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A method for estimating the temporal and spatial patterns of carbon dioxide emissions from national fossil-fuel consumption

By J. S. GREGG* and R. J. ANDRES†, *Department of Space Studies, University of North Dakota, Grand Forks, ND 58202, USA*

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ABSTRACT

A proportional methodology is presented for estimating fossil-fuel consumption and concomitant anthropogenic carbon dioxide (CO_2) emissions. This methodology employs data from representative sectors of the fossil-fuel market to determine the temporal (monthly) and spatial (provincial/state) patterns of fuel consumption. These patterns of fuel consumption are then converted to patterns of CO_2 emissions. The purpose is to provide a procedure for determining anthropogenic emissions from countries where a full accounting of emissions is impracticable due to limited data availability. To demonstrate the effectiveness of the proportional methodology, it is applied to data from the United States (U.S.) and the results are compared to those from an independent methodology that employs a thorough accounting of all fuel sectors. Although there are some discrepancies between the two sets of CO_2 emissions estimates, overall, the approaches yield similar results. Thus, the proportional methodology developed here represents a viable method for estimating anthropogenic CO_2 emissions for other countries with limited data availability.

1. Introduction

Global warming from greenhouse gases such as carbon dioxide (CO_2) has been an issue of increasing scientific concern since Keeling (1960) published the Mauna Loa, Hawaii atmospheric CO_2 concentration time series. Over the last four decades, further tabulation and modelling has been done to monitor and predict atmospheric CO_2 concentrations and the resultant climactic effects. Today, atmospheric CO_2 levels are higher than they have been in the last 420 000 yr and perhaps the last 20 million years (IPCC, 2001). Moreover, the rate of increase in the atmospheric concentration over the last century is the greatest it has been in at least 20 000 yr (IPCC, 2001). Of the anthropogenic activities that are related to increased atmospheric CO_2 concentrations, fossil-fuel combustion is the most substantial contributor, representing 80% of all anthropogenic CO_2 emissions (Marland et al., 1994).

Currently, many researchers are conducting a multitude of detailed observations of carbon (C) flux from natural processes, land cover change and atmospheric concentrations of greenhouse gases on increasingly finer temporal and spatial scales. These observations feed a number of models to project past and present potential climates using different assumptions about natural and anthropogenic processes. Yet, fossil-fuel-based emissions are still only compiled at an annual time step for most countries; comparatively little work has been done to determine the seasonal distribution and subcountry spatial distribution of those emissions.

For example, the Carbon Dioxide Information Analysis Center (CDIAC) in the Earth Sciences Division at Oak Ridge National Laboratory (ORNL) maintains an extensive database on annual CO_2 emissions from each country (http://cdiac.esd.ornl.gov/trends/emis/tre_coun.htm) (Marland et al., 2005). These data were derived from apparent fuel consumption, summing domestic fuel production and imports, and subtracting exports, bunker fuels, changes in stock and production of non-fuel products (Marland et al., 1989). To ascertain the anthropogenic C emissions from fuel consumption, the C content of each specific fuel was determined via chemistry and empirical observation (Marland and Rotty, 1984; Marland et al., 1994). Similarly, the United Nations Framework Convention on Climate Change (UNFCCC) (2005) maintains an annual database of national greenhouse gas emissions based on self-reports from participating countries, based on reports by the Intergovernmental Panel on Climate Change (IPCC) methodological documents (IPCC, 1996). In addition, the Emission Database for Global

*Corresponding author address: Department of Geography, University of Maryland, College Park, MD 20742, USA. e-mail: gregg.jay@gmail.com
†Present address: Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, 37831, USA.
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Atmospheric Research (EDGAR) (Olivier, 2002) employs sectoral energy consumption data from the International Energy Agency (IEA) and other consumption and production data to derive annual anthropogenic greenhouse emissions into the atmosphere for each country and on a global grid. A comparison of the national annual emissions estimates contained in these databases can be found in the State of the Carbon Cycle Report (SOCCR) (Marland et al., 2006).

The lack of fossil-fuel-based emissions estimates on a seasonal and subnational resolution are due to a lack of detailed fuel consumption data. Nevertheless, estimates of the seasonal distribution of fossil-fuel-based emissions are essential for enhancing models of potential future climates.

To date, the most spatially and temporally detailed account of fossil-fuel-based CO_2 emissions stem from the work of Blasing et al. (2004a,b, 2005a,b) at CDIAC. In these studies, a full accounting approach (utilizing complete statistics on consumption of all fossil fuel end-products by all market sectors) was used to produce monthly CO_2 emissions estimates for the United States (U.S., Blasing et al., 2004b, 2005a), and annual CO_2 emissions estimates for each state and the District of Columbia (Blasing et al., 2004a, 2005b). These are notable achievements, given that the U.S. is responsible for over a fifth of global emissions in 2003 [calculated from Marland et al. (2005)]. That year, 20 countries were responsible for 75% of the global fossil-fuel-based CO_2 emissions [calculated from Marland et al. (2005)]. However, among the top 20 fossil-fuel consuming countries in the world, not all countries maintain data detailed enough to yield monthly fossil-fuel-based CO_2 emissions estimates from a full accounting approach. Thus, the Blasing et al. (2004a,b, 2005a,b) studies represent the limit in spatiotemporal resolution for CO_2 emissions estimates from a full accounting approach, which cannot feasibly be applied to all countries.

To improve the temporal resolution to monthly time intervals for countries besides the U.S., other methods of estimating CO_2 emissions from fossil-fuel consumption are necessary. A technique developed by Rotty (1987b) explores other variables that are potential indicators of fossil-fuel use (e.g. electricity production and climatological comparisons to similar countries). These can be used as estimators for fossil-fuel use, and hence CO_2 emissions. Varying proxies, depending on the country, are used to estimate emission levels (Rotty, 1987a), but because different proxies are employed for each country, these methodologies lack universal applicability. In addition, population distribution has been used as a proxy to estimate the spatial distribution of emissions on a $1^\circ \times 1^\circ$ latitude–longitude grid (Andres et al., 1996; Brenkert, 2003). While this improves the estimates for the spatial distribution of emissions, these studies are only on an annual time scale and there is some evidence that population distribution is not perfect as a proxy for the distribution of emissions (Blasing et al., 2005b).

Therefore, the goal is to devise a methodology that can be universally applied to determine monthly fossil-fuel consumption for all countries, while at the same time, producing results that are consistent with the annual data based on the U.N. statistics as prepared by CDIAC. Below, a proportional methodology is illustrated and assessed using U.S. data. The U.S. is an ideal case for which to evaluate this methodology, not only because it is the world leader in fossil-fuel-based CO_2 emissions, but because of the detailed fuel consumption data that is maintained by the Energy Information Administration (EIA) of the U.S. Department of Energy. The U.S. data availability allows a direct comparison of the proportional method proposed here against the full accounting-based approach used by Blasing et al. (2005a,b). Moreover, the proportional methodology is able to produce estimates on a monthly state-to-state level, enhancing the spatiotemporal resolution of emissions estimates from the Blasing et al. (2004a,b, 2005a,b) studies. Most importantly, the proportional methodology provides a means to estimate monthly CO_2 emissions for countries that do not have the same data collection commitments as the U.S.

This paper represents the publication of the methodology that produced the monthly national CO_2 emissions data that led to the results published in Bakwin et al. (1998), Lee et al. (2001) and Losey et al. (2006). Other publications that use the results of this methodology are in various stages of manuscript preparation by the authors of this manuscript and by other carbon cycle researchers.

2. Methodology

The underlying principle of the proportional methodology is to determine a set of market sectors whose combined fuel consumption closely approximates the monthly distribution of total fuel use for each state (or other subnational geographic unit). Data for fuel consumption in these sectors is used to parse the annual emissions data for a given country into subannual and subgeopolitical units. Representative data is collected for each fuel type, solid (coal), liquid (petroleum-based fuel products) and gas (natural gas), and are assumed to accurately represent the seasonal and spatial distribution of the entire fossil-fuel market if they comprise a substantial portion of the entire market.

Government agencies and industry-kept statistics serve as the source for direct and indirect indicators of fuel consumption. The data employed are in physical (mass) units rather than monetary units to avoid complications from commodity pricing. For the U.S., all data are obtained from the EIA, which keeps monthly fuel consumption data for each state.

Natural gas data are obtained from the EIA (1984–2004) publication, *Natural Gas Monthly*. The EIA maintains monthly records of deliveries to all consumers by state, which occur after changes in stock (injections less withdrawals into storage) in the production chain. It is assumed that changes in stock at the consumer side of the market are small compared to actual consumption. These data also do not take into account 'lease and plant fuel' and 'pipeline and distribution use' (gas used in the

Table 1. Sectoral distribution of U.S. CO_2 emissions from natural gas (1997–2004) [calculated from EIA (1984–2004)]

Consumer	Percentage of CO_2 emissions	Cumulative percentage
Industrial	34.5%	34.5%
Electric power	22.2%	56.7%
Residential	21.5%	78.2%
Commercial	13.8%	92.0%
Vehicle fuel	0.1%	92.1%

production/processing and delivery/storage stages), which account for approximately 5 and 3% of total gas consumption, respectively [calculated from EIA (1984–2004)]. Data for gas consumed in these processes are not maintained at the monthly per state level. Therefore, the proxy coverage accounts for roughly 92% of all natural gas consumed in the U.S. as seen in Table 1.

Liquid fossil fuels present a more daunting challenge as crude oil is converted into many products, both fuel and non-fuel. From the EIA (1983–2004) publication, *Petroleum Marketing Monthly*, this method uses average daily sales data of four main types of fuel: motor gasoline (all grades), distillate fuel oils including kerosene, kerosene-type jet fuel and propane. These four products were chosen because together they best predicted the spatiotemporal distribution of total liquid consumption when analysed in a multiple regression-based model selection. In addition, they represent the most complete records of all individual petroleum products and the four top products of petroleum refining, together comprising about 86% [calculated from EIA (1983–2004)] of the U.S. petroleum market (Table 2). The daily mean sales values were multiplied by the calendar days per month to obtain monthly sales. Again, this assumes consumer changes in stock are insignificant to consumption, which may be more problematic for products such as propane.

Electrical utility coal consumption is the proxy chosen to represent CO_2 emissions from solid fossil fuels, as 87.3% of the coal consumed in the U.S. for the years 1984–1999 [calculated from EIA (1999)] was by this sector. These data are maintained by the EIA (1980–2003) in their publication, *Electric Power Monthly*.

For a given state, month and fuel type (i.e. gas, liquid and solid), the reported consumption is divided by the sum of all states' consumption for that fuel type for theentire year. The resulting quotient, state monthly consumption over national annual consumption, represents the proportion of national fuel consumed by a given state in a given month. This proportion is then multiplied by the national annual CO_2 emissions estimate by CDIAC (Marland et al., 2005) based on statistics from the U.N. for each specific fuel type. For a given state and given month, this gives an estimate of the proportion of CO_2 emissions that occurred from combustion of a particular fuel. For example, in December 2000, California consumed 213 789 MMcf (6.05×10^9 m^3) of natural gas, which is about 1% of the 20 772 594 MMcf (5.88×10^{11} m^3) of natural gas consumed in all states for the entire year (EIA, 1984–2004). Given that annual CO_2 emissions from natural gas consumption in the U.S. were 355 Tg C (Marland et al., 2005), the relative proportion of consumption implies that about 3.65 Tg C were emitted in December in California.

This procedure is carried out for all months and all fuel streams to create three separate time series for CO_2 emissions, one for each fuel type. Summing these across the different fuel types gives a fourth time series, the total monthly CO_2 emissions. For a given period a, time step i, m subgeopolitical units j and fuel type k, the total emissions (C) are expressed as follows:

$$(\mathrm{C})_{i,j} = \sum_k \frac{x_{i,j,k} T_{a,k}}{\sum_{i=1}^{n} \sum_{j=1}^{m} x_{i,j,k}},$$

where x_i is the sales or consumption value for time step i, and T is the total CO_2 emissions estimate. The application of this methodology to the U.S. produces monthly estimates for CO_2 emissions by state, so the time step i is set to one month, the period length n is assumed to equal 12 months (1 yr) and m is equal to 51 for the U.S. (50 states plus the District of Columbia). Because the monthly state proportions of consumption sum to unity, emissions estimates are mutually consistent with the CDIAC annual emissions data set, T, for the whole U.S. The application to other countries may require different values for i, n and m, based on the temporal and spatial resolution of the fuel consumption proportional data. This paper uses the elemental mass of carbon in CO_2 emissions estimates; the molecular mass can be obtained by multiplying by the factor 44/12.

Gaps in the proportional data, resulting from missing reports and in the case of the U.S., non-disclosure policies of the EIA, are filled using an interpolation strategy. When a gap is encountered, this strategy first computes the discrepancy between the reported total country consumption and the sum of the consumption from the individual states. This discrepancy is then used to fill the gap. In the case of multiple gaps within a single month, the discrepancy is apportioned according to the ratio of the means of the corresponding month from previous complete years. This procedure thus retains 'true zeros' in states that do not consume a particular fuel. For example, California, Connecticut (for most years), the District of Columbia, Hawaii, Idaho, Maine, Rhode

Table 2. Sectoral distribution of U.S. CO_2 emissions from liquid fuels (1983–2002) [calculated from EIA (1983–2004)]

Fuel type	Percentage of CO_2 emissions	Cumulative percentage
Motor gasoline	47.8%	47.8%
Distillate fuels and kerosene	23.5%	71.3%
Kerosene type jet fuel	10.0%	81.3%
Propane (LPG)	4.2%	85.5%

Table 3. Zeros filled in proportional data sets. Discrepancy represents the difference between the reported national total and the state sum, and thus the amount filled by the gap filling procedure

Fuel type	Consumption = 0 (%)	Filled (%)	Mean discrepancy (per state/per month)
Natural gas	0.72	0.72	272.25 MMcf (7.71 × 10^6 m^3)
Liquids			
Gasoline	0.01	0.01	1370 US gal (5186 l)
Distillates	0.19	0.19	38 US gal (143.7 l)
Jet fuel	6.57	4.61	302 US gal (1144 l)
Propane	7.08	5.12	129 US gal (490 l)
Solids	16.09	2.70	140 short tons (127 000 kg)

Island and Vermont consume no coal in the utilities sector, so these 'true zeros' are retained. Table 3 displays the percentage of zeros encountered in each data set, and the percentage of zeros filled by this procedure and the mean discrepancy per month per state from the national total.

3. Results

Figure 1 shows the seasonal pattern of emissions for each fuel type for the entire U.S. from 1980 to 2002 produced by the proportional method described above. Because of the varying inception dates for the beginning of data collection by the EIA, the total emissions are computed only for the years 1984–2002, representing the overlap of available proportional data sets. Table 4 summarizes the CO_2 emissions from fossil-fuel consumption in the U.S. for these years. This table includes the percentage of emissions from each fuel type, the long-term trends (the slope from least-squares regression), descriptions of the seasonal and spatial distributions and notes the states with the greatest seasonal flux for each fuel (ranked by the quotient of the standard deviation over the mean).

Natural gas is the most distinctively seasonal, with higher winter use. This suggests that natural gas is primarily used for heating in the U.S. There is also a small summer peak that is becoming more prominent in recent years due to the increased use of natural gas for electricity generation to meet the electrical demand created by air conditioning. In contrast, liquid fuels, which are predominately consumed by the transportation sector, are relatively constant throughout the year. Coal use has two peaks, a winter peak due to electric heating and a summer peak due to electricity generation for air conditioning.

These trends are also apparent in Fig. 2, showing the mean January and July emissions of each fuel type for all states over the years 1984–2002. In general, northern states have a more drastic increase in natural gas use in the winter than southern states. In contrast, the southern states have a higher demand for coal-fired electricity in the summer than northern states. Emissions from combustion of liquid fuels are relatively constant all year and the spatial distribution is highly correlated to population, with coefficient of determination equal to 0.92 for all years in the data set. Of all fuel types, the per capita use of liquid fuels is the most consistent state to state (Fig. 3). In contrast, population versus annual natural gas carbon emissions is 0.78, and for coal, this correlation drops to 0.37. The correlation between state population and total annual fossil-fuel-based emissions is 0.70. However, there are some notable outliers for per capita emissions in all fuel types. Texas and Louisiana have large petrochemical industries, so consume a disproportionately large amount of natural gas and petroleum. Alaska, with a low population and large reserves, also has disproportionately high per capita petroleum products and natural gas use. Because electricity is more readily transported than coal, electricity generation is done closer to the areas of coal production rather than population centres. States

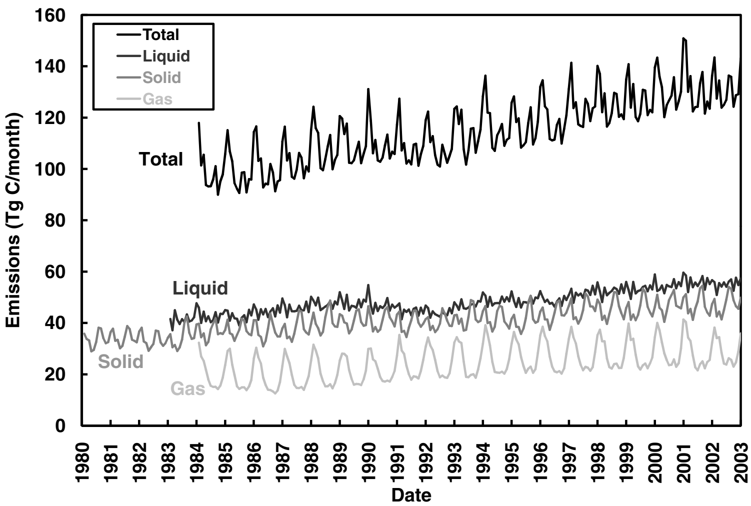

Fig. 1. Monthly U.S. CO_2 emissions estimates from fossil-fuel consumption produced by the proportional method. Tick corresponds to January.

Table 4. Summary of U.S. CO_2 emissions from fossil-fuel consumption (for the period 1984–2002)

Fuel type	Percentage of U.S. fossil fuel CO_2 emissions	Long-term trend	Seasonal trend	Spatial distribution: areas of highest emissions	Maximum spatial-seasonal flux (100% × std.*SD*/mean)
Gas	21%	Increasing 7.4 Tg yr^{-1}	Peaks in winter	Great Lakes region, TX, LA and CA	Northern states (SD, IL, OH, MN,WI, ND, MI) (52–48)
Liquids	42%	Increasing 8.3 Tg yr^{-1}	Relatively uniform; follow ength of calendar months	Strongly correlated to population	Northeast (RI, NH, MA, CT, VT) (18–15)
Solids	37%	Increasing 7.8 Tg yr^{-1}	Large peak in summer, smaller peak in winter	Bluegrass area, mountain states, WY, ND and WV	Northwest (OR, WA) (43, 30)
Total	100%	Increasing 23 Tg yr^{-1}	Large peak in winter, smaller peak in summer	Densely populated areas (Atlantic Sea Board, CA), and industrial areas (TX, LA, Great Lakes region)	Northeast (RI, CT, NH, MA, VT, NY) (19–16)

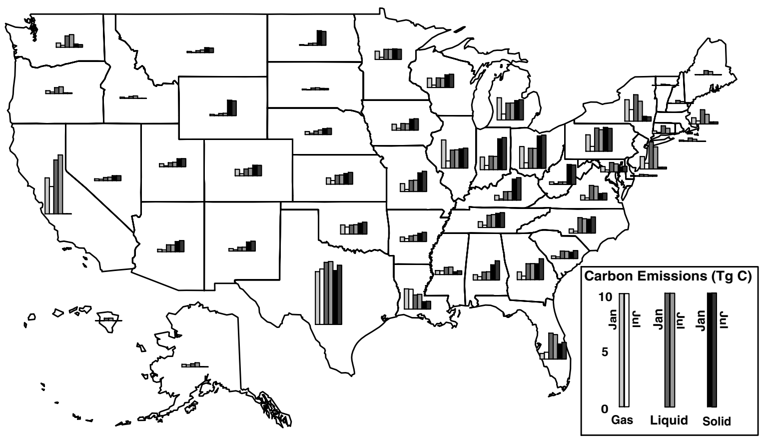

Fig. 2. Winter–summer distribution of CO_2 emissions from fossil-fuel consumption produced by the proportional method. For display purposes, DC and MD data are combined.

such as Wyoming, North Dakota and West Virginia, which are net exporters of coal-based electricity, have per capita emissions rates an order of magnitude higher than the other states.

4. Discussion

To assess the ability of the proportional method to produce reliable CO_2 emissions estimates, the results for the U.S. are compared to the results produced by independent studies. Blasing et al. (2004a,b, 2005a,b) produced emissions estimates by conducting a data-intensive accounting of all market sectors, the fuel quality (heat content) and C content of all fuel combusted, and the combustion coefficients (to account for incomplete combustion and soot production) for every state in the U.S. on an annual time scale (Blasing et al., 2005b). This full accounting method was also applied to the entire U.S. on the monthly time scale (Blasing et al., 2005a). Thus, the comparative analyses between the results from the proportional methodology and the results from the accounting methodology are performed on the temporal and spatial components separately, because the Blasing et al. approach (2005a,b) produced only annual emissions estimates on a state-to-state level (Blasing et al., 2004a); monthly emissions estimates were only able to be done for the entire U.S. (Blasing et al., 2004b).

The two methods (proportional and accounting) produce data sets that show very similar seasonal patterns of CO_2 emissions for each fuel type. The differences in the estimates, normalized by the mean total emissions for each given month, are presented in Fig. 4. In this figure, a positive result indicates the proportional method gave a higher total than the accounting method. Interannual shifts (e.g. the shift that occurs in the gas time series in Fig. 4 between 1990 and 1991) are a result of the differences between the CDIAC annual emissions time series (Marland et al., 2005) based on UN statistics for the U.S. (which the proportional method employs as the total emissions to be parsed) and the 12-month sums of the estimates produced by Blasing et al. (2004b). Blasing et al. (2004b) gives an error estimate of 3–4% for each fuel, and by a sum of squares argument, the total error would be 5–7%. The discrepancies between the seasonal estimates of the two methods, proportional and accounting, are within this range; the percentage differences are predominantly less than 3%, only once reaching as high as 5% (liquid fuels, December, 1991). Moreover, the mean absolute differences between the results from the two approaches result in a range from

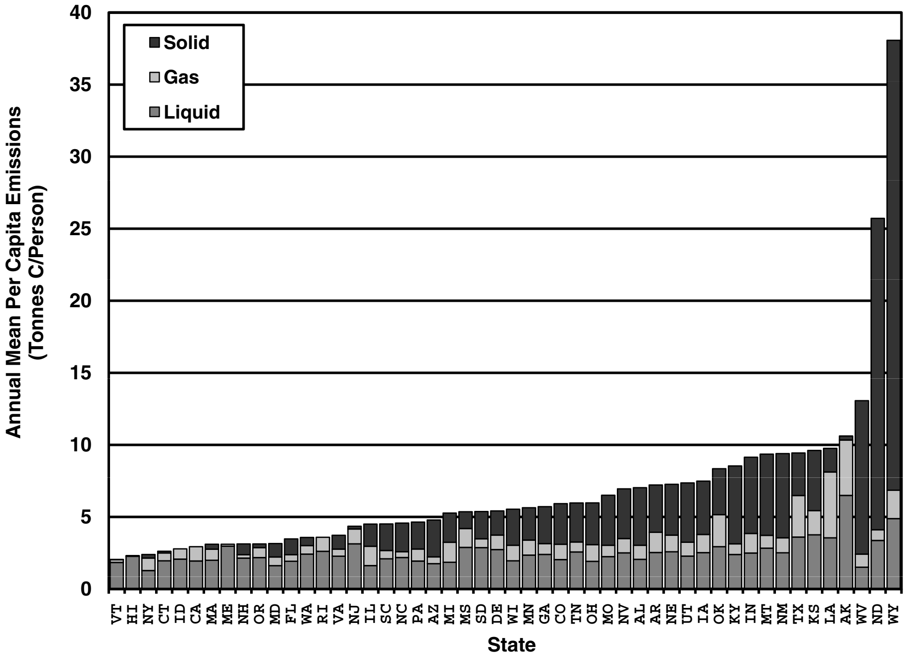

Fig. 3. Mean annual CO_2 emissions per capita, by state, produced by the proportional method (1984–2002). DC and MD data are combined. Population data from U.S. Census (2001).

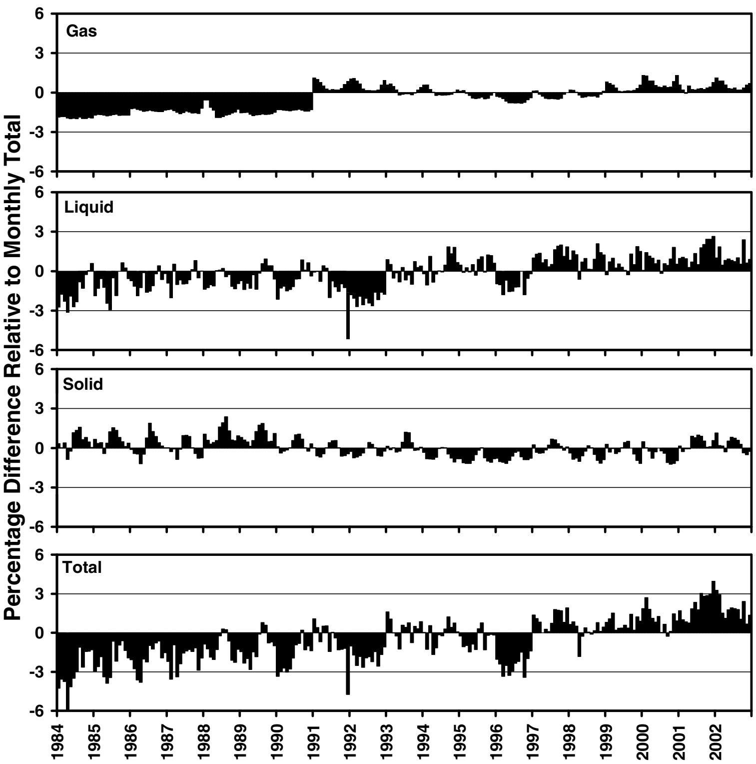

Fig. 4. Percentage differences in U.S. monthly emissions estimates between the proportional method and Blasing et al. (2004b) divided by the mean of the total emissions from the two approaches. Tick corresponds to January. Interannual shifts in discrepancies are due to differences between the CDIAC annual database (Marland et al., 2005) and the Blasing et al. (2004b) estimates.

Table 5. Mean absolute difference between proportional method and Blasing et al. (2004b) for U.S. CO_2 emissions, 1984–2002 (temporal component)

Fuel type	Absolute difference (Tg C)	Percentage relative to total U.S. emissions	Mean monthly emissions, both methods (Tg C)	Percentage relative to mean monthly emissions
Gas	0.92	0.83	24.66	3.73
Liquids	1.17	1.02	48.67	2.40
Solids	0.66	0.58	42.04	1.57
Total	1.70	1.50	115.36	1.47

about 1 Tg C for each fuel type and about 2 Tg C for total emissions. This gives percentage differences (relative to the mean of the total monthly emissions estimates of both approaches) of 1% or less for all fuel types and less than 2% for the total emissions. These statistics are summarized in Table 5.

Because no independent monthly data are available at a state-level spatial resolution, to assess the accuracy of the spatial distributions, the annual state totals for each fuel type from the proportional method are compared to the corresponding annual estimates from the Blasing et al. (2005a,b) method. Spatially, a few states represent a large fraction of the U.S. CO_2 emissions, thus the greatest absolute discrepancies between the proportional and accounting methodologies tend to occur for those states.

The top ten differences for the total CO_2 emissions per state are given in Table 6. In this table, a positive value indicates an emissions estimate from the proportional methodology that is higher than the corresponding estimate in the accounting methodology; a negative value indicates a lower emissions estimate from the proportional methodology. Pennsylvania is at the top of the list, having the largest absolute difference as well as a high percentage

Table 6. Greatest mean absolute differences between proportional method and Blasing et al. (2004a) data set for total individual state CO_2 emissions, 1984–2001 (spatial component)

State	Difference (Tg C)	Percentage difference	Percentage relative to total U.S. emissions	Mean annual total emissions, both methods (Tg C)
Pennsylvania	−14.64	−22.84	−1.06	64.10
Texas	13.94	8.39	1.01	166.24
New York	−10.81	−21.96	−0.78	49.24
Louisiana	−7.78	−16.68	−0.56	46.63
Florida	−5.54	−10.96	−0.40	50.52
Kansas	5.38	24.90	0.39	21.61
West Virginia	−4.75	−18.10	−0.34	26.25
California	−4.17	−4.54	−0.30	91.78
Missouri	3.72	11.63	0.27	32.03
Alaska	−3.71	−46.39	−0.27	7.99

difference (relative to the mean of the estimates from both data sets). The absolute and percent differences do not rank uniformly, however. For example, Texas and California both have high absolute differences but relatively small percentage differences. On the other hand, Alaska has a very high percentage difference but a low absolute difference. In general, the absolute difference is sensitive to the states with high emissions levels whereas the percentage difference is sensitive to the states with low emissions levels. Moreover, the absolute differences are highly interdependent due to the proportioning from annual state sum employed in the proportional methodology. Therefore, an underestimate in one state necessarily leads to an overestimate in at least one other state and vice versa.

To further elucidate these relative measures, weighted difference scores are employed. The difference scores in Fig. 5 represent the percentage difference relative to the given state's proportion of the total consumption. This is algebraically equivalent to the percentage difference relative to the total annual emissions for the entire U.S. In Fig. 5, the difference scores for total emissions are less than 2% for all states, indicating a good overall agreement with the Blasing et al. (2004a) data set. The largest individual fuel discrepancies occur in coal consumption emissions estimates for Pennsylvania and Texas.

In Pennsylvania, there is a large amount of coal that is consumed in non-utility uses. For the years 1984–1999, the coal used in electric utilities accounts for roughly 73.2% of the total coal use in the state [calculated from EIA (1999)], whereas the total percentage of coal used in electric utilities for the U.S. was 87.3% for those years [calculated from EIA (1999)]. This causes an underestimation of Pennsylvania emissions estimates by the proportional method presented here because the proportional variable is assumed constant for all states. A low electrical utility use in this state creates an underestimation, because in this case, the method assumes only a 12.7% (=100% – 87.3%) non-utility coal use, when this number is actually 26.8% (=100% – 73.2%) for Pennsylvania.

Overestimation of emission levels for Texas in comparison to the Blasing et al. (2004a) data set is due to three causes. First, the underestimation of states such as Pennsylvania causes an overestimation in other states to produce a national total that is consistent with the U.N. national data. Due to the use of relative proportions, this effect is more pronounced in the states with higher emissions, such as Texas. Second, there is a high proportion of electric utility coal use (about 94.9% in 1984–1999) in Texas [calculated from EIA (1999)], compared to a national average of 87.3% [calculated from EIA (1999)]. The reasoning is similar to the Pennsylvania case discussed above, except in the opposite direction. Third, the coal consumed in Texas has a heat content 31% lower than the national average (14.71 Mbtu/short ton or 17.1 MJ kg^{-1} compared to a U.S. average of 21.57 Mbtu/short ton or 25.1 MJ kg^{-1} for 1984–1999 [calculated from EIA (1984–1999)]. Because the Blasing et al. (2005b) method uses inputs in units of heat content and

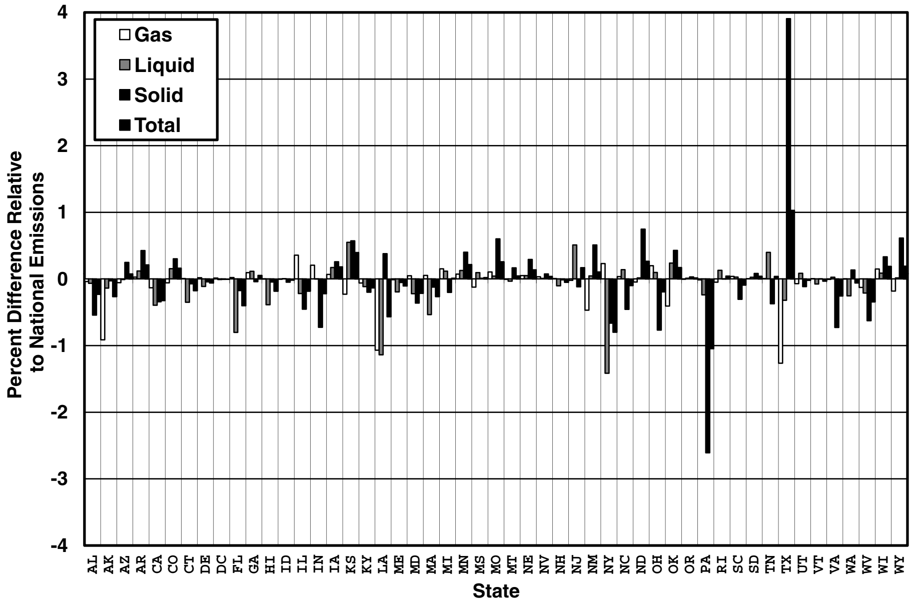

Fig. 5. 1984–2001 mean percentage difference between the proportional method estimates and Blasing et al. (2004a) relative to each state's proportion of national emissions (percentage difference to total national emissions) per fuel type.

specifically accounts for this lower heat content, this creates a lower estimate of CO_2 emissions relative to the proportional methodology, which does not incorporate this state specific information. Differences in C content can also impact the estimates, but in this case, the C content of the coal in Texas is essentially equivalent to the national average (212 lbs CO_2/Mbtu or 24.9 g C $(MJ)^{-1}$ versus a national average of 209 lbs CO_2/Mbtu or 24.5 g C $(MJ)^{-1}$ for the years 1984–1999; only about 1.5% higher than the national average) [calculated from EIA (1999)] (English units presented above are industry standards).

When the distribution is heavily skewed, the use of relative proportions produces a phenomenon where as the point estimates increase, the percentage error associated with those points also tends to increase [a.k.a. heteroscedastic (Neter, 1996)]. For example, Pennsylvania and Texas are the two leading coal consumers in the U.S. and these states have the largest discrepancies for coal combustion data. Totalling over several types of fuel and larger areas helps alleviate this problem. The national total consumption value from the CDIAC database has an error rate of only 3–4% (Marland et al., 1989), therefore, at higher levels of spatial aggregation the error rates will diminish. In other words, though the proportions may be slightly incorrect with respect to each other, all fossil-fuel consumption in the country will be accounted for when the proportions are multiplied by the national total. Finally, judicious choice of proportional variables will lead to satisfactory results. In this case, the use of electrical utility coal consumption as the proportional variable resulted in a maximum of 4% error in the spatial distribution of emissions (relative to national emissions from coal consumption) when compared with an independent method. This is an acceptable level or error for a methodology that can be applied to other countries with less robust data collection commitments than the U.S.

5. Conclusions

The proportional method presented here produces similar distributions of CO_2 emissions, both temporarily and spatially, when compared to the results from the Blasing et al. (2005a,b) method. The proportional method tends to perform best when the distribution it attempts to estimate is relatively uniform. When the distribution is skewed, which can be the case with distributions across states/provinces, the proportional method is apt to produce larger errors in the emissions estimates for the geopolitical regions with higher emissions. For this reason, the uncertainty increases in point estimates (e.g. the emissions from a specific fuel for a given state during a given month) when the distribution is greatly skewed. This is usually less problematic in the temporal component than the spatial component as the seasonal distribution of fuel use tends to be less skewed than the spatial distribution. The close agreement in the temporal component between the results produced by the proportional methodology and the Blasing et al. (2004b) data set suggests that the proportional methodology can be applied confidently to other countries to produce accurate time series of seasonal CO_2 emissions from fossil-fuel consumption.

The proportional method presented here can be susceptible to data errors and missing records. Because the effectiveness of any method is dependent on the quality of the data inputs, incorrect source data values will diminish the capacity of any method to estimate emissions. The proportional method uses comparatively little data and hence erroneous data points will have a more substantial impact on the overall estimates. In addition, problems associated with improper scaling or systematic bias in the input data sets will be exacerbated in the CO_2 emissions estimates that this method produces. On the other hand, the proportional method minimizes some of the effect of inaccurate data points upon aggregation by apportioning the error overall point estimates.

Many aspects of the proportional method make it an attractive alternative to the data-intensive, bottom-up accounting methods. The proportional method is computationally simple. The principle of utilizing relative proportions is applicable on many different temporal and spatial scales, allowing estimates at very detailed or broad temporal and spatial resolutions (although the uncertainty in the estimates increases at finer spatial and temporal resolutions). The ultimate benefits of the proportional method are its simplicity, wide applicability, capacity to compensate for errors and its ability to estimate the temporal and spatial distribution of emissions from comparatively very little data. With the scarcity of available records and data for some countries, this method is particularly attractive and perhaps the only currently available option to produce monthly estimates for the CO_2 emissions in those countries. It provides a means to discern the pattern of emissions where a lack of data renders other methods inapplicable.

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