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Carbon dioxide emissions from fossil-fuel use, 1751–1950

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ABSTRACT

Newly compiled energy statistics allow for an estimation of the complete time series of carbon dioxide (CO_2) emissions from fossil-fuel use for the years 1751 to the present. The time series begins with 3×10^6 metric tonnes carbon (C). This initial flux represents the early stages of the fossil-fuel era. The CO_2 flux increased exponentially until World War I. The time series derived here seamlessly joins the modern 1950 to present time series. Total cumulative CO_2 emissions through 1949 were 61.0×10^9 tonnes C from fossil-fuel use, virtually all since the beginning of the Industrial Revolution around 1860. The rate of growth continues to grow during present times, generating debate on the probability of enhanced greenhouse warming. In addition to global totals, national totals and 1° global distributions of the data have been calculated.

1. Introduction

The concentration of carbon dioxide (CO_2) in the atmosphere has unambiguously increased since 1751 (Neftel et al., 1985; Friedli et al., 1986; Keeling et al., 1995; Etheridge et al., 1996). This rise in CO_2 concentration has raised concerns about the possible impacts of enhanced greenhouse warming. One of the prime contributors to this increase has been the combustion of fossil fuels (Keeling et al., 1989a; 1989b; 1995).

This paper documents a 200-year time series of fossil-fuel CO_2 emissions. The time series begins in 1751, essentially the beginning of the fossil-fuel era. It ends in 1950 where it overlaps with the well-established, modern time series produced by the Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge National Laboratory. The modern time series spans the years 1950 to present and is updated annually as new energy statistical data become available from the United Nations (Boden et al., 1995). The time series presented by Marland et al. (1998) includes both the modern emissions data and the earlier emissions data described and documented here. Like the modern time-series, the time series presented here is disaggregated to provide CO_2 emissions estimates from solid, liquid and gaseous fuels for each nation and for each year.

2. Methodology

In general, procedures used to estimate CO_2 emissions from fossil-fuel use follow those used in the modern time series (Marland and Rotty, 1984; Boden et al., 1995). However, modifications specific to the older time series were dictated by the nature of the available data and are described below.

2.1. *Fossil-fuel production and trade*

A summary compilation of fossil-fuel production has been published by Etemad et al. (1991).

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The compilation is divided into 2 parts. The first part tabulates coal, brown coal, peat, and crude oil production, expressed in units of thousand metric tonnes. It also tabulates natural gas production in units of millions of cubic meters. Production quantities are listed by nation and year. The primary tables document fuel production dating back to 1800, but footnotes extend the time series back to 1751. The second part of Etemad et al. (1991) converts these quantities, for selected years, into various energy equivalent units such as tonnes coal equivalent and terajoules.

Summary compilations of international fossil-fuel trade since 1816 have been published by Mitchell (1983, 1992, 1993, 1995). This work tabulates solid and liquid fuel imports and exports in a variety of units. Trade quantities are listed by nation and year.

Production and trade data from Etemad et al. (1991) and Mitchell (1983, 1992, 1993, 1995) were entered into an electronic data file. The variables for each of the 7810 production records and 5506 trade records in the data file are listed in Table 1.

The CONVERT variable can encompass 2 factors. The first factor is a conversion from one physical unit to another, e.g., gallons to tonnes. This converts all reported data into standardized units of tonnes (solids and liquids) or terajoules (gases). Where necessary, the second factor converts from the standardized unit to the preferred CDIAC energy equivalent unit, e.g., tonnes coal to tonnes coal equivalent. These second factors were extracted from Etemad et al. (1991) for gaseous fuels (i.e., natural gas) and solid fuels (i.e., coal, brown coal and peat). For those countries and fuels in which these factors change with time, the factors were calculated from the second part of Etemad et al. (1991), in which, for specific years, both the standardized unit (e.g., tonnes) and the preferred unit (e.g., tonnes coal equivalent) are given. For intermediate years, factors were interpolated. Occasionally, the two parts of Etemad et al. (1991) could not be reconciled with the factors given. In these few cases, RJA used his best judgement to make suitable corrections.

Table 1. *Description of electronic data file variables*

Variable	Description
transaction	production, import or export of fuel
year	year of transaction activity
country	country involved in the transaction
commodity	fuel type (e.g., coal, crude oil, natural gas, ...)
units	amount of fuel transacted (in original source units)
convert	conversion factor from original to preferred CDIAC units
quantity	amount of fuel transacted (in preferred CDIAC units)
code	units of quantity (e.g., metric tonnes)

Almost all political entities represented in the pre-1950 production and trade data were already represented in the modern CDIAC time series. The major exception was a united Korea, under Japanese hegemony, which existed from 1905 to 1944 and was assigned the discrete country code of 409. Land exchanges between countries were also accommodated, when possible. For example, the emissions from Alsace-Lorraine were included with Germany or France, reflecting which political unit governed these lands at any given time. This maintained the integrity of political entities despite changes in national borders.

Both the production and trade compilations are limited by the availability of accurate and complete records on pertinent quantities. Several instances are noted in Etemad et al. (1991) where reported quantities are known to be incompletely tallied, e.g., pre-1950 coal production for Colombia and many Asian and European nations during the World War II years. In addition, independent verification of the data is difficult, especially in the earlier parts of the time series. Finally, the production and trade data sometime show clear discrepancies or incomplete coverage. For example, data in Etemad et al. (1991) indicate that the first production of crude oil anywhere in the world occurred in Romania in 1858. Data in Mitchell (1992) indicate that France began importing crude oil in 1855 and the United Kingdom in 1856. Unfortunately, the trade data do not include the country of origin for fuel quantities traded. Fortunately, the quantities involved in the early parts of the time series are relatively small and thus the global implications are lessened. These limitations are propagated into the CO_2 emission calculations.

2.2. *CO_2 emission calculations*

Having created a file for fuel production and trade prior to 1951, CO_2 emission calculations generally followed the procedures discussed in Boden et al. (1995) and Marland and Rotty (1984). Fossil-fuel CO_2 emissions, CO_2, are estimated as the product of three terms:

$$CO_{2,i} = P_i \times FO_i \times C_i \quad (1)$$

where P represents the quantity of fuel i, FO represents the fraction oxidized, and C is the carbon content. Boden et al. (1995) list the values for FO and C used in the calculations. The P quantities were taken from the pre-1950 data file discussed above and were calculated in 2 different ways.

The first approach was used to estimate global total CO_2 emissions. In this approach, the values of P were taken as the sum of production quantities only (by year, country and commodity). This approach is used to calculate global CO_2 emission totals and assumes that fuel is consumed in the year that it is produced. This assumption is not completely valid due to annual changes in stocks and non-energy fuel uses (e.g., lubricants). This approach is used to calculate global total CO_2 emissions because the production data are believed to be the most consistent and error free (Andres et al., 1996). Marland and Rotty (1984) estimated a 6 to 10% error on global total CO_2 emissions for the modern time series. As the pre-1950 time series is not significantly different, this error range should provide some guidance on this time series as well.

A second approach was used to estimate national CO_2 emissions. In this approach, the values of P represent apparent consumption (by year, country and commodity) where apparent consumption is defined as

$$\text{consumption}_i = \text{production}_i + \text{imports}_i - \text{exports}_i - \text{bunkers}_i - \text{changes in stocks}_i \quad (2)$$

This approach is used to calculate national CO_2 emission totals. The inclusion of these five terms is necessary for accurate national totals because no individual nation produces only the amount of energy it consumes in a given year. Bunker fuels are those used in international commerce and are included in global total emissions (as calculated with production data) but are not included in national data (as calculated with consumption data). Note that for the pre-1950 time series the last two terms are set to zero since the original references contain no information on these transactions. These terms are generally not zero in the modern time series where bunker fuels range from 1.7% to 3.3% of annual global totals calculated by apparent consumption. For liquid fuels, apparent consumption is further modified by the subtraction of non-energy fuel uses on the right-hand side of the equation.

Obviously, on a global basis equation 2 reduces to

$$\text{consumption}_i = \text{production}_i - \text{changes in stocks}_i \quad (3)$$

For a given nation in a given year and for a given fuel, the ratio of changes in stocks to consumption can take on a wide range in values, but on a global basis this value has a maximum of 3% and a mean of less than 1% (based on the modern time-series data) for any given fuel. Thus, on a global basis, the vast majority of fuel is consumed in the year it is produced. This lends credence to the calculation of global total CO_2 emissions from production data only (as discussed above) and does not significantly add to the 6–10% error range estimated for those estimates.

Andres et al. (1996, 1999) and Marland and Boden (1993) offer insights into the quality of the national CO_2 emission estimates for the modern time series. While independent verification is not always available for a given country, these three studies suggest that the average national emission total has perhaps an 8% uncertainty associated with it. However, the same analyses also indicate uncertainties may range from −340% to 90% for a given country and year. Due to the even poorer statistical basis for the pre-1950 data, individual national CO_2 emission estimates could have very large errors for a given year even though the global magnitudes and temporal trends are believed to be accurately captured.

A data processing departure in the pre-1950 time series involved the international trade of some liquid fuels. Some of the trade data report both crude and processed liquids combined into one quantity. This is not the case in the modern time series where primary (crude) and secondary (processed) fuels are accounted for separately. This distinction between primary and secondary fuels becomes important when calculating CO_2 emissions from the consumption of fossil fuels because some secondary fuels are consumed in non-energy uses such as plastics manufacture. However, because the relative proportions of primary and secondary fuels are not given in the Mitchell (1983, 1992, 1993, 1995) data, these quantities were given the description "other petroleum products" (code PP in Boden et al. (1995)). Thus, category PP is treated differently in the pre-1950 (as a secondary fuel) and post-1950 (as a secondary non-energy fuel) parts of the data series.

A final consideration is the constant values used for FO and C in eq. (1). Andres et al. (1996) state that these two terms combined contribute 2–4% uncertainty in calculated CO_2 emissions in the modern time series. While C has not likely varied considerably since 1751, the components of FO have. FO incorporates combustion efficiencies as well as non-fuel uses. Non-fuel uses are only significant for liquid fuels which find appreciable uses in plastics, lubricants, ... While these non-fuel uses have been increasing with time, so have combustion efficiencies. These 2 components counter each other and therefore we have kept FO constant with time. While one can construe situations where FO and C may appreciably change, from a commercial and global perspective, the uncertainty they contribute to calculating CO_2 emissions is far less than that contributed by energy production and apparent consumption statistics.

3. Results

Global total CO_2 emissions from fossil-fuel production rose over 500-fold from 1751 to 1950 (Fig. 1). Solid fuels provide the vast majority of CO_2 throughout this time period. Liquid and gas fuels noticeably increase their significance after 1900. Note that the mass of emissions is expressed in terms of C, not CO_2.

The fuel consumption data give nearly an identical plot and thus are not shown here. This similarity is due to the relatively good agreement between imports and exports on an annual basis (Fig. 2). While the trade data begin in 1816, there is not an imbalance until 1840 (i.e., the global sum of imports is equal to the global sum of exports). In 1840, the difference between the sum of imports and the sum of exports is 1×10^6 tonnes C or 3% of global production for that year. The largest difference between imports and exports is 40×10^6 tonnes C in 1949. This is 2.8% of the 1411×10^6 tonnes C produced that year. On average, the export-import imbalance is only 0.12% for this 200-year period.

Of the 4669 national totals calculated, 52 have negative totals. In some cases, this occurs because data only exist for exports and not for any within-country production. In other cases, exports exceed

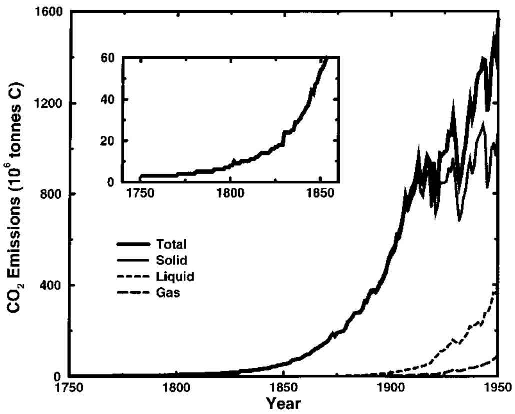

Fig. 1. CO_2 emissions from fossil-fuel production, 1751–1950. This compilation was based on energy production data in Etemad et al. (1991). The full set of numerical data can be found in Marland et al. (1998). The inset is an enlargement of the first 100 years of data when only solid fuels were an important source of emissions.

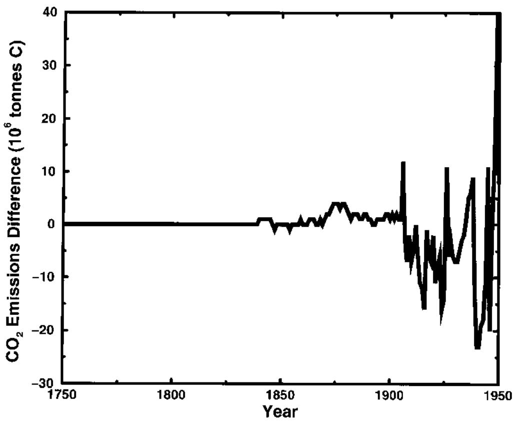

Fig. 2. Difference in the global total CO_2 emissions estimates when emissions estimates derived from consumption data are subtracted from emissions estimates derived from production data. Positive values indicate that the sum of exports is greater than the sum of imports. Data based on energy statistical data of Etemad et al. (1991) and Mitchell (1983, 1992, 1993, 1995).

Table 2. *Comparison of global, apparent consumption estimates derived in this work with those in Marland et al. (1998) for 1950*

Data series	Solid	Liquid	Gas	Total fossil fuel
this study	1067	406	93	1567
Marland et al. (1998)	1070	423	97	1589
% difference	0.28	4.0	4.1	1.4

Total is the sum of solid, liquid and gas fuel components and includes round off error. All units in 10^6 tonnes C.

imports plus within-country production. In most cases, the differences are small and are likely due to different accounting systems being used by various government entities from which the energy statistics were compiled.

The new data presented here compare very well with the modern time series (Table 2). Because of this agreement and the fact that the modern time series is already firmly established, the 1950 data derived in the present study will not be considered further. Rather the 1751 to 1949 data now precede the 1950 to present data available in Marland et al. (1998).

The pre-1950 data presented here do not contain information on CO_2 emissions from natural gas flaring or cement manufacture. In the modern time series, each of these contributes less than 4% annually to the total CO_2 emitted. Marland et al. (1998) contains some data on emissions from cement manufacture back to 1921, but these data are not discussed below.

4. Discussion

The pre-1950 data presented here also agree well with the 1860–1953 time series of CO_2 emissions given in Keeling (1973). For the 91 years common to both time series, annual values are always within 5% of each other and average 99.9% of each other. This agreement is in part due to the substantial overlapping of original data sources for both series. The advantage of the pre-1950 time series given here is its extension back to 1751. This extension should obviate the need for tenuous extrapolations back to the beginning of the fossil-fuel era. The Keeling (1973) time series begins in 1860 with a 93.3×10^6 tonnes C fossil-fuel CO_2 flux. The pre-1950 time series presented here begins in 1751 with a 3×10^6 tonnes C fossil-fuel CO_2 flux.

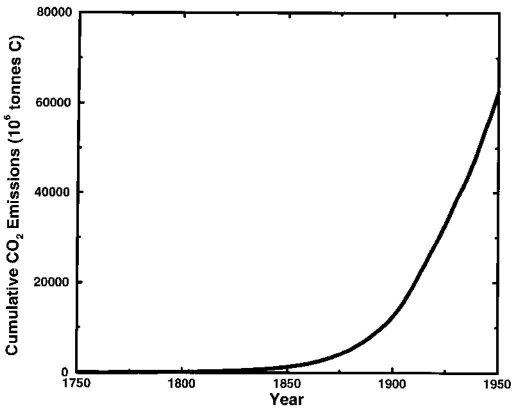

Fig. 3. Cumulative emissions of CO_2 from the production of fossil fuels. Curve based on energy production data in Etemad et al. (1991).

Between 1751 and 1860, a cumulative emission of 2040×10^6 tonnes C occurred from fossil-fuel combustion (Fig. 3). While various workers, especially modelers, have used various means to extrapolate annual emissions to the beginning of the fossil-fuel era, the present data offer a carefully documented time series of data for this period. While pre-1751 emissions cannot be estimated quantitatively at this time (and may never be due to a lack of records), the present data suggest an exponential increase in emissions from 1751 until World War I starts (prior to 1914). This suggests that pre-1751 emissions are minimal, especially when compared to other fluxes in the global carbon cycle. This increased definition of the history of fossil-fuel CO_2 releases should enhance global carbon cycle models by providing a more realistic time series than previously used extrapolations.

This extended time series also gives better detail to the observation in Andres et al. (1996) that the bulk of emissions is slowly shifting south with time (Fig. 4). From 1775 to 1995, the median in emissions has shifted south 15 degrees while the peak in emissions shifted south 10 degrees. These trends show that while the mid-northern latitudes are still home to countries heavily dependent on fossil fuels, the more equatorial countries are also

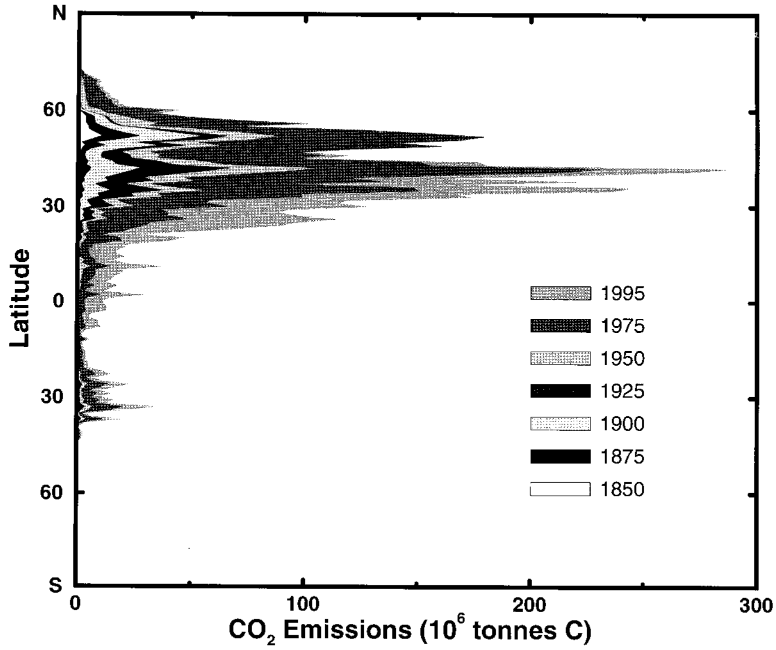

Fig. 4. Latitudinal distribution of CO_2 emissions from fossil-fuel consumption. The time increment shown is 25 years except for 1995 which was the latest data available at the time of publication. The data for years 1775, 1800 and 1825 are not shown for clarity since they fall within the 1850 peak. The alternating light and dark bands show the growth in emissions at all latitudes with population data. This alternating pattern is disrupted where growth is not continuously increasing, e.g., northern latitudes.

becoming major contributors to the global fossil-fuel CO_2. This is a reflection of the spread of significant fossil fuel use from Europe to North America to Asia and the rest of the world to support the growing economies and populations in these regions.

These statistics on the latitudinal distribution of emissions were derived by first distributing national CO_2 emissions on a 1 degree grid. Following the methods in Andres et al. (1996), the entire time series, 1751–1995, has been distributed and visualizations are available at http://www.arsc.edu/science/EngEnvSci.html

While instructive, the visualizations provide only rough approximations for the pre-1950 time series. In general, the errors discussed in Andres et al. (1996) apply not only to the modern time series, but also the pre-1950 time series. Within-country distributions are proportional to 1985 population distributions and thus may be inappropriate for other years in the time series. Countering this error is the probable concentration of fossil-fuel use in urban areas early in the time series. In addition, short term territorial changes associated with wars have not been accommodated due to a lack of information regarding changing political boundaries and the amount of fuel consumed within those boundaries.

5. Conclusions

With an emission rate of 3×10^6 tonnes C emitted in 1751, the new time series provides a continuous record of CO_2 emissions from fossil-fuel combustion from essentially the beginning of the fossil-fuel era. This increased definition of the history of fossil-fuel CO_2 emissions should aid the efforts of global carbon cycle modelers. This time series seamlessly joins the modern time series beginning in 1950.

From 1751 to 1995, the cumulative global total CO_2 emissions from fossil fuel production were 250×10^9 tonnes C. Only 25% of this total was emitted by 1950, 50% by 1973, and 75% by 1985. This accelerating growth in emissions has led to numerous deliberations on the potential for enhanced greenhouse warming.

This paper summarizes the large scale implications of this emissions time series. Additional details, especially national emissions, can be found on the CDIAC web site (http://cdiac.esd.ornl.gov/ndps/ndp030.html). Finally, specialized data sets can be created in response to specific requests by contacting CDIAC.

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