PART II OVERVIEW

# Energy, Industry, and Waste Management Activities: An Introduction to $CO_2$ Emissions From Fossil Fuels

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## II.1 THE CONTEXT

Fossil fuels (coal, oil, and natural gas) are used primarily for their concentration of chemical energy, energy that is released as heat when the fuels are burned. Fossil fuels are composed primarily of compounds of hydrogen and carbon, and when the fuels are burned, the hydrogen and carbon oxidize to water and carbon dioxide ($CO_2$) and heat is released. If the water and $CO_2$ are released to the atmosphere, the water will soon fall out as rain or snow. The $CO_2$, however, will increase the concentration of $CO_2$ in the atmosphere and join the active cycling of carbon that takes place among the atmosphere, biosphere, and hydrosphere. Since humans began taking advantage of fossil-fuel resources for energy, we have been releasing to the atmosphere, over a very short period of time, carbon that was stored deep in the Earth over millions of years. We have been introducing a large perturbation to the active cycling of carbon.

Estimates of fossil-fuel use globally show that there have been significant emissions of $CO_2$ dating back at least to 1750, and from North America, back at least to 1785. However, this human perturbation of the active carbon cycle is largely a recent process, with the magnitude of the perturbation growing as population grows and demand for energy grows. Over half of the $CO_2$ released from fossil-fuel burning globally has occurred since 1980 (Figure II.1).

Some $CO_2$ is also released to the atmosphere during the manufacture of cement. Limestone ($CaCO_3$) is heated to release $CO_2$ and produce the calcium oxide (CaO) used to manufacture cement. In North America, cement manufacture now releases less than 1% of the mass of $CO_2$ released by fossil-fuel combustion. However, cement manufacture is the third largest human-caused (anthropogenic) source of $CO_2$ (after fossil-fuel use and the clearing and oxidation of forests and soils; see Part III this report). The $CO_2$ emissions from cement manufacture are often included with the accounting of anthropogenic $CO_2$ emissions from fossil fuels.

Over half of the $CO_2$ released from fossil-fuel burning globally has occurred since 1980.

Part II of this report addresses the magnitude and pattern of $CO_2$ emissions from fossil-fuel consumption and cement manufacture in North America. This introductory section addresses some general issues associated with $CO_2$ emissions and the annual and cumulative magnitude of total emissions. It looks at the temporal and spatial dis-

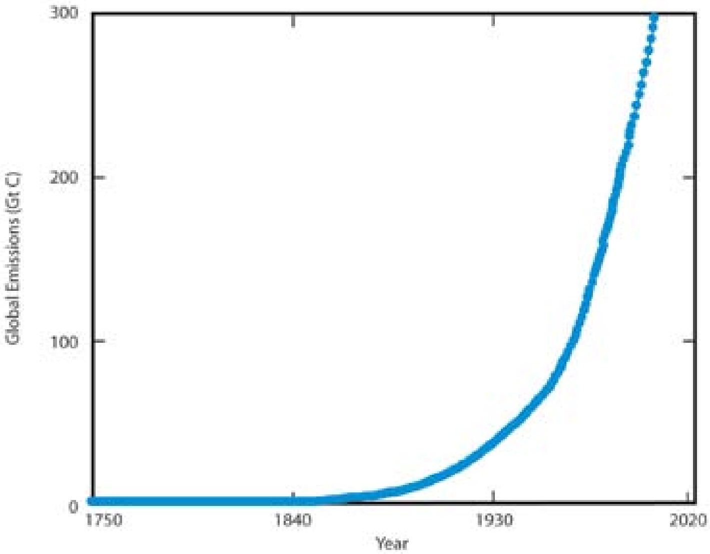


**Figure II.1** Cumulative global emmissions of $CO_2$ from fossil-fuel combustion and cement manufacture from 1751 to 2002. *Source data:* Marland *et al.* (2005).

tribution of emissions and other data likely to be of interest. The following four chapters delve into the sectoral details of emissions so that we can understand the forces that have driven the growth in emissions to date and the possibilities for the magnitude and pattern of emissions in the future. These chapters reveal, for example, that 38% of $CO_2$ emissions from North America come from enterprises whose primary business is to provide electricity and heat and another 31% come from the transport of passengers and freight. This introduction focuses on the total emissions from the use of fossil fuels and the subsequent chapters provide insight into how these fuels are used and the economic and human factors motivating their use.

## II.1.1 Estimating Carbon Dioxide Emissions

It is relatively straightforward to estimate the amount of $CO_2$ released to the atmosphere when fossil fuels are consumed. Because $CO_2$ is the equilibrium product of oxidizing the carbon in fossil fuels, we need to know only the amount of fuel used and its carbon content. For greater accuracy, we adjust this estimate to take into consideration the small amount of carbon that is left as ash or soot and is not actually oxidized. We also consider the fraction of fossil fuels that are used for things like asphalt, lubricants, waxes, solvents, and plastics and may not be soon converted to $CO_2$. Some of these long-lived, carbon-containing products will release their contained carbon to the atmosphere as $CO_2$ during use or during processing of waste. Other products will hold the carbon in use or in landfills for decades or longer. One of the differences among the various estimates of $CO_2$ emissions is the way they deal with the carbon in these products.

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Fossil-fuel consumption is often measured in mass or volume units and, in these terms, the carbon content of fossil fuels is quite variable. However, when we measure the amount of fuel consumed in terms of its energy content, we find that for each of the primary fuel types (coal, oil, and natural gas) there is a strong correlation between the energy content and the carbon content. The rate of $CO_2$ emitted per unit of useful energy released depends on the ratio of hydrogen to carbon and on the details of the organic compounds in the fuels; but, roughly speaking, the numerical conversion from energy released to carbon released as $CO_2$ is about 25 kg C per $10^9$ joules for coal, 20 kg C per $10^9$ joules for petroleum, and 15 kg C per $10^9$ joules for natural gas. Figure PII.2 shows details of the correlation between energy content and carbon content for more than 1000 coal samples. Detailed analysis of the data suggests that hard coal contains 25.16 ± 2.09% kg C per $10^9$ joules of coal (measured on a net heating value basis[1]). The value is slightly higher for lignite and brown coal (26.23 kg C ±

**Table II.1 A sample of the coefficients used for estimating $CO_2$ emissions from the amount of fuel burned.**

| Fuel | Emissions coefficient (kg C/$10^9$ J net heating value) |
|---|---|
| Lignite | 27.6 |
| Anthracite | 26.8 |
| Bituminous coal | 25.8 |
| Crude oil | 20.0 |
| Residual fuel oil | 21.1 |
| Diesel oil | 20.2 |
| Jet kerosene | 19.5 |
| Gasoline | 18.9 |
| Natural gas | 15.3 |

*Source:* IPCC (1997).

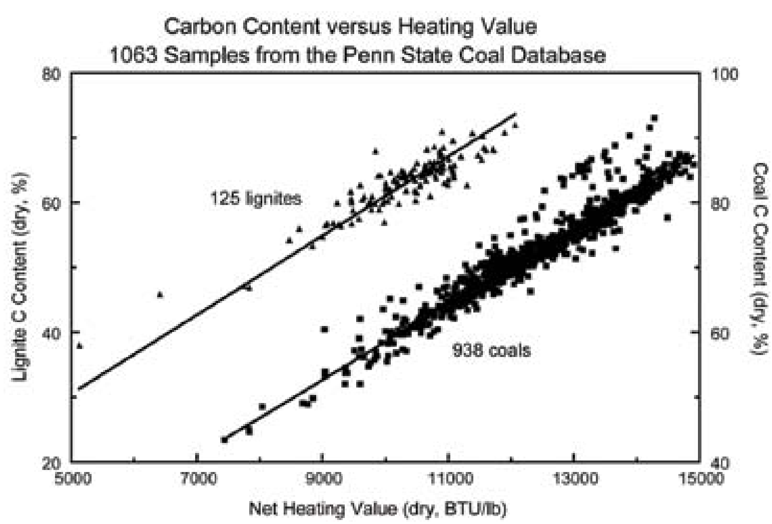


**Figure II.2** The carbon content of coal varies with the heat content, shown here as the net heating value. To make them easier to distinguish, data for lignites and brown coals are shown on the left axis, while data for hard coals are offset by 20% and shown on the right axis. Heating value is plotted in the units at which it was originally reported, Btu/lb, where 1 Btu/lb = 2324 J/kg. *Source:* Marland *et al.* (1995).

[1] Net heating value (NHV) is the heat release measured when fuel is burned at constant pressure so that the water ($H_2O$) is released as $H_2O$ vapor. This is distinguished from the gross heating value (GHV), the heat release measured when the fuel is burned at constant volume so that the $H_2O$ is released as liquid $H_2O$. The difference is essentially the heat of vaporization of the $H_2O$ and is related to the hydrogen content of the fuel.

2.33% per $10^9$ joules (also shown in Figure II.2). Similar correlations exist for all fuels and Table PII.1 shows some of the coefficients reported by the Intergovernmental Panel on Climate Change (IPCC) for estimating $CO_2$ emissions. The differences between the values in Table II.1 and those in Figure II.2 are small, but they begin to explain how different data compilations can end up with different estimates of $CO_2$ emissions.

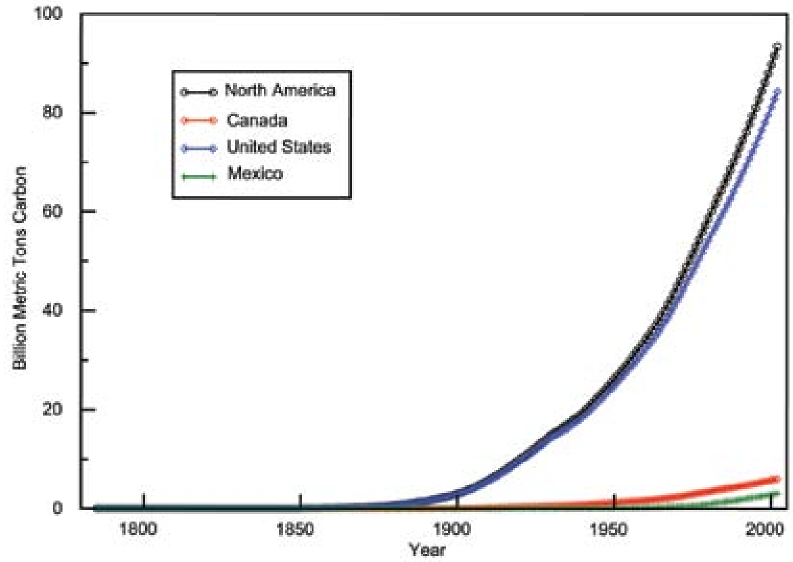


**Figure II.3** The cumulative total of $CO_2$ emissions from fossil-fuel consumption and cement manufacture, as a function of time, for the three countries of North America and for the sum of the three. *Source:* Marland *et al.* (2005).

Data on fossil-fuel production, trade, consumption, *etc.* are generally collected at the level of some political entity, such as a country, and over some time interval, typically a year. Estimates of national, annual fuel consumption can be based on estimates of fuel production and trade, estimates of actual final consumption, data for fuel sales or some other activity that is clearly related to fuel use, or on estimates and models of the activities that consume fuel (such as vehicle miles driven). In the discussion that follows, some estimates of national, annual $CO_2$ emissions are based on "apparent consumption" (defined as production + imports – exports +/– changes in stocks), while others are based on more direct estimates of fuel consumption. All of the emissions estimates in this chapter are as the mass of carbon released[2].

The uncertainty in estimates of $CO_2$ emissions will thus depend on the variability in the chemistry of the fuels, the quality of the data or models of fuel consumption, and on uncertainties in the amount of carbon that is used for non-fuel purposes (such as asphalt and plastics) or is otherwise not burned. For countries like the United States—with good data on fuel production, trade, and consumption—the uncertainty in national emissions of $CO_2$ is on the order of ±5% or less. In fact, the U.S. Environmental Protection Agency (USEPA, 2005) suggests that their estimates of $CO_2$ emissions from energy use in the United States are accurate, at the 95% confidence level, within –1 to +6% and Environment Canada (2005) suggests that their estimates for Canada are within –4 to 0%. The Mexican National Report (Mexico, 2001) does not provide estimates of uncertainty, but our analyses with the Mexican data suggest that uncertainty is larger than for the United States and Canada. Emissions estimates for these same three countries, as reported by the Carbon Dioxide Information Analysis Center (CDIAC) and the International Energy Agency (IEA) (see the following section), will have larger uncertainty because these groups are making estimates for all countries. Because they work with data from all countries, they use global average values for things like the emissions coefficients, whereas agencies within the individual countries use values that are more specific to the particular country. When national emissions are calculated by consistent methods it is likely that year-to-year changes can be estimated more accurately than would be suggested by the uncertainties of the individual annual values.

### II.1.2 The Magnitude of National and Regional Carbon Dioxide Emissions

Figure II.3 shows that from the beginning of the fossil-fuel era (1751 in these graphs) to the end of 2002, there were 93.5 billion tons of carbon (Gt C) released as $CO_2$ from fossil-fuel consumption (and cement manufacture) in North America: 84.4 Gt C from the United States, 6.0 from Canada, and 3.1 from Mexico. All three countries of North America are major users of fossil fuels and this 93.5 Gt C was 31.5% of the global total. Among all countries, the United States, Canada, and Mexico ranked as the first, eighth, and eleventh largest emitters of $CO_2$ from fossil-fuel consumption, respectively (for 2002) (Marland *et al.*, 2005). Figure II.4 shows, for each of these countries and for the sum of the three, the annual total of emissions and the contributions from the different fossil fuels.

The long time series of emissions estimates in Figures II.1, II.3, and II.4 are from the CDIAC (Marland *et al.*, 2005). These estimates are derived from the "apparent consumption" of fuels and are based on data from the United Nations Statistics Office back to 1950 and on data from a mixture of sources for the earlier years (Andres *et al.*, 1999). There are other published estimates (with shorter time series) of national, annual $CO_2$ emissions. Most notably the IEA (2005) has reported estimates of emissions for many coun-

[2] The carbon is actually released to the atmosphere as $CO_2$ and it is accurate to report (as is often done) either the amount of $CO_2$ emitted or the amount of C in the $CO_2$. The numbers can be easily converted back and forth using the ratio of the molecular masses, *i.e.* (mass of C) x (44/12) = (mass of $CO_2$).

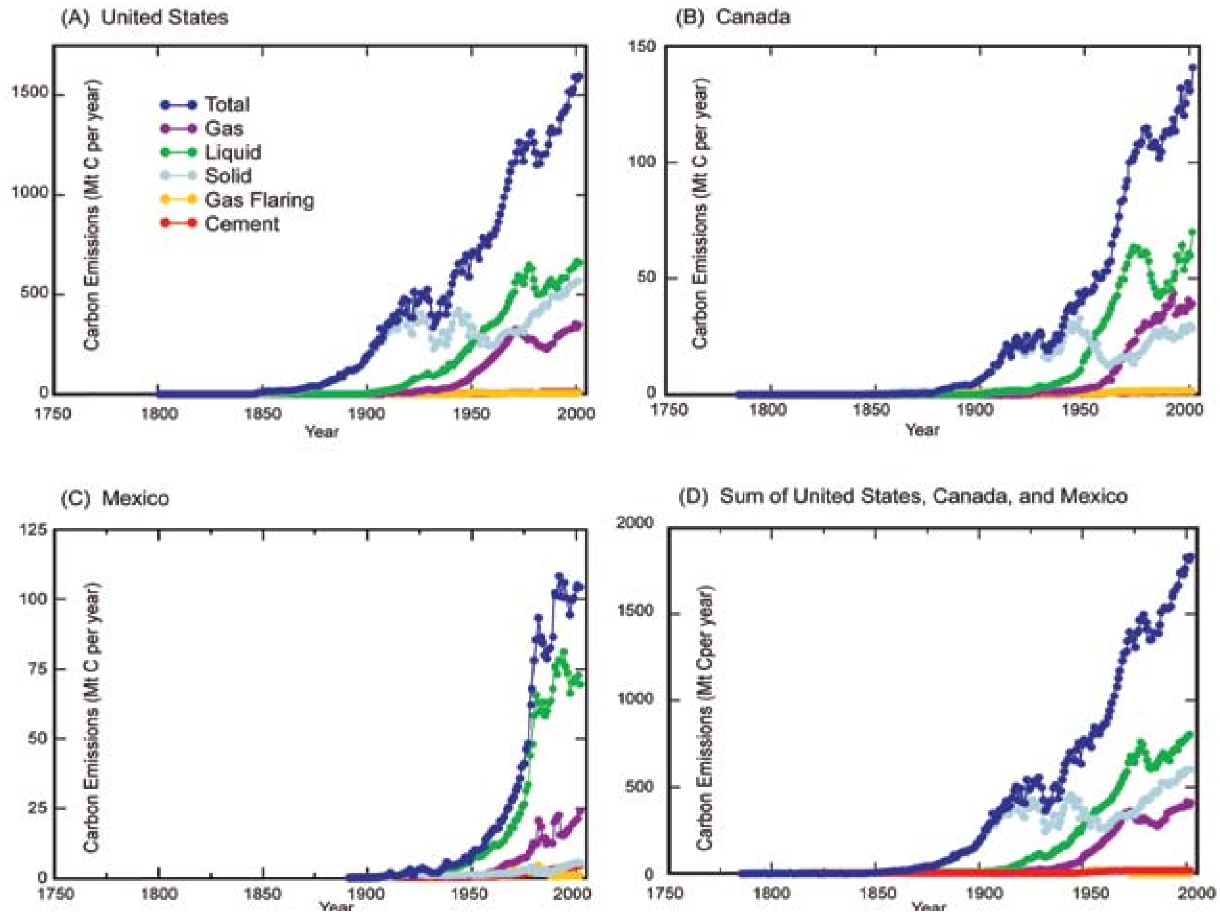


**Figure II.4** Annual emissions of $CO_2$ from fossil-fuel use by fuel type for (A) the United States, (B) Canada, (C) Mexico, and (D) North America, as the sum of the data shown in the other three panels. *Note* that in order to illustrate the contributions of the different fuels, the four plots are not to the same vertical scale. *Source*: Marland *et al.* (2005).

tries for all years back to 1971, and most countries have now provided some estimates of their own emissions as part of their national obligations under the United Nations Framework Convention on Climate Change (UNFCCC, see http://unfccc.int). These latter two sets of estimates are based on data on actual fuel consumption and thus are able to provide details as to the sector of the economy where fuel use is taking place[3].

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Comparing the data from multiple sources can give us some insight into the reliability of the estimates, generally. These different estimates of $CO_2$ emissions are not, of course, truly independent because they all rely, ultimately, on national data on fuel use; but they do represent different manipulations of this primary data and in many countries there are multiple potential sources of energy data. Many developing countries do not collect or do not report all of the data necessary to precisely estimate $CO_2$ emissions and in these cases differences can be introduced by how the various agencies derive the basic data on fuel production and use. Because of the way data are collected, there are statistical differences between "consumption" and "apparent consumption" as defined above.

To make comparisons of different estimates of $CO_2$ emissions we would like to be sure that we are indeed comparing estimates of the same thing. For example, emissions from cement manufacture are not available from all of the sources, so they are not included in the comparisons in Table II.2. All of the estimates in Table II.2, except those from the IEA, include emissions from flaring natural gas at oil production facilities. It is not easy to identify the exact reason the estimates differ, but the differences are generally small. The differences have mostly to do with the statistical difference between consumption and apparent consumption, the way in which correction is made for non-fuel usage of fossil-fuel resources, the conversion from mass or volume to energy

[3] The International Energy Agency provides estimates based on both the reference approach (estimates of apparent consumption) and the sectoral approach (estimates of actual consumption) as described by the IPCC (IPCC, 1997). In the comparison here, we use the numbers that they believe to be the most accurate, those based on the sectoral approach.

**Table II.2 Different estimates (in MtC) of CO2 emissions from fossil-fuel consumption for the United States, Canada, and Mexico.**

| Country | 1990 | | 1998 | | 2002 | |
|---|---|---|---|---|---|---|
| **United States** | CDIAC | 1305 | CDIAC | 1501 | CDIAC | 1580 |
| | IEA | 1320 | IEA | 1497 | IEA | 1545 |
| | USEPA | 1316 | USEPA | 1478 | USEPA | 1534 |
| **Canada** | CDIAC | 112 | CDIAC | 119 | CDIAC | 139 |
| | IEA | 117 | IEA | 136 | IEA | 145 |
| | Canada | 117 | Canada | 133 | Canada | 144 |
| **Mexico** | CDIAC | 99 | CDIAC | 96 | CDIAC | 100 |
| | IEA | 80 | IEA | 96 | IEA | 100 |
| | Mexico | 81 | Mexico | 96 | Mexico | NA |

Notes:
Many of these data were published in terms of the mass of $CO_2$, and these data have been multiplied by 12/44 to get the mass of carbon for the comparison here.
All data except CDIAC include oxidation of non-fuel hydrocarbons.
All data except IEA include flaring of gas at oil and gas processing facilities.
*Sources:* CDIAC (Marland *et al.*, 2005), IEA (2005), USEPA (2005), Canada (Environment Canada, 2005), and Mexico (2001).

units, and/or the way in which estimates of carbon content are derived. Because the national estimates from CDIAC do not include emissions from the non-fuel uses of petroleum products, we expect them to be slightly smaller than the other estimates shown here, all of which do include these emissions[4]. The comparisons in Table II.2 reveal one number for which there is a notable relative difference among the multiple sources, emissions from Mexico in 1990. Losey (2004) has suggested, based on other criteria, that there is a problem in the United Nations energy data set with the Mexican natural gas data for the three years 1990-1992, and these kinds of analyses result in re-examination of some of the fundamental data.

The IEA (2005, p. 1.4) has systematically compared their estimates with those reported to the UNFCCC by the different countries and they find that the differences for most developed countries are within 5%. The IEA attributes most of the differences to the following: use of the IPCC Tier 1 method that does not take into account different technologies, use of energy data that may have come from different "official" sources within a country, use of average values for net heating value of secondary oil products, use of average emissions values, use of incomplete data on non-fuel uses, different treatment of military emissions, and a different split between what is identified as emissions from energy and emissions from industrial processes.

## II.1.3 Emissions by Month and/or State

With increasing interest in the details of the global carbon cycle there is increasing interest in knowing emissions at spatial and temporal scales finer than countries and years. For the United States, energy data have been collected for many years at the level of states and months and thus estimates of $CO_2$ emissions can be made by state or by month. Figure II.5 shows the variation in United States' emissions by month and preliminary analyses by Gurney *et al.* (2005) reveal that proper recognition of this variability can be very important in some exercises to model the details of the global carbon cycle.

Because of differences in the way energy data are collected and aggregated, it is not obvious that an estimate of emissions from the United States will be identical to the sum of estimates for the 50 United States' states. Figure II.6 shows that estimates of total annual $CO_2$ emissions are slightly different if we use data directly from the U.S. Department of Energy (DOE) and sum the estimates for the 50 states or if we sum the estimates for the 12 months of a given year, or if we take United States' energy data as aggregated by the United Nations Statistics Office and calculate the annual total of $CO_2$ emissions directly. Again,

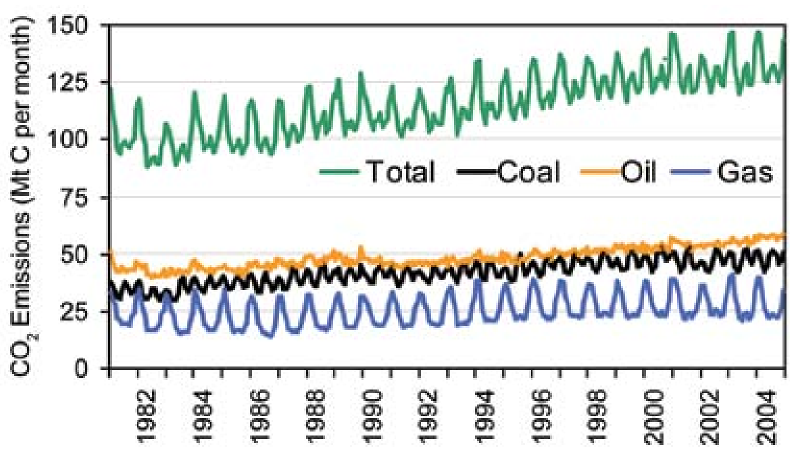


**Figure. II.5** Emissions of $CO_2$ from fossil-fuel consumption in the United States, by month. Emissions from cement manufacturing are not included. *Source:* Blasing *et al.* (2005a).

[4] The CDIAC estimate of global total emissions does include estimates of emissions from oxidation from non-fuel use of hydrocarbons.

the state and monthly emissions data are based on estimates of fuel consumption while the national emissions estimates calculated using United Nations' data result from estimates of "apparent consumption." There is a difference between annual values for consumption and annual values of "apparent consumption" (the IEA calls this difference simply "statistical difference") that is related to the way statistics are collected and aggregated. There are also differences in the way values for fuel chemistry and non-fuel usage are averaged at different spatial and temporal scales, but the differences in $CO_2$ estimates are seen to be within the error bounds generally expected.

Data from DOE permit us to estimate emissions by state or by month (Blasing *et al*., 2005a and 2005b), but they do not permit us to estimate $CO_2$ emissions for each state by month directly from the published energy data. Nor do we have sufficiently complete data to estimate emissions from Canada and Mexico by month or province. Andres *et al.* (2005), Gregg (2005), and Losey (2004) have shown that we can disaggregate national total emissions by month or by some national subdivision (such as states or provinces) if we have data on some large fraction of fuel use. Because this approach relies on determining the fractional distribution of an otherwise-determined total, it can be done with incomplete data on fuel use. The estimates will, of course, improve as the fraction of the total fuel use is increased. Figure II.7 is based on sales data for most fossil-fuel commodities and the CDIAC estimates of total national emissions and shows how the $CO_2$ emissions from North America vary at a monthly time scale.

To understand the trends and the driving forces behind the growth in fossil-fuel emissions, and the opportunities for controlling emissions, it is necessary to look in detail at how the fuels are used.

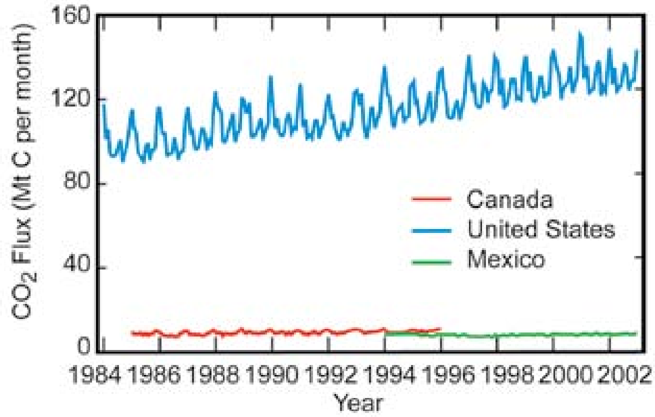


**Figure II.7** Carbon dioxide emissions from fossil-fuel consumption in North America, by month. Monthly values are shown where estimates are justified by the availability of monthly data on fuel consumption or sales. *Source:* Andres *et al.*, (2005).

### .II.1.4 Emissions by Economic Sector

To understand how $CO_2$ emissions from fossil-fuel use interact in the global and regional cycling of carbon, it is necessary to know the masses of emissions and their spatial and temporal patterns. We have tried to summarize this information here. To understand the trends and the driving forces behind the growth in fossil-fuel emissions, and the opportunities for controlling emissions, it is necessary to look in detail at how the fuels are used. This is the goal of the next four chapters of this report.

Before looking at the details of how energy is used and where $CO_2$ emissions occur in the economies of North America, however, there are two indices of $CO_2$ emissions at the national level that provide perspective on the scale and distribution of emissions. These two indices are emis-

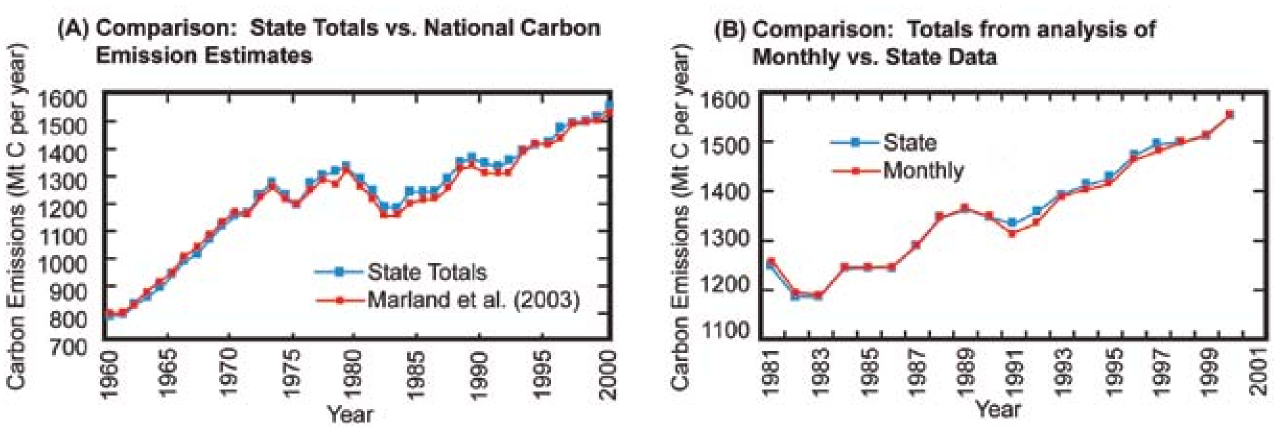


**Figure. II.6** A comparison of three different estimates of national annual emissions of $CO_2$ from fossil-fuel consumption in the United States. (A) Estimates from U.S. Department of Energy data on fuel consumption by state (blue squares) vs. estimates based on UN Statistics Office data on apparent fuel consumption for the full United States (red squares). (B) Estimates based on DOE data on fuel consumption in the 50 U.S. states (blue squares) vs. estimates based on national fuel consumption for each of the 12 months (red squares). The state and monthly data include estimates of oxidation of non-fuel hydrocarbon products; the UN-based estimates do not. *Source*: Blasing *et al.*, (2005b).

**Table II.3 Emissions of $CO_2$ from fossil-fuel consumption (cement manufacture and gas flaring are not included) per unit of GDP for the United States, Canada, Mexico and for the global total.**

| Country | $CO_2$ emissions per unit of GDP[a] Year | | |
|---|---|---|---|
| | 1990 | 1998 | 2002 |
| **United States** | 0.19 | 0.17 | 0.15 |
| **Canada** | 0.18 | 0.18 | 0.16 |
| **Mexico** | 0.13 | 0.12 | 0.11 |
| **Global Total** | 0.17 | 0.15 | 0.14 |

[a] Carbon dioxide is measured in kg carbon and GDP is reported in 2000 US$ purchasing power parity.
*Source:* IEA (2005).

sions *per capita* and emissions per unit of economic activity, the latter generally represented by $CO_2$ per unit of gross domestic product (GDP). Figure II.8 shows the 1950–2002 record of $CO_2$ emissions *per capita* for the three countries of North America and for perspective includes the same data for the Earth as a whole. Similarly, Table II.3 shows $CO_2$ emissions per unit of GDP for the three countries of North America and for the world total. These are, of course, very complex indices and though they provide some insight they say nothing about the details and the distributions within the means. The data on $CO_2$ *per capita* for the 50 United States' states (Figure II.9) show that values range over a full order of magnitude, differing in complex ways with the structure of the economies and probably with factors like climate, population density, and access to resources (Blasing *et al.*, 2005b; Neumayer, 2004).

Chapters 6 through 9 of this report discuss the patterns and trends of $CO_2$ emissions by sector and the driving forces behind the trends that are observed. Estimating emissions by sector brings special challenges in defining sectors and assembling the requisite data. Readers will find that there is consistency and coherence within each of the following chapters but will encounter difficulty in aggregating or summing numbers across chapters. Different experts use different sector boundaries, different data sources, different conversion factors, *etc.* Different analysts and literature sources will find data for different base years and may treat electricity and biomass fuels differently. The national reports of the United States, Canada, and Mexico do not cover the same time periods, nor do they present data in the same way. In a discussion of the possibilities for reducing $CO_2$ emissions in the building sector it is not obvious, for example, whether to include the relevant electricity within the building sector, to leave electric power generation as a separate sector, or to accept some overlap in the discussion. The authors of Chapters 6, 7, 8, and 9 have chosen the system boundaries and data they find most useful for the individual sectors, even though it makes it more difficult to aggregate across sectors.

Despite these differences in accounting procedures, the four chapters that follow accurately characterize the patterns of emissions and the opportunities for controlling the growth in emissions. They reveal that there are major differences between the countries of North America where, for example, the United States derives 51% of its electricity from coal, Mexico gets 68% from petroleum and natural gas, and Canada gets 58% from hydroelectric stations. Partially as a reflection of this difference, 40% of United States' $CO_2$ emissions are from enterprises whose primary business is to generate electricity and heat, while this number is only 31% in

Forty percent of the United States' $CO_2$ emissions are from enterprises whose primary business is to generate electricity and heat, while this number is only 31% in Mexico and 23% in Canada.

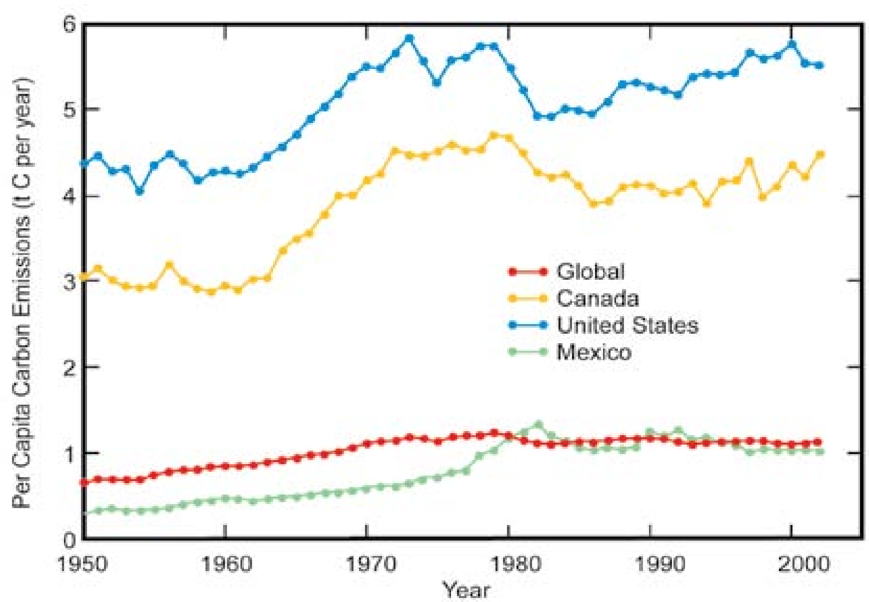


**Figure II.8** *Per capita* emissions of $CO_2$ from fossil-fuel consumption and cement manufacture in the United States, Canada, and Mexico and for the global total of emissions. *Source:* Marland *et al.*, (2005).

Mexico and 23% in Canada (for 2003; from IEA, 2005). Chapter 8 reveals that the sectors are not independent as, for example, a change from fuel burning to electricity in an industrial process will decrease emissions from the industrial sector but increase emissions in the electric power sector. The database of the IEA allows us to summarize $CO_2$ emissions for the three countries according to sectors that closely correspond to the sectoral division of chapters 6 through 9 (Table II.4).

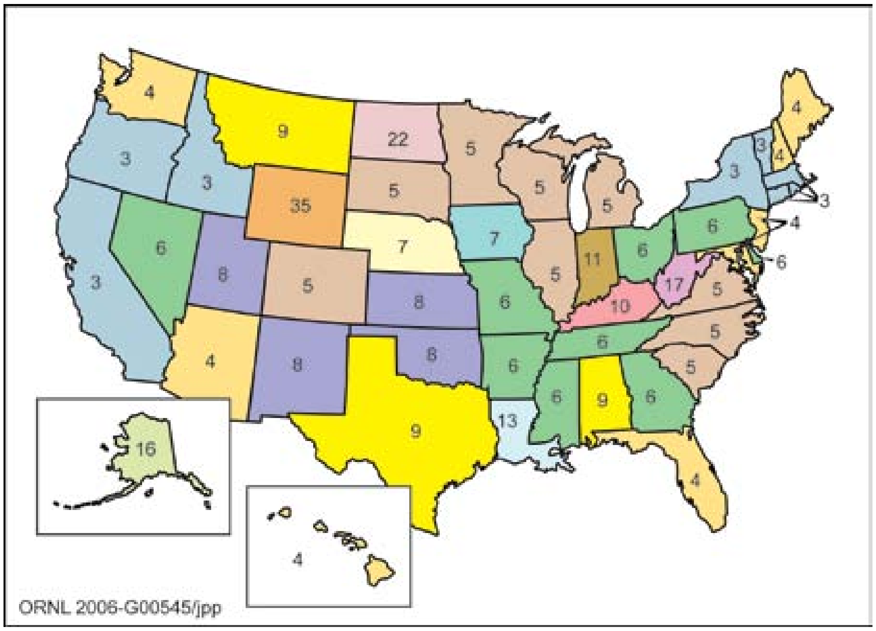


**Figure II.9** *Per capita* emissions of $CO_2$ from fossil-fuel consumption for the 50 United States in 2000. To demonstrate the range, values have been rounded to whole numbers of metric tons carbon *per capita*. A large portion of the range for extreme values is related to the occurrence of coal resources and inter-state transfers of electricity. *Source*: Blasing *et al.* (2005b).

## II.2 CONCLUSION

There are a variety of reasons that we want to know the emissions of $CO_2$ from fossil fuels, there are a variety of ways of coming up with the desired estimates, and there are a variety of ways of using the estimates. By the nature of the process of fossil-fuel combustion, and because of its economic importance, there are reasonably good data over long time intervals that we can use to make reasonably accurate estimates of $CO_2$ emissions to the atmosphere. In fact, it is the economic importance of fossil-fuel burning that has assured us of both good data on emissions and great challenges in altering the rate of emissions.

**Table II.4 Percentage of $CO_2$ emissions by sector for 2003.**

| Sector | United States | Canada | Mexico | North America |
|---|---|---|---|---|
| Energy extraction and conversion[a] | 46.2 | 36.2 | 47.7 | 45.4 |
| Transportation[b] | 31.3 | 27.7 | 30.3 | 31.0 |
| Industry[c] | 11.2 | 16.8 | 13.6 | 11.8 |
| Buildings[d] | 11.3 | 19.3 | 8.4 | 11.8 |

[a] The sum of three IEA categories, "public electricity and heat production," "unallocated autoproducers," and "other energy industries."
[b] IEA category "transport."
[c] IEA category "manufacturing industries and construction."
[d] IEA category "other sectors."
*Source:* IEA (2005).