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An integrated approach for estimating greenhouse gas emissions from 100 U.S. metropolitan areas

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Abstract

Cities have become key players in climate change mitigation policy. To develop their climate policies, cities need good assessments of their current and future emissions. We use publically available national datasets to develop an integrated approach for estimating GHG emissions at the metropolitan level over time, between multiple locations, and across sectors. We estimate consistent production-based GHG emissions for the 100 most populated metropolitan areas in the United States in 2014. We find that total 2014 metropolitan CO_2 emissions range from 4.1 million metric tons in Lancaster, Pennsylvania to nearly 170 million metric tons in the Houston, Texas; with an overall average of 27 million metric tons. The top 20 absolute emitters and top 20 per capita emitters only overlap for 9 locations. Per capita emissions also show a wide variation: from 5 metric tons per person in the Tucson, Arizona to 65 metric tons per person in the Baton Rouge, Louisiana; with an overall average of 14 metric tons per person. We also compute estimates for 2002 and 2011 and compare to our 2014 emission estimates. Across all locations analyzed, average total emissions increased by 3% and average per capita emissions decreased by 14%. Where possible, we also compare our emission estimates to those reported by the cities in their climate action plans and find an average absolute difference between our estimates and those reported by the cities of 5.6 metric tons CO_2 per person, likely due to temporal and scope differences between the two estimates. Our integrated emission estimation approach complements bottom-up approaches typically employed by municipalities and helps practitioners divert their attention and resources away from continuous emission accounting toward more impactful emission mitigation efforts.

Introduction

Since the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and the five Assessment Reports subsequently produced by the organization, knowledge and concerns about climate change have been steadily increasing (IPCC 1992, 1995, 2007, 2011, 2014). In response to these concerns, several international, regional, and national greenhouse gas (GHG) management and reduction policies have been adopted—the most notable of which are likely the Kyoto Protocol and the recent COP21 agreements reached in Paris in December 2015.

In conjunction with these policies, numerous cities across the world have adopted Climate Action Plans (CAPs) in an attempt to estimate and reduce their greenhouse gas (GHG) emissions. In the United States, over 1000 mayors have committed to the U.S Conference of Mayors' Climate Protection Agreement, over 450 local governments have joined the International Council for Local Government Initiatives (ICLEI—Local Governments for Sustainability), and 14 cities in North America have joined the C40 network of global cities striving to reduce GHG emissions (U.S. Conference of Mayors 2008, ICLEI 2015a, C40 Cities 2011). Given that over 80% of the United States' population lives in metropolitan areas and roughly 75% of the earth's natural resources are consumed in urban areas (U.S. Census Bureau 2013, Swilling *et al* 2013), CAPs provide an important

contribution to addressing the challenges posed by climate change—especially when considering that metropolitan mitigation strategies can better address local conditions and be more flexible than a national GHG policy.

The implementation of climate action plans typically involves completing regular GHG inventories. In the United States, city-level GHG inventories are commonly completed with the help of ICLEI's Clean Air Climate Protection (CACP) software, or, more recently, ICLEI's ClearPath software (OpenEI 2015, ICLEI USA 2015b). While the software allows for emission estimates from a wide range of categories, it is most commonly used to provide bottom-up emission estimates for five sectors within a given city: 1) use of electricity by the community, 2) fuel use in residential, commercial, and industrial buildings (e.g. natural gas or fuel oil), 3) fuel use for on-road passenger and freight motor vehicle travel, 4) energy use in the treatment and distribution of potable water and waste water, and 5) emissions from the collection and degradation of solid waste generated by the community (ICLEI USA 2013).

The protocols and resources described above have greatly enhanced the ability of cities to form and assess GHG inventories. However, there are still some challenges with estimating local-level GHG emissions. First, the bottom-up approach commonly employed can be time consuming and expensive. In a series of National Research Council (NRC) workshops, lack of funds and institutional wherewithal have been described as primary barriers to the successful implementation of sustainability-oriented actions in metropolitan areas (NRC 2010, 2011, 2013, 2014). Second, the sources, scope, and overall robustness of data changes from assessment to assessment. Thus, the source data, time, money, and skills needed to collect and analyze the information necessary for completing a GHG inventory can inhibit the progress of developing and implementing a Climate Action Plan. It is not uncommon for communities to enter into a repetitive cycle of emissions accounting rather than shifting their focus to the implementation of mitigation strategies.

Another issue with current GHG inventories is that they do not necessarily cover the full geographic or sectoral extent of a metropolitan area's emissions. Due to common practices and jurisdiction issues, inventories are often confined to the city limits of a given area and to the five emission-producing activities described above. In response to these concerns, several researchers have developed approaches for supplementing the traditional 'bottom-up' inventory approach employed by cities. Kennedy *et al* (2010), Hillman and Ramaswami (2010), and Ramaswami *et al* (2008) have employed Life Cycle Analysis (LCA) concepts to measure the embodied impact of important urban materials consumed (e.g. water, food, and fuel) and spatial allocation techniques to better account for surface and airline transportation emissions. Similarly, Blackhurst *et al* (2011) developed an approach to more effectively consider the impacts and uncertainty that varying weather conditions and electricity-sector emission factors can have on inventories. More recently, Zhou and Gurney (2010) and Gurney *et al* (2012) developed methods to quantify GHG emissions at the building and street scale.

These and other studies provide valuable insight and allow for some comparative analyses across locations, but have typically been limited to specific locations. For example, Blackhurst *et al* (2011), Hillman and Ramaswami (2010), and Kennedy *et al* (2010) compare emissions across all sectors but are limited to the geographic extent of between 8 and 19 cities. On the other hand, studies that cover a larger set of locations have been limited in the number of sectors covered. Glaeser and Kahn (2010) compare emissions from 66 metropolitan areas in the U.S., while Brown *et al* (2009) and Brown and Cox (2015) compare emissions from 100 metropolitan areas. However, both of these studies only account for residential and personal transportation emissions, while omitting emissions from the industrial, commercial, and waste sectors. Although some meaningful conclusions can be gathered from the existing work, the results, analysis, and comparisons are not broadly applicable to all metropolitan areas in all scenarios. Having the ability to make such comparisons is important because it allows for better overall assessment of the progress being made across the country, and allows cities to more easily adopt best practices. Blackhurst *et al* (2011) propose that one potential method for accomplishing this task is to perform 'research merging national and local inventory methods'—an approach we employ in this article.

Given the above issues, we develop an approach for integrating publically available national datasets to estimate production-based GHG emissions by sector at the metropolitan level. We then demonstrate this approach on the 100 most populated metropolitan areas in the United States in order to form GHG emissions estimates for the years 2002, 2011, and 2014. This method provides emission estimates for the same activities specified by the 2013 ICLEI protocol, while also supplementing and complementing the previous body of knowledge in a variety of ways. First, the use of publically available national datasets to form metropolitan emission estimates significantly reduces the time, funding, and human capital that would otherwise be required for a traditional 'bottom-up' inventory—thereby addressing some of the research needs expressed by Blackhurst *et al* (2011) and the NRC workshops. Second, our estimation of GHG emissions for 100 U.S. metropolitan areas expands upon the emission estimates and comparisons formed by Glaeser and Kahn (2010), Brown *et al* (2009), and Brown and Cox (2015) by including more emission

producing activities (industrial, commercial, and waste) and (in the case Glaeser and Kahn) many more locations. Finally, the analysis presented here complements the enhanced inventory techniques proposed by Kennedy *et al* (2010), Hillman and Ramaswami (2010), Ramaswami *et al* (2008), and Gurney *et al* (2012) by providing an initial assessment tool to help practitioners more effectively determine the circumstances in which it would be most beneficial for them to pursue more detailed analysis when trying to identify the most effective climate mitigation strategies.

The rest of our paper is organized as follows. We first describe the data used in our estimates, followed by a description of the methods. In the results section, we start by analyzing the results from our year 2014 estimates for 100 U.S. metropolitan areas. We then compare our year 2014 emission estimates with our year 2002 and 2011 emission estimates and discuss the changes in key locations. Then, we also compare our 2014 estimates with self-reported estimates from various cities. Finally, we conclude and provide policy recommendations.

Data and methods

We estimate production-based GHG emissions from electricity generation, industrial activity, residential buildings, commercial buildings, on-road transportation, and waste for the 100 most populous metropolitan areas in the U.S.

The data sources used in this work vary in their geographic specification (i.e. facility-level versus county-level). All of the facility-level data is aggregated to the Metropolitan Statistical Area (MSA) level - see section A2 of the Supplemental Information (SI) for more information on MSAs. All data sources use a production-based emissions accounting method, in which emissions are attributed to where they geographically occur. Self-reported emission estimates produced by cities are often accounted as consumption-based emissions: emissions attributed to where the end-use occurs, independent of where it was actually emitted. Normally, the distinction between production-based estimates and consumption-based estimates would make consistent comparison between our approach and other estimates difficult. However, with the exception of electricity generation, the emissions estimates in the city CAPs appear to be generally comparable to the production-based emission methods we employ. For example, production and consumption based emissions for buildings (non-electricity) and transportation both occur in the same location.

Emissions from electricity generation are a case where production-based estimates and consumption-based estimates could potentially lead to significantly different results. For example, under a consumption-based approach, a majority of the electricity sector emissions would be attributed to the city of Chicago and/or Cook County. However, under a production-based approach, a majority of the electricity sector emissions for that metropolitan area would be attributed to outlying/rural counties in Illinois, Indiana, and Michigan (where the electricity generation facilities are likely located) (see for example Weber *et al* 2010). A regression-based approach to relate the amount of electricity consumed in a county to the amount of electricity produced in a county has also exhibited a fairly large range of uncertainty (Tamayao *et al* 2014). By comparing our emission estimates to self-reported estimates produced by cities, our analysis allows for additional comparison between consumption-based and production-based estimates and places any disparities in the context of the overall emissions profile of a metropolitan area.

Emissions from industrial processes are another possible situation where production-based estimates and consumption-based estimates can have fairly different results. In most cases, the products of industrial processes are transported to and consumed by populations elsewhere. Thus, one can raise important policy/philosophical questions about whether it is more appropriate to allocate industrial emissions to the location of production or the location of consumption (The National Academies of Sciences 2016, Ramaswami *et al* 2008, Hillman and Ramaswami 2010). In depth analysis and comparison of these two approaches is outside the scope of this paper and is left for future work. However, as seen in the results below, the use of a production-based estimate approach likely has a strong influence on the relatively high per capita emissions we estimate for locations with high levels of industrial activity (e.g. Baton Rouge, Louisiana; Birmingham, Alabama; etc).

Our emission estimates for 2002 come from carbon emission data provided by the Vulcan Project (Gurney *et al* 2009a, Gurney *et al* 2009b). To form their database, the Vulcan researchers convert carbon monoxide (CO) emission estimates from sources like the EPA's National Emissions Inventory (NEI) (U.S. EPA 2010), the EPA's National Mobile Inventory Model (NMIM) (U.S. EPA 2013a), and the EPA's Continuous Emissions Monitoring program (CEMS) (U.S. EPA 2016d) to carbon emissions and form gridded 10km by 10km production-based emissions estimates for the entire United States (Gurney *et al* 2009b, Gurney *et al* 2009a). The CO-to-C conversion process employed in Vulcan involves using EPA Source Classification Codes (SCC) and emission factors to convert between the two pollutant types. We provide additional information on Vulcan's method in supplemental information (SI) stacks.iop.org/ERL/12/024003/mmedia, section A1. We convert the carbon emissions (from Vulcan) to carbon dioxide emissions by using the ratio of molecular weights for the two compounds—44

grams mol^{-1} CO_2 to 12 grams mol^{-1} C. 2002 is the most recent year in the Vulcan database with a full set of emission estimates for all sectors at the appropriate scale for all locations of our analysis. Therefore, as described below, additional data sources were used to develop emission estimates for years more recent than 2002.

Our estimates for 2011 and 2014 are based on explicit CO_2 measurements/estimates from a combination of the EPA's NEI and the EPA's mandatory GHG reporting program (U.S. EPA 2016a, 2016b, 2016c) (i.e. the CO-to-C conversion process used by Vulcan is not necessary). An important distinction of the 2011 and 2014 NEI and mandatory GHG reporting data is that direct emission estimates from the residential and commercial building sector are not provided. Therefore, we use state-level data from the U.S. Energy Information Administration (U.S. EIA 2015) to approximate emissions from residential and commercial buildings. In this approach, state-level residential and commercial CO_2 estimates from the EIA are divided by the total population for a given state (U.S. Census Bureau 2016a) and given year in order to determine the per capita emissions for these two sectors for each state. The residential and commercial per capita emissions are then multiplied by the population of a given MSA (U.S. Census Bureau 2016b) in a given year to arrive at estimates for total MSA-level residential and commercial GHG emissions. An additional approach that assumed 2002 per capita emission estimates for residential and commercial buildings (based on Vulcan data) hold in 2011 and 2014 was also applied. However, comparison of these two approaches to independent estimates conducted by the California Energy Commission (2015) reveals that the approach using EIA state-level data appears to be more accurate—see section A3 of the SI. Therefore, the results presented reflect commercial and residential emissions based on EIA state-level data. One additional alternative method would be to use data from the Energy Information Administration's Commercial Buildings Energy Consumption Survey (CBECS) and Residential Energy Consumption Survey (RECS) (U.S. EIA 2016a, 2016b). However, this approach was not used in our analysis due to temporal and geographic constraints of the RECS and CBECS data (i.e. the data are aggregated to the level of Census region and are from 2009/2012). Table 1 provides a summary of the different data sources used in our analysis.

We compare our estimates to emission values reported directly by municipalities from the Carbonn Climate Registry (2014), the Carbon Disclosure Project (2015), and the municipalities themselves. More information about the self-reported emission estimates from the cities is available in section A4 of the SI. State-level emissions estimates were available from the EPA's State Energy CO_2 Emissions data set (U.S. EPA 2015).

Results

What are the highest and lowest emitting metropolitan areas? Figure 1 summarizes the total GHG emissions (by sector) and per capita GHG emissions for the 50 metropolitan areas with the largest total emissions. A similar summary of the emission estimates for the remaining 50 locations is included the SI (figure A6). Emission estimates for 2011 are shown in the SI (figures A7 and A8), and emission estimates based entirely on 2002 data are shown in figures A9 and A10 of the SI.

While it is unsurprising that the four MSAs with the highest population have the highest total emissions, we also find that St Louis, Pittsburgh, Baton Rouge, Cincinnati, and Birmingham are within the top 15 because of relatively high per capita emission rates that are driven by high levels of industrial activity and carbon-intensive electricity production. Across the three time periods (2002, 2011, and 2014), the same locations rank among the top 15 in terms of highest overall emissions—the one exception is Cleveland, which fell from number 10 in 2002 to number 30 in 2014. There is more turnover for the locations ranked among the bottom 15 in total emissions—only 8 locations remained in the bottom 15 in total emissions across all three time periods.

We find that in 2014, the average for MSA emissions is roughly 27 million metric tons CO_2 and the average per capita emission rate is approximately 14 metric tons CO_2 per person. On average across all locations, on-road transportation accounted for the largest proportion of emissions (36%), followed by electricity generation (29%), industrial processes (18%), residential buildings (9%), commercial buildings (6%), and finally waste generation (2%).

We find total 2014 emissions range from roughly 4.1 million metric tons in the Lancaster, Pennsylvania MSA to roughly 166 million metric tons in the Houston, Texas MSA. The top 20 absolute emitters and top 20 per capita emitters only overlap for 9 locations—Baton Rouge, LA; Birmingham, AL; Cincinnati, OH; Houston, TX; Kansas City, MO; New Orleans, LA; Pittsburgh, PA; San Antonio, TX; and St Louis, MO. 2014 per capita emissions range from roughly 5.0 metric tons per person in the Tucson, Arizona MSA to roughly 66 metric tons per person in the Baton Rouge, Louisiana MSA.

How have emissions changed since 2002? Figure 2 depicts the percent change in emissions between 2002 and 2014. During this time period, the average percent change in emissions for a given location was +7%, and the average net change in emissions for a given location was +0.8 million metric tons. Similarly, between 2002 and 2014, the average percent change in per capita emissions for a given location was −10%, and the average net change in per capita emissions for a given location was −2.3 metric tons per person. Additionally, the average percent change in emissions

Table 1. Summary of data and sources.

Sector	Data source and notes	
	2011 and 2014	2002
Industrial activity	The data comes from the EPA's mandatory GHG reporting program (U.S. EPA 2016c), where the raw data is reported for each facility and includes the facility's latitude and longitude. Industrial activities include petroleum systems, refineries, chemicals, minerals, metals, pulp and paper, coal mines, food processing, ethanol production, and manufacturing. We aggregate all the reported emissions from industrial activities for which the latitude and longitude are within the boundary of the metropolitan area for each of our study's 100 locations.	The data comes from the Vulcan database (Gurney *et al* 2009b, Gurney *et al* 2009a), where the raw data is reported for each county. We aggregate all the reported emissions from industrial activities for which the counties are within the boundary of the metropolitan area for each of our study's 100 locations
Commercial buildings energy related emissions (excluding electricity)	We approximate commercial building GHG emissions based on state-level data from the U.S. EIA (2015). State-level commercial GHG estimates are divided by the total population of a given state (U.S. Census Bureau 2016a) in a given year in order to determine the per capita emissions for each state. The per capita emissions are then multiplied by the population (U.S. Census Bureau 2016b) of a given MSA in a given year to arrive at the total commercial building GHG emissions for each MSA.	The data comes from the Vulcan database (Gurney *et al* 2009b, Gurney *et al* 2009a), where the raw data is reported for each county. We aggregate all the reported emissions from commercial buildings for which the counties are within the boundary of the metropolitan area for each of our study's 100 locations
Residential buildings energy related emissions (excluding electricity)	We approximate residential building GHG emissions based on state-level data from the U.S. EIA (2015). State-level residential GHG estimates are divided by the total population of a given state (U.S. Census Bureau 2016a) in a given year in order to determine the per capita emissions for each state. The per capita emissions are then multiplied by the population (U.S. Census Bureau 2016b) of a given MSA in a given year to arrive at the total commercial building GHG emissions for each MSA.	The data comes from the Vulcan database (Gurney *et al* 2009b, Gurney *et al* 2009a), where the raw data is reported for each county. We aggregate all the reported emissions from residential buildings for which the counties are within the boundary of the metropolitan area for each of our study's 100 locations
Electricity Production	The data comes from the EPA's mandatory GHG reporting program (U.S. EPA 2016c), where the raw data is reported for each facility and includes the facility's latitude and longitude. We aggregate all the reported emissions from industrial activities for which the latitude and longitude are within the boundary of the metropolitan area for each of our 100 studied locations	The data comes from the Vulcan database Gurney *et al* 2009b, Gurney *et al* 2009a), where the raw data is reported for each county. We aggregate all the reported emissions from electricity generation for which the counties are within the boundary of the metropolitan area for each of our study's 100 locations
On-Road Transportation	The data comes from the EPA's NEI, where the raw data is reported for each county (U.S. EPA 2016a, 2016b). We aggregate all of the reported emissions from on-road transportation activities (both light duty and heavy duty vehicles) for which the county is within the boundary of the metropolitan area for each of our 100 studied locations.	The data comes from the Vulcan database (Gurney *et al* 2009b, Gurney *et al* 2009a), where the raw data is reported for each county. We aggregate all the reported emissions from on-road vehicles for which the counties are within the boundary of the metropolitan area for each of our study's 100 locations
Waste	The data comes from the EPA's mandatory GHG reporting program (U.S. EPA 2016c), where the raw data is reported for each facility and includes the facility's latitude and longitude. We aggregate all the reported emissions from industrial activities for which the latitude and longitude are within the boundary of the metropolitan area for each of our 100 studied locations	N/A

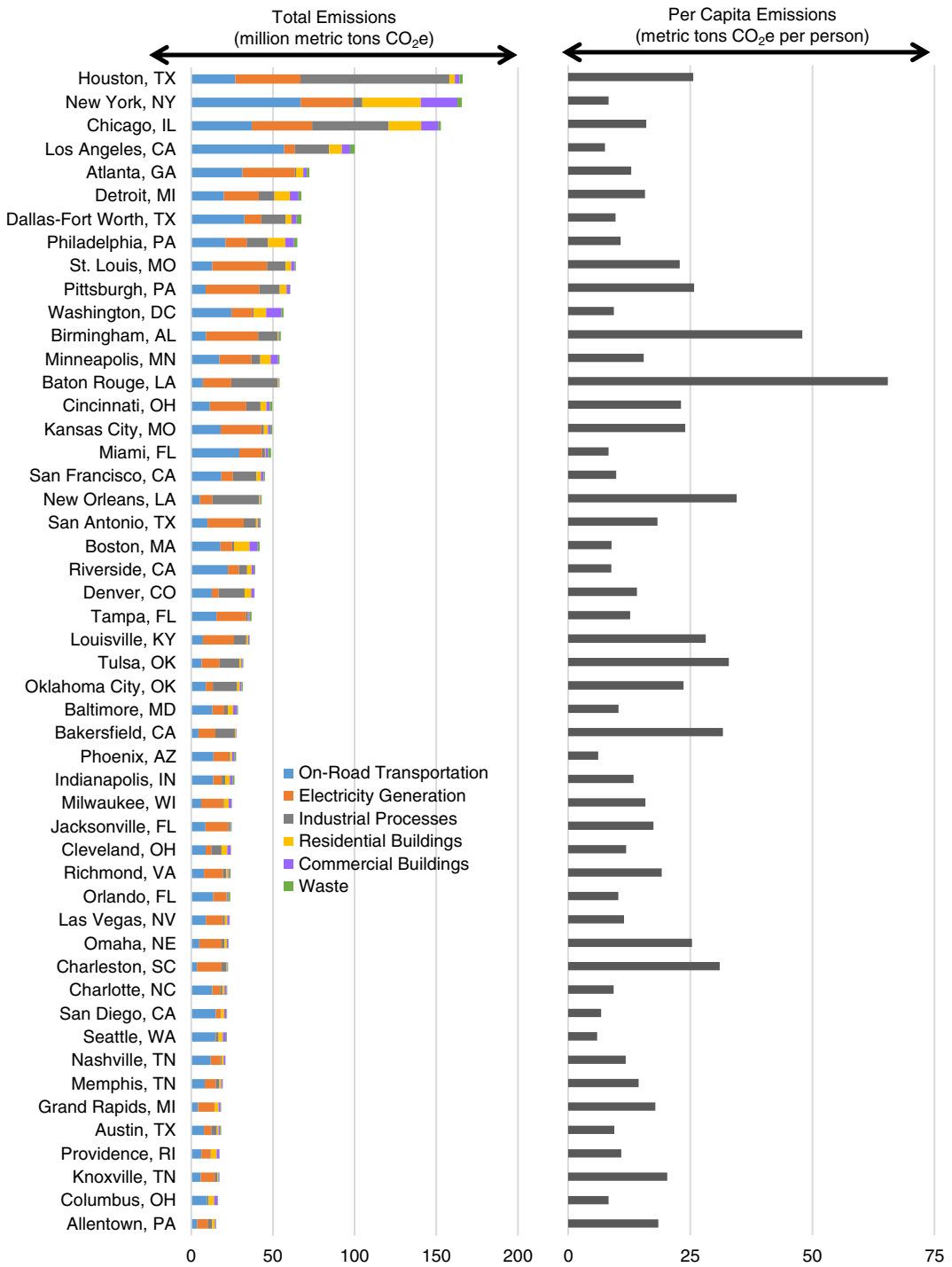

Figure 1. Total GHG emissions by sector and per capita GHG emissions for the 50 MSAs with the largest total emissions in 2014.

for a given location between 2011 and 2014 was +2.3% —see section A5 (figures A11–A14) of the SI for more detailed comparisons across all three years.

Focusing only on percent change in emissions can sometimes give a misleading sense of overall progress—a large percent reduction to a small baseline may be the same as a small percent reduction to a large baseline. For example, the Atlanta MSA had the 5th highest overall emissions in 2014, and while its percent decrease in emissions between 2002 and 2014 did not place in the top 15, it had the 5th largest overall decrease in total emissions and the 11th largest decrease in per capita emissions. Overall, those changes point to a degree of success in terms of overall GHG reductions. However, if only looking at percent change, this success would not be as apparent.

It is likely that most of the observed changes between 2002 and 2014 are the result of changes in population, efficiency, and/or the presence of high emission activities (e.g. industry, coal-fired power plants. etc). However, it is also possible that these discrepancies are due to scope differences across the datasets. The EPA's mandatory GHG reporting program (the primary data source for 2011 and 2014 estimates) has a reporting

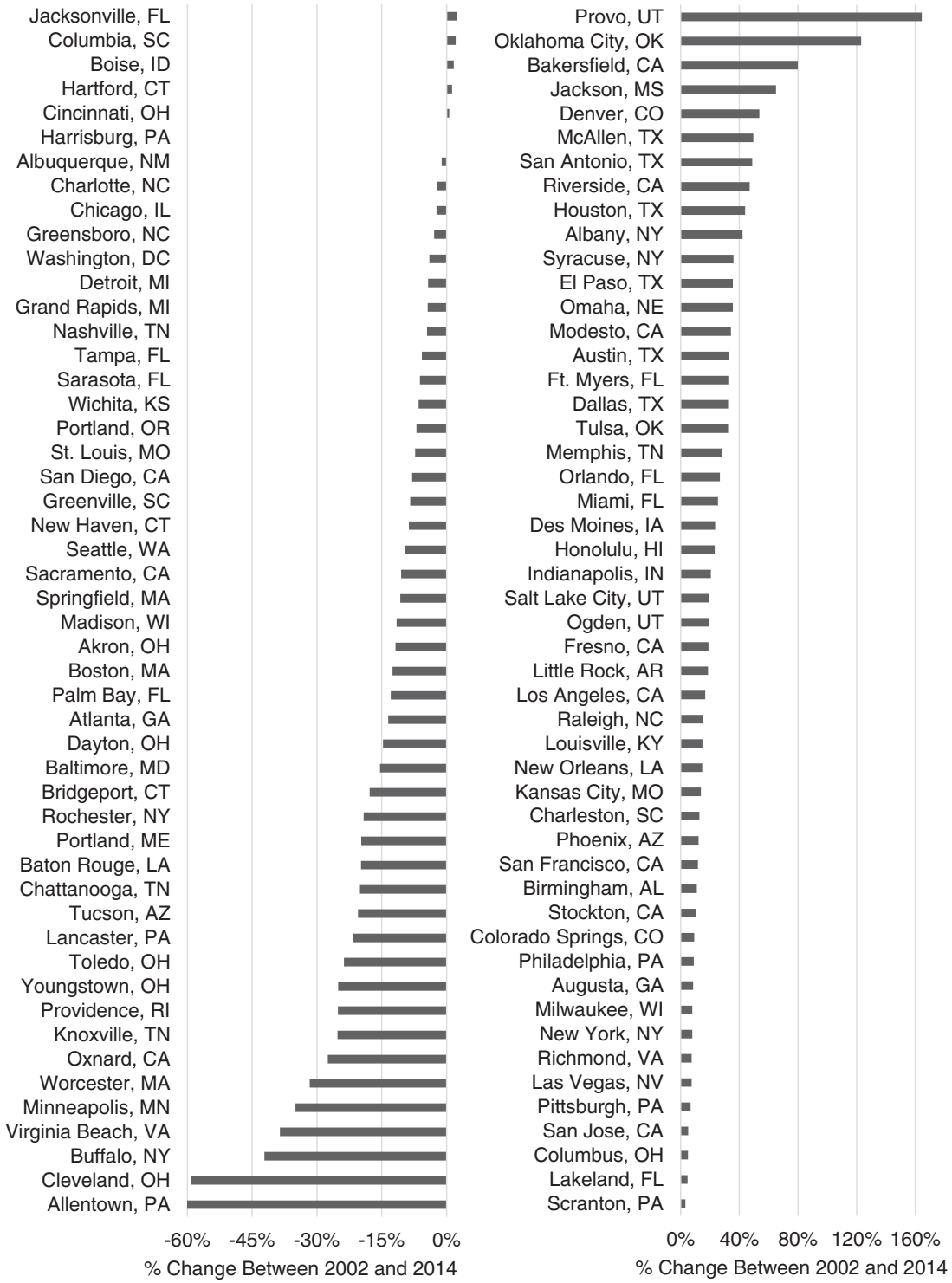

Figure 2. Percent change in total GHG emissions from 2002 to 2014 for the 100 largest metropolitan areas in the United States.

threshold of 25 000 metric tons per year (i.e. any facility emitting less than this threshold does not have to report their emissions to the program) (U.S. EPA 2013b). It is possible that some facilities in the NEI (one of the primary underlying data sources for the 2002 Vulcan estimates) fall under the 25 000 metric tons per year threshold – thus, only appear in the 2002 estimates but not the 2011 and 2014 estimates. Additional information about potential uncertainties is presented in section A6 of the SI.

How do our estimates compare to cities' self-reported values? Currently, only 31 of the 100 locations we analyze have reported their emissions to the Carbonn Climate Registry (2014). Thus, figure 3 shows the absolute difference in per capita emissions between these 31 self-reported estimates and our 2014 estimates. Some of the self-reported data are at the county-level, as opposed to the city level. The dates next to each location indicate the year in which the self-reported GHG inventory was conducted. Additional details about the

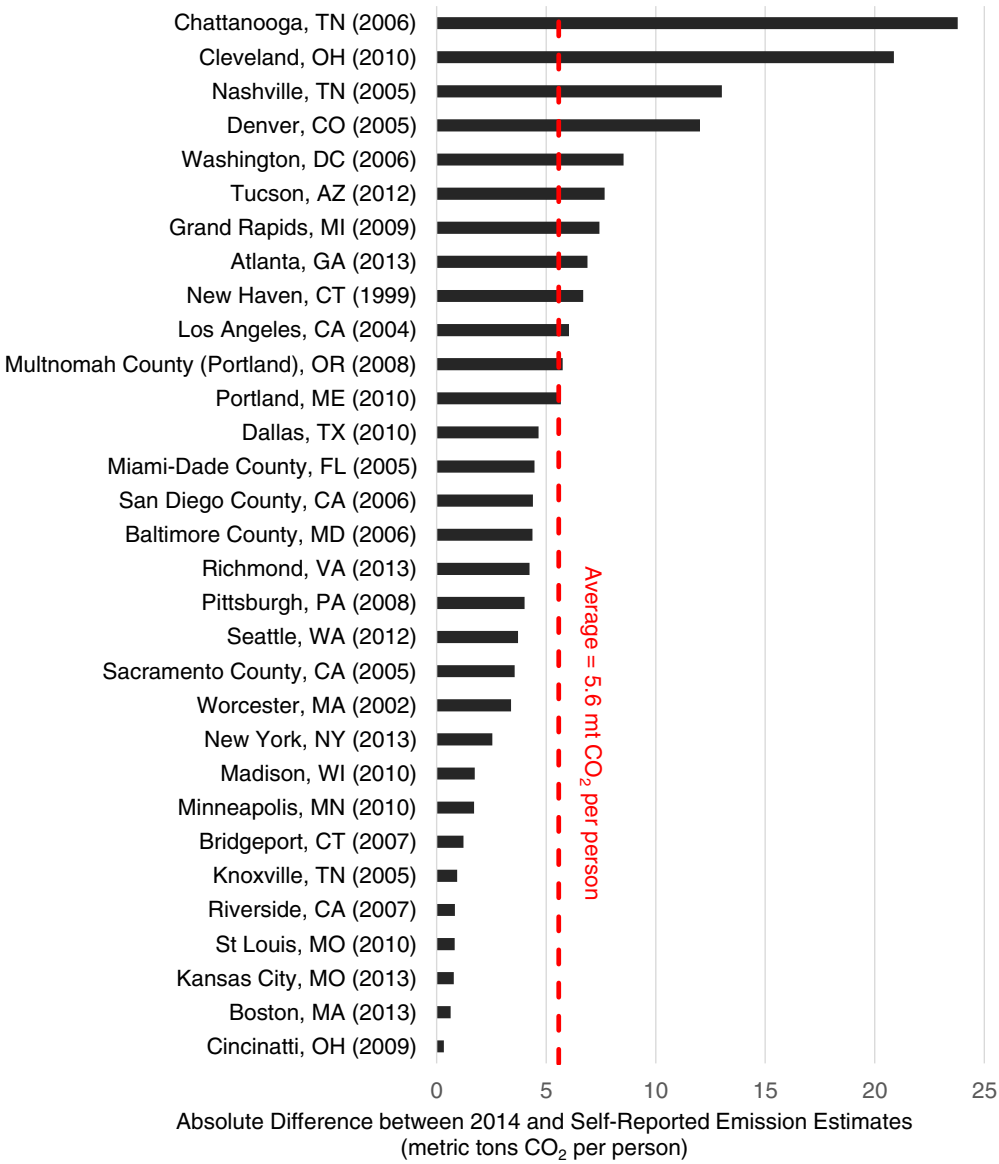

Figure 3. Comparison of absolute difference between self-reported per capita emissions and our base case 2014 estimates. The average absolute difference for all comparisons is indicated by the red dashed-line.

self-reported estimates (including links to each location's GHG inventory) are provided in section A4 of the SI, and additional comparisons and analysis are included in section A7 of the SI.

Our per capita emission estimates and those reported by the cities have absolute differences ranging from 0.3 metric tons per person in Cincinnati, Ohio to 24 metric tons per person in Chattanooga, TN, with an average of 5.6 metric tons CO_2 per person. As a reference, the average per capita emissions rate in the U.S. is roughly 80 metric tons per person (U.S. EPA 2016e). Analyzing the real (as opposed to absolute) difference between self-reported estimates and our estimates reveals that the self-reported estimates were higher for a majority of the locations—23 of 31 locations we compared. This tendency may be due to differences in scope, boundary, and/or timing of our approach compared to the approaches employed by the cities.

Chattanooga, Tennessee has the largest difference between our estimates and the city's self reported value—the city reported value was nearly 24 metric tons per person higher than our estimate. The primary cause of this discrepancy is likely due to the fact that we use a production-based estimate approach, while the city uses a consumption-based approach. There are no emission producing electricity generating units within the Chattanooga MSA. Therefore, our approach estimates zero emissions for the electricity sector, while the city estimated roughly 2.5 million metric tons. On a per capita basis the electricity sector emissions reported by the city are roughly 15 metric tons per person (Chattanooga Green Committee 2009), which accounts for a large portion of the discrepancy between our estimates and the self-reported estimates.

In contrast to Chattanooga, the self-reported estimate for Grand Rapids, Michigan is almost 7 metric tons per person lower than our estimate. Again,

electricity generation drives the discrepancy between the two estimates. According to the 2014 integrated data and the EPA's mandatory GHG reporting program, there were 9 electricity generating units within the Grand Rapids MSA responsible for combined emissions over 10 million metric tons of CO_2—the J H Campbell facility alone is responsible for over 8.5 million metric tons of CO_2 (U.S. EPA 2016c). For context, Grand Rapids' self-reported total estimate is 10 million metric tons across all sectors (City of Grand Rapids 2009).

In addition to discrepancies that emerge from production-based vs consumption-based electricity sector estimates, differences in scope and boundary choices may also lead to discrepancies in emission estimates. For example, Denver also exhibits a relatively large difference between the self-reported emissions and our estimate. Denver's self-reported estimate is the only location we analyzed to include emissions from jet fuel consumption at the airport and the embodied energy of materials consumed within the city (Ramaswami *et al* 2007). Neither of these components is included in our production-based emission estimates, but warrant further consideration in future work.

Although differences in data, time period of analysis, and sectors analyzed make direct comparisons difficult, we also compare our estimates to those developed by Glaeser and Kahn (2010) and Brown and Cox (2015). Generally speaking, there is only modest agreement amongst the methods over which locations have the highest and lowest emissions. For per capita transportation emissions, only 6 locations appear in the top 15 (highest emitters) of both our estimates and Glaeser and Kahn's estimates. Similarly, only 7 locations appear in the bottom 15 (lowest emitters) of both our estimates and Glaeser and Kahn's estimates. For per capita residential emissions, Brown and Cox estimate San Jose, San Francisco, and Fresno as the three locations with the lowest emissions. However, based on our estimates, these three locations rank no better than the 27th lowest emissions. Overall, comparison to estimates from these other studies reveals that locations like Atlanta, Birmingham, and Charlotte appear to consistently have high GHG footprints (regardless of estimation method) and locations like Boston, New York City, and San Francisco appear to consistently have relatively low GHG footprints (regardless of estimation method). The comparisons also reveal some relatively large differences across the different methods, which highlights the influence that different methods, data, scope, and boundary choices can have on estimating and comparing emissions across locations.

Conclusions and policy recommendations

We develop and use an integrated approach for estimating metropolitan greenhouse gas emissions using publically available datasets. We compare emissions in 2014, 2011, and 2002, and compare the estimates from our approach to estimates reported by cities in their climate action plans.

We find that our approach provides consistent estimates that cities could use to compare to other locations and to monitor how their emissions evolve over time. We also note that our method may lead to differences in emissions from what the cities are self-reporting. Two key issues drive these differences: (i) whether the cities report electricity emissions on a consumption basis or a production basis; and (ii) whether cities include additional emission sources and/or overall life-cycle emissions, rather than just direct emissions. Moving forward, some of the challenges and uncertainty associated with the integrated approach can be addressed through stronger collaboration between the EPA and local practitioners. Nationally, the EPA could work to provide more consistency and transparency between different data sets like the NEI and the mandatory GHG reporting program, and work to expand these datasets to include direct GHG emission estimates for a broader and more consistent set of sectors.

Of the 100 largest metropolitan areas in the U.S., 31 have reported at least one GHG inventory (and 14 have reported multiple GHG inventories) to the Carbonn Climate Registry (Carbonn Climate Registry 2014), with an average time period between inventories of roughly 2 years. We argue that there may not be a need for such frequent inventorying—especially considering the time and cost often associated with completing an inventory. Comparison of our 2002 and 2011 estimates suggest that emissions change by about 1% per year. Thus, cities might consider conducting inventories about every 5 years and shift a greater portion of their time and energy toward mitigation efforts in the interim.

With the method and proposed changes described above, the integrated emissions estimate approach can increasingly contribute to the process of forming GHG inventories and climate action plans at the local level. In complement to the CACP and ClearPath software typically employed by cities, our approach can help decision makers get an initial understanding of the primary contributors to their overall emissions without having to invest heavily in collecting and analyzing 'bottom-up' data. In some cases, this initial assessment may be enough for the decision makers to move forward with prioritizing and implementing GHG mitigation strategies. In other cases, the initial assessment can still be valuable in helping the decision makers decide where it may be worthwhile for them to invest time and resources to obtain more specific and detailed data. Finally, by having a database of consistently estimated emissions for multiple locations, decision makers could more confidently compare themselves to their peers in whatever manner they see fit.

In addition to expanding this analysis to more metropolitan areas, an important future extension of this work will be to develop alternative approaches for estimating building sector emissions. For example, residential and commercial fuel consumption data from the EIA may provide data that allows for more robust estimation of GHG emissions in these sectors. Additionally, we plan to further explore the implications that scope and boundary choices have on emission estimates, comparisons, and decision making.

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References

Blackhurst M, Matthews H S, Sharrard A, Hendrickson C and Azevedo I L 2011 Preparing US community greenhouse gas inventories for climate action plans *Environ. Res. Lett.* **6** 034003

Brown M A, Southworth F and Sarzynski A 2009 The geography of metropolitan Carbon footprints *Policy and Society* **27** 285–304

Brown M A and Cox M 2015 Progress in energy and Carbon managment in large U.S. metropolitan areas *Energy Procedia* **75** 2957–62

C40 Cities Climate Leadership Group 2011 *About C40: Sustainable Action on Climate Change* (www.c40.org/about) (Accessed: November 2013)

Carbon Disclosure Project (CDP) 2015 *Reports and Data* (www.cdp.net/reports) (Accessed: 8 September 2015)

Carbonn Climate Registry 2014 *Entity Data: United States* (http://carbonn.org/data/) (Accessed: 8 September 2015)

Chattanooga Green Committee 2009 *The Chattanooga Climate Action Plan* (www.chcrpa.org/Divisions_and_Functions/Design_Studio/Projects/Climate_Action_Plan/Final_CAP_adopted.pdf) (Accessed: 6 October 2016)

City of Grand Rapids Office of Energy and Sustainability 2009 *Energy Baselines and Greenhouse Gas Inventory* (http://grcity.us/enterprise-services/officeofenergyandsustainability/Documents/2009%20City%20of%20Grand%20Rapids%20EECS%20GHG%20Inventory.pdf) (Accessed: 8 October 2016)

Glaeser E L and Kahn M E 2010 The greenness of cities: Carbon dioxide emissions and urban development *J. Urban Econ.* **67** 404–18

Gurney *et al* 2009a High resolution fossil fuel combustion CO_2 emission fluxes for the United States *Environ. Sci. Technol.* **43** 5535–41

Gurney *et al* 2009b *Vulcan Science Methods Documentation, Version 2.0* (http://vulcan.project.asu.edu/pdf/Vulcan.documentation.v2.0.online.pdf)

Gurney K R, Razlivanov I, Song Y, Zhou Y, Benes B and Abdul-Massih M 2012 Quantification of fossil fuel CO_2 emissions on the building/street scale for a large U.S. city *Environ. Sci. Technol.* **46** 12194–202

Hillman T and Ramaswami A 2010 Greenhouse gas emission footprints and energy use benchmarks for eight U.S. cities *Environ. Sci. Technol.* **44** 1902–10

ICLEI—Local Governments for Sustainability USA 2013 *U.S. Community Protocol for Accounting and Reporting of Greenhouse Gas Emissions—Version 1.1*

ICLEI—Local Governments for Sustainability USA 2015a *Measuring Up 2015: How US Cities are Accelerating Progress Toward National Climate Goals* (http://icleiusa.org/wpcontent/uploads/2015/08/Measuring_Up_2015.pdf) (Accessed: 7 September 2015)

ICLEI USA 2015b *ClearPath* (http://icleiusa.org/clearpath/) (Accessed: 7 September 2015)

Intergovernmental Panel on Climate Change (IPCC) 1992 *First Assessment Report—Overview Chapter* (www.ipcc.ch/ipccreports/1992%20IPCC%20Supplement/IPCC_1990_and_1992_Assessments/English/ipcc_90_92_assessments_far_overview.pdf) (Accessed: 7 September 2015)

Intergovernmental Panel on Climate Change (IPCC) 1995 *IPCC Second Assessment: Climate Change 1995* (www.ipcc.ch/pdf/climate-changes-1995/ipcc-2nd-assessment/2nd-assessment-en.pdf) (Accessed: 7 September 2015)

Intergovernmental Panel on Climate Change (IPCC) 2007 *Climate Change 2007: Synthesis Report* (www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_full_report.pdf) (Accessed: 7 September 2015)

Intergovernmental Panel on Climate Change (IPCC) 2011 *Climate Change 2001: Synthesis Report (Third Assessment Report)* (www.grida.no/publications/other/ipcc_tar/) (Accessed: 7 September 2015)

Intergovernmental Panel on Climate Change (IPCC) 2014 *Climate Change 2014: Synthesis Report* (www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf) (Accessed: 7 September 2015)

Kennedy C *et al* 2010 Methodology for Inventorying Greenhouse Gas Emissions from Global Cities *Energy Policy* **38** 4828–37

The National Academies of Sciences 2016 *Pathways to Urban Sustainability: Challenges and Opportunities for the United States* (Washington, DC: The National Academies Press)

National Research Council (NRC): Committee on the Challenge of Developing Sustainable Urban Systems 2010 *Pathways to Urban Sustainability: Research and Development of Urban Systems—Summary of a Workshop* (Washington, DC: The National Academies Press)

National Research Council (NRC): Committee on Regional Approaches to Urban Sustainability 2011 *Pathways to Urban Sustainability: Lessons from the Atlanta Metropolitan Region—Summary of a Workshop* (Washington, DC: The National Academies Press)

National Research Council (NRC): Committee on Pathways to Urban Sustainability 2013 *Pathways to Urban Sustainability: A Focus on the Houston Metropolitan Region—Summary of a Workshop* (Washington, DC: The National Academies Press)

National Research Council (NRC): Committee on Regional Approaches to Urban Sustainability 2014 *Pathways to Urban Sustainability: Perspective from Portland and the Pacific Northwest—Summary of a Workshop* (Washington, DC: The National Academies Press)

Open Energy Information (OpenEI) 2015 *International Council for Loacl Environmental Initiatives (ICLEI) Clean Air and Climate Protection Software Tools* (http://en.openei.org/wiki/International_Council_for_Local_Environmental_Initiatives_(ICLEI)_Clean_Air_and_Climate_Protection_Software_Tools) (Accessed: 7 September 2015)

Ramaswami A *et al* 2007 *Greenhouse Gas Inventory for the City and County of Denver* (www.denvergov.org/Portals/771/documents/Climate/Denver%20GHG%20Inventory%20Report%20May15_formatted_final.pdf) (Accessed: 6 October 2016)

Ramaswami A, Hillman T, Janson B, Reiner M and Thomas G 2008 A demand-centered, Hybrid life-cycle methodology for city-scale greenhouse gas inventories *Environ. Sci. Technol.* **42** 6455–61

Swilling M, Robinson B, Marvin S and Hodson M 2013 *City-level decoupling: Urban resource flows and the governance of infrastructure transitions* UNEP

Tamayao M M, Blackhurst M F and Matthews H S 2014 Do US metropolitan core counties have lower scope 1 and 2 CO_2 emissions than less Urbanized Counties? *Environ. Res. Lett.* **9** 104011

U.S. Census Bureau 2013 *2010 Census Urban Area Facts* (www.census.gov/geo/reference/ua/uafacts.html) (Accessed: 7 September 2015)

U.S. Census Bureau 2016a *State Population Totals Datasets: 2010–2016* (www.census.gov/data/datasets/2016/demo/popest/state-total.html)

U.S. Census Bureau 2016b *Metropolitan and Micropolitan Statistical Area Population Totals Tables: 2010–2015* (www.census.gov/data/tables/2015/demo/popest/total-metro-and-micro-statistical-areas.html)

The U.S. Conference of Mayors 2008 *U.S. Conference of Mayors Climate Protection Agreement* (www.usmayors.org/climateprotection/agreement.htm) (Accessed: November 2013)

U.S. Energy Information Administration (EIA) 2015 *State Carbon Dioxide Emissions* (www.eia.gov/environment/emissions/state/) (Accessed: 8 October 2016)

U.S. Energy Information Administration (U.S. EIA) 2016a *2009 RECS Survey Data* (www.eia.gov/consumption/residential/data/2009/)

U.S. Energy Information Administration (U.S. EIA) 2016b *2012 CBECS Survey Data* (www.eia.gov/consumption/commercial/data/2012/index.cfm?view=characteristics)

U.S. Environmental Protection Agency 2010 *2002 National Emissions Inventory Data and Documentation* (www.epa.gov/ttn/chief/net/2002inventory.html#inventorydata) (Accessed: 1 October 2014)

U.S. Environmental Protection Agency 2013a *National Mobile Inventory Model (NMIM)* (www.epa.gov/otaq/nmim.htm) (Accessed: 3 October 2014)

U.S. Environmental Protection Agency (EPA) 2013b *Fact Sheet: Greenhouse Gases Reporting Program Implementation* (www.epa.gov/sites/production/files/2014-09/documents/ghgrp-overview-factsheet.pdf) (Accessed: 6 October 2016)

U.S. Environmental Protection Agency (U.S. EPA) 2015 *State Energy CO_2 Emissions* (http://epa.gov/statelocalclimate/resources/state_energyco2inv.html) (Accessed: 7 September 2015)

U.S. Environmental Protection Agency (EPA) 2016a *2011 National Emissions Inventory (NEI) Data* (www.epa.gov/air-emissions-inventories/2011-national-emissions-inventory-nei-data)

U.S. Environmental Protection Agency (EPA) 2016b *2014 National Emissions Inventory Data* (www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data)

U.S. Environmental Protection Agency (EPA) 2016c *Facility Level Information on Greenhouse gases Tool (FLIGHT)* (https://ghgdata.epa.gov/ghgp/main.do)

U.S. Environmental Protection Agency (U.S. EPA) 2016d *Continuous Emission Monitoring—Information, Guidance, etc* Technology Transfer Network Emission Measurement Center (www3.epa.gov/ttn/emc/cem.html) (Accessed: 29 August 2016)

U.S. Environmental Protection Agency (EPA) 2016e *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014* (Washington, DC)

Weber C L, Jaramillo P, Marriott J and Samaras C 2010 Life cylce assessment and grid electricity: what do we know and what can we know? *Environ. Sci. Technol.* **44** 1895–901

Zhou Y and Gurney K 2010 A new methodology for quantifying on-site residential and commercial fossil fuel CO_2 emissions at the building spatial scale and hourly time scale *Carbon Management* **1** 45–56