Concurrently Measured Concentrations of Atmospheric Mercury in Indoor (household) and Outdoor Air of Basel, Switzerland

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ABSTRACT: Indoor air pollution can be a major health risk because urban populations spend up to 90% of their time in closed rooms. Gaseous elemental mercury (GEM) has not been measured as routinely as other indoor air pollutants due to the high costs and limited mobility of active Hg analyzers. However, household GEM concentrations may exceed Hg air quality guidelines as a result of potential indoor GEM sources like broken Hg thermometers. Here we deploy novel low-cost mercury passive air samplers (MerPAS) in 27 households (7 days) and at 14 outdoor locations (29–31 days) in Basel, Switzerland. Average Hg concentrations ranged from 2.0 to 10.8 ng m$^{-3}$ indoors and from 1.8 to 2.5 ng m$^{-3}$ outdoors. These results reveal that households are a net source of Hg to the urban atmosphere and exceed outdoor Hg levels by a factor of 2 on average. We estimated an average weekly intake rate of 0.01 μg of Hg/kg of body weight for adult residents in Basel, which is usually lower than Hg exposure of people with dental amalgam fillings. Our campaign demonstrates that air monitoring programs can easily be complemented by straightforward Hg measurements using MerPAS.

INTRODUCTION

Air pollution is one of the greatest environmental risks to human health, causing ~7 million deaths globally each year. In Europe, the health of urban populations is particularly affected by the major air pollutants, including particulate matter (PM) largely from combustion, dust from construction and natural sources, and nitrogen dioxide (NO$_2$) derived mainly from road traffic. Indoor sources of these pollutants include smoking, cooking, and burning wood or candles. Emissions of toxic metals (arsenic, cadmium, nickel, lead, and mercury) add to the atmospheric burden of air pollutants.

Mercury (Hg) is a global pollutant that is emitted to the atmosphere and subject to long-range global transport. Atmospheric Hg is either emitted from anthropogenic Hg sources (∼2.5 × 10$^6$ kg year$^{-1}$), mobilized naturally from the Earth’s crust through volcanic eruptions and rock weathering (∼0.5 × 10$^6$ kg year$^{-1}$), or re-emitted from ocean and land surfaces. Urban centers contribute to the global atmospheric Hg burden largely through fossil fuel combustion (e.g., coal combustion in power plants and residential heaters), waste incineration, hospitals/dental facilities, and cremation. Mean urban atmospheric Hg concentrations have been found to range from 1.46 ng m$^{-3}$ in Toronto, Canada, to 9.72 ng m$^{-3}$ in Guayang, China (see Table S1 in section S1). The northern hemispheric background concentration is approximately 1.5 ng m$^{-3}$.

Indoor Hg air concentrations can be elevated due to Hg evaporating from past spills of liquid Hg contained in thermometers or fluorescent light bulbs and Hg switches or from Hg-containing biocide added to paint employed in buildings between 1950 and 1990. A previous study estimated that the level of gaseous Hg in 10% of U.S. households exceeds the U.S. EPA reference concentration of 300 ng m$^{-3}$. Previous studies of Hg pollution of indoor air, largely conducted in workplaces, revealed maximum Hg levels of 28.5 ng m$^{-3}$ in Toronto, 522 ng m$^{-3}$ in New York, and 1293 ng m$^{-3}$ in Chongqing. Chronic exposure to elevated ambient Hg concentrations may produce harmful effects on the nervous, digestive, and immune systems, the lungs, and the kidneys.

While a few studies reported indoor Hg levels at workplaces, Hg concentrations in households are usually not systematically investigated. Comprehensive studies of household Hg pollution are lacking because of the high costs and limited mobility of active measurement systems, which require a power supply and in some cases compressed carrier gas. Active systems are therefore ill-suited for Hg measurements in multiple households simultaneously. An alternative approach to measuring gaseous elemental mercury (GEM) in households is deploying novel mercury passive air samplers (MerPAS), which provide the necessary accuracy and precision for atmospheric Hg monitoring. The MerPAS can be deployed in multiple households simultaneously without requiring power supplies or compressed carrier gases.
exposed indoors or outdoors for extended periods (1 week to 1 year) without maintenance work and are therefore well suited for large-scale and long-term GEM measurement campaigns.

The objective of this study was to determine the average GEM exposure of residents in the city of Basel. To achieve this goal, we deployed MerPAS to study GEM concentrations in indoor air of multiple households and urban outdoor air simultaneously. In both indoor and outdoor settings, potential GEM sources were examined. We tested the potential of MerPAS to complement short-term air monitoring campaigns of major air pollutants with GEM measurements.

■ MATERIALS AND METHODS

We measured indoor and outdoor GEM concentrations using commercially available MerPAS.20,21 MerPAS almost exclusively collect GEM because only ≤6% of the gaseous oxidized Hg (GOM) can pass through the diffuse barrier,22 and GEM is the dominant atmospheric Hg species (typically >90% of total atmospheric Hg: GEM, GOM, and particulate Hg).12 MerPAS are thus considered to collect GEM22,23 (see section S2 for details). We determined the level of GEM in 27 households along with major air pollutants (PM2.5 and NO2) and at 14 outdoor sites in Basel, Switzerland (Figure 1). The greater triborder region of Basel has a population of about 852000 inhabitants and is located at the southern end of the Upper Rhine Valley.24 The location of the 27 households was determined on the basis of recruitment into the EU Horizon 2020 project ICARUS (Integrated Climate forcing and Air pollution Reduction in Urban Systems) that aims to assess air pollution in nine European cities.25 Recruitment of households did not follow a formal sampling design. Rather, households were recruited via advertisement on social media and the institute Web site, and flyers were distributed to households on selected streets in an attempt to broadly capture areas with both higher and lower ambient air pollution and socio-economic status. For the indoor GEM measurements, we followed a previously described setup21,26 of a sulfur-impregnated activated carbon (AC) sorbent with a white Radiello diffuse barrier. The white Radiello was screwed onto a wooden platform without a protective shield. Subsequently, MerPAS were deployed at heights of 1−1.5 m in 27 living rooms for 7 days. The average indoor air temperature was 21.3 °C. Along with GEM concentrations, major air pollutants were monitored in households using the commercial uHoo indoor air quality sensor (uHoo Limited, Hong Kong). See details about the uHoo sensor in AQMD27 and in section S6. The NO2 and PM2.5 measurements from one household were not included due to device malfunction.

Outdoor GEM concentrations were measured at 14 sites using MerPAS with white Radiello with a protective shield20,21 between November 5 and December 7, 2018. The average outdoor air temperature during this period was 6.6 °C. Data from simultaneous temperature and wind speed monitoring were available from eight outdoor MerPAS sites. Ten MerPAS were installed in the vicinity of possible Hg point sources, and four MerPAS in city outskirts and residential areas (see photodocumentation of the outdoor MerPAS setup in Figure S2 in section S8).

The total mass of Hg in the sulfur-impregnated activated carbon sorbent (AC) of each MerPAS was measured by thermal desorption, amalgamation, and atomic absorption spectroscopy using a DMA-80 instrument (Milestone Inc.). Sections S3 and S4 give details about the GEM analysis and respective quality control. The mean replicate precision and overall uncertainty of MerPAS outdoor deployments are 4% and 9%, respectively, which were determined through the analysis of hundreds of replicated samples deployed around the globe.20 This is similar to the uncertainty of active sampling instruments.28,29 The uncertainty of indoor deployments has been estimated to be double that of outdoor deployments because indoor deployments are predominantly subject to wind speeds of <1 m s−1; wind speeds in this range are known to result in increased variability on the MerPAS sampling rate compared to wind speeds of >1 m s−1 typical of outdoor deployments.20 We estimate the replicate precision and overall

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**Figure 1.** Sampling locations of air pollution measurements in the Basel metropolitan area. Indoor (circles) and outdoor (triangles) GEM concentrations (nanograms per cubic meter) are given in 25 percentile bins. The Basel city limits are indicated by the brown contour line. Base map reproduced with permission under a Creative Commons CC BY-SA 2.0 license from OpenStreetMap (accessed February 26, 2020).
The highest household GEM concentration (10.8 ng m\(^{-3}\)) was 5-fold elevated compared to the average outdoor concentration (2.21 ng m\(^{-3}\)) (see Table S2 in section S6). The absolute difference between the average indoor and average outdoor GEM levels (2.0 ng m\(^{-3}\)) was smaller compared to those of studies in Chongqing (3.5 ng m\(^{-3}\) in winter), Toronto (13.5 ng m\(^{-3}\)), and New York (18.6 ng m\(^{-3}\)) difference between median indoor and outdoor GEM).\(^{15,17}\) Variations in indoor and outdoor total gaseous mercury (TGM) concentrations at nine residential locations in downtown Chongqing, China, were measured to identify possible sources and evaluate diurnal and seasonal fluctuations.\(^{17}\) Indoor TGM concentrations (eight buildings in summer and two in winter) were significantly elevated over outdoor concentrations. Overall, TGM concentrations were highly variable, likely as a result of changes in anthropogenic emissions (e.g., coal combustion, mobile sources, and iron refinery), fluctuations in atmospheric variables, and unique events (e.g., use of mercury-containing skin cream, presence of Hg-based dental amalgams, thermometer spill, etc.). Elevated indoor GEM concentrations are likely the result of current or past indoor use of Hg-containing appliances like thermometers, barometers, florescence tubes, or paints. A survey conducted among ICARUS residents to identify potential indoor Hg sources revealed that the average GEM concentration was not statistically different between households where Hg thermometers had been broken (2 yes, 17 no), where walls were painted within the last 3 years before measurements (11 yes, 11 no), or with residents having dental amalgam fillings (8 yes, 16 no) [Wilcoxon two-sample t test; \(p > 0.01\) (see Figure S1 in section S7)]. Despite the fact that we could not identify specific household Hg sources, elevated indoor GEM concentrations still indicated the presence of diffuse sources (e.g., past spills or appliances containing Hg) of which residents might not be aware.\(^{55}\)
Outdoor GEM levels were ∼50% higher than northern hemispheric background concentrations (1.5 ng m⁻³) (see Table S3 in section S8). Outdoor GEM concentrations can be elevated during heating season in the winter when the extent of vertical mixing of air masses is reduced during high-pressure periods. The average GEM concentration measured in this study (2.21 ± 0.20 ng m⁻³) was lower than the GEM concentration measured 39 m above ground in the center of Basel in February 2012 (4.1 ng m⁻³). GEM concentrations were slightly elevated compared to GEM concentrations determined in downtown Zurich (median of 1.81 ng m⁻³) from December 2013 to December 2015 as well as at the Zurich zoo on the outskirts of the city (median of 1.62 ng m⁻³) over a period from January to February 2016. Concurrent MerPAS deployments were also made across Toronto, Canada, and the average summertime GEM concentration (1.77 ± 0.28 ng m⁻³) was lower than in the current study. The spatial Hg concentration variability in Basel ranged from 1.83 ng m⁻³ in the Hörrnli cemetery area (RFH) close to the crematory to 2.52 ng m⁻³ at a residential area (B07). GEM concentrations were not elevated close to potential emission sources such as the crematory, the waste incineration plant, dental offices, the Basel University Hospital, or the industrial area Schweizerhalle (see Table S3 in section S8).

The total Hg emission to the atmosphere in Basel was estimated by the Swiss Pollutant Release and Transfer Register (PRTR). In 2017, the city of Basel reportedly emitted 14 kg of Hg to the atmosphere. This results in a per capita Hg emission of 0.08 g year⁻¹. Basel per capita Hg emissions were comparable to per capita emissions in Zurich (0.06–0.10 g year⁻¹) quantified by active measurements using a Tekran 2537X instrument from December 2013 to December 2015. Mercury emissions in Basel, Zurich, or Toronto mainly emerged from small scale point sources close to the area of interest with the value of 0.01 μg kg⁻¹ of body weight per week for adults (respiration rate of 20 m³ day⁻¹, body weight of 70 kg). Such an exposure is small compared to exposure from dental amalgam of ∼2–16 μg per adult and week.

We conclude that indoor and outdoor air Hg concentrations in the city of Basel were clearly below the reference value given by Carpi and Chen (300 ng m⁻³) at least during 1 week in late autumn when the GEM concentrations are expected to be elevated compared to summertime. Consequently, the average inhalation exposure to GEM for Basel ICARUS residents is of no concern. However, the assessment of chronic toxic effects on local residents remains ambiguous. Our study demonstrates that low-cost MerPAS are suitable to complement measurement campaigns of GEM with other air pollutants. Indoor and outdoor GEM monitoring with MerPAS offers great potential to locate unknown Hg sources and to assess the contribution of indoor Hg sources to total urban emissions. Additionally, MerPAS can help to identify indoor Hg vapor exposure at the workplace or at home.

**ASSOCIATED CONTENT**

**Supporting Information**

An overview of recently measured atmospheric Hg concentrations in different cities (Table S1 in section S1), a paragraph about the sample analyte GEM (section S2), details about the sulfur-impregnated activated carbon analysis (section S3), including QA/QC (section S4), uncertainties for indoor MerPAS measurements (section S5), an overview of results from indoor GEM, PM₂.₅, and NO₂ concentration measurements (Table S2 in section S6), the influence of potential Hg indoor sources on GEM concentration (Figure S1 in section S7), results from outdoor GEM measurements (Table S3), and photodocumentation (Figure S2) of the MerPAS outdoor deployment (Section S8) (PDF).

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**Author Contributions**

S.O. initiated and coordinated the study. L.W. and S.O. deployed outdoor MerPAS. B.F. and D.V. set up indoor
MerPAS, provided uHoo data, and produced Figure 1. L.W. analyzed MerPAS and determined GEM concentrations. D.M. provided crucial methodological know-how. S.O. and L.W. wrote the manuscript with major contributions from D.M., D.V., and B.F.

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS
This work has received funding from the European Union’s Horizon 2020 Program for research, technological development and demonstration under Grant Agreement 690105 [Integrated Climate forcing and Air pollution Reduction in Urban Systems (ICARUS)]. This work reflects only the authors’ views, and the European Commission is not responsible for any use that may be made of the information it contains. The study was also funded internally by the Department of Environmental Geosciences, University of Basel. L.W. received funding from the SNSF Ambizione grant (PZO0P2_174101). D.M. was funded by DFG and NSERC Postdoctoral Fellowship (PDF - 516216 - 2018). SO received funding from the Research Fund for Junior Researchers of the University of Basel and the SNSF Postdoc. Mobility grant (P400P2_180796). The authors acknowledge Dr. Martin Jiskra for assistance with Hg analysis and thank Dr. Andreas Wicki from the Atmospheric Science Group of the University of Basel for site access to measurement stations B01–B08 and for providing temperature and wind data. The authors thank Sandra Andris-Ogorka from the agency of air surveillance of the two Basel cantons for granting access to their air monitoring stations (LH1–LH4) as well as meteorological data recorded at the sites. The installation of MerPAS at stations RFH and KVA was supported by Bernhard Meister (BVD Basel-Stadt) and Johannes Allesch (IWB), respectively. The authors gratefully acknowledge Lukas Forlin and Lukas Müller for their assistance with MerPAS deployment and collection, the partners involved in designing the ICARUS measurement campaign, and all of the participants in the ICARUS Basel case study.

REFERENCES
(1) World Health Organization. Clean Air for Health: Geneva Action Agenda. First WHO global conference on air pollution and health - Summary Report. 2018.
(2) European Environment Agency. Air quality in Europe - 2019 Report. 2019.
(3) Franchi, M.; Carrer, P.; Kotzias, D.; Rameckers, E. M. a. L.; Seppänen, O.; van Bronswijk, J. E. M. H.; Viegi, G.; Gilder, J. A.; Valovirta, E. Working towards healthy air dwellings in Europe. Allergy 2006, 61, 864–868.
(4) UNEP. Technical background report to the Global Mercury Assessment 2018. Arctic Monitoring Assessment Programme. 2019.
(5) Outridge, P. M.; Mason, R. P.; Wang, F.; Guerrero, S.; Heimbürger-Boavidia, L. E. Updated global and oceanic mercury budgets for the United Nations Global Mercury Assessment 2018. Environ. Sci. Technol. 2018, 52, 11466–11477.
(6) Driscoll, C. T.; Mason, R. P.; Chan, H. M.; Jacob, D. J.; Pirrone, N. Mercury as a global pollutant: sources, pathways, and effects. Environ. Sci. Technol. 2013, 47, 4967–4983.
(7) Fu, X.; Feng, X.; Qiu, G.; Shang, L.; Zhang, H. Speciated atmospheric mercury and its potential source in Guiyang, China. Atmos. Environ. 2011, 45, 4205–4212.
(8) Streets, D. G.; Hao, J.; Wu, Y.; Jiang, J.; Chan, M.; Tian, H.; Feng, X. Anthropogenic mercury emissions in China. Atmos. Environ. 2005, 39, 7789–7806.
(9) McLagan, D. S.; Hussain, B. A.; Huang, H.; Lei, Y. D.; Wania, F.; Mitchell, C. P. J. Identifying and evaluating urban mercury emission sources through passive sampler-based mapping of atmospheric concentrations. Environ. Res. Lett. 2018, 13, 074008.
(10) Pacyna, E. G.; Pacyna, J. M.; Sundseth, M.; Munthe, J.; Kindbom, K.; Wilson, S.; Steenhuisen, F.; Maxson, P. Global emission of mercury to the atmosphere from anthropogenic sources in 2005 and projections to 2020. Atmos. Environ. 2010, 44, 2487–2499.
(11) Streets, D. G.; Devane, M. K.; Lu, Z.; Bond, T. C.; Sunderland, E. M.; Jacob, D. J. All-time releases of mercury to the atmosphere from human activities. Environ. Sci. Technol. 2011, 45, 10485–10491.
(12) Sprovieri, F.; Pirrone, N.; Bencardino, M.; D’Amore, F.; Carbone, F.; Cinnirella, S.; Mannarino, V.; Landis, M.; Ebinghaus, R.; Weigelt, A.; Brunke, E.-G.; Labuschagne, C.; Martin, L.; Munthe, J.; Wängberg, I.; Artaxo, P.; Morais, F.; Barbosa, H. de M.; Brito, J.; Cairns, W.; Barbante, C.; Dieguèz, M. d. C.; García, P. E.; Dommergue, A.; Angot, H.; Magand, O.; Skov, H.; Horvat, M.; Kotnik, J.; Read, K. A.; Neves, L. M.; Gawluk, B. M.; Sena, F.; Madronich, N.; Obokai, V.; Trap, P.; Feng, X. B.; Zhang, H.; Fu, X.; Ramachandran, R.; Cossa, D.; Knovoy, J.; Maruszczak, N.; Néretorp, M.; Norström, C. Atmospheric mercury concentrations observed at ground-based monitoring sites globally distributed in the framework of the GMOS network. Atmos. Chem. Phys. 2016, 16, 11915–11935.
(13) Baughman, T. A. Elemental mercury spills. Environ. Health Perspet. 2006, 114, 147–152.
(14) Horowitz, H. M.; Jacob, D. J.; Amos, H. M.; Streets, D. G.; Sunderland, E. M. Historical mercury releases from commercial products: Global environmental implications. Environ. Sci. Technol. 2014, 48, 10242–10250.
(15) Carpi, A.; Chen, Y. Gaseous elemental mercury as an indoor air pollutant. Environ. Sci. Technol. 2001, 35, 4170–4173.
(16) Cairns, E.; Tharanakulasigam, K.; Athar, M.; Yousaf, M.; Cheng, I.; Huang, Y.; Lu, J.; Yap, D. Source, concentration, and distribution of elemental mercury in the atmosphere in Toronto, Canada. Environ. Pollut. 2011, 159, 2003–2008.
(17) Li, J.; Yang, Y.; Chen, H.; Xiao, G.; Wei, S. Sourcing contributions of gaseous mercury in indoor and outdoor air in China. Environ. Forensics 2010, 11, 154–160.
(18) WHO. Exposure to mercury: A major public health concern. 2007.
(19) Jiskra, M.; Maruszczak, N.; Leung, K.-H.; Hawkins, L.; Prestbo, E.; Sonke, J. E. Automated stable isotope sampling of gaseous elemental mercury (ISO-GEM): Insights into GEM emissions from building surfaces. Environ. Sci. Technol. 2019, 53, 4346–4354.
(20) McLagan, D. S.; Mitchell, C. P. J.; Steffen, A.; Hung, H.; Shin, C.; Stipple, G. W.; Olson, M. L.; Luke, W. T.; Kelley, P.; Howard, D.; Edwards, G. C.; Nelson, P. F.; Xiao, H.; Sheu, G.-R.; Dreyer, A.; Huang, H.; Abdul Hussain, B.; Lei, Y. D.; Tavshunsky, I.; Wania, F. Global evaluation and calibration of a passive air sampler for gaseous mercury. Atmos. Chem. Phys. 2018, 18, 5905–5919.
(21) McLagan, D. S.; Mitchell, C. P. J.; Huang, H.; Lei, Y. D.; Cole, A. S.; Steffen, A.; Hung, H.; Wania, F. A high-precision passive air sampler for gaseous mercury. Environ. Sci. Technol. Lett. 2016, 3, 24–29.
(22) Stipple, G.; McLagan, D.; Steffen, A. In situ reactive gaseous mercury uptake on Radiello diffusive barrier, cation exchange membrane and Teflon filter membranes during atmospheric mercury depletion events. 14th ICMGP Krakow; 2019.
(23) Szponar, N.; Vega, C.; McLagan, D.; Pillaca, M.; Gerson, J.; Bernhardt, E.; Mitchell, C.; Wania, F.; Fernandez, L.; Bergquist, B. Atmospheric mercury and mercury isotopes from ASGM activity in the Madres de Dios Region, Peru. 14th ICMGP Krakow; 2019.
(24) StatisticsBS. City Statistics Basel. Ausgabe 2019. Statistical Office Canton Basel-Stadt. 2019. https://www.statistics.bs.ch/nm/2019-city-statistics-basel-2019-pd.html (accessed 2020-03-13).

https://dx.doi.org/10.1021/acs.estlett.0c00110
Environ. Sci. Technol. Lett. XXX, XXX, XXX–XXX
(25) Sarigiannis, D.; Gotti, A.; Karakitsios, S.; Chapizanis, D. D.1.2 Report on conceptual framework of ICARUS. WP 1 Methodological framework development. Horizon 2020 Project 690105 ICARUS; 2017.

(26) McLagan, D. S.; Mitchell, C. P. J.; Huang, H.; Abdul Hussain, B.; Lei, Y. D.; Wania, F. The effects of meteorological parameters and diffusive barrier reuse on the sampling rate of a passive air sampler for gaseous mercury. Atmos. Meas. Tech. 2017, 10, 3651−3660.

(27) AQMD. Sensor Detail UHoo. General description. South Coast Air Quality Management District 2019. http://www.aqmd.gov/aq-spec/sensorDetail/uhoo (accessed 2020-03-13).

(28) Aspno, K.; Guachard, P.-A.; Steffen, A.; Temme, C.; Berg, T.; Bahmann, E.; Banic, C.; Dommergue, A.; Ebinghaus, R.; Ferrari, C.; Pirrone, N.; Sprovieri, F.; Vibetoe, G. Measurements of atmospheric mercury species during an international study of mercury depletion events at Ny-Ålesund, Svalbard, Spring 2003. How reproducible are our present methods? Atmos. Environ. 2005, 39, 7607−7619.

(29) Temme, C.; Blanchard, P.; Steffen, A.; Banic, C.; Beauchamp, S.; Poissant, L.; Tordon, R.; Wiens, B. Trend, seasonal and multivariate analysis study of total gaseous mercury data from the Canadian Atmospheric Mercury Measurement Network (CAMNet). Atmos. Environ. 2007, 41, 5423−5441.

(30) Tekran. MerPAS Configuration Options. Revision 121319. 2020. https://www.tekran.com/files/MerPAS-Config-Options.pdf (accessed 2020-03-13).

(31) Jeon, B.; Cizdziel, J. V. Can the MerPAS passive air sampler discriminate landscape, seasonal, and elevation effects on atmospheric mercury? A feasibility study in Mississippi, USA. Atmosphere 2019, 10, 617.

(32) McLagan, D. S.; Monaci, F.; Huang, H.; Lei, Y. D.; Mitchell, C. P. J.; Wania, F. Characterization and quantification of atmospheric mercury sources using passive air samplers. J. Geophys. Res.: Atmos. 2019, 124, 2351−2362.

(33) Gotschi, T.; Oglesby, L.; Mathys, P.; Monn, C.; Manalis, N.; Koistinen, K.; Jantunen, M.; Hanninen, O.; Polanska, L.; Kuniz, N. Comparison of black smoke and PM2.5 levels in indoor and outdoor environments of four European cities. Environ. Sci. Technol. 2002, 36, 1191−1197.

(34) Levy, J. I. Impact of residential nitrogen dioxide exposure on personal exposure: An international study. J. Air Waste Manage. Assoc. 1998, 48, 553−560.

(35) Brewer, W. F. Autobiographical memory and survey research. In Autobiographical memory and the validity of retrospective reports; Schwarz, N., Sudman, S., Eds.; Springer: New York, 1994; pp 11−20.

(36) Denzler, B.; Bogdal, C.; Kern, C.; Tobler, A.; Huo, J.; Hungerbühler, K. Urban source term estimation for mercury using a boundary-layer budget method. Atmos. Chem. Phys. 2019, 19, 3821−3831.

(37) Osterwalder, S.; Fritsche, J.; Alewell, C.; Schmutz, M.; Nilsson, M. B.; Jocher, G.; Sommar, J.; Rinne, J.; Bishop, K. A dual-Inlet, single detector relaxed eddy accumulation system for long-term measurement of mercury flux. Atmos. Meas. Tech. 2016, 9, 509−524.

(38) Huang, J.; Hopke, P. K.; Choi, H.-D.; Laing, J. R.; Cui, H.; Zananski, T. J.; Chandrasekaran, S. R.; Rattigan, O. V.; Holsen, T. M. Mercury (Hg) emissions from domestic biomass combustion for space heating. Chemosphere 2011, 84, 1694−1699.

(39) Jiskra, M.; Sonke, J. E.; Obrist, D.; Bieser, J.; Ebinghaus, R.; Myhre, C. L.; Pfaffhuber, K. A.; Wängberg, I.; Kylönen, K.; Worthy, D.; Martin, L. G.; Labuschagne, C.; Mkolofo, T.; Ramonet, M.; Magand, O.; Dommergue, A. A vegetation control on seasonal variations in global atmospheric mercury concentrations. Nat. Geosci. 2018, 11, 244−250.

(40) Schmutz, M.; Vogt, R.; Feigenwinter, C.; Parlow, E. Ten years of eddy covariance measurements in Basel, Switzerland: Seasonal and interannual variabilities of urban CO2 mol fraction and flux. J. Geophys. Res. Atmospheres 2016, 121, 8649−8667.

(41) Song, X.; Cheng, I.; Lu, J. Annual atmospheric mercury species in Downtown Toronto, Canada. J. Environ. Monit. 2009, 11, 660−669.