The Temporal and Spatial Distribution of Carbon Dioxide Emissions from Fossil-Fuel Use in North America

J. S. GREGG

Department of Geography, University of Maryland, College Park, College Park, Maryland

L. M. LOSEY

Department of Space Studies, University of North Dakota, Grand Forks, North Dakota

R. J. ANDRES, T. J. BLASING, AND G. MARLAND

Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee

ABSTRACT

Refinements in the spatial and temporal resolution of North American fossil-fuel carbon dioxide (CO_2) emissions provide additional information about anthropogenic aspects of the carbon cycle. In North America, the seasonal and spatial patterns are a distinctive component to characterizing anthropogenic carbon emissions. The pattern of fossil-fuel-based CO_2 emissions on a monthly scale has greater temporal and spatial variability than the flux aggregated to the national annual level. For some areas, monthly emissions can vary by as much as 85% for some fuels when compared with monthly estimates based on a uniform temporal and spatial distribution. The United States accounts for the majority of North American fossil carbon emissions, and the amplitude of the seasonal flux in emissions in the United States is greater than the total mean monthly emissions in both Canada and Mexico. Nevertheless, Canada and Mexico have distinctive seasonal patterns as well. For the continent, emissions were aggregated on a $5° \times 10°$ latitude–longitude grid. The monthly pattern of emissions varies on both a north–south and east–west gradient and evolves through the time period analyzed (1990–2007). For many areas in North America, the magnitude of the month-to-month variation is larger than the total annual emissions from land use change, making the characterization of emissions patterns essential to understanding humanity's influence on the carbon cycle.

1. Introduction

With the increasing concentration of carbon dioxide (CO_2) in the atmosphere and its implications for global climate (Solomon et al. 2007), there is a growing need for developing a more detailed description of the various components within the global carbon cycle. Scientific inquiries and analyses now call for data on anthropogenic CO_2 emissions at spatial and temporal scales finer than the countries and years at which emissions inventories have traditionally been conducted. Mechanistic understanding of carbon cycling relies on mathematical modeling and on detailed measurements at monitoring sites (Gurney et al. 2002, 2005) to determine carbon fluxes among the terrestrial biosphere, atmosphere, and ocean (Wigley 1993). Gurney et al. (2005) revealed that, for example, the lack of detailed information on the seasonal cycle of anthropogenic emissions has a large impact on results derived from inverse modeling of atmospheric concentrations and interchanges with the biosphere. The purpose of this paper is to provide detailed information on the monthly and subnational spatial distribution of fossil-fuel CO_2 emissions in North America. We know that fossil-fuel consumption varies widely across North America and that there are temporal variations with season and with the other patterns of weather change (Blasing et al. 2005a,b). Recognizing these variations allows us to describe more accurately the biophysical and human processes that are involved in the global carbon cycle.

Corresponding author address: Jay Gregg, Department of Geography, University of Maryland, College Park, College Park, MD 20742.
E-mail: gregg.jay@gmail.com

Nearly four-fifths of global anthropogenic carbon emissions are from the combustion of fossil fuels. There are at least five available datasets for global annual emissions of CO_2 from fossil-fuel use by country: four that cover most countries (Energy Information Administration 2004; International Energy Agency 2007; Boden et al. 2009; Olivier et al. 2005) and one compilation of individual national reports that covers many of the largest-emitting countries (United Nations Framework Convention on Climate Change 2005). The International Energy Agency (2008), United Nations Framework Convention on Climate Change (2005), and Olivier et al. (2005) datasets contain information on emissions by market sector (commercial, residential, industrial, etc.). All of these emissions inventories are at the spatial and temporal scale of countries and years. Sectoral emissions data for the United States are maintained by the U.S. Environmental Protection Agency (Environmental Protection Agency 2009). Blasing et al. (2005a,b) have used state-level energy data to estimate annual carbon emissions for the 50 U.S. states and for the total United States by month but were not able to estimate emissions by month and state because of limitations in the resolution of the underlying energy consumption data.

Prior studies have used various methods to estimate the geographical distribution of emissions at finer levels of detail. Andres et al. (1996), Brenkert (2009), and Olivier et al. (2005) attempted to describe anthropogenic CO_2 emissions on a 1° latitude by 1° longitude grid. In these studies, the CO_2 emissions estimates were only available on an annual time step, at best, so no discernment of seasonal patterns of emissions was possible. Also, the CO_2 emissions estimates in these studies relied mostly on population density to distribute emissions within the political boundaries of each country, the scale at which energy data are traditionally collected. Blasing et al. (2005a) have demonstrated that population density may be a useful first approximation for the distribution of emissions within countries but that it has serious limitations—strikingly so when, for example, electricity is generated from coal combustion in sparsely populated areas and then transmitted by a regional electricity grid.

To estimate the seasonal flux in emissions, Erickson et al. (2008) employed a Fourier series on a preliminary subset of the data presented here and extrapolated to get a rough estimate of global seasonality in fossil-fuel CO_2 emissions. Though the study's conclusions were not based on a comprehensive database of actual emissions, it nevertheless demonstrated that the temporal variability in fossil-fuel CO_2 emissions typical of mid-northern latitudes could significantly impact estimates of other components of the carbon cycle as well as atmospheric inversion models (Erickson et al. 2008).

The Vulcan inventory (Gurney et al. 2009) contains the most detailed estimates for fossil-fuel CO_2 emissions, produced by combining multiple detailed datasets and in some cases using other pollutant gases as well as road and census data as proxies for CO_2 emissions. The Vulcan inventory includes both point and nonpoint sources of CO_2, at temporal scales of less than 100 m^2 on an hourly time step (Gurney et al. 2009). This approach shows great promise, but its scope is currently limited to the conterminous United States and is only available for 2002.

Gregg and Andres (2008) have developed an approach for capitalizing on a variety of data sources to disaggregate national, annual emissions estimates into a consistent dataset of emissions at monthly and subnational scales. Here, we apply this approach to describe the spatial and temporal distribution of CO_2 emissions among the states and provinces of the United States and Canada and the temporal distribution of emissions in Mexico (data limitations preclude finer spatial breakdown there). We then discuss the results, their causes as related to energy use patterns, and the global carbon cycle. As of 2004, all 3 countries in North America are within the top 11 countries in the world in terms of annual CO_2 emissions from fossil-fuel consumption (Boden et al. 2009). Fossil-fuel emissions from North America make up roughly one-quarter of current global annual emissions and nearly one-third of global cumulative emissions since 1751 (Marland et al. 2007).

2. Methods

Most countries collect some data on energy production, consumption, and trade. These data can be used, along with data on fuel chemistry and fuel use, to estimate CO_2 emissions from fossil fuels by country and by year. To estimate emissions on finer temporal and spatial scales, in the ideal case the CO_2 emissions would be calculated in a similar way from complete data on consumption of all fossil fuels from all economic sectors. To do this with accuracy, we would need to know the amount and quality of each fuel consumed, when exactly it was consumed, and what fraction of it is consumed in ways that do not lead to oxidation of the fuel (incomplete combustion, sequestration of carbon in products such as asphalt or plastics, etc.), from all countries, provinces, and states. For example, using fuel consumption data from the Energy Information Administration (EIA), Blasing et al. (2005b) created a detailed dataset of monthly emissions from the United States and annual emissions for each state (Blasing et al. 2005a). However, such an approach requires a level of detail in the underlying energy data that is typically not available

for most countries. These detailed data are available at the annual level for many developed countries, but they are typically not available at the subnational level because collecting and managing detailed monthly energy data by subnational region is labor intensive and expensive. Even for the United States, the data are not available to produce seasonal patterns for each state using this approach.

We have adopted an approach that capitalizes on extensive data collections where they exist but that also allows us to estimate emissions at finer spatial and temporal scales even when complete, detailed data on fuel consumption are not available. When lacking data on fuel consumption, close estimates can be made from fuel supply data by calculating "apparent consumption" as the sum of production and imports less the sum of exports and changes in stockpiles (Marland and Rotty 1984). When these data are not available, data on fuel sales for domestic consumption can be used. Fuel sales data can provide a factor for apportioning consumption even if all fuel is not accounted for, although they do raise uncertainties concerning fuel storage between the times of purchase and combustion of a fuel. The apportioning can be done with data on only a fraction of total consumption but will generally be more accurate the greater the fraction of total consumption that is represented.

To estimate emissions subnationally, the apportioning method uses data on the major energy consumption sectors of a country's economy to parse annual national emissions both spatially and temporally (Gregg and Andres 2008). In a trial using the U.S. data, this approach was shown to produce estimates that were within the uncertainties of the underlying data (Gregg and Andres 2008). The method was also applied to Brazil, showing its applicability despite gaps in the underlying data (Losey et al. 2006). The basic approach used here is detailed in Gregg and Andres (2008), though in the current study we have used annual state and provincial consumption data to estimate better the state-to-state (for the United States) and province-to-province (for Canada) spatial distribution of emissions. No subnational data were available for Mexico.

For this analysis, fuel consumption statistics were taken from the 2008 British Petroleum (BP) *Statistical Review of World Energy* (available online at http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622). Annual carbon emissions estimates T for year a and fuel k were calculated as

$$(T_{a,k}) = \text{Consumption}_{a,k} \text{ (Mtoe)}$$
$$\times \text{CarbonConversion}_k \text{ (TgC Mtoe}^{-1})$$
$$\times \text{FractionOxidized}_k$$

[BP reports fuel consumption in million metric tons of oil equivalent (Mtoe), which is equal to 42×10^{15} J]. The carbon conversion rates were based on data from the EIA State Energy Data System (SEDS; available online at http://www.eia.doe.gov/emeu/states/_seds.html). For natural gas and coal, the carbon conversion factors were assumed to be the same for all countries. For petroleum, the weighted average of consumption of petroleum products is calculated for each country to determine the mean national carbon content of all petroleum products consumed. The carbon conversion and fraction oxidized factors are given in Table 1.

Monthly data on fuel consumption or sales were collected for each fossil-fuel type from government and industry statistical reports. Table 1 shows the fraction of each country and fuel category represented by the monthly consumption or sales data used. We used the monthly consumption or sales data to parse the national total carbon emissions among states/provinces and months. Missing monthly data points were filled using an interpolation strategy, which first calculated the discrepancy between the national monthly total and the sum of the existent data points for the given month, and used the difference to fill the missing datum. In months for which there was more than one missing datum, the discrepancy was apportioned by the relative weights of the mean values of the corresponding month and states/provinces in previous complete years. The apportioning approach is such that emissions-estimates totals are mutually consistent with the annual emissions dataset when summed both spatially and temporally.

3. Results

a. The monthly distribution of North American CO₂ emissions

Figure 1 shows the monthly time series of CO_2 emissions for each fuel type for North America, the United States, Canada, and Mexico for the years 1990–2007. There is roughly an order-of-magnitude difference between emissions in the United States versus emissions in Canada or Mexico, and thus the pattern of total North American emissions (Fig. 1a) closely resembles that of the United States (Fig. 1b). In addition, the rate of annual growth in emissions for the continent is also dominated by the United States, a large portion of which is from increased petroleum consumption (Table 2). For all three countries, more emissions are from petroleum fuels than from natural gas or coal, but the strong seasonality of the emissions from natural gas and coal in the United States and Canada is clearly reflected in the national and regional totals.

TABLE 1. Summary of data sources, emissions portfolio, and percentage coverage of monthly proxy data relative to the 2008 BP *Statistical Review of World Energy* (see section 2 for URL) annual data for 1990–2007.

	United States[a]	Canada[b]	Mexico[c]
Natural gas			
Percentage of total annual fossil carbon emissions	19	29	21
Monthly proxy data	Total deliveries	Direct and utility sales	Domestic sales
Percent of annual consumption represented	90	80	56
C conversion (TgC Mtoe^{-1})	0.5742	0.5742	0.5742
Fraction oxidized[d]	0.98	0.98	0.98
Petroleum			
Percentage of total annual fossil carbon emissions	42	47	71
Monthly proxy data	Sales of gasoline, distillates, jet fuel, and propane	Domestic sales of all refined petroleum products	Domestic sales of all refined petroleum products
Percent of annual consumption represented	77	86	100
C conversion (TgC Mtoe^{-1})	0.7798	0.7773	0.7595
Fraction oxidized[d]	0.918	0.918	0.918
Coal			
Percentage of total annual fossil carbon emissions	39	24	8
Monthly proxy data	Coal consumption by electric utilities	Conventional steam electricity, weighted by provincial coal-based electricity	Flat distribution assumed
Percent of annual consumption represented	84	90, from Stone (2007)	Not available
C conversion (TgC Mtoe^{-1})	1.0222	1.0222	1.0222
Fraction oxidized[d]	0.982	0.982	0.982
Total			
Percent of annual consumption represented	82	85	82

[a] The U.S. fossil-fuel consumption data are maintained by the U.S. Department of Energy EIA [for coal from 1980 to 2008, see "Consumption of Coal for Electricity Generation by State" in *Electric Power Monthly* (288 issues); for petroleum from 1983 to 2008, see "Prime Supplier Sales Volumes of Motor Gasoline by Grade, Formulation, PAD District, and State, Prime Supplier Sales Volumes of Aviation Fuels, Propane, and Residual Fuel Oil by PAD District and State, and Prime Supplier Sales Volumes of Distillate Fuel Oils and Kerosene by PAD District and State" in *Petroleum Marketing Monthly* (264 issues); for natural gas, see "Natural Gas Deliveries to All Consumers, by State, Form EIA-857, Monthly Report of Natural Gas Purchases and Deliveries to Consumers" in *Natural Gas Monthly* (252 issues)]. Natural gas data include all deliveries less losses from distribution and processing, representing approximately 90% of the gas consumed in the United States (Gregg and Andres 2008). Petroleum fuel data are from average daily sales of gasoline (all grades), distillate fuels (including diesel fuel), kerosene-type jet fuel, and propane. Monthly data on utility consumption of coal are used as a proxy for total coal consumed in the United States. Annual state fuel consumption data are from the EIA SEDS (available online at http://www.eia.doe.gov/emeu/states/_seds.html). The relative state-to-state proportions were projected for the years 2006–07 based on 2005 data.

[b] Canada energy data are maintained by Statistics Canada [for monthly electric power statistics from 1977 to 2007 (Table 127-0001), see, e.g., online at http://www.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=57-001-X&chropg=1&lang=eng; for annual electricity generated from fossil fuels (GW h) from 1977 to 2007 (Table 128-0014), see, e.g., online at http://cansim2.statcan.gc.ca/cgi-win/cnsmcgi.exe?Lang=E&RootDir=CII/&ResultTemplate=CII/CII___&Array_Pick=1&ArrayId=1280014; for monthly supply and disposition of refined petroleum products (m^3) from 1977 to 2007 (Table 134-0004), see, e.g., online at http://cansim2.statcan.gc.ca/cgi-win/cnsmcgi.exe?Lang=E&RootDir=CII/&ResultTemplate=CII/CII___&Array_Pick=1&ArrayId=1340004; for monthly supply and disposition of natural gas (m^3) from 1985 to 2007 (Table 131-0001), see, e.g., online at http://cansim2.statcan.gc.ca/cgi-win/cnsmcgi.exe?Lang=E&RootDir=CII/&ResultTemplate=CII/CII___&Array_Pick=1&ArrayId=1310001; for monthly coal consumption by province from 1992 to 1996, see *Energy Statistics Handbook* (48 issues). Natural gas data include the sum of total utility sales and total direct sales of gas for each province by month. For petroleum, monthly provincial domestic sales data for all refined petroleum products are used. Statistics Canada at one time estimated monthly provincial coal consumption data. This series was terminated in 1996; now all coal consumption statistics are aggregated to the national level on an annual time step per nondisclosure legal agreements with the Canadian coal industry. Instead, we use monthly provincial data for conventional steam electricity generation (MW h), scaled by annual provincial data on coal electricity generation. For each province, the mean value for the years 2002–06 of this scaling factor is applied to the monthly conventional steam electricity time series.

[c] Mexico sales data for natural gas and petroleum consumption from 1990 to 2005 are from Petróleos Mexicanos (PEMEX; see online at http://www.ri.pemex.com/index.cfm?action=content&sectionID=21&catID=12177). Coal consumption in Mexico is comparatively small; there are only two coal-fired power plants in Mexico, both near the U.S. border, with a total capacity of 2600 MW, representing only 7% of Mexico's total electricity generation capacity (North American Energy Working Group 2009). No monthly data are publically available for coal consumption at these facilities, and we therefore assume that these power plants provide base-load power and that emissions from coal consumption in Mexico have a uniform temporal distribution.

[d] Fraction oxidized values are from Marland and Rotty (1984) and are available online at CDIAC (http://cdiac.ornl.gov/pns/convert.html).
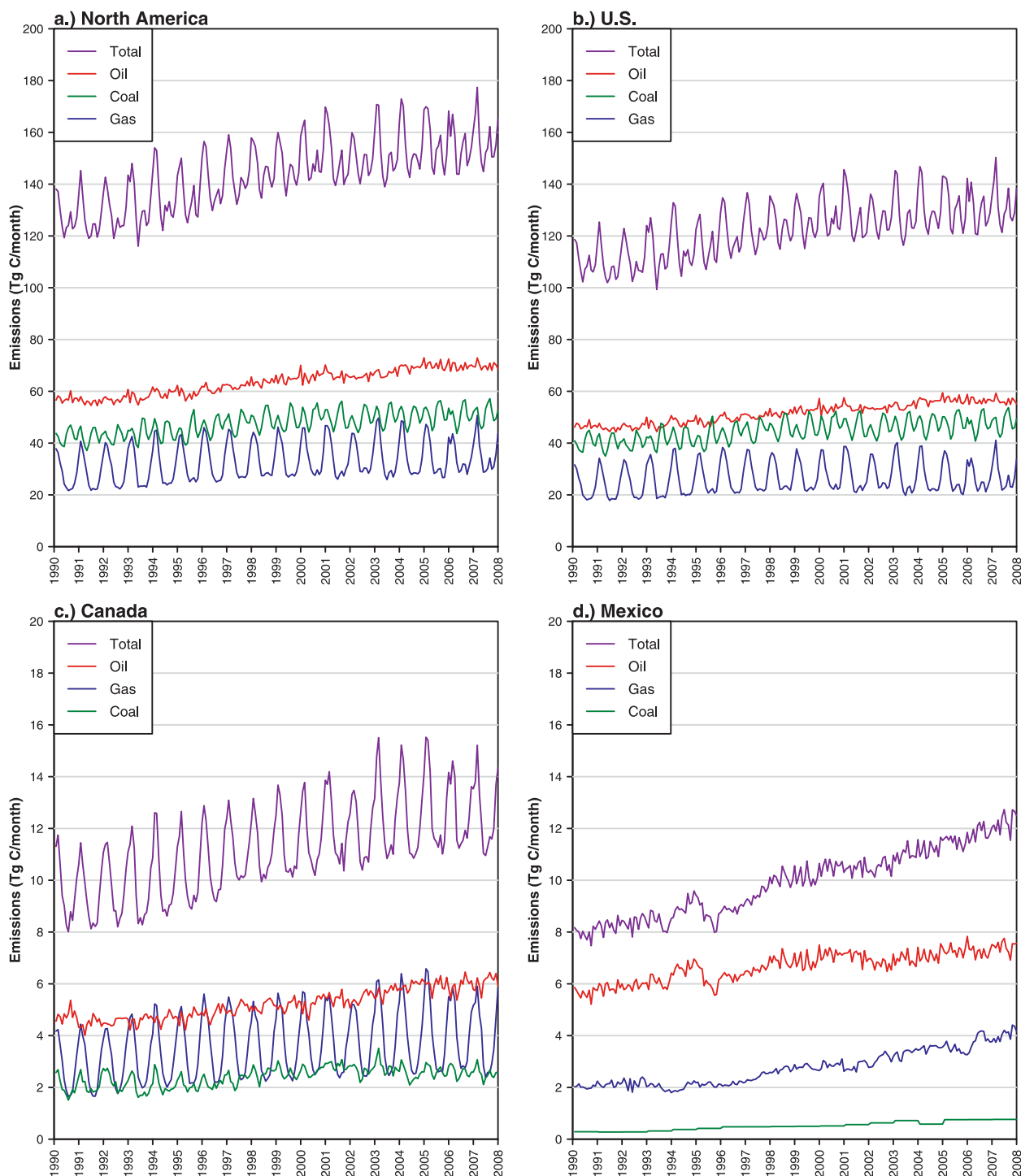
FIG. 1. Monthly fossil-fuel carbon emissions for (a) North America, (b) the United States, (c) Canada, and (d) Mexico, by fuel type. Note that the Canada and Mexico plots use a different scale than the North America and U.S. plots.

In the United States, there is a general upward trend in emissions from all fuel types (Fig. 1b; Table 2). Emissions from natural gas are the most distinctively seasonal, peaking in the winter. This pattern is evolving through time, with a growing secondary summer peak. Emissions from petroleum consumption are relatively constant throughout the year on the national scale. There is a slight peak in December, in part from increased gasoline

TABLE 2. Mean annual increase (i.e., slope) in fossil-fuel CO_2 emissions, 1990–2007 (TgC yr^{-2}). Columns and rows may not sum exactly because of rounding.

Emissions source	North America	United States	Canada	Mexico
Natural gas	4.7	2.4	0.9	1.5
Petroleum	10.8	8.4	1.2	1.2
Coal	6.9	6.1	0.5	0.4
Total	22.4	16.8	2.6	3.0

and jet fuel consumption: gasoline consumption and jet fuel consumption in the United States are respectively 9% and 7% higher on average in December versus January. Summer driving increases emissions from the transportation sector, but this is offset by a decrease in heating-fuel use in the summer (discussed below). The national seasonal distribution of emissions from coal use is bimodal, with peaks in both winter and summer. An analysis by Pétron et al. (2008) has shown a correlation between emissions from power plants and temperature, with a minimum of emissions at approximately 10°C, increases in emissions with temperatures below 10°C (suggesting increased heating demand), and increasing emissions with increasing temperature (suggesting higher air conditioning use).

Though fossil-fuel-based CO_2 emissions in Canada are considerably lower than those of the United States, the seasonal patterns of emissions are similar, with higher emissions in winter than in summer (Fig. 1c). Like in the United States, petroleum use is not highly seasonal on the national scale. In Canada, approximately 80% (by energy content) of liquid fuel is consumed by the transportation sector (41% gasoline, 31% diesel, and 8% aviation fuel). There is a slight summer peak in most areas, though some fuel oil is consumed in the winter. The seasonal distribution of natural gas consumption is also similar to that in the United States, but with an even greater relative seasonal amplitude. Absent, however, is the small summer increase that has begun to appear in the U.S. emissions patterns for natural gas. Coal represents a smaller proportion of the energy portfolio of Canada, and no conspicuous summer peak in emissions from coal combustion is evident. The pattern in coal-based CO_2 emissions is evolving to a flatter seasonal distribution—in particular, since the mid-1990s.

Petroleum constitutes the majority of Mexico's energy portfolio, and the total of fossil-fuel CO_2 emissions closely follows the pattern of petroleum consumption (Fig. 1d). The mean annual rate of growth in emissions is 2.5% (slope divided by mean emissions, 1990–2007), a rate larger than both the United States (1%) and Canada (1.5%), though less than the United States in

terms of absolute growth (Table 2). Coal consumption is also rapidly increasing (about 6% per year), although absolute emissions from coal consumption in Mexico are still minimal. Electricity generation has been growing steadily in Mexico for the last 30 years, predominately from petroleum and natural gas power plants. As of 2000, Mexico dramatically increased its use of natural gas for electricity generation, displacing some petroleum use in this sector (International Energy Agency 2009).

b. The spatial distribution of North American CO_2 emissions

The CO_2 emissions differ widely among U.S. states and Canadian provinces—in total magnitude, in per capita terms, and in the seasonal distribution. Mexico does not maintain publicly available data that would allow estimation of emissions from Mexico by state. Figures 2 and 3 characterize (for the United States and Canada, respectively), the magnitude, per capita distribution, and seasonal variation in CO_2 emissions by state or province. For the sake of illustration, mean 1990–2007 emissions values are shown for the three winter months (December, January, and February) and for the three summer months (June, July, and August). The distributions for the three fuel types reflect the magnitude of energy demand, the nature of energy demand, and the access to resources. For example, coal consumption is higher in states such as North Dakota, Wyoming, and West Virginia where coal is mined, natural gas consumption is higher in Alberta, Canada; Louisiana; and Texas where it is produced. Coal consumption is small in Alaska, Hawaii, and northern Canada where access to this resource is limited. Seasonal distribution for natural gas is more extreme in northern climates where it is used for heating.

In Figs. 2 and 3, we also calculate the 2000 per capita emissions for each state and province using population data from U.S. Census Bureau (2009), Statistics Canada (2009), and Instituto Nacional de Estadística y Geografía (2009). The national annual per capita emissions in the United States and Canada are similar (5.5 and 4.6 metric tons of carbon per person per year, respectively); Mexico's were much lower at 1.3 tons of carbon per person per year. The spatial distribution of CO_2 emissions from combustion of petroleum fuels is highly correlated with population distribution; of all fuel types, the per capita use of petroleum fuels is the most similar from state to state and province to province. The exceptions to this are states and provinces with large petrochemical and refinery use (Texas, Louisiana, and Alberta), leading to higher per capita emissions from petroleum in these states. Alaska, with a low population and high rate of energy production, also has high per capita emissions from petroleum (as well as gas) consumption. Despite
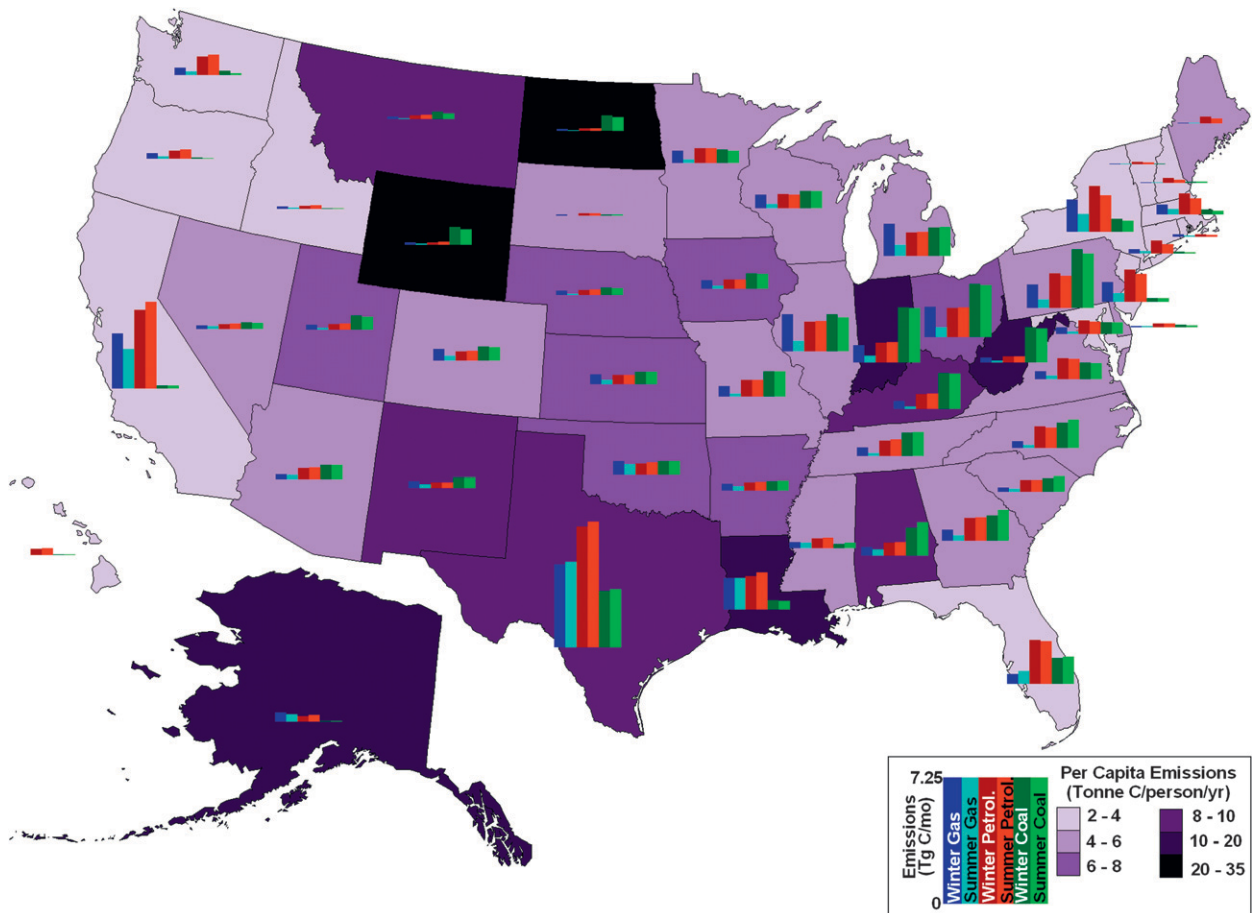
FIG. 2. Mean winter and summer spatial fossil-fuel carbon emissions and per capita emissions in the United States, 1990–2007. Population data are from U.S. Census Bureau (2009).

petroleum use being relatively constant on a per capita basis, there is nevertheless high variability from state to state (province to province) because of natural gas and coal availability. For example, total annual per capita emissions are highest in the coal-producing states of Wyoming (33.9 tons of carbon per person per year) and North Dakota (21.1 tons of carbon per person per year). Alberta and Louisiana, where natural gas resources are concentrated, also have relatively high per capita emissions (15.5 and 12.8 tons of carbon per person per year, respectively).

c. The temporal and spatial distribution of North American CO_2 emissions

In Figs. 4 and 5, the monthly patterns of emissions are characterized as a function of latitude and longitude. These were calculated by sorting each U.S. state, Canadian province, and the national total of Mexico into classes based on the nearest latitude and longitude line to the political unit's geographic centroid (latitude and longitude lines can be seen in Fig. 7, described below).

Using the values from 1990 to 2007, the mean (weighted by state and provincial total emissions per fuel type) monthly distribution was calculated for each latitude and longitude group. These were then compared with a hypothetical flat-line distribution to determine the percent error that would result from assuming a uniform monthly distribution for emissions. This gives an approximate spatial distribution of emissions and is done to illuminate and summarize general spatial trends in the emission patterns, although in some areas the spatial resolution of the underlying data may be greater or less than the corresponding latitude and longitude.

Again, natural gas has the largest seasonal amplitude of all fuel types, varying as much as 85% from a uniform distribution at 50°N. In the southernmost latitudes, the annual peak occurs in the summer (for electricity generation), and as one progresses north the seasonal peak moves to the winter months as the number of heating degree-days increases. The amplitude is dampened in northern latitudes, and overall usage is generally lower because of smaller populations and lack of access to
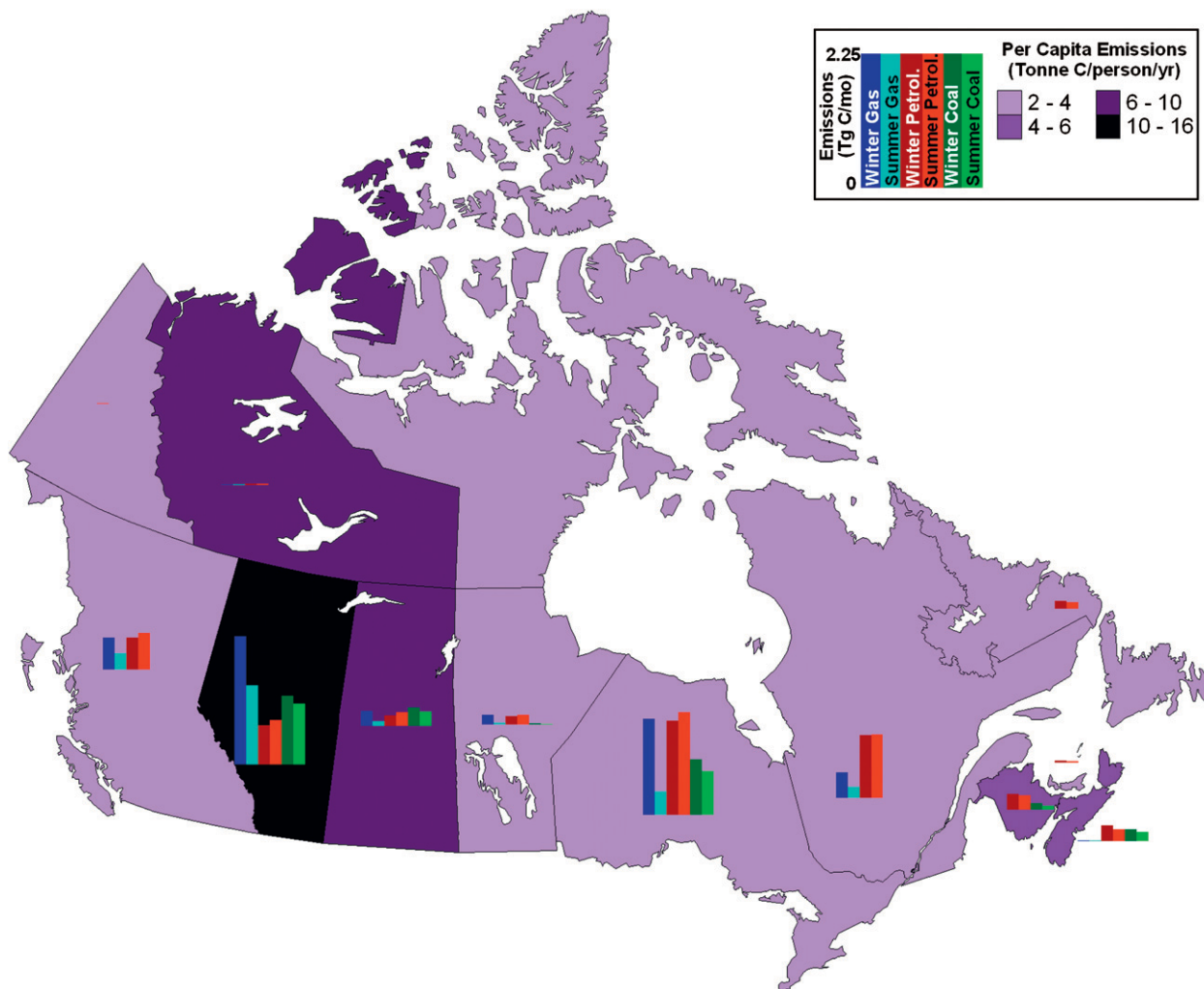
FIG. 3. Mean winter and summer spatial fossil-fuel carbon emissions and per capita emissions in Canada, 1990–2007. Population data are from Statistics Canada (2009).

natural gas. The seasonal amplitude follows a similar pattern on an east–west gradient, having a more distinct winter peak toward the center of the continent, correlated with climate extremes. The exception to this trend is at 100°W, which is dominated by Mexico and Texas. The mild winters in Mexico and Texas and the large amount of petrochemical use in Texas flatten the distribution at this longitude.

Emissions from petroleum have the smallest amplitude in the seasonal cycle but can still vary as much as 20% from a uniform distribution. However, contrasting with the emissions from other fuel types, emissions from petroleum have a seasonal pattern that increases in amplitude as a function of latitude and peaks in late summer at 60°–70°N. This is a result of an increase in transportation in Alaska during the summer months; gasoline and jet fuel consumption in Alaska are on

average 50% and 38% higher (respectively) in July versus January. Although the pattern of petroleum emissions in Fig. 1 shows little seasonality for North America, emissions from petroleum use are seasonal at both the most extreme east and west longitudes. In the east (60°–70°W), there is a winter peak due to increases in the use of distillate fuels for heating; the mean increase in distillate fuel consumption in January versus July in New England (Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont) is 222% while the mean increase for the rest of the United States is only 11%. In the west (130°–160°W) there is a distinct summer peak from increased consumption of gasoline in Alaska. When aggregated to the national or continental level, these regional patterns offset each other and the finescale variability is lost.
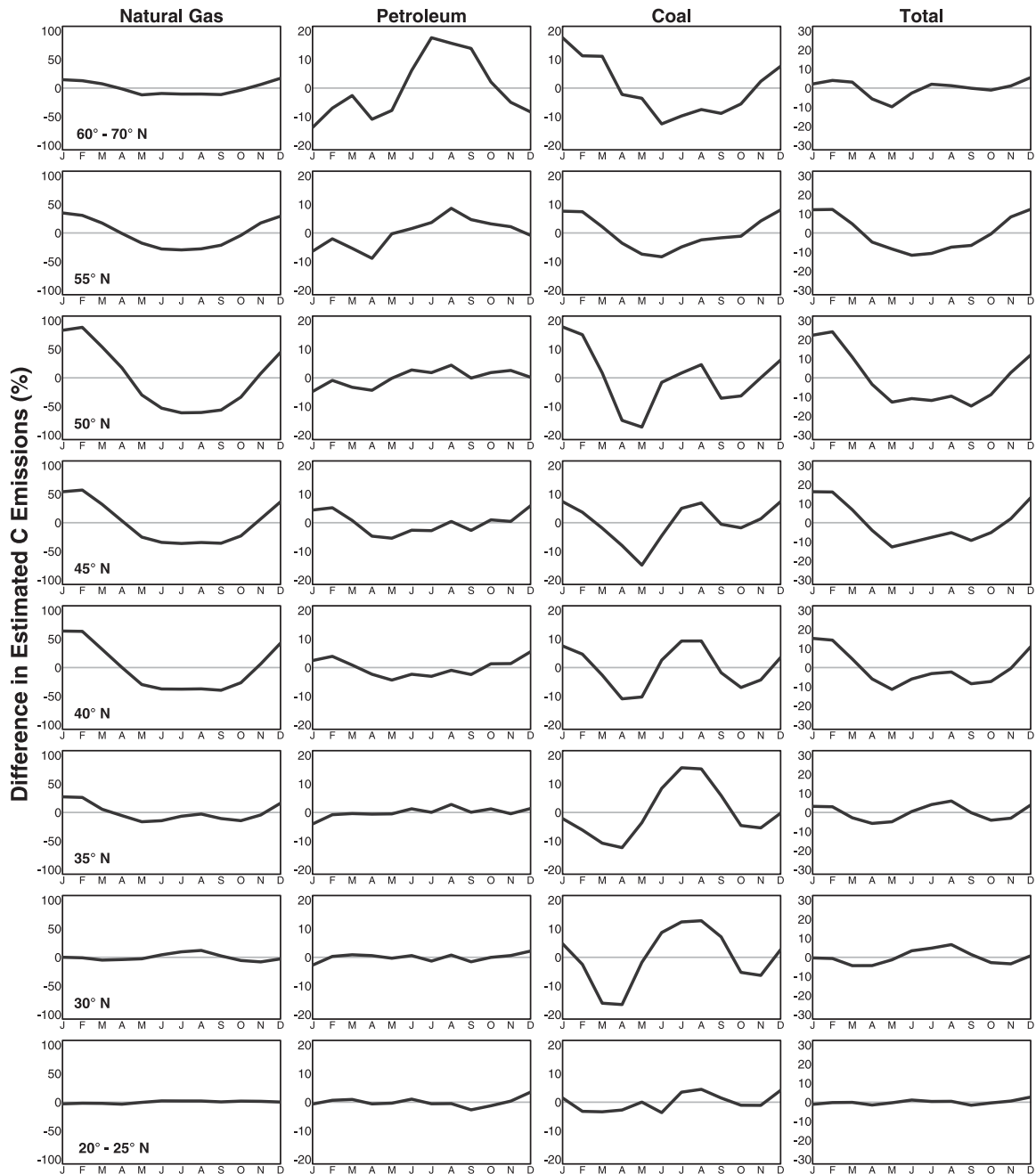
FIG. 4. Latitudinal mean monthly distribution of emissions by fuel type. The difference from a uniform distribution is shown, given in percent. Note the different vertical scales.

Coal produces a pattern of emissions that peaks predominately in the summer at low to midlatitudes and predominately in the winter at higher latitudes. The seasonal pattern for coal creates differences of up to 20% from a flat-line distribution. Emissions from coal consumption are seasonal in North America with the highest peak at 35°N and 80°W, a distinctive summer peak. These coordinates represent the Appalachian re-

gion in the United States, where coal is used to generate electricity. As one moves north, the seasonal pattern changes to peak in the winter months. In a similar way, the summer peak diminishes as one moves west. The area 130°–160°W is dominated by Hawaii and Alaska, where little coal is consumed and the data are more erratic.

In general, total emissions have the largest amplitude of variability, 25% different than a uniform distribution
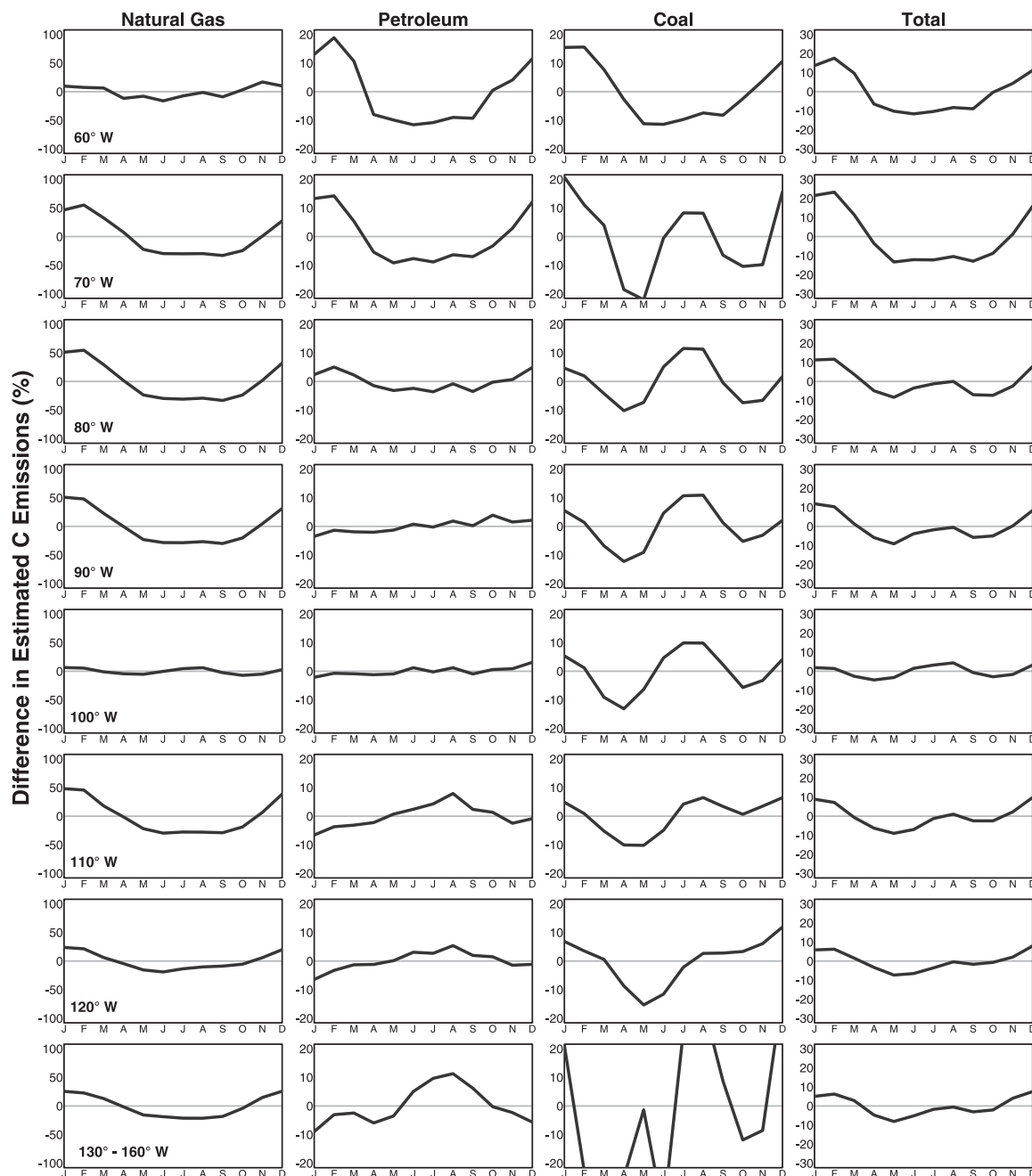
FIG. 5. Longitudinal mean monthly distribution of emissions by fuel type. The difference from a uniform distribution is shown, given in percent. Note the different vertical scales.

at 45°–50°N and about 70°–80°W (the eastern side of the continent, near the United States–Canada border). Erickson et al. (2008) suggested that the amplitude increases from south to north, but our observation is that the amplitude decreases at latitudes north of 50°N. Moreover, Erickson et al. (2008) assumed a uniform longitudinal distribution, yet we observe that the pattern of emissions changes on an east–west gradient, with

emissions more highly seasonal in the east than in the west.

The pattern of fossil-fuel-based CO_2 can be summarized spatially on a month-to-month level by using the monthly emissions per fuel type to weight each state's geographic centroid. In Fig. 6, the geographic centroid of North American monthly emissions is plotted for each fuel type to depict month-to-month changes in the spatial
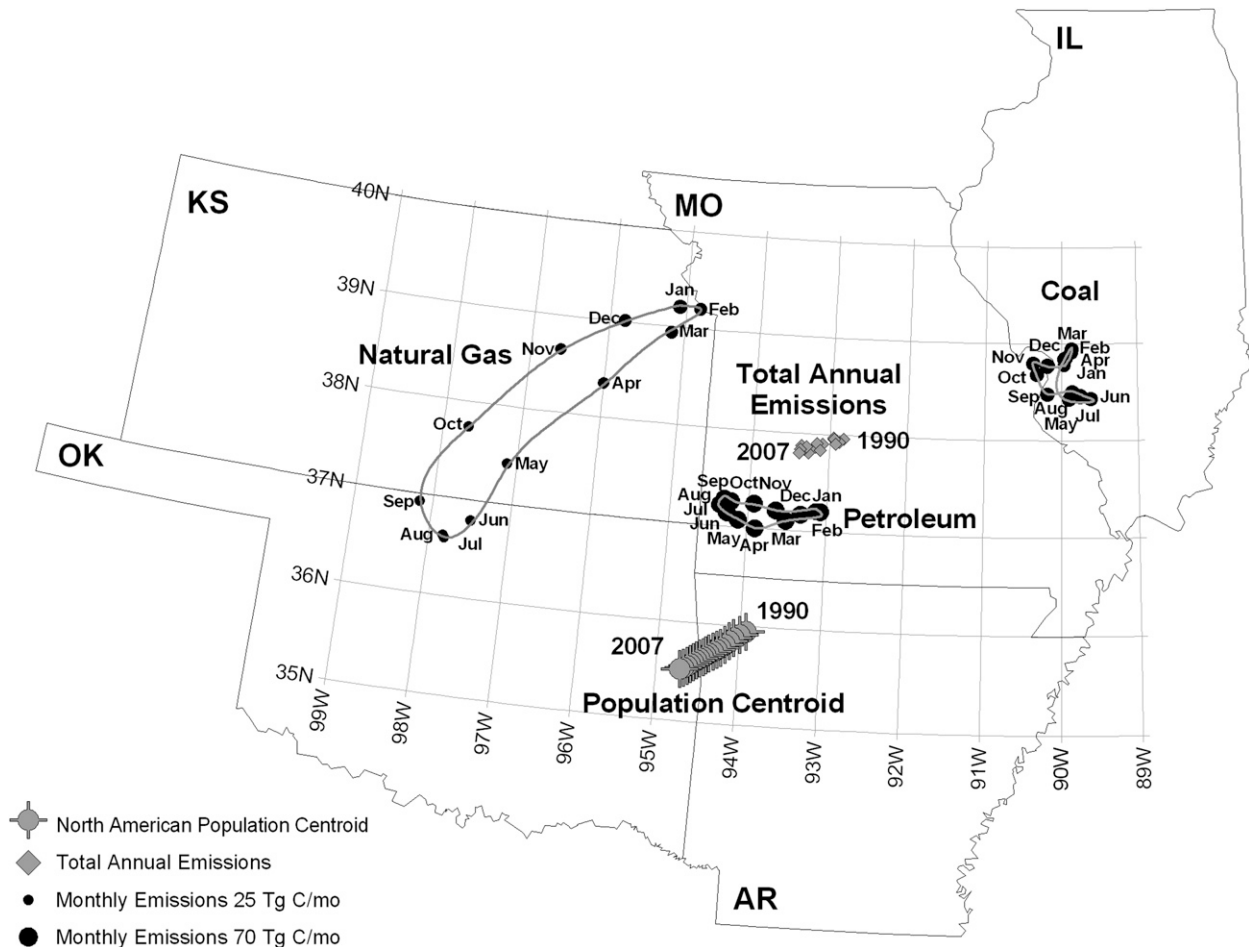
FIG. 6. Monthly and annual mean centroid of fossil-fuel CO_2 emissions for North America for 1990–2007. Population data are from U.S. Census Bureau (2009), Statistics Canada (2009), and the Instituto Nacional de Estadística y Geografía (2009).

distribution of emissions. The monthly spatial variation is many times larger in magnitude than annual changes in emissions, thus highlighting the increased value of finer spatial- and temporal-scale descriptions of fossil-fuel CO_2 emissions for specific applications. The month-to-month variation in emissions is also larger in scale than the year-to-year changes in population demography. The total emissions centroid for North American emissions lies to the north of the population centroid for the continent [population data are from U.S. Census Bureau (2009), Statistics Canada (2009), and the Instituto Nacional de Estadística y Geografía (2009)], because per capita emissions are higher in the United States and Canada than in Mexico, but has been slowly moving westward and slightly south from 1990 to 2007, reflecting changes in demographics and economic development. However, the centroid of emissions is still well removed from the population centroid, illustrating both that the distribution of emissions is changing with time and that the distribution of emissions is very different from the distribution of

population. Monthly average centroids for the three individual fuels show that the geographic distribution of emissions changes in systematic ways through the year, with the greatest variability in the natural gas emissions. During the winter months, the centroid of emissions from natural gas moves toward the northeast and during the summer it moves back to the southwest in reflection of the changing demand for natural gas. The spatial pattern of emissions from petroleum is seen to change less than for the other fuels, and the centroid of emissions from petroleum is closest to that of the population, due to the fact that petroleum has the most uniform per capita demand of all three fuel types. Emissions from petroleum shift westward in the summer months, as noted earlier. Electricity generation from coal tends to follow a less distinct pattern, but moves north in the winter and drops to the southeast in the summer.

When carbon fluxes from fossil-fuel combustion are integrated with fluxes from the terrestrial biosphere, the common denominator will be emissions per unit area,
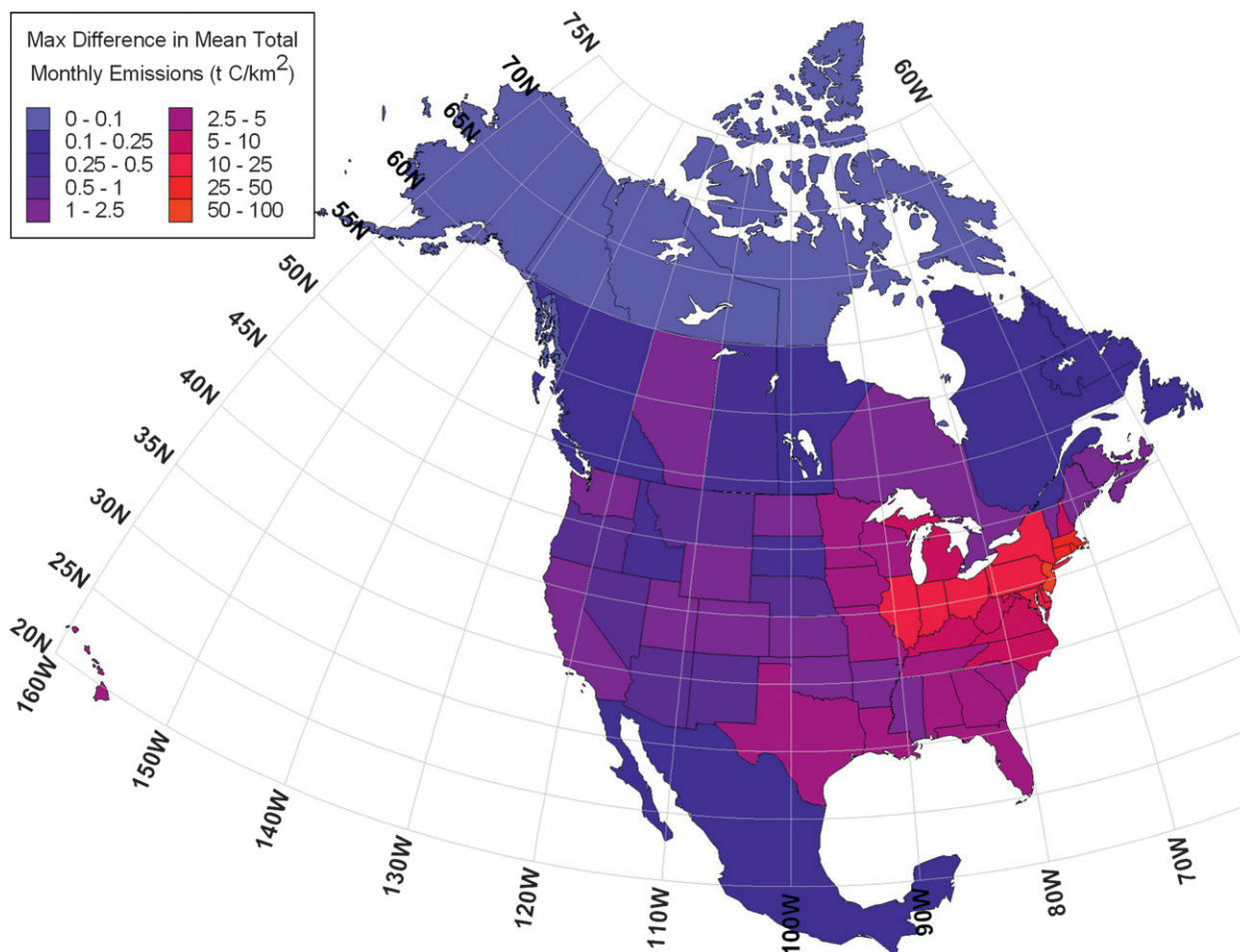
FIG. 7. Maximum annual range in fossil-fuel CO_2 emissions for North America, normalized by area.

not emissions by political unit or emissions per capita. In Fig. 7 we show the monthly variability in emissions from fossil-fuel use on a per-unit-area basis (i.e., the peak-to-trough difference in monthly fossil-fuel emissions per state divided by the area of the state). The seasonal aspect of emissions in absolute emissions per area is most pronounced in the northern continental interior regions with large populations, in the Midwest and northern Atlantic states where total emissions are relatively high and the annual cycle is highly seasonal. In terms of magnitude, the seasonal variability in fossil-fuel emissions is similar or even larger than the annual fluxes from land use activities (discussed below).

4. Discussion

a. Assumptions and uncertainties

We assume that the seasonal and spatial distributions for nonrepresented sectors of a given fuel are relatively similar to the subset of consumption sectors chosen to represent the entire national consumption patterns for a given fuel type and that any differences are small enough not to affect the total estimates significantly. Even though over 80% of total fuel consumption is represented in the underlying data for each country, it is possible to exaggerate or underestimate the seasonal amplitude when only looking at a subset of the entire market for a given fuel. For example, using electricity production as the sole proxy for emissions from coal consumption is likely to slightly exaggerate the seasonal amplitude of emissions, because coal use for steel manufacturing and other industrial purposes is not likely to be as seasonal as heating and lighting.

Another assumption implied by using sales data is that sales are equivalent to combustion and that the effects of storage and stockpiling of fuels are minimal. For example, coal is regularly stockpiled by electrical utilities during periods of lower power generation. Because of this, electricity generation (used here) is a better proxy for the monthly pattern of emissions than are actual coal sales.

However, we do rely on sales data to estimate emissions from petroleum consumption in the United States, Canada, and Mexico. Because consumers do not immediately combust fuel upon purchase, there is a temporal offset between sales and combustion for motor fuel. Thus the actual emissions peaks and troughs may lag inferred values. For the United States, EIA gasoline consumption data were compared with sales tax data from 2001 to 2008 from the Federal Highway Administration ("Monthly Motor Fuel Reported by States," Federal Highway Administration Table MF-33G, available online at http://www.fhwa.dot.gov/ohim/mmfr/), giving a comparison of distributor sales versus end consumer sales. Distributor and consumer sales agree within 10% for the majority of states, and the difference for the United States is less than 1%; however, it is unclear how meaningful this comparison is given differing amounts of seasonal ethanol blends per state, uncertainties in both datasets, missing and omitted data, and other differences in accounting. Moreover, this gives no further insight into the amount of time that passes between purchase and the point where the end consumer actually combusts the gasoline in a vehicle. This analysis does not indicate a discernable or consistent lag at the monthly level of analysis, though it would likely be a larger problem at finer temporal scales.

In a similar way, motor gasoline sold in one jurisdiction may be actually consumed in adjacent areas. Here we assume that the majority of motor gasoline sold in a state or province is combusted within that state or province and that the net flux of vehicles at all political boundaries is zero. For fine resolution in cities straddling state lines, where commuters buy gasoline in one state although they may actually live in the other, this assumption will break down, especially as prices may vary across political boundaries through time. The spatial displacement is more problematic for jet fuel that is purchased in airports where the fuel costs are low but is combusted along long flight paths (though the temporal displacement for jet fuel is likely less than that of gasoline and diesel).

When using this approach to estimate emissions, we assume that emissions per unit of energy content of each fuel type remain seasonally and geographically constant. We also assume that the fraction oxidized remains constant across each country. The fraction oxidized can vary from region to region—in particular, in states/provinces such as Texas and Alberta where a larger proportion of petroleum is converted to nonfuel products. The result will be a slight overestimate of emissions from petroleum in these areas. Our approach assumes an average carbon value for all coal combusted. For the United States, the carbon content for coal combusted

varies slightly from region to region. For example, in 1999 this value ranged from 23.7 $gC\ MJ^{-1}$ in Oregon to 26.7 $gC\ MJ^{-1}$ in Rhode Island and Vermont (Energy Information Administration 2009).

Because the effectiveness of any method is dependent on the quality of the data inputs, incorrect or missing source data values will diminish the descriptive capacity of any method. Also, changes in accounting procedures in the source data can lead to errors in the results presented here. However, because this approach keeps the total annual national emissions value constant, the input errors are spread over all point estimates, and thus this approach is able to produce reasonable estimates even with many missing values and data errors (Gregg and Andres 2008).

Because of the apportioning method, errors are not independent; therefore, the uncertainty surrounding any one specific estimate (emissions in a given state/province for a given month) must be understood in the context of all other estimates for that country. We find that estimates of U.S. annual emissions from this method are within 2% of the estimates given in Blasing et al. (2005a,b) and Boden et al. (2009). Total monthly emissions for the entire United States are within 3% in comparison with Blasing et al. (2005b) relative to the monthly mean of both datasets (Gregg and Andres 2008). In a comparison with Blasing et al. (2005a), annual state-to-state emissions for the United States are within 0.5% (relative to the proportion of national emissions), except for Texas, which is 1.5%. Though different data tables were used in producing the estimates presented in this study, the ultimate source for much of the data used in this study and the previous studies by Blasing et al. (2005a,b) is the EIA, so the studies are not necessarily independent. Error rates are likely higher for Canada and Mexico, but no independent datasets at the monthly time step or provincial spatial scale (for Canada) are currently available.

b. Fossil-fuel carbon emissions in North America

Though Canada and Mexico occupy positions among the list of the world's top 11 emitters of anthropogenic CO_2, the combined emissions from Mexico and Canada are less than one-fifth of that from the United States. More fossil-fuel-based CO_2 emissions currently come from Texas than from Mexico and Canada combined. Moreover, the amplitude of the seasonal variation in U.S. carbon emissions is greater than the total combined mean monthly carbon emissions from Canada and Mexico. Both Canada and Mexico are net exporters of energy to the United States; the United States, for example, consumes about one-half of Canada's total annual natural gas production (North American Energy

Working Group 2009). The pattern of CO_2 emissions in North America is dominated by emissions occurring in the United States.

Fossil-fuel emissions are a substantial anthropogenic component of the carbon cycle. In absolute terms, the annual emissions from fossil fuel are an order of magnitude larger than those from land use change, for most states and provinces in North America. The 1990–2005 mean annual carbon fluxes from land use change in the United States and Canada are, respectively, estimated at -31.9 and 19.1 TgC yr^{-1} (Houghton 2009), whereas fossil-fuel carbon emissions averaged 1460 and 132 TgC yr^{-1} over the same period. On average, land use emissions were -3.2 and 1.9 tC km^{-2} yr^{-1} for the United States and Canada, respectively. For many places, such as New England, the seasonal variability in fossil-fuel carbon emissions is many times larger than the total annual emissions from land use change on a per-area basis (see Fig. 7). Total 2007 fossil-fuel emissions are 173 tC km^{-2} in the United States, 50 tC km^{-2} in Mexico, and 17 tC km^{-2} in Canada. We have shown that these changes in fossil-fuel emissions fluxes are highly variable temporally and spatially among the states in the United States and provinces in Canada (and likely in Mexico also, although we could not show this). Thus, accurate depiction of the seasonal flux and subnational spatial distribution of fossil-fuel-based CO_2 emissions are essential to understanding the dynamics of the anthropogenic component of the carbon cycle. As compared with national, annual emissions inventories currently available, the higher-resolution detailed data presented here allow more accurate determination of terrestrial carbon fluxes where background levels of fossil-fuel-based CO_2 emissions are needed to calibrate measurements and models. The complete datasets of CO_2 emissions by state/province and month, for the period up through 2007, are available from the Carbon Dioxide Information Analysis Center (CDIAC) (http://cdiac.ornl.gov/trends/emis/meth_reg.html).

5. Conclusions

The seasonal and spatial patterns of fossil-fuel CO_2 emissions in North America are an essential component to a complete understanding of the carbon cycle. Because of the complex pattern of variation in emissions, it is difficult to describe either the spatial or temporal pattern in simple ways or to extrapolate from one place to another. Temporal patterns are often sufficiently clear that it may be possible to extrapolate usefully over time, but spatial variations are more difficult to infer, which fact, for the present, precludes finer spatial resolution in Mexico.

We have been able to characterize that the annual cycle of emissions varies most with emissions from natural gas, and most at midlatitudes. Nevertheless, natural gas is not equally available everywhere, and there are important variations with longitude and with the balance of economic sectors that characterize energy demand in a given location. While emissions from petroleum use are the most closely tied to population distribution of the three fuel types, there are nevertheless differences in the seasonal distribution of emissions as a function of location. Emissions from coal consumption are not well correlated with population, and, like petroleum carbon emissions, the seasonal pattern varies with location.

We conclude from this analysis that the spatial distribution of emissions is far different than would be achieved with a uniform per capita distribution and that the temporal variation is large with respect to biospheric net fluxes from land use change. Recognition of the temporal and spatial variability in fossil-fuel CO_2 is an important component of a detailed, mechanistic understanding of the global carbon cycle.

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