Uncertainties in Accounting for CO_2 From Fossil Fuels

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Carbon accounting is now firmly on the agenda of science, politics, and business. Individuals are estimating their "carbon footprint." Scientists try to understand the details of the global carbon cycle, policy makers try to limit carbon dioxide (CO_2) emissions to the atmosphere, countries and companies analyze CO_2 emissions and trade emissions permits, and individuals try to be environmentally sensitive. It is not surprising that there is a need to estimate emissions and to understand the accuracy of these estimates. There has been considerable discussion about the challenges of measuring carbon sources and sinks in the biosphere, but there has been less recognition that emissions from fossil-fuel combustion are also subject to uncertainty.

How accurate are CO_2 emissions estimates, and how accurate do they need to be? Can we measure the emissions from fossil-fuel combustion well enough to understand their implications for the global carbon cycle, to know whether a country that agrees to reduce emissions by x% has achieved its goal, or to be sure that a company that buys permits to offset its emissions has received what it paid for?

CO_2 emissions are actually measured in only a few places, and then with still considerable uncertainty. CO_2 is monitored at some large power plants, where instruments measure the concentration of CO_2 in the stack gas and the flow rate of gas up the stack.[1] But CO_2 is the equilibrium product for carbon when we burn coal, oil, or natural gas, and we can estimate emissions from the quantity of fuel consumed and the amount of carbon in the fuel—with correction for incomplete combustion and for fuel products that are used in ways that do not lead to complete oxidation. The mass balance tool, so familiar in other domains of industrial ecology, is crucial here. For asphalt, plastics, lubricants, solvents, and other products from fossil fuels (or from wood or agricultural products), the carbon will be oxidized to CO_2 at varying rates over time.

Marland and colleagues (1999) conducted a comparison of two large, "(partially) independent" efforts to estimate national emissions of CO_2. . . . The two estimates for the United States differed by only 0.9%, but the absolute value of this difference was greater than total emissions from 147 of the 195 countries analyzed.

Accurate accounting for CO_2 emissions also depends on a clear understanding of system boundaries. Does an estimate of emissions per liter of gasoline consumed include only emissions at the time and place of combustion, or does it include emissions related to the production, refining, and delivery of the gasoline—incorporating more of a life cycle perspective? Does an estimate of emissions from a country include only emissions from combustion within the national borders, or does it include combustion of fuels to generate imported electricity and other imported (or exported) goods? The relevance of these distinctions depends on the question asked, but any

Supplementary material is available on *JIE* Web site

DOI: 10.1111/j.1530-9290.2008.00014.x

Volume 12, Number 2

accounting should clearly establish the boundaries of the accounts.

I focus here on the uncertainty of national and global emissions estimates. The Intergovernmental Panel on Climate Change (IPCC) has published guidelines for countries to estimate their CO_2 emissions (i.e., emissions from within their national borders), guidelines that include coefficients for converting fuel used to CO_2 emitted. These guidelines perform an important role by harmonizing methodologies and focusing on transparency, consistency, comparability, completeness, and accuracy. They facilitate comparisons across countries, and they eliminate some potential sources of error in estimates of "trend uncertainty"—that is, the difference in emissions during some base period and during a subsequent "commitment period." In addition, they focus attention on uncertainty.

A hint of the inherent uncertainty can be seen in comparisons such as that of Bournazian (2002). Bournazian compared the volume of sales of petroleum products (distillate fuel oil, residual fuel oil, and motor gasoline) in the United States from four reporting forms collected within two U.S. agencies. Conceptual differences with data collection, different survey concepts and methodologies, differences in point and time measurements, metadata issues, and possibly misreporting led to differences in annual sales volume that ranged from 0% to sometimes over 30%. Blasing and colleagues (2005) compared estimates of CO_2 emissions from the United States and found small but real differences even when estimates seemed to originate from the same data sources. Differences of up to 2% were found when estimates were summed for the 50 U.S. states, as opposed to summed over the 12 months of a year.

A report from the petroleum industry (IPIECA/API 2007) pointed out, for example, errors in measuring volume of gas flow in pipes and noted the extent to which errors can result from inaccuracies regarding the operating conditions: "A 0.26 bar error in pressure would lead to a 0.5 per cent error in flow rate, and a 2°C error in temperature would amount to a 0.4 per cent (error) in derived flow rate." Further variability is introduced by measurement frequency and heterogeneity in fluid composition. Nevertheless, IPIECA/API suggested that within the oil and gas industry, uncertainties of CO_2 emissions are typically less than 3%.

The carbon content of fuels is not necessarily uniform, nor is it generally measured. Fuel consumption is measured in tons, barrels, or cubic meters—and often the energy content is measured. Fortunately, there is a correlation between the energy content of fuels and their carbon content. Marland and colleagues (2007) showed, for example, that hard coal contains 25.16 kgC/10^9 joules (higher heating value),[2] with a standard error of the mean of 2.09%.

Given all of the issues of measurement, evaluation, and data collection, the United States has estimated that its national calculation of CO_2 emissions has an uncertainty (at the 95% confidence level) of −1% to 6%, and Environment Canada reported a comparable value of −4% to 0%. Other countries with good systems of data collection and management report comparable, and sometimes smaller, uncertainty. Rypdal and Winiwarter (2001) reported that the 2 sigma uncertainty for countries with "well-developed energy statistics and inventories" (113) could be as small as 2% to 4%. Olivier and Peters (2002) estimated that emissions from Organisation for Economic Co-operation and Development (OECD) countries may have—on average—an uncertainty of 5% to 10%, whereas the uncertainty may be 10% to 20% for other countries. The International Energy Agency did not report the uncertainty of its emissions estimates but relied on Intergovernmental Panel on Climate Change (IPCC) methodologies and cited the IPCC estimate that "for countries with good energy collection systems, this [IPCC Tier I method] will result in an uncertainty range of ± 5%. The uncertainty range in countries with 'less well-developed energy data systems' may be on the order of ± 10%."

Gregg and colleagues (2008) estimated that China became the largest national source of fossil-fuel CO_2 emissions during the summer of 2006, but the authors recognized large uncertainty (15% to 20%) in the Chinese estimates. Satellite-based measurements of nitrogen dioxide (NO_2) concentrations have indicated problems with energy data from China, and Akimoto and colleagues (2006) and others have noted substantial differences in coal consumption as reported in three different sets of official statistics. There has long been concern about the Chinese energy statistics, especially a perceived underreporting of coal consumption. Recently, the major international compilations of energy data have reported revisions in the Chinese data for the period following 1996. As a consequence, estimates of CO_2 emissions from China in 2000, for example, were revised upward by 23% from the 2006 to the 2007 data releases of the Carbon Dioxide Information Analysis Center (CDIAC). Although this correction has been important, it is also indicative of the uncertainty in the Chinese emissions estimates.

Marland and colleagues (1999) conducted a comparison of two large, "(partially) independent"(265) efforts to estimate national emissions of CO_2. The data differed significantly for many countries but showed no systematic bias, and the global totals were very similar. Relative differences were largest for countries with weaker national systems of energy statistics, and absolute differences were largest for countries with large emissions. The two estimates for the United States differed by only 0.9%, but the absolute value of this difference was greater than total emissions from 147 of the 195 countries analyzed. The 10 countries with the largest absolute differences between the two estimates (for 1990) included the USSR, North Korea, India, Venezuela, and China. When the differences between the two estimates were summed, without regard to sign, the difference for the top 5 emitting countries was larger than the sum of the differences for the remaining 190 countries.

The uncertainty of CO_2 emissions is currently large enough that it poses challenging questions for the evaluation of international commitments, and it begins to put limits on understanding of the global carbon cycle. The fundamental processes of the global carbon cycle can be aggregated into the annual net transfers between the atmosphere and the oceans, between the atmosphere and the terrestrial biosphere, and from fossil-fuel combustion and industrial processes to the atmosphere. The first two of these can be bounded if we know the annual increase in the atmosphere and the anthropogenic emissions from fossil fuels and industrial processes. The atmosphere is well mixed and accurately monitored, and global mean annual growth of CO_2 can be estimated with an uncertainty (1 sigma standard deviation) of $\pm$ 0.07 to 0.10 ppm/yr, which amounts (2 sigma uncertainty) to about $\pm$ 0.3 to 0.4 petagrams of carbon/year (Pg C/yr).[3] By contrast, the emissions from fossil-fuel combustion are now (in 2006) at an estimated 8.4 Pg C/yr. Ralph Rotty and I reported in 1984 that our estimate of global fossil-fuel emissions had an uncertainty of $\pm$ 6% to 10% (90% confidence interval, which amounts to 0.6 to 1.0 Pg C uncertainty at the 95% confidence level), a range that seems appropriate still. The uncertainty in the emissions term is thus 1.5 to 3.3 times larger than the uncertainty in the atmospheric accumulation term.

The bottom line is that the details of the global carbon cycle and the details of compliance with emissions commitments are limited by the uncertainty of the emissions estimates. And the uncertainty in the global total of emissions is increasing as the contribution increases of emissions from countries with higher uncertainty.

Notes

1. Detailed citations to supporting literature can be found as Supplementary Material on the Web.
2. One joule (J, SI) $\approx 2.4 \times 10^{-4}$ kilocalories (kcal) $\approx 9.5 \times 10^{-4}$ British Thermal Units (BTU).
3. One petagram (Pg) = one billion tonnes (10^9 t) = 10^{12} kilograms (kg, SI) $\approx 1.102 \times 10^9$ short tons.

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Supplementary Material

The following supplementary material is available for this article:

Appendix S1.

This material is available as part of the online article from:
http://www.blackwellpublishing.com/doi/abs/10.1111/j.1530-9290.2008.00014.x
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