	259
20°-15°N	18	30	53	91	77	125
15°-10°N	11	18	36	53	46	76
10°- 5°N	8	14	27	43	36	58
5°- 0°N	5	8	21	37	26	52
0°- 5°S	2	5	9	23	12	33
5°-10°S	2	5	9	19	24	23
10°-15°S	2	4	7	11	11	10
15°-20°S	2	5	8	14	12	16
20°-25°S	5	10	17	30	39	35
25°-30°S	14	23	36	52	52	65
30°-35°S	19	31	50	69	60	84
35°-40°S	7	11	17	23	20	29
40°-45°S	2	3	4	6	4	7
45°-50°S	1	1	1	2	1	2
50°-55°S	0	0	1	1	0	1
55°-60°S	0	0	0	0	0	0
60°-65°S	0	0	0	0	0	0
65°-70°S	0	0	0	0	0	0
70°-75°S	0	0	0	0	0	0
75°-80°S	0	0	0	0	0	0
80°-85°S	0	0	0	0	0	0
85°-90°S	0	0	0	0	0	0

Emissions are given in 10^6 metric tons C.

contributors to the major emissions peaks in Plate 3. The peak at 47°-53° N actually decreased slightly from 1980 to 1990, reflecting decreasing emissions in western Europe. The curve which describes the distribution of emissions emphasizes the concentration of high carbon-emitting countries in the northern hemisphere. With time, the mass of emissions is shifting slowly southward toward the midnorthern latitudes as energy consumption rises to support the growing populations and economies of Asia.

Uncertainties

Error enters these 1° x 1° data sets of CO_2 emissions through each of the three primary data sets: the estimates of national CO_2 emissions; the distribution of human population density; and, to a lesser extent, the political unit data set.

Emissions Data Set

Marland and Rotty [1984] estimated that the error in the global total estimates of CO_2 emissions were of the order of 6-10%. Estimates of fuel production, fuel chemistry, and of the efficiency of fuel oxidation all contributed to this error term. It has been assumed that the values of the last two items have remained constant throughout this analysis. Because of the greater detail of data required to calculate national emissions (i.e., data on world trade) and the need of the U.N. Statistical Office to rely on national statistical offices, the errors in national CO_2 estimates can be both larger and more difficult to estimate. *Marland and Boden* [1993] showed that the global emissions total is dominated by a small number of countries; hence the error in the global total depends largely on the quality of the data from these few countries. *Marland and Boden* [1993] and *Andres et al.* [1996] have also offered some qualitative discussion on the quality of the national data. For example, it was noted above that emissions from Iran were assigned a zero in 1950 because of data problems. Specifically, strict calculation of CO_2 emissions from Iran in 1950 using U.N. energy statistics results in a negative number because apparent fossil fuel use in Iran is calculated largely as the difference between production and exports. Therefore a small error in one of the large numbers results in a negative number for consumption. While the number calculated is probably not far off from the correct value (most likely a small positive number), it is difficult to estimate the error in either an absolute or fractional sense.

In order to get further insight into the magnitude of errors in the national emissions estimates, the magnitude of data revisions in the U.N. energy data set were examined. The U.N. issues annual energy yearbooks which contain both the latest year of available data and revisions of previously published data. Revisions reflect access to new or refined data and are concentrated in the more recent portions of the data series [*Marland and Boden*, 1993; *Andres et al.*, 1996]. Revisions can be very extensive for countries where the data series are regularly revisited or can be minimal for countries where the data series are not revisited after initial dissemination. The rationale in this approach is that the magnitude of revisions that occur subsequent to initial publication will provide some clues to both the magnitude of initial uncertainty and the precision which is deemed meaningful. This error analysis is limited to the energy consumption statistics and disregards errors introduced by estimates of the fraction of fuel oxidized and the carbon content of the fuels which separately amount to 2-4% additional error.

Table 4 contains statistics on emissions estimates for 1982, calculated from U.N. energy statistics published in 1983, 1988, and 1993. That is, CO_2 emissions for 1982 were estimated for each country from the data initially released in 1983, from the data as revised during the first 5 years after initial publication, and from the data as revised 10 years after initial publication. Table 4 shows that since the 1982 national data were originally released in 1983, revisions have resulted in the CO_2 emissions estimates varying from a decrease of 340% to an increase of 88% with an average of an 8.3% decrease (with reference to the 1993 value). Since 1983, only 25 countries had revisions larger than $\pm 10\%$, and only 6 of these have annual emissions greater than 10^6 metric tons C (1 metric ton = 1000 kg). These six nations account for 33 x 10^6 of 5081 x 10^6 tons C emitted globally in 1982 [*Andres et al.*, 1996].

Table 3. Notes on the Prominent Peaks of the 1° Latitudinal Distribution

Peak	Latitude	Geography	Notes/Features
1	52°-51°N	London Belgium Netherlands Germany Poland Former Soviet Union (FSU)	Contains decreasing European and increasing FSU contributions with time. Constant 40 x 10^6 metric tons growth per decade except for -10 x 10^6 tons from 1980 to 1990.
2	42°-41°N	Chicago	Decreasing U.S. emissions countered by increased emissions from Italy and Asia.
3	35°-34°N	Los Angeles China South Korea Kobe-Osaka Kyoto	United States decreases rapidly as Asia increases rapidly and surpasses U.S. contribution by 1990. Only peak which broadens with time so that mode shifts out of latitudinal band, in this case north because of developing Asia.
4	19°-18°N	Puerto Rico Bombay	Similar to peak 3 with North America declining while Asia rises but smaller in magnitude. Peak height is about 30% (about 15 x 10^6 tons C in 1990) too high because we have used the U.S. per-capita emissions estimate to distribute emissions to Puerto Rico and thus have exaggerated emissions from Puerto Rico.
5	11°-10°N	Caracas Nigeria India	South American emissions decline while those from Africa and Asia increase.
6	33°-34°S	Santiago Cape Town Sydney	Regional emissions remain constant relative to each other over time.

Peak numbers correspond to those in Plate 3. Geography contains the prominent political units of the band. Notes/Features mainly describes the decreasing and increasing relative contributions of global regions to the total emissions from the latitudinal band.

Assuming that annual revisions to the U.N. national energy data are indicative of the magnitude of the uncertainty in the data, the data should result in CO_2 emissions estimates with a mean error of the order of 8%. A similar comparison of emissions estimates for 1950, based on data published in 1983, 1988, and 1993, shows that revisions are less important in the older portions of the time series. With time, the range in revisions decreases as well as the average national error. This analysis does not give any clues whether data contained a systematic bias.

In another exercise aimed at providing insight on data quality, the 194 countries in the 1993 U.N. energy data set have been grouped into seven categories by increasing emissions within each category (Figure 1). These categories represent a subjective judgement of national data quality based on our experience with the energy data and discussions with others familiar with the international data. The seven categories, in order of anticipated increasing uncertainty, are (1) Organization for Economic Cooperation and Development countries, (2) other European countries, (3) Organization of Petroleum Exporting Countries, (4) developing countries with stronger national statistical bases, (5) former USSR and eastern Europe, (6) China and centrally planned Asia, and (7) developing countries with weaker national statistical bases. The first four categories include 56 nations, represent 57% of total CO_2 emissions in 1990,

Table 4. Estimate of Error for National CO_2 Emissions Estimates

Emission Year	Data Year	Minimum	Average	Maximum	Countries
1950	1983	-280	-2.4	7.7	137
1950	1988	-19	-0.47	2.0	136
1982	1983	-340	-8.3	88	189
1982	1988	-79	-0.093	44	190

Emission year refers to the year emissions were made. Data year refers to the year energy statistics were reported. Minimum, average, and maximum are given in percent difference from data year 1993 and were calculated from 100 x (1993 value - data year value)/1993 value. Countries refers to the number of countries included in the average; it differs year to year because of data quality errors.

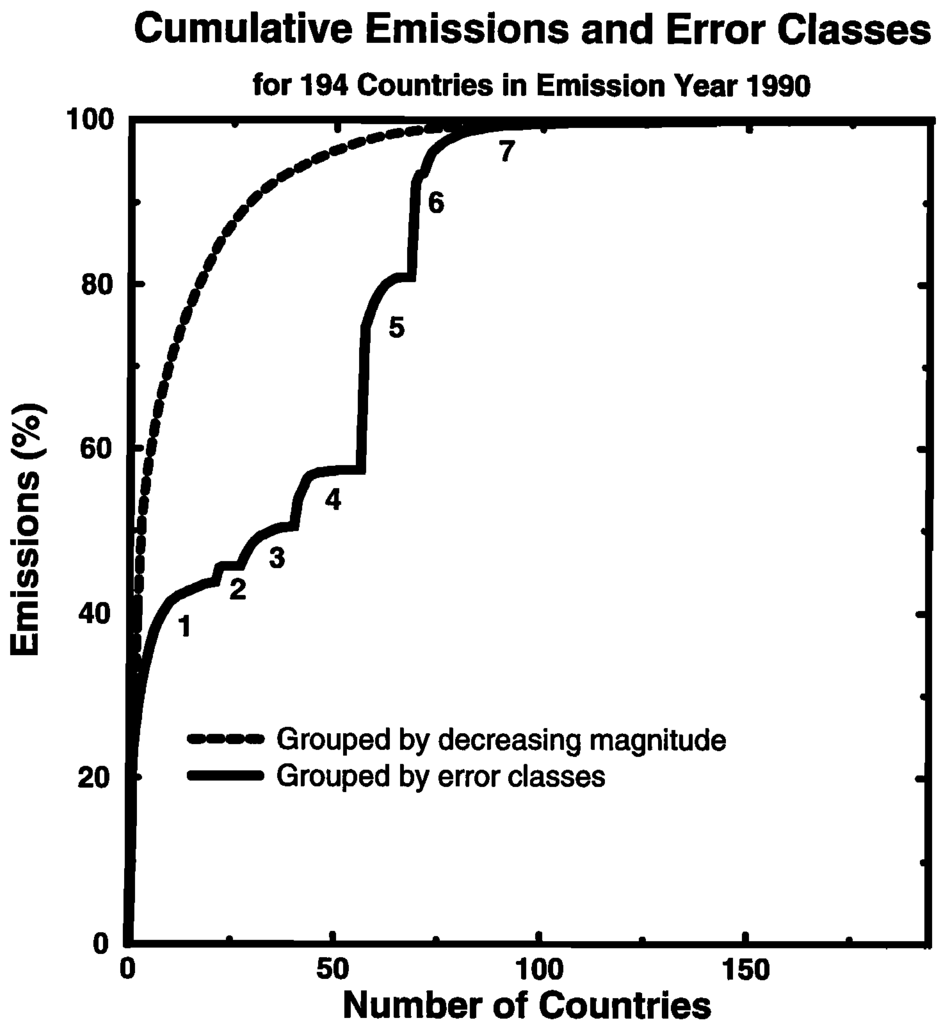

Figure 1. Cumulative emissions and error classes. Data are presented for year 1990. This alternative look to the data in Table 4 gives a better regional breakdown of the data quality and data magnitude. The solid curve represents the countries ordered by decreasing magnitude of emissions. The dashed curve is similar, but countries are first grouped into relative quality classes. The breaks is this curve represent transitions to other classes. Classes numbered as listed in the text.

and are believed to have relatively small uncertainty in their energy statistics. The overall message of Figure 1 is not altered by our sometimes rather arbitrary inclusion of countries in category 4 versus category 7. The big uncertainties are the former USSR and China.

Population Data Set

Errors associated with the 1° x 1° population mapping are of three types: the accuracy of the 1984 population distribution, the accuracy with which population distribution represents the distribution of CO_2 emissions, and the appropriateness of the 1984 population distribution for representing population distribution in other years. Because the population data set assigns specific locations to urban areas of over 100,000 people, a large portion of the error is in assuming a uniform density of the rural population and errors are likely to be largest in countries with large rural populations spread over large areas, for example, Russia. However, a consequence of using population for an emissions proxy is that national emission totals are preserved and that errors are of distribution rather than of magnitude, that is, emissions not attributed to the correct cell are probably not displaced very far. In many of the larger countries, energy consumption data are available at the state, province, or regional level, and subsequent versions of this analysis will incorporate those data to reduce reliance on the population data set and achieve more accurate within-country distribution of emissions.

Errors associated with using population density as a proxy for the distribution of CO_2 emissions were discussed by *Marland et al.* [1985]. Embodied in this assertion are several important assumptions: that energy use and CO_2 emissions occur in the same places that people live, that per capita energy use is uniform over the political unit, and that the fuel mix (i.e., CO_2 emissions per unit of energy consumption) is constant throughout the political unit.

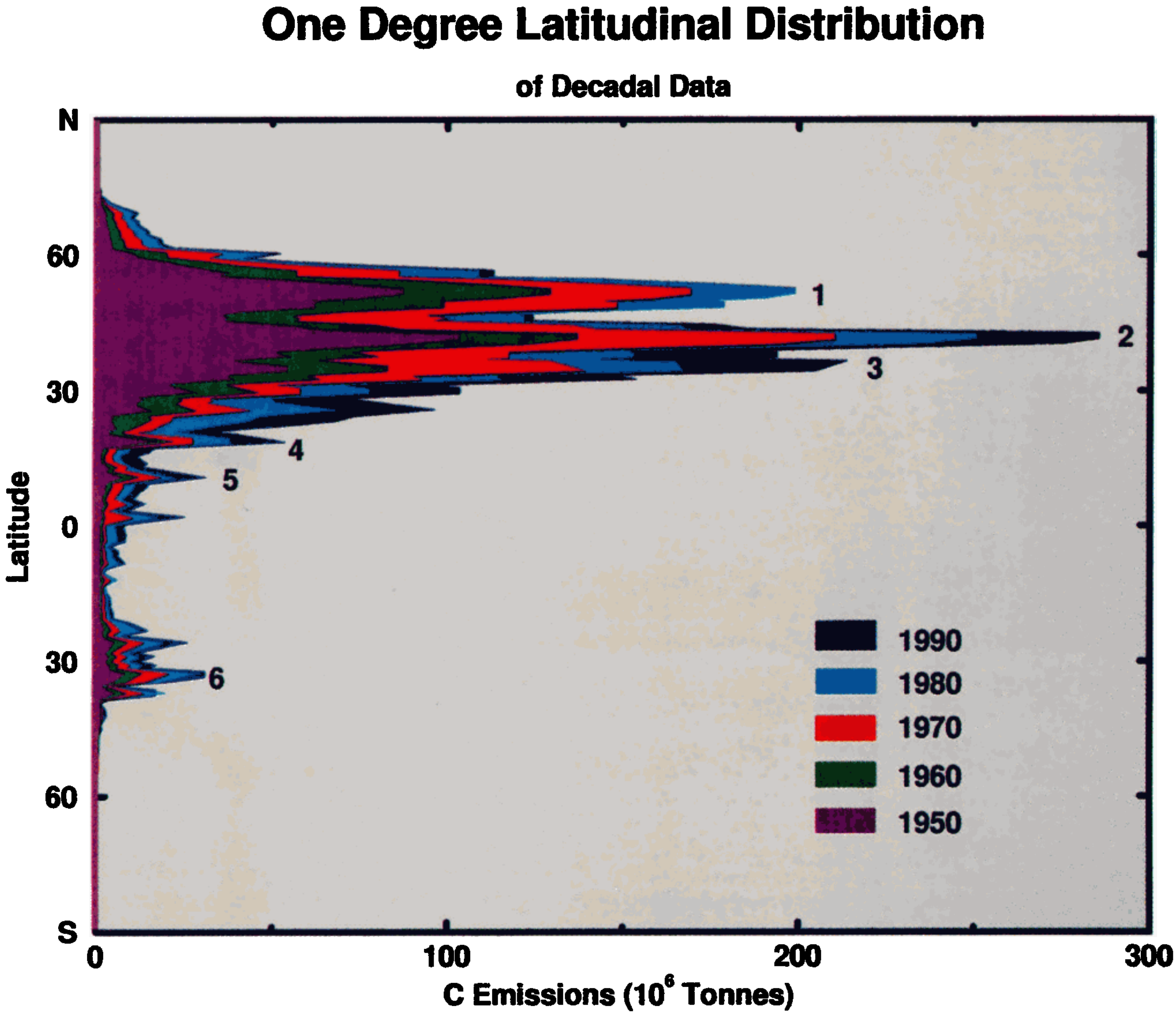

Plate 3. The latitudinal distribution of the decadal carbon emissions data. Description of prominent peaks located in Table 3.

The appropriateness of using the 1984 population data set for distributing CO_2 introduces some temporal error into the 1° x 1° CO_2 emission data sets. Since the population distribution remained fixed in all data sets, the urbanization and other demographic shifts of national populations which occurred from 1950 to 1990 were ignored. For example, emissions from the Lagos cell grow in the same proportion as those from any other cell in Nigeria. The error this introduces into CO_2 emission distributions is variable, depending upon the size of the country and the amount of urbanization. The largest distribution errors of within-country CO_2 emissions likely occur in 1950, when rural populations were largest. On a global basis, 16% of the world's population switched from rural to urban living from 1950 to 1985 [*Rogers*, 1984; *Wright*, 1990]. An advantage of leaving the population distribution fixed is that spatial changes observed in CO_2 emission distribution 1° x 1° data sets are solely a function of the increasing CO_2 emissions from each political unit.

Political Unit Data Set

Errors associated with the 1° x 1° political unit data set center upon whether an individual cell has been associated with the proper political unit. It is important to note that errors in the political unit data set are concentrated along adjacent cells at political borders because of one cell being assigned to one political unit only. Larger countries are generally homogenous within their borders; thus locational errors are zero. Compared to published areas of political units [*Food and Agricultural Organization*, 1985], the areas of the unmodified 1° x 1° data set agree within 1 and 5% for large- and medium-sized countries, respectively.

The conclusion of this uncertainty discussion is that very large error bars could be envisioned for the absolute numbers reported for individual cells. However, any specific cell in the data set can have a small or large error associated with it. Nonetheless, the global pattern of emissions is probably well represented, and most emissions are located close to their proper location. The more the data are aggregated into larger geographic or political units, the greater the absolute accuracy that can be expected.

Conclusions

By combining national estimates of CO_2 emissions from fossil fuel combustion and cement manufacture with 1° x 1° data sets of political units and population density, estimates of CO_2 emissions were attained at 1° x 1° global resolution. Data sets of CO_2 emissions in 1950, 1960, 1970, 1980, and 1990 embody many approximations and uncertainties at the scale of individual cells but convey current and changing patterns of emissions. Incorporation of energy data at the state, province, and regional levels within the largest countries, planned for the future, will increase the geographic accuracy of the CO_2 emissions. The data show emissions growing continually at most locations, with emissions concentrated between 30° and 60°N latitude. Few areas show declining emissions. The pattern of recent decades shows a slight shift to lower latitudes as the developing economies of Asia increase energy consumption to support growing economies and populations.

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