INCREASING THE TEMPORAL AND SPATIAL RESOLUTION OF FOSSIL-FUEL CARBON EMISSIONS ESTIMATES FOR THE UNITED STATES OF AMERICA

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ABSTRACT
Numerical models of the carbon cycle are becoming increasingly sophisticated. One result of this is that these models now require fossil-fuel carbon-dioxide emissions data with sub-annual (e.g., seasonal) time resolution. They also require finer spatial resolution than national averages (i.e., than one point per nation). Finer spatial resolution is especially needed for countries as large in area as the United States of America (U.S.A.). Here we present a summary of monthly data for the entire nation, and annual data for each state in the U.S.A.

INTRODUCTION
The Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge National Laboratory has provided estimates of annual emissions of carbon in the carbon dioxide (CO_2) emitted from fossil-fuel combustion and cement manufacture, on a country-by-country basis, at http://cdiac.esd.ornl.gov/trends/emis/em_cont.htm. These data are freely available and have been very useful to carbon-cycle modelers. However, as carbon-cycle models become more sophisticated, finer spatial and temporal resolution is required. Therefore, we have calculated fossil-fuel carbon emissions for the U.S.A. on a monthly basis. We have also calculated annual state-by-state fossil-fuel carbon emissions, and per-capita emissions, for each state in the U.S.A., back to 1960. The U.S.A. accounts for about 23 percent of global fossil-fuel CO_2 emissions. Cement manufacture accounts for only about 0.7 percent of the carbon emitted from and fossil-fuel combustion in the U.S.A. Carbon emissions from cement manufacture are not included in this report, but are being studied separately.

METHODS
Monthly data on sales of fossil fuels for the entire U.S.A. were obtained from the Energy Information Administration of the U.S. Department of Energy (EIA/DOE). These data are available on a monthly basis for natural gas, as well as for several types of coal and several petroleum products. The time period covered is limited by petroleum data, which only go back to 1981. Monthly data are not available on a state-by-state basis; therefore, we could only calculate state-by state carbon emissions on an annual basis. Sales data for each type of fuel were first multiplied by the appropriate thermal conversion factor, to obtain the heat realized in quads (10^{15} Btu), and subsequently multiplied by the appropriate carbon coefficient to convert the heat realized to teragrams (10^{12} grams) of carbon. Most of the thermal conversion factors used can be found in Appendix A of any edition of *Monthly Energy Review*, published by the EIA/DOE. Most of the appropriate carbon coefficients can be found in Annex 2 of any recent *Inventory of U.S. Greenhouse Emissions and Sinks* published annually by the U.S. Environmental Protection Agency.

FINDINGS
Fossil-fuel carbon emissions from the U.S.A. have a distinct annual cycle, ranging from about 100 teragrams/month in summer to about 120 teragrams/month in winter in the early 1980s, and from about

120 teragrams in summer to about 140 teragrams in winter in recent years. This cycle is dominated by combustion of natural gas for heating purposes, which explains the winter peak and summer trough. Coal combustion, much of which is for electricity generation, contributes to the same annual pattern because more electricity is required for indoor activities during the winter months. However, a secondary peak in coal combustion during the summer has emerged in recent years as more people use air conditioning for indoor cooling during the warmer months.

Because our basic fossil-fuel data are broken down by fuel type, it is possible to estimate the amount of carbon-13 ($\delta^{13}C$) emitted from the U.S.A. for each month. The annual cycle is dominated by natural gas, which has the lowest $\delta^{13}C$ value of the fossil fuels, so that a clear summer peak and winter trough are evident. The annual average value is about minus 29.5 per mil, and is related to the decline in observed $\delta^{13}C$ in atmospheric CO_2 as the percentage of atmospheric carbon originating from fossil fuels continues to increase.

Although the original purpose of this research was to aid carbon-cycle modelers, the results have socio-economic implications. The data clearly show past responses of petroleum-related CO_2 emissions to changes in oil prices. Recent events, however, suggest that the magnitude of this correlation may be decreasing. The state-by-state breakdown of carbon emissions from coal combustion also shows that some states can honestly claim to have reduced their CO_2 emissions. However, those same states tend to purchase electricity generated from coal combustion in other states, so that the associated CO_2 emissions are just transferred to another location rather than eliminated, and overall carbon emissions may not be reduced. These results pose challenges for trying to use state-level per-capita emissions as a measure of equity or to provide mitigation targets.

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

Although we have made progress in increasing the temporal and spatial resolution of carbon emissions from fossil-fuel combustion, there is much more to be done. State by state data have only been estimated on an annual basis. We are currently working on monthly emissions estimates from countries other than the U.S.A.. We believe that such efforts are clearly justified in terms of the usefulness of the results.