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COMMENTARY

Advances in urban greenhouse gas flux quantification: The Indianapolis Flux Experiment (INFLUX)

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Those responsible for implementing efforts to reduce greenhouse gases (GHG) need more timely and accurate emissions data to guide their activities. But measuring GHG emissions poses significant technical and scientific challenges. During the 2016 Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCC) in Paris, 162 nations submitted emission reduction goals in the form of Nationally Determined Contributions (NDCs). The U.S. NDC states that, "the United States intends to achieve an economy-wide target of reducing its greenhouse gas emissions by 26–28 percent below its 2005 level in 2025 and to make best efforts to reduce its emissions by 28 percent." Other developed nations have put forth NDCs of similar magnitude. To judge progress toward these NDCs, and determine whether they are ultimately attained, will require measurements to a particular degree of certainty. How much certainty will be required is currently not determined. However, it may be anticipated that for emission reduction claims to be credible, uncertainties that are a fraction of target levels will be desired.

Cities and metropolitan areas are major contributors to a nation's total GHG emissions inventory. Therefore, measurements that better quantify urban emissions can greatly increase the credibility of U.S. GHG emissions data. Prior to 2010, most atmospheric greenhouse gas measurement capabilities were focused on continental and global scales (with the notable U.S. exception of research efforts in Salt Lake City (Strong et al., 2011, Lin et al., 2018)). In 2010, the Indianapolis Flux Experiment (INFLUX) began. INFLUX is focused on developing and demonstrating urban-scale GHG flux measurement capabilities. Urban environments, which currently account for approximately 50% of global GHG emissions to the atmosphere, are excellent test beds for advancing these technologies. The objective of INFLUX is to improve emission inventory data quality by investigating, assessing, and improving the performance of emissions measurement approaches with high spatial and temporal resolution (Davis et al., 2017). This special issue of Elementa features 14 articles describing on-going measurement science research aimed at improving GHG emission flux quantification methods within Indianapolis and the surrounding region.

Indianapolis was chosen because of its moderate size (about 1.8 million inhabitants in the city and surrounding area), relative isolation from other strong emissions sources, and location in a landscape of flat terrain with minimal impact on its meteorology. In addition, Indianapolis was already the site for development of urban-scale, spatially and temporally resolved emissions data products that bridged the gap in temporal and geospatial scales between atmospheric observing methods and more traditional inventory data and reports (Gurney et al., 2012 & 2017). These features made the challenge of measuring GHG emission fluxes in Indianapolis tractable relative to other urban settings.

In addition to being excellent test beds, urban regions having well-characterized GHG emission flux estimates can provide a useful information base for comparison to and assessment of remote sensing instrument performance whether these are satellite, airborne, or surface-based platforms. Combining high-quality, mole fraction measurements with well-characterized meteorology can provide flux estimates with stated uncertainty (Lauvaux et al., 2016). Use of these to assess satellite instrument performance, such as those on GOSAT, OCO 2, and future satellite missions, for example GeoCARB and OCO 3, contributes to improving the quality of both atmospheric observation-based estimates and traditional GHG inventory data and reports.

The INFLUX project has been funded wholly by NIST since its inception. As a measurement science project, it reflects NIST GHG measurements program goals. First, to advance urban GHG quantification capabilities based on traditional economic-sector and emission process-based methods (the bottom-up approach; Gurney et al., 2012 & 2017) and those based on atmospheric observations (the top-down approach; Lauvaux et al., 2016 & in prep.). Most emissions reports are based solely on bottom-up methods, and generally report on a yearly basis by economic sector. In contrast, top-down methods yield

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time- and location-specific data on scales of hours to weeks and several to tens of kilometers. The second, longer-term goal is to develop methods for objectively comparing the results from these two method classes to move toward a comparative capability, or reference frame, a challenge for both method classes. In addition, research results such as those produced by INFLUX will strengthen the basis for making bottom-up and top-down methods independent of one another. Evaluating their relative performance provides critical insights into the strengths and deficiencies of both and identifies paths toward improvement. Finally, combining information from both approaches is likely to produce results that have greater accuracy, lower uncertainties, than either approach alone.

The atmospheric observation methods utilized as part of INFLUX include aircraft mass balance methods designed to measure whole-city emission fluxes (e.g. Heimburger et al., 2017). While these methods do not provide spatially resolved emissions information, they can be rapidly deployed to many environments and produce a quantitative snapshot of emission flux information. INFLUX was initially designed as a mass balance experiment combining aircraft with surface observations taken at two locations across the city along the prevailing wind direction. Shortly after INFLUX began, NIST expanded the effort to investigate the performance of a spatially dense, surface-based atmospheric observing network. These measurements coupled with atmospheric inversion methodologies provide capability to locate and quantify emission fluxes within an urban environment or similarly sized region. By 2012, the INFLUX team deployed mole fraction measurement devices at existing communications towers to sample the atmosphere at heights from 40 to 130 meters. This effort expanded to include 12 towers located at a background inflow position and at locations through the city core (Miles et al., 2017). The surface observing network continuously measures the city's incremental concentrations of CO_2 and methane (Richardson et al., 2017).

In addition to real-time measurements, several observing points have been fitted with flask sampling devices. Analyses of these flask samples include $^{14}CO_2$ and approximately 40 other atmospheric trace gases. To improve performance of atmospheric simulation, a Doppler LIDAR instrument was installed to provide real-time estimates of boundary layer heights and dynamics (one of the papers in this issue discusses the benefits gained from the LIDAR system.) With variable wind direction data and the use of Bayesian inversion methods, this network yields emission fluxes that are spatially resolved to roughly 1–2 km^2.

When INFLUX was launched, an extensive and sophisticated emissions model, HESTIA, was under active development at Purdue. HESTIA employs a bottom-up emissions modeling approach based on detailed data from local socioeconomic activities to produce fossil fuel CO_2 emissions flux data at temporal and spatial resolutions that equal or exceed those of the top-down approaches used in INFLUX. Indeed, one goal of HESTIA was to provide local decision-makers with high-fidelity information useful in assessing and improving effectiveness of their CO_2 emissions reduction strategies.

HESTIA is an important component of INFLUX. For instance, INFLUX compares the bottom-up emission flux determinations from HESTIA with the top-down results from INFLUX's several atmospheric observing methods (Cambaliza et al., 2014; Lauvaux et al., 2016). Articles in this issue expand upon those developments. Atmospheric inversion analyses for CO_2 have been a mainstay of INFLUX research. Such analyses use HESTIA data as an initial estimate for CO_2 emissions. Several articles (Lauvaux et al., 2016; Gurney et al., 2017) address aspects of this type of Bayesian analysis approach.

Although the HESTIA modeling approach is quite effective for fossil fuel CO_2 emissions, applications of this approach to methane emissions are considerably less mature. However, progress is being made toward a similar emissions data product for methane. Several ground-based and aircraft campaigns, most aimed at identifying and quantifying important point sources of methane emissions, have also been developed using Indianapolis as a testing location (Lamb et al., 2016; Cambaliza et al., 2017).

Progress on INFLUX, and similar urban studies begun after the start of INFLUX, indicate that the combination of top-down and bottom-up methods has excellent potential for providing urban CO_2 emission flux measurements sufficiently accurate to clearly assess progress toward NDC targets. Indeed, the combination of methods strengthens the result of the comparison itself by identifying the strengths and weaknesses of each. For example, with bottom-up methods, unknown sources are not included in data products such as Hestia, nor in U.S. GHG inventory reports. On the top-down side, large discrepancies with HESTIA may reflect uncertainty, or they may point toward the possibility of an unknown source in an area of the city. For example, INFLUX demonstrated that atmospheric inversion could identify sources not included in the prior estimate obtained from Hestia. In that case, further investigation, including potential sources of bias in the inversion method, revealed that a small power plant located on the outskirts of the city had not been included in the HESTIA bottom-up estimates because its emissions were below EPA reporting requirements.

However, significant scientific and technological challenges remain. These include improving CO_2 flux measurement and quantification, which will help those faced with the challenge of more effectively managing emissions mitigation efforts. Another challenge is improving the quantification of urban methane emissions. Significant progress on that front will likely occur in the next few years. Finally, the scientific community is developing the capability to distinguish between biogenic and combustion-based CO_2 emissions in urban settings (e.g. Turnbull, et al., 2015; Reinmann, 2017).

This is a significant challenge, as biospheric dynamics in urban areas appear to differ from those outside the urban environment. Addressing this challenge will require greater knowledge, enhanced measurements, and improved process models of urban biospheric fluxes (Wu et al., 2018), both above ground vegetation and soil microbial contributions.

Other problems in top-down approaches that complicate analysis at regional or continental scales persist or are magnified in urban environments. Examples include properly accounting for the variable mole fraction of incoming air masses to an urban area, ensuring higher fidelity of atmospheric transport and dispersion modelling products, and correctly attributing GHG enhancements to sectorial activity. Although advances in higher-resolution meteorological measurements and modeling capabilities have been made by INFLUX research (e.g. Deng et al., 2017; Sarmiento et al., 2017; Gaudet et al., 2017), the need for better measurement and modeling of planetary boundary layer dynamics and height remains a significant challenge. Further advances in chemical species mole fraction measurements of proxy gases will also contribute to better understanding of GHG emissions and their underlying processes (Nathan et al., 2017; Vimont et al., 2017). Meeting these challenges will require continued research aimed at making measurement capabilities more robust. These in turn will support efforts to assess mitigation performance.

Although initial development and research results for INFLUX have been published previously, this special issue of Elementa provides an opportunity for a comprehensive description, in a single compilation, of the INFLUX project and its progress toward advanced urban GHG emission flux measurement methods. The fourteen articles in this issue describe various aspects of INFLUX research, and provide a view of the current state of urban GHG measurement science and technology.

INFLUX is the prototype for NIST's Urban GHG Measurements Testbed System that includes two additional test beds: The South Coast Air Basin of Southern California, including Los Angeles and its surrounding area, and the U.S. Northeast Corridor stretching from the Washington, DC to Boston. These testbeds have distinct meteorological, geographic, population, and GHG emissions profiles that can be used to further challenge, test, extend, and demonstrate advances in urban-scale GHG measurement capabilities and standards.

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