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► To cite this version:

K L Mueller, T Lauvaux, K R Gurney, G Roest, S Ghosh, et al.. An emerging GHG estimation approach can help cities achieve their climate and sustainability goals. *Environmental Research Letters*, 2021, 16 (8), pp.084003. 10.1088/1748-9326/ac0f25 . hal-03320576

HAL Id: hal-03320576

<https://hal.science/hal-03320576>

Submitted on 16 Aug 2021

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LETTER • OPEN ACCESS

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To cite this article: K L Mueller *et al* 2021 *Environ. Res. Lett.* **16** 084003

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ENVIRONMENTAL RESEARCH
LETTERS

LETTER

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OPEN ACCESS

RECEIVED
25 March 2021REVISED
3 June 2021ACCEPTED FOR PUBLICATION
28 June 2021PUBLISHED
20 July 2021

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E-mail: Kimberly.Mueller@nist.gov**Keywords:** emissions, cities, approaches, greenhouse gas, carbon accounting, GHG observations, GHG mitigation targetsSupplementary material for this article is available [online](#)**Abstract**

A credible assessment of a city's greenhouse gas (GHG) mitigation policies requires a valid account of a city's emissions. However, questions persist as to whether cities' 'self-reported inventories' (SRIs) are accurate, precise, and consistent enough to track progress toward city mitigation goals. Although useful for broad policy initiatives, city SRIs provide annual snapshots that may have limited use to city managers looking to develop targeted mitigation policies that overlap with other issues like equity, air quality, and human health. An emerging approach from the research community that integrates 'bottom-up' hourly, street-level emission data products with 'top-down' GHG atmospheric observations have begun to yield production-based (scope 1) GHG estimates that can track changes in emissions at annual and sub-annual timeframes. The use of this integrated approach offers a much-needed assessment of SRIs: the atmospheric observations are tied to international standards and the bottom-up information incorporates multiple overlapping socio-economic data. The emissions are mapped at fine scales which helps link them to attribute information (e.g. fuel types) that can further facilitate mitigation actions. Here, we describe this approach and compare results to the SRI from the City of Indianapolis which shows a yearly difference of 35% in scope 1 emissions. In the City of Baltimore, we show that granular emission information can help address multiple issues, e.g. GHG emissions, air pollution, and inequity, at the sub-zip code scale where many roots and causes for each issue exist. Finally, we show that the incorporation of atmospheric concentrations within an integrated system provides rapid, near-real-time feedback on CO₂ emissions anomalies that can uncover important behavioral and economic relationships. An integrated approach to GHG monitoring, reporting and verification can ensure uniformity, and provide accuracy to city-scale GHG emissions, scalable to states and the nation—ultimately helping cities meet stated ambitions.

1. Introduction

Many cities across the globe recognize their impact on climate change and have committed to long-term, ambitious greenhouse gas (GHG) emission mitigation targets. The fact that cities are pledging to reduce their GHG emissions suggests that self-organized, city-scale actions might compensate for

the shortcomings of international climate treaties, regulation, and climate finance/carbon markets (Seto *et al* 2014, IPCC 2018). Typical near-term city mitigation targets range between 30% and 50% reductions by 2030 compared to emissions estimated in a city's chosen baseline year. More ambitious cities aim to achieve carbon neutrality or be net-zero emitters by 2050 (ARUP, C40 2014).

A comprehensive accounting, or inventory, of GHG emissions not only establishes a baseline from which to prioritize actions but also helps a city monitor progress if regularly updated. Although there are different ways to account for emissions, all approaches aim to yield estimates that are accurate, comparable, comprehensive, and complete (Ibrahim *et al* 2012, Ramaswami *et al* 2012). Several guidelines have been developed, each having a slightly different perspective on how a city should account for their emissions (Arioli *et al* 2020).

The original city-scale guidelines borrowed much from the IPCC framework for nations (IPCC 2006, ICLEI 2009). Using this framework, emissions are estimated by combining activity data with sectoral emission factors obtained from, for instance, the IPCC emission factor database (www.ipcc-nggip.iges.or.jp/EFDB/main.php), to provide emissions by economic sector. From this perspective, only scope 1 GHG emissions are inventoried (i.e. those emissions directly resulting from activities that take place within a city's jurisdiction). For example, electricity generation-related emissions are tied to those from powerplants that are physically located within a city as opposed to those from any powerplant (inside and outside a city) caused by the consumption of electricity by city residents (Pichler *et al* 2017).

Since then, work on corporate supply-chain (Chen *et al* 2017) and life-cycle analysis (Ramaswami *et al* 2008, Hillman and Ramaswami 2010, Kennedy *et al* 2010), and trade (Lin *et al* 2015), provided additional perspectives on carbon accounting. These perspectives included inventorying any emissions associated with the consumption of electricity (scope 2) and emissions associated with the complete supply-chain of goods and services (scope 3). A scope 3 approach allows a city to allocate emissions from factories and commercial business worldwide to residents that consume products. A 'consumption-based' approach generally involves all three scopes' emissions, while a 'production-based' perspective considers only scope 1 emissions.

Numerous mixtures and hybrids of consumption- and production-based accounting have been developed and applied at the city-scale (Ramaswami and Chavez 2013, Chen *et al* 2016, Seto *et al* 2016, Lombardi *et al* 2017, Jones *et al* 2018). For example, many incorporate full transboundary activities to avoid truncation errors at physical boundaries, e.g. for aviation or marine sectors, or ways to avoid the double counting of emissions (Creutzig *et al* 2015). Most recently, some yield spatially disaggregated emission information (Gately and Hutyra 2017, Gurney *et al* 2019a, Han *et al* 2020, Gurney *et al* 2020b) or the use thereof (Lin *et al* 2014).

While the academic literature has presented differing accounting perspectives, cities and non-government organizational (NGO) networks have taken up the practical task of building

inventories to support target-setting and mitigation policy. Generally, a city itself accounts for its own emissions following one of several protocol guidance documents/tools e.g. ICLEI (2012). Once developed, cities can report their self-reported inventory (SRI) publicly, e.g. through the CDP (formally the Carbon Disclosure Project) (<https://data.cdp.net/>). In 2017, over 229 cities worldwide reported emissions on the CDP (<https://data.cdp.net/widgets/kyi6-dk5h>, accessed March 2021) including 45 of the 100 most populated cities in the US (Markolf *et al* 2020).

Although mitigation targets set by cities are impressive, questions have been raised about the accuracy and numerical integrity of reported emissions (Satterthwaite 2008, Deetjen *et al* 2018, Hsu *et al* 2019). This is due, in part, to the city-centric nature of the guideline approach. Urban practitioners make multiple subjective decisions based on political, demographic, and socioeconomic circumstances and goals (Kramers *et al* 2013). They collect and quality control data that may come from different years, national statistics, assumptions, and difficult to find sources if local data is not available (Bader and Bleischwitz 2009, Hsu *et al* 2019, Nangini *et al* 2019). Ideally, default emission factors should be refined (but are not always) to represent local processes (Shan *et al* 2019). Compiling an SRI takes time, resources, and expertise: maintaining consistent up-to-date inventories is challenging (Nangini *et al* 2019, Markolf *et al* 2020). Many of these logistical and practical issues are likely the cause of discrepancies noted in Gurney *et al* (2021) rather than fundamental flaws within the protocol guidelines themselves.

It is unclear whether progress can be independently evaluated since there are no universal standards to chart progress (Markolf *et al* 2020). Indeed, the decentralized nature of climate action largely puts the onus on a city itself to independently evaluate progress. Protocol guidelines recommend that cities choose the verification that meets their needs and capacity (ICLEI 2012) with only a few having the budget and staff to do so (Blackhurst *et al* 2011, Markolf *et al* 2018). Uncertainties associated with SRIs can be >50%, larger than many reduction goals (Blackhurst *et al* 2011). Reporting provides a measure of transparency but choices made by practitioners may not be documented or publicly accessible (Markolf *et al* 2020). But, details of SRIs and third-party scrutiny are critical to developing/monitoring a mitigation strategy (Hoornweg *et al* 2011). The extent to which an SRI is accurate, comparable, comprehensive, and complete is largely city dependent. Comparing one city's SRI to another's is extraordinarily difficult.

Recent peer-reviewed literature raises questions about the accuracy of SRIs (specifically CO₂) due to large differences between reported city emissions and those published by academics. These differences cast doubt on whether cities are reducing their emissions

as planned or reporting accurate totals. For example, Gurney *et al* (2019a) provides on-road 2010 emissions that are 10.7% larger than those reported by the local metropolitan planning agency in Los Angeles. Chen *et al* (2020) reported differences that range from -62% to $+148\%$ when comparing SRIs to a downscaled emission product for 12 cities across the globe. In an analysis of SRIs from 48 U.S. cities, Gurney *et al* (2021) argues that cities under-report their scope 1 emissions by 18.3% on average with a range of -145.5% to 63.5% when compared to a fine-scale emission product (aka Vulcan). Note, the Vulcan emission product is consistent with atmospheric radiocarbon ($14\text{ }^{\circ}\text{C}$) measurements at the continental scale (Basu *et al* 2020, Gurney *et al* 2020a).

These reported discrepancies suggest that SRIs are inconsistent with one another and may contain systematic biases or omissions. The comparisons also raise numerous questions such as: how well can we determine whether a city is moving toward meeting its targets? Can we assess whether activities at the city scale, when aggregated, have a national/global impact on emissions? Could new perspectives and methods help check the accuracy of reported emissions while providing an additional level of consistency?

To this end, the geoscience research community has developed approaches to quantify city and regional CO_2 and methane (CH_4) emissions (Hutyra *et al* 2014). These methods integrate ‘top-down’ atmospheric GHG observations with granular ‘bottom-up’ emissions data products using atmospheric inversion techniques (Tarantola 2004, Enting 2018). Atmospheric inversions have a rich history in carbon cycling science (Law 1999, Gurney *et al* 2002, Peters *et al* 2007, Ogle *et al* 2015). Their application over the last decade at urban scales have begun to yield estimates that can track changes in GHG emissions at annual and sub-annual timeframes (Lauvaux *et al* 2016, Sargent *et al* 2018, Turnbull *et al* 2019, Yadav *et al* 2019, Lauvaux *et al* 2020, Yadav *et al* 2021).

Each component of the integrated approach, i.e. atmospheric observations, the inversion process, and the granular data products, brings unique value to the estimation of emissions. Atmospheric observations are key since they root the granular emission data to an atmospheric measurement of GHG tied to international standards (Tans *et al* 1990, Tsutsumi *et al* 2009). Thus, the atmospheric observations provide a measure of accuracy to the estimates missing from other carbon accounting techniques. Observations also contain the integral of all sources in a defined area including anthropogenic emissions and biological fluxes. The granular emissions, whose development has accelerated in the last decade, provide detailed information built from multiple data sources, including directly observed emission quantities (e.g. from continuous emission monitoring systems, aka CEMS), providing added specificity (at hourly/building-level scales) (Gurney *et al* 2012,

2019b, Gately and Hutyra 2017). The inversion process provides the translation between atmospheric concentrations and surface emissions (Stauffer *et al* 2016, Nickless *et al* 2018, Lauvaux *et al* 2020, Yadav *et al* 2021); it is in this translation where a fair amount of uncertainty arises at sub-city spatial scales (refer to the implication section).

Here, we present three case studies that brings together data from the published literature. This work focuses on scope 1 GHG emissions because they (a) can be linked with atmospheric observations (Nangini *et al* 2019)—the most important feature, (b) are largely co-located with issues of air quality (Bares *et al* 2018), environmental justice (Cushing *et al* 2018), heat island effects (Chakraborty *et al* 2019), etc, (c) are usually $\sim 50\%$ of a city’s overall emissions (Kennedy *et al* 2009), and (d) are more straightforward to estimate (Dodman 2009, Hsu *et al* 2019) and thus, should be easier to estimate (and more well-known) than other types of emissions. Thus, any discrepancies in scope 1 estimates between reported emissions (by the city and other groups) suggest similar inconsistencies in emissions associated with other scopes that require more assumptions, even more data inconsistencies, etc.

The first case study compares the SRI (scope 1 emissions only) for Indianapolis, Indiana with whole-city emissions estimated with an integrated approach. We use Baltimore, Maryland in a second case study to show how spatially and temporally explicit emissions can point to specific places where the city can achieve co-benefits. Identifying underlying spatial processes not only helps city planners contextualize aggregated annual city-wide totals but provides support for targeted action. Finally, our third case study, focused on the City of Baltimore, demonstrates that relationships between citizen behavior, market forces, and stressors (like weather shocks), are best uncovered using emission information at sub-annual scales. Understanding relationships can explain year to year variability in annual emissions and allow cities to concentrate on levers to reduce emissions that are within their control. Such case studies have not been previously presented in the literature, largely because there are only a few applications of an integrated approach at the urban scale. A summary of SRIs and the integrated approach is provided in table 1.

2. Data and methods

In our whole-city case study (figure 1), we extract scope 1 CO_2 emissions and associated uncertainties from those reported in Lauvaux *et al* (2020), for the city of Indianapolis’ jurisdictional boundary ($\sim 950\text{ km}^2$) and sum them annually for 2013 and 2014. Lauvaux *et al* (2020) employed an integrated approach to estimate $1\text{ km}^2/5$ day emissions for a nine county domain for 2013 and 2014 using (a) high-accuracy atmospheric CO_2 observations from

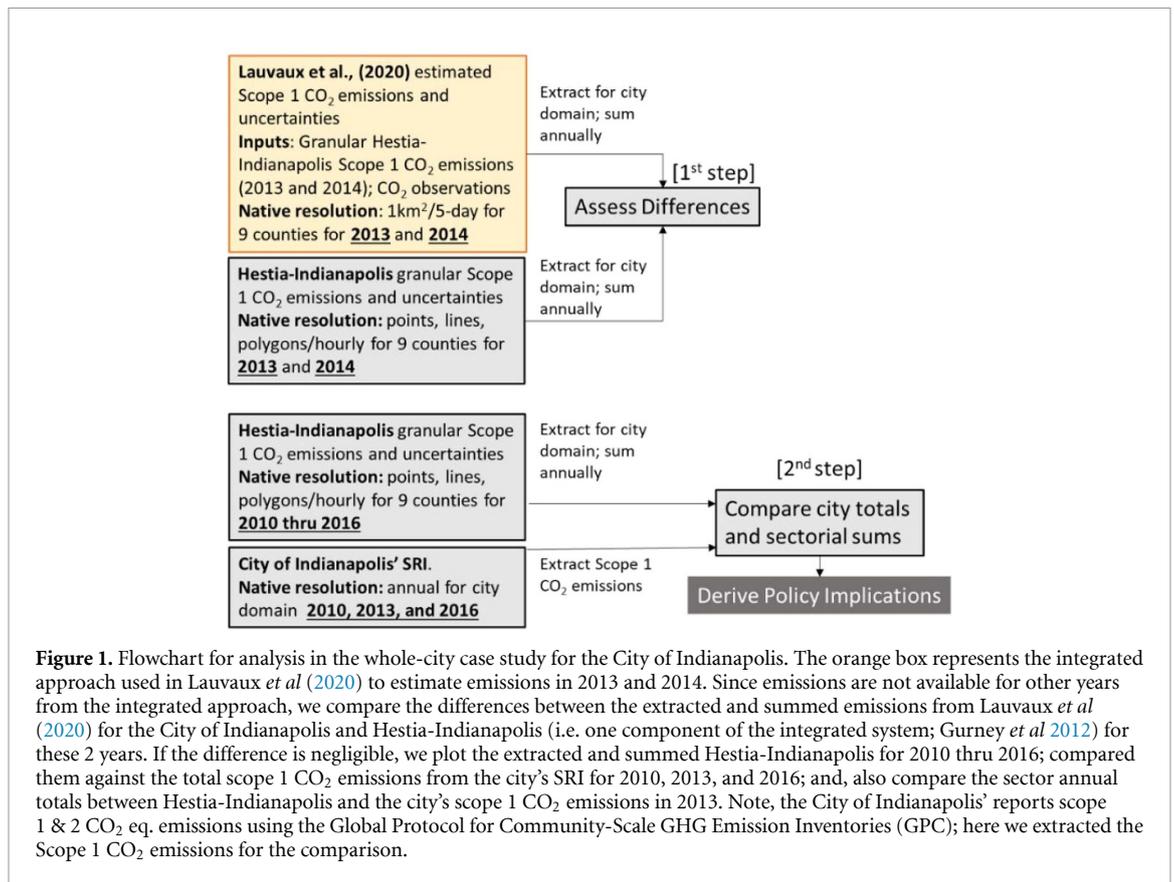
Table 1. Descriptions of SRIs and an integrated approach which includes granular GHG emissions, atmospheric observations, and an inversion link. Symbols, definitions, and references include: (*) CO₂ equivalents, or CO₂ eq, allows for the combination of multiple GHG emissions into a single number using global warming potentials (GWPs); (†) Hestia, (Gurney et al 2012); (††) Vulcan; (Gurney et al 2020b); and (†††) ACES, (Gately and Hutyra 2017); (††††) (Michalak et al 2017); (ˆ) observations are available sub-hourly but generally used at the hourly timescale; (ˆˆ) e.g. (Karrion et al 2020); (ˆˆˆ) uncertainties from inversion components discussed in the implication section, generally much larger than observational uncertainties.

Characteristics	Integrated approach		
	Self reported inventories (SRIs)	Granular emissions	Atmospheric observations/inversion link
Units	CO ₂ eq* (mass/year)	CO ₂ and CH ₄ (mass/time)	CO ₂ and CH ₄ (mass)
Spatial scale	Whole city	Points/lines/polygons at hourly timescales; Gridded (1 km ² or greater) at various temporal resolutions	NA
Temporal scale	Annual	Hourly	Hourly ^ˆ
Latency	Periodic updates with multiple yearly gaps	~Lags current year	Real time
Input data	Socio-economic data (activity data) and emission factors. Default, nationally, regionally, or locally derived. Choices by cities.	Socio-economic data (activity data) and emission factors. Nationally, regionally or locally derived. Consistent across cities. Choices by developer.	Granular emissions, meteorological-dispersion model, assumptions on error characteristics for model components, atmospheric observations from <i>in-situ</i> networks, aircraft, satellite, others. Choices by developer.
Reported scope 1	Yes (but may not be reported separately than scope 2)	Yes	NA
Reported production-based total	Can be hard to isolate total in-boundary scope 1 from scope 2 depending on reporting.	Yes	—
Location specified	No (only whole-city total)	Yes	—
Reported sectors	On-road Industrial Residential Commercial Non-road Other	On-road Industrial Residential Commercial Non-road Other In-domain electrical prod.	— — — — — — —

(Continued.)

Table 1. (Continued.)

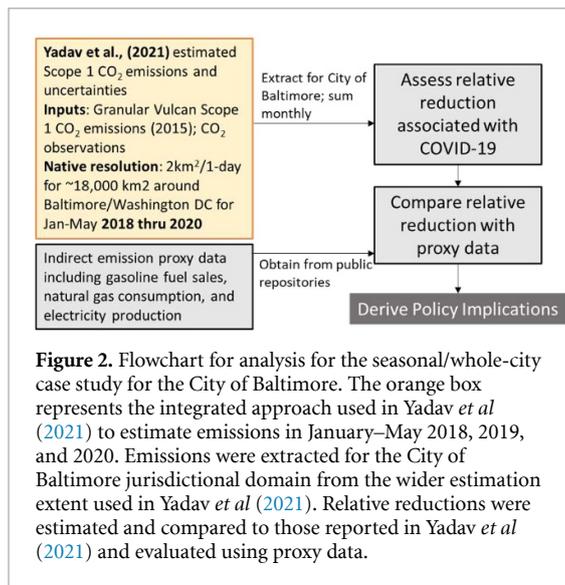
Characteristics	Self reported inventories (SRIs)	Integrated approach	
		Granular emissions	Components
Reported scope 2	Yes (but may not be reported separately than scope 1) No Electricity prod. Depends	Depends if emissions are available outside city boundaries — — No	NA — — NA
Reported scope 3	No Waste Food	— — —	— — —
Validated	City-dependent. No uncertainty reported.	Reported whole city uncertainties	Uncertainties associated with observations ^{^^} ; uncertainties associated with inversion link ^{^^^}
Reporting	CDP, carbonne, others	Academic literature, public portals, etc.	Academic literature, public portals, etc.



an urban *in-situ* tower network (figure 3(a)), and (b) year-specific scope 1 CO₂ Hestia-Indianapolis granular emissions (1 km² hr⁻¹, figure S1 (available online at stacks.iop.org/ERL/16/084003/mmedia)) (Gurney *et al* 2012) linked through an inversion. We also separately show Hestia-Indianapolis CO₂ emissions and uncertainties (Gurney *et al* 2012) for the city domain since they cover a longer timespan (2010–2016). A summary of the model used in Lauvaux *et al* (2020), the Hestia-Indianapolis method, means of extracting city emissions and uncertainties, and conversion of CO₂eq to CO₂ are provided in the SI along with annual totals and sectoral emission sums (table S1). We compare the extracted and aggregated city-wide emissions from Lauvaux *et al* (2020) with those of Hestia-Indianapolis. We derive scope 1 CO₂ emission from the City of Indianapolis' Thrive report and GHG Inventory (2018, 2021) (detailed in table S2). We directly compare the (a) city-wide totals (2010, 2013, 2016), (b) city reported scope 1 sectoral emissions (2013) to (c) Hestia-Indianapolis emissions.

In our sub-city case study, we use the annual sum of the on-road sector CO₂ emissions from the granular Hestia-Baltimore data product (for the city domain only; Roest *et al* 2020). A city-scale integrated approach cannot be used to estimate emissions for 2014 given atmospheric observation limitations for that year. We assume that Hestia-Baltimore provides a realistic spatial representation of on-road emissions that would result from an application of

an integrated approach. These emissions have been compared to the City of Baltimore SRI and differences were diagnosed by Roest *et al* (2020). Hestia on-road emissions are estimated for each road segment as detailed in Gurney *et al* (2020a). Briefly, the developers used an inverse distance weighting of average annual daily traffic (AADT) from the Federal Highway Administration's vehicle counting station data, which were disaggregated by road type. The AADT were then used with the road segment length to estimate the vehicle miles travelled for each road segment, which provides a relative metric to distribute county-level FFCO₂ emissions from the 2011 EPA National Emissions Inventory (NEI). Local gap-filled traffic data were used to distribute emissions in time to the hourly scale, though only annual emissions are used in this study. More details on the on-road emission methods can be found in the Vulcan (Gurney *et al* 2020a) and Hestia-Baltimore (Roest *et al* 2020). We also use a housing market typology (HMT) map employed by the city to target interventions and guide municipal investments based on neighborhood conditions (<https://planning.baltimorecity.gov/maps-data/housing-market-typology>). Additionally, we utilize the Environmental Protection Agency's (EPA) National Air Toxic Assessment (2014) (www.epa.gov/national-air-toxics-assessment) which lists zip-codes where air toxins and emission source types pose respiratory health risks for each state. Zip codes used in this study were highlighted as having poor air quality



due primarily to on-road emissions. More information on data is provided in the SI.

For our seasonal/whole-city case study (figure 2), we extract and aggregate monthly scope 1 CO₂ emissions and uncertainties for the City of Baltimore (~240 km²) from those reported in Yadav *et al* (2021). Yadav *et al* (2021) used an integrated approach, for the Baltimore/Washington DC region, to discern the impact of COVID-19 on CO₂ emissions. Yadav *et al* (2021) estimated daily emissions at a native resolution of 2 km²/daily for these metropolitan regions (~18 000 km² for both domains). Emissions were estimated for January–May 2020 along with coincident time-periods for 2019 and 2018 (the averages providing baseline months). The integrated approach used high accuracy atmospheric observations from *in-situ* tower networks (figure 4(a)) and 2015 granular emissions from Vulcan (Gurney *et al* 2020a). A summary of the method is provided in the SI. To diagnose cause and effect relationships at the whole-city scale, we compare features in emission proxy data with the extracted and summed CO₂ emission estimates. The emission proxy data includes natural gas consumption and gasoline data for the State of Maryland from the Energy Information Administration (EIA; www.eia.gov/state/?sid=MD); (www.eia.gov/dnav/pet/hist). We also use monthly emission data from EPA’s Clean Air Market Database (CAMD; www.epa.gov/airmarkets) for a powerplant within the Baltimore city domain.

3. Results and discussions

3.1. Annual/whole-city comparison: Indianapolis

After extracting and summing the Lauvaux *et al* (2020) emissions for the City of Indianapolis (as estimated using an integrated approach), we find them statistically consistent with those from Hestia-Indianapolis for 2013 and 2014, with less than 3%

difference. This mirrors the results in Lauvaux *et al* (2020). Note, that the reported agreement is not happenstance. Lauvaux *et al* (2020) biased Hestia-Indianapolis emissions by up to 10% and achieved almost identical results at the nine-county scale. The convergence in estimates demonstrates that high-accuracy atmospheric CO₂ observations within an integrated system provide the necessary constraint to adjust granular emissions (if biased) to be consistent with atmospheric CO₂—which accounts for all possible city sectoral CO₂ emissions. We do not have emissions from the integrated approach for other years. However, we assume the consistency between Hestia-Indianapolis’ city-wide emissions and those extracted/summed from Lauvaux *et al* (2020) allow us to confidently use Hestia-Indianapolis’ emissions as an independent point of comparison to those reported by the city.

The Hestia-Indianapolis emissions and the city’s scope 1 reported emissions trend well together for each of the three reporting years (figure 3(b)). Note, this trend does not necessarily reflect reductions stemming from the implementation of city-policies but mainly reflects market forces in the electricity production sector. For example, the Hestia-Indianapolis’ electricity sector emissions indicate a decrease in emissions from 2014 to 2016 due to fuel switching at the two largest in-domain power plants (figure S1), e.g. Harding St. (a 12 unit, 1196 MW capacity) and Perry K. (a small steam producing multi-fired power station). The city’s 2013 and 2016 emissions also capture this change.

However, unlike the trend, the absolute magnitudes of both the annual, sectoral totals of Hestia-Indianapolis and the city’s SRI are significantly different (figure 3(b)). The city’s reported emissions are consistently 35% lower for 2010, 2013 and 2016 compared to the Hestia-Indianapolis emissions. Further analysis suggests that almost all emission sectors are underreported in the city’s SRI by different amounts for various reasons (City of Indianapolis 2018, tables 2 and S3). The city’s SRI attributes the majority of GHG emissions to Indianapolis’ in-domain residential buildings and traffic. But the difference in the transportation sector is substantial (43%). Given the size of the sector’s emissions, the discrepancy questions whether the city will be able to assess whether it can achieve its goal of reducing on-road emissions by ~67% in 2025 from a 2016 baseline (refer to tables S4 and S5 for policies outlined in Thrive including public benchmarking).

As cities commit to becoming net-zero emitters by 2050, the differences in total emissions will increasingly be important to reconcile; assessing trends will not be enough. As a signatory to the UNFCCC Initiative ‘Race to Net Zero’ (<https://unfccc.int/climate-action/race-to-zero-campaign>), the City of Indianapolis will have to balance any of its 2050 emissions with carbon offsets. Currently, the absolute difference

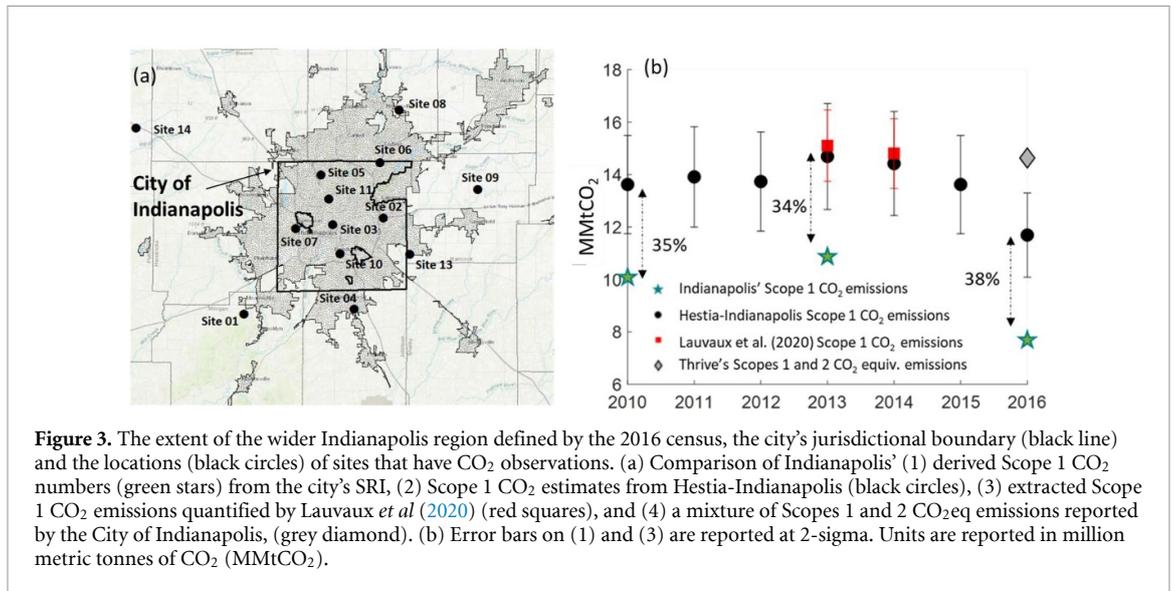


Figure 3. The extent of the wider Indianapolis region defined by the 2016 census, the city's jurisdictional boundary (black line) and the locations (black circles) of sites that have CO₂ observations. (a) Comparison of Indianapolis' (1) derived Scope 1 CO₂ numbers (green stars) from the city's SRI, (2) Scope 1 CO₂ estimates from Hestia-Indianapolis (black circles), (3) extracted Scope 1 CO₂ emissions quantified by Lauvaux *et al* (2020) (red squares), and (4) a mixture of Scopes 1 and 2 CO₂eq emissions reported by the City of Indianapolis, (grey diamond). (b) Error bars on (1) and (3) are reported at 2-sigma. Units are reported in million metric tonnes of CO₂ (MMtCO₂).

Table 2. Summary of Indianapolis Scope 1 CO₂ and Hestia-Indianapolis emissions (City of Indianapolis 2018; MMtCO₂/year) per sector including percent differences.

Reported sectors	Indianapolis scope 1	Hestia-Indianapolis	Perc. difference	Comments
Airport	500 000	174 175	97%	
Commercial	650 000	966 541	−39%	
Industrial	500 000	785 029	−44%	
Onroad/nonroad/railroad	4249 656	6587 072	−43%	Less confidence (largest source)
Residential	1050 000	1130 791	−7%	More confidence (second largest source)
Elec. Prod. (Scope 1)	3919 026	5036 484	−25%	
Total	10 868 682	14 680 091	−35%	

between Hestia-Indianapolis emissions and the city's reported totals is significant (2-sigma) with an average annual discrepancy of ~ 4 MMtCO₂—raising questions as to whether the city will be able to confidently assess their emissions for proper offsetting. For example, as an interim step to 2050, the city aims to reduce ~ 5.86 MMtCO₂ by 2025, with 2.2 MMtCO₂ from the on-road sector (Scope 1) alone. Since annual/whole-city emissions estimated from an integrated approach are consistent with atmospheric levels of CO₂, they could provide a credible point of comparison to SRIs to ensure proper accounting.

3.2. Sub-city case study: Baltimore

Mitigating GHG emissions can have co-benefits that improve quality of life by addressing air pollution and equity issues which occur at the local scale. In the City of Baltimore, the overlay of zip codes associated with very high respiratory risk from transportation (aka on-road) emissions specified in EPA's National Air Toxic Assessment with Hestia-Baltimore and the city's HMT map enables us to identify neighborhoods and roads that have large associated CO₂ emissions and air quality criteria pollutants like PM_{2.5}. As in other studies (Levy *et al* 2007), figure 4(b) highlights

economically disadvantaged communities that are disproportionately impacted by air pollution. Note that at an aggregate city-scale, emissions along interstates and arterial roadways make up the largest percentage of on-road emissions. However, exposure to vehicle exhaust that causes increased respiratory risk are generally associated with proximity to local roadways (Zwack *et al* 2011). Indeed, for these zip codes, those streets that contribute 50% or more to overall GHG emissions are smaller arterial roads (table 3) which suggests that congestion and 'street canyons' may cause significant air pollution levels at these localities rather than major thoroughfares (Gately 2017). The city aims to use planning activities outlined in their CAP (e.g. City of Baltimore, 2014; activity LUT1. A further outlined in table S7) to decrease transportation related GHG emissions and improve residents' quality of life overall. Figure 4(b) implies that information at the zip-code scale may be too coarse to effectively achieve such co-benefits, since hotspots and intersections and specific roads within these areas are responsible for most emissions and air pollutants.

Beyond achieving co-benefits, sectoral emissions resolved at granular scales can enable city planners detect the largest emitters in the wider

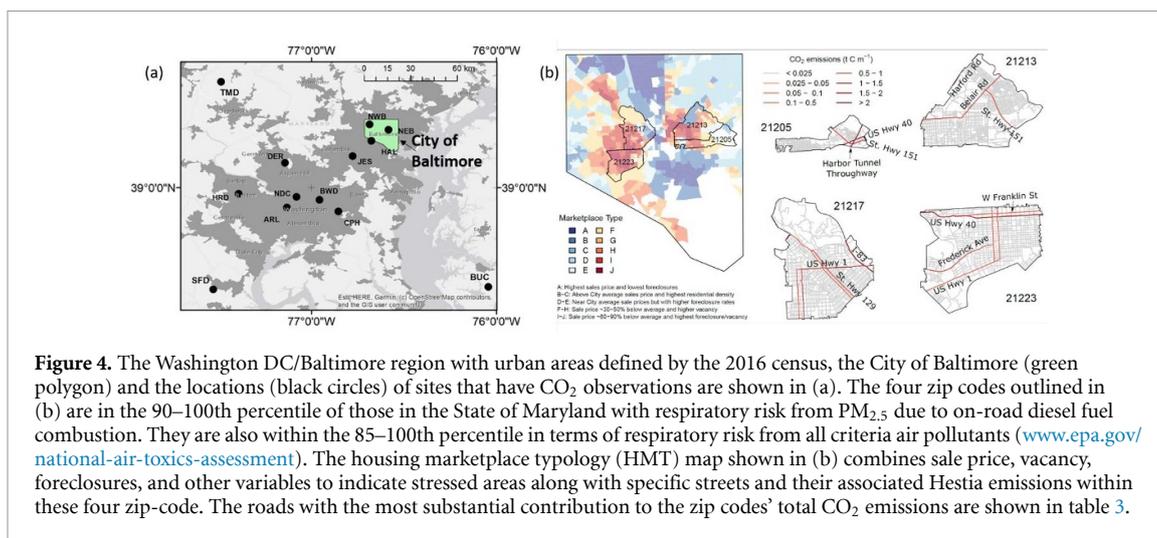


Figure 4. The Washington DC/Baltimore region with urban areas defined by the 2016 census, the City of Baltimore (green polygon) and the locations (black circles) of sites that have CO₂ observations are shown in (a). The four zip codes outlined in (b) are in the 90–100th percentile of those in the State of Maryland with respiratory risk from PM_{2.5} due to on-road diesel fuel combustion. They are also within the 85–100th percentile in terms of respiratory risk from all criteria air pollutants (www.epa.gov/national-air-toxics-assessment). The housing marketplace typology (HMT) map shown in (b) combines sale price, vacancy, foreclosures, and other variables to indicate stressed areas along with specific streets and their associated Hestia emissions within these four zip-code. The roads with the most substantial contribution to the zip codes’ total CO₂ emissions are shown in table 3.

Table 3. Roadways ranked by their relative contribution to on-road CO₂ emissions within each zip code shown in figure 4.

Zip code →	21205		21213		21217		21223	
Rank ↓	Name	Percent	Name	Percent	Name	Percent	Name	Percent
1	Harbor Tunnel Throughway	41.0	Belair Rd	23.1	I- 83	47.0	US Hwy Route 40	20.8
2	US Hwy 40	24.0	State Hwy 151	13.5	US Hwy 1	17.2	W Franklin St	19.9
3	State Hwy 151	22.8	Harford Rd	13.0	State Hwy 129	8.2	US Hwy 40	13.5
4	E Monument St	0.9	E North Ave	12.8	Druid Hill Ave	5.3	US Hwy 1	11.7
5	E Madison St	0.6	Edison Hwy	0.9	N Monroe St	3.6	Frederick Ave	7.9
6	Ashland Ave	0.6	E Federal St	0.8	Reisterstown Rd	2.0	N Monroe St	3.0
7	E Eager St	0.5	Sinclair Ln	0.8	State Hwy 26	1.5	S Monroe St	2.6
8	McElderry St	0.4	E Biddle St	0.7	W North Ave	1.1	S Fulton Ave	2.5
9	Jefferson St	0.3	Erdman Ave	0.7	W Lafayette Ave	0.3	W Baltimore St	0.6
10	Wright Ave	0.3	N Broadway	0.6	Eutaw Pl	0.3	Edmondson Ave	0.5

urban extent—helping cities achieve their climate goals. Within its CAP, the city has targeted improving the energy efficiency of buildings. The city intends to audit commercial and industrial buildings over 10 000 sqft to identify simple and low-cost energy efficiency measures (City of Baltimore, 2014; activity ESS.1.C). This amounts to ~3800 buildings with 76% being commercial (according to Hestia-Baltimore). Roest *et al* (2020) implied that a large fraction of commercial building emissions (~76%) are from a small number of structures. Hestia-Baltimore could help the city prioritize which buildings should be audited first based on their emissions profiles (table S7). In doing so, Hestia-Baltimore may also be able to provide a more realistic GHG reduction estimate based on efficiency measures implemented at these structures compared to the reduction numbers provided in Baltimore’s CAP.

3.3. Seasonal analysis/whole-city analysis: Baltimore

Sub-annual emission information can provide valuable insights into the causes of emissions changes

(e.g. weather events, sudden shifts in behavior, and abrupt market forces) that might be obscured in annual totals (Perugini *et al* 2021). However, estimates often have latency that lags real-time by 3–5 years (figure S2). This may change in the future as more city-specific data becomes available without too much delay that can be ingested in granular emission products. In contrast, atmospheric observations are available near real-time (figure S2). When using an integrated approach, the atmospheric observations use ‘older’ granular emissions (for spatial and temporal patterns) but ‘pull’ emissions to capture abnormal events for more recent years (Yadav *et al* 2019, Turner *et al* 2020). Note, the specificity of granular information within an integrated approach, even for a prior year, is important to achieve city-totals consistent with atmospheric CO₂ (Oda *et al* 2017).

We show this with our extracted Yadav *et al* (2021) emissions and associative uncertainties for the City of Baltimore. Our extracted monthly summed CO₂ emissions show nearly identical relative reductions (31% in April 2020; figure 5(a)) in Baltimore as Yadav

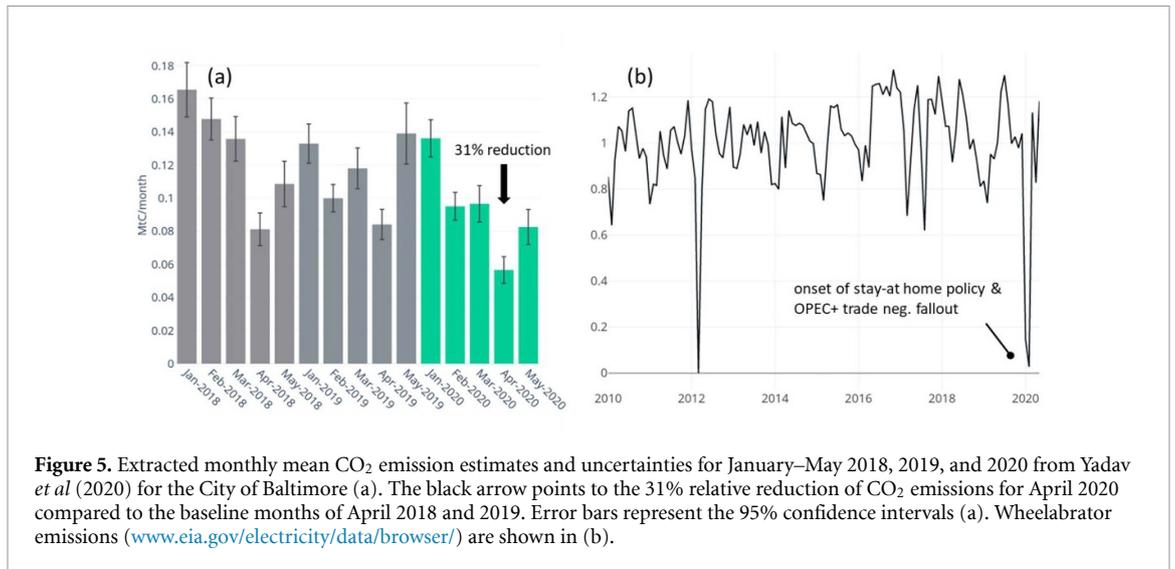


Figure 5. Extracted monthly mean CO₂ emission estimates and uncertainties for January–May 2018, 2019, and 2020 from Yadav *et al* (2020) for the City of Baltimore (a). The black arrow points to the 31% relative reduction of CO₂ emissions for April 2020 compared to the baseline months of April 2018 and 2019. Error bars represent the 95% confidence intervals (a). Wheelabrator emissions (www.eia.gov/electricity/data/browser/) are shown in (b).

et al (2021) (33%) but with much wider uncertainty bounds (1-sigma 30% compared to 11% respectively). These large uncertainties reflect, in part, that some high-accuracy observations in the city were not available during the height of the change in emissions (April 2020).

For the City of Baltimore, variations in emission proxy data (e.g. gasoline fuel sales and natural gas consumption) explain much (but not all) of the relative drop in emissions during this time, particularly gasoline fuel sales (figure S3). These relationships are explored in Yadav *et al* (2021). Herein, we look at electricity output since, at the national scale, emissions from this sector have been shown to correlate with pandemic shifts (−15.1% April–May relative decline; Gurney *et al* 2021) when compared to emission baseline years. There are several powerplants within the city’s boundary. The large Wheelabrator waste-to-energy facility (partially fueled by petroleum waste products) experienced a steep decline in February/March 2020 (figure 5(b)). Global petroleum coke (petcoke) supply was affected by OPEC+ negotiation fallout and events associated with COVID-19 (Deloitte 2020) which likely explains this jump. The sudden drop in Wheelabrator emissions may have contributed to the 30% relative reduction in the Baltimore emissions.

The density of people and activities in cities make their citizens, economies, and carbon emissions vulnerable to various stressors—both natural and man-made. Understanding the relationships between CO₂ emissions and shocks can help cities (a) design policies to adapt to unexpected events while mitigating emissions and (b) tease apart those emissions that can be influenced by polices (e.g. building codes) compared to others outside of the city’s control (e.g. market forces).

4. Implications

Cities have emerged as vanguards of climate leadership and have a stronger relationship with their citizens. But they have a limited set of policy levers to alter their emissions alone. Coordination and consistency with state, regional, and national emissions is crucial; e.g. cities like Baltimore are counting on state and national measures to help cut their emissions (20% from the state’s renewable portfolio in 2022, and 11% from EPA’s passenger vehicle and light duty fuel efficiency standards) but little coordination is evident. If estimated for a large enough area, emissions from an integrated approach are completely consistent across metropolitan, state, regional, and national domains while being tied to atmospheric observations whose accuracy is ensured by international standards. Nested national to regional systems could (a) use various levels of data more quickly, (b) enable policy levers at different scales of government, (c) foster private-public relationships, (d) avoid truncation issues associated with transportation (e.g. on-road, aviation, and commercial marine shipping), and (e) allow for an assessment of the progress of action across the county. In this manner, they complement existing tools/methods.

To provide the type of emission data shown herein, continued progress is needed. This involves grappling with observational constraints (e.g. *in-situ*, flask, low-cost, and aircraft GHG measurements, along with satellite retrievals), improving latency issues, enhancing workforce capabilities, tackling costs, and engaging stakeholders. Presently, implementation is prohibitively expensive for most city governments. Organizations like the World Meteorological Organization’s Integrated Global GHG Information System initiative (WMO-IG³IS; <https://ig3is.wmo.int/en/welcome>), NGOs, documentary

standards organizations, etc must also help. These organizations can develop a scientifically-based and internationally recognized framework that would ensure that methods are tied to verifiable standards.

Researchers are also actively improving elements of the inversion process that lead to a fair amount of uncertainty on estimated emissions. These include: improving transport models which link observations to emissions in specific locations (Deng *et al* 2017), separating atmospheric CO₂ entering a city's domain (Karion *et al* 2021), distinguishing anthropogenic sources from biogenic fluxes (Miller *et al* 2020), and expanding the suite of measurements to constrain specific sectors (Nathan *et al* 2018), etc. Confidently estimating biological contributions using the observations could also help with accounting for programs like composting, increasing green areas, etc.—but more work is needed to do so.

5. Conclusions

In this paper, we show that combining atmospheric GHG observations with granular emissions data products in an integrated approach could help assess the uncertainty of SRIs, support city climate and sustainability goals, and uncover relationships between GHG emissions and their drivers. Near real-time feedback offers the potential for the 'course-correction' of policies if needed.

The United Nations Environment Programme (UNEP) estimates that the world would need to cut carbon emissions by 7.6% per year for the next decade to prevent the globe from warming more than 1.5 °C above pre-industrial levels (UNEP 2020). To do so, most cities must achieve net-zero emissions by mid-century. But without atmospherically checked emission data that speaks to scales of human behavior, this will be difficult. The discrepancies between SRI and our emission estimates shown herein are too large to have assurance in reported emissions. Methods like the integrated approach, as demonstrated within this work, can help cities achieve multiple goals and point global climate efforts in a new and more effective direction—all of which are needed to drive down emissions locally and globally.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

Support for K Gurney, S Ghosh, G Roest, and P DeCola was provided by NIST grants 70NANB10H245, 70NANB19H132, 70NANB19H129, and 70NANB19H131 respectively. T Lauvaux was supported by the French

program Make Our Planet Great Again (CIUDAD). The opinions/recommendations/findings/conclusions expressed do not necessarily reflect the views/policies of NIST/US Government.

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