Citizen Science and International Collaboration through Environmental Monitoring with Simple Chemical Sensors

Peter G. Mahaffy, Kristopher J. Ooms, and Andrew F. Tappenden, The King's University, Edmonton, Alberta Canada; Jonathan E. Forman, the Organization for the Prohibition of Chemical Weapons, The Hague, NL; Ulrich Mans, Centre for Innovation, Leiden University, NL, John Sabou, Institute for Security and Global Affairs, Leiden University.

Abstract: Building capacity for carrying out and understanding responsible science that is relevant to local challenges is a key ingredient in the OPCW's strategy for achieving and maintaining a world free of chemical weapons. Two important contexts for building that capacity for responsible science are (1) The global attention being drawn to the rapidly increasing human chemical footprint on our planet and (2) the pervasive use of digital technologies. We describe an effort coordinated by the Organization for the Prohibition of Chemical Weapons to build capacity among young people around the world to harness the power of small mobile chemical sensors to develop data literacy in complex chemical analysis based on measuring analytes that are relevant to their lives and local contexts. This new type of data literacy is an emergent element in educational programs and is key to developing the capacity for decision making on chemical measurement data. The project brings together student and faculty collaborators from the fields of chemistry, social sciences and informatics, to provide proof of concept in four areas that support the overall goal of building a collective effort for scientific analysis; the development of low cost environmental sensors for air and water samples; the collection of representative test data sets on priority contaminants; the assessment and visualization of data; and education about the effect of priority pollutants on human and environmental health. We report on the project goals and preliminary steps taken to achieve them.

I. The global context: Equipping citizens to understand the responsible and peaceful uses of chemical substances, technologies, and processes, along with the significance of measuring environmental parameters has taken on compelling dimensions in light of two global multi-dimensional challenges.

The first is a set of interdisciplinary research efforts that attempt to guide human development in the context of the impacts of the rapidly growing human footprint on the life support systems of our planet.[1,2] Nine planetary boundaries are defined that describe quantitatively the state of earth system control variables that define a safe operating space for humanity. Measurements of changes to fundamental chemical parameters are central to the definition and quantification of the nine proposed planetary boundaries, and efforts to mitigate the effects of exceeding those boundaries. Chemical measurements relevant to these boundaries include the levels of stratospheric ozone, concentration of atmospheric carbon dioxide, global mean saturation state of aragonite in surface seawater, amount of anthropogenic nitrogen removed from the atmosphere, amount of anthropogenic phosphorus deposited in the oceans, and overall atmospheric particulate (aerosol) concentration. Chemistry educators, working in both formal and informal educational settings, are being challenged to contextualize the learning of chemistry concepts through sustainability rich contexts related to these planetary boundaries.[3]

Secondly, making progress toward achieving the United Nations Sustainable Development Goals implies building capacity for citizens to understand the role for responsible and peaceful uses of chemistry to contribute to addressing climate change, providing clean water and energy, sustaining food security systems, conserving and sustainably using the oceans and marine resources, managing biomass and terrestrial ecosystems, and alleviating poverty.

For most citizens, awareness of these global challenges begins at the local level. Young people with an awareness of the power of science as a tool for development and who live in poverty or conditions of economic uncertainty might ask: How does my understanding of local measurements of substances with environmental significance impact on the quality of my life, or that of my family, or my city? Is the air that I'm breathing causing ill health effects? Is the water my family uses contaminated with harmful chemical substances or microbes? Learning how to answer these questions can build an empowering capacity to use knowledge about chemistry to improve the human condition. But answering these questions requires the development of some fundamental knowledge about chemical substances and measurements and also enough data literacy to make sense of those measurements.

II. ***The Project: Environmental Monitoring by Citizens with Simple Chemical Sensors.*** We describe an effort proposed by the Organization for the Prohibition of Chemical Weapons with funding support from the European Union to build capacity among young people around the world to harness the power of small mobile chemical sensors to develop data literacy in complex chemical analysis based on measuring analytes that are relevant to their lives and local contexts. This new type of data literacy is an emergent element in educational programs and is key to developing the capacity for decision making on chemical measurement data.

This emphasis on equipping citizens to engage in responsible science and make sense of environmental measurements of chemical parameters that define the quality of local environments is also resonant with the strategic medium-range plan for the Organisation for the Prohibition of Chemical Weapons (OPCW). OPCW is a global, treaty-based international organisation with responsibilities for disarmament and non-proliferation. As OPCW has achieved considerable success in freeing the world of chemical weapons, recognized with the awarding of the 2013 Nobel Peace Prize, it has turned new attention to the even greater challenge of working with partners and collaborators to prevent their re-emergence. As outlined in the first paper in this ConfChem Series by OPCW's Ballard and Forman, the new emphasis on education and outreach "*represents a potential sea-change in the way that the OPCW interacts with the world. It represents the recognition that achieving the aims of the Chemical Weapons Convention (CWC) will in the future require a whole new kind of engagement – one that is underpinned with robust strategies, with flexible and modern educational tools, and with the support of new stakeholders. Most importantly it means that education and outreach has a clear strategic role in the future of the Organisation*."[4]

II A. Priority Air Pollutants: Air pollution has long been one of the major byproducts of industrialized human activity that dramatically affects the health of entire human populations. The World Health Organization estimates that ambient outdoor air pollution was responsible for 3.7 million deaths in 2012, with around 88% of those deaths being in developing countries.[5] From an educational perspective, the monitoring and control of air pollution has historically been a key motivator for governmental intervention and regulation and therefore serves as an ideal example of the interplay between pollution, public health, scientific data, and governmental policy. The World Health Organization lists four pollutants in their air quality guidelines: ozone, particulate matter, nitrogen dioxide, and sulfur dioxide.[5]

Particulate matter (PM) is the most prevalent air pollutant and is generated by many natural and anthropogenic processes. Natural sources of PM include fine airborne dust generated by wind and smoke from forest fires, while anthropogenic sources include smoke from burning wood, coal combustion, and other fossil fuel combustion. PM can be either small solid or liquid particles, usually made of sulfates, nitrates, ammonia, sodium chloride, carbon or mineral dust.[5] PM is classified by size and often divided into two regions: PM_{10} includes all particles smaller than 10 microns and is dominated by larger particles created by mechanical processes, such as wind-blown soil erosion. $PM_{2.5}$ includes particles less than 2.5 microns that are often formed in the atmosphere from substances generated primarily by combustion processes. The increased toxicity of $PM_{2.5}$ can be linked both to the ability of small particles to penetrate deeper into the lungs and the chemical composition of the particles.

One of the greatest concerns about $PM_{2.5}$ is its ability to penetrate the thoracic region of the respiratory system. Though many complicating factors exist in determining the relationship between PM levels and mortality, studies generally suggest a strong link between the two, particularly with mortality caused by cardiovascular and respiratory disease.[6-8] The exact reason for the toxicity of PM varies widely, but is certainly related to the nature of the chemical substances adsorbing to the surface of the particles. This includes compounds such as oxidative transition metals, polycyclic aromatic hydrocarbons, and other toxic organic compounds.[6]

WHO Guidelines for $PM_{2.5}$ and NO_2 [9]

$PM_{2.5}$	10 μg/m^3 annual mean
	25 μg/m^3 24-hour mean
PM_{10}	20 μg/m^3 annual mean
	50 μg/m^3 24-hour mean
NO_2	40 μg/m^3 annual mean
	200 μg/m^3 1-hour mean

$PM_{2.5}$ levels in ambient air vary substantially across the world (Figure 1). Since PM emissions from industrialization have been one of the driving factors for the introduction of governmental air quality regulations, anthropogenic PM has dropped substantially in North America and Europe. Currently the highest levels of $PM_{2.5}$ are in equatorial regions. These high PM levels are largely dominated by natural sources, however in highly industrialized centers of South and East Asia, significant contributions from anthropogenic sources can be measured.[10] Despite PM levels being lower in North America and Europe, a large fraction of the ground monitoring of PM is focused in these geographical regions.[10] This highlights a key challenge for environmental scientists and epidemiologists who want to better understand the effects of high PM levels on human populations and ecosystems. The potential to use small devices in the hands of citizens around the globe to advance air quality monitoring is very large and could have the greatest impacts in regions where PM levels are abnormally high yet monitoring is limited.[11]

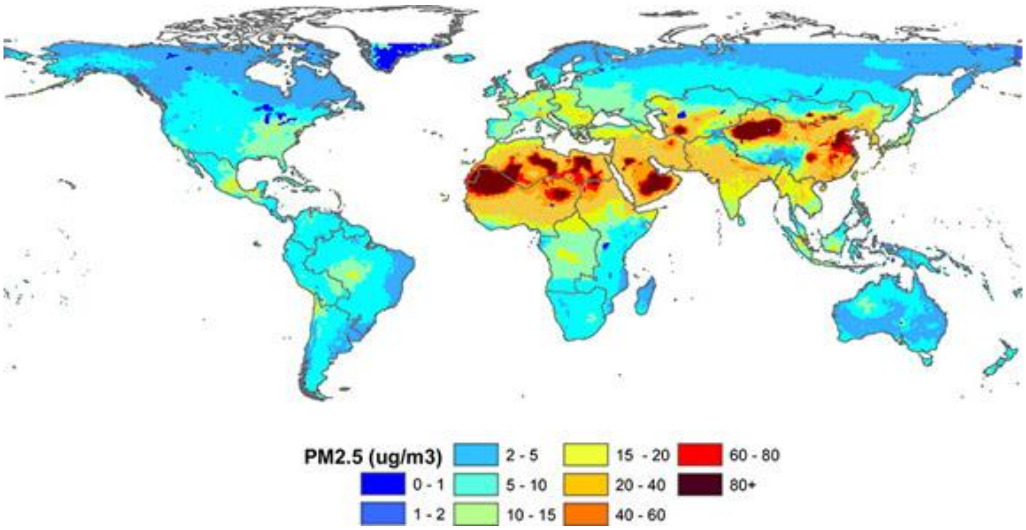

Figure 1. Estimated annual average concentration of $PM_{2.5}$ in 2005 in μg / m^3.[10]

A second priority air pollutant identified by the WHO and most governmental monitoring agencies is NO_x. NO_x is a byproduct of high temperature combustion reactions, and is formed by the oxidation of nitrogen gas. While NO_x is an important primary pollutant it is also linked to secondary air pollutants such as tropospheric ozone. NO_x describes the mixture of NO and NO_2 in the atmosphere. NO is the dominant primary pollutant formed during combustion, which is converted to NO_2 by oxidation mechanisms in the atmosphere. For this reason most air quality standards are based on NO_2 levels.

The health effects of NO_2 levels are challenging to specify because NO_2 pollution is closely related to other combustion pollutants. Most studies suggest that elevated levels of NO_2 can cause respiratory issues and decreased lung function growth in children.[9]

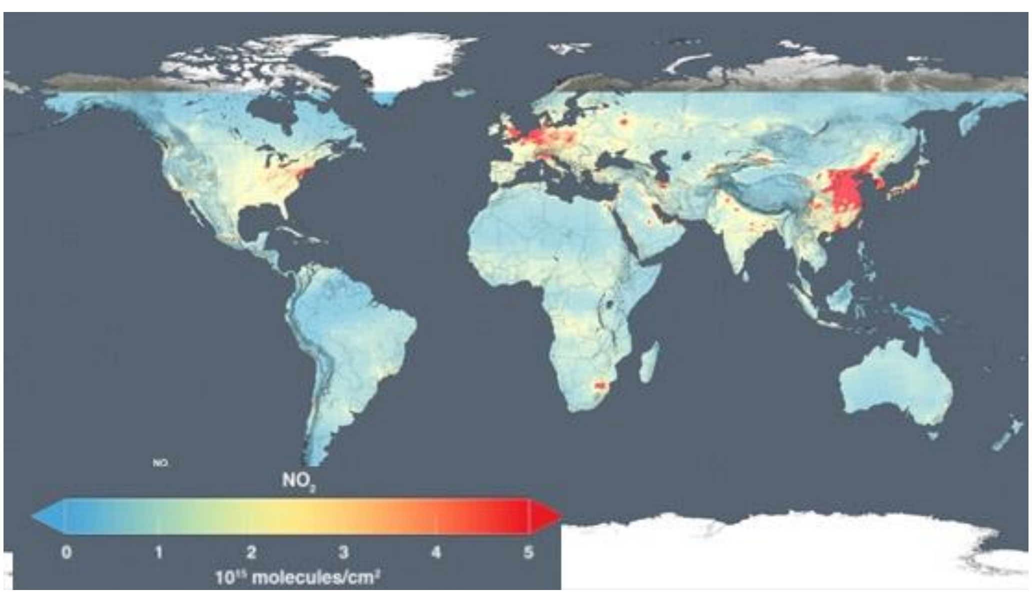

Figure 2. This global map shows the concentration of nitrogen dioxide in the troposphere as detected by the Ozone Monitoring Instrument aboard the Aura satellite, averaged over 2014. Credits: NASA[12]

The global distribution of NO_2 has been mapped by NASA's Aura satellite (Figure 2) and clearly shows the link between NO_2 pollution and heavy industrialization.[12] Elevated levels of NO_2 pollution are centered around the Northeast United States and industrial centers in Europe and China. Comparative data shows that NO_2 levels in Europe and the United States have been decreasing over the past decade. This decrease can be linked to public awareness and government intervention and demonstrates the important role the public has in controlling air pollutants.[12] Educational efforts, such as this sensor project, therefore have the potential to significantly improve air quality by linking public awareness, scientific data, and governmental action. This same framework is at the heart of the OPCW's educational mandate and provides a valuable starting point for educating people about the way they interact with and influence the chemical environment around them.

While global maps like Figure 2 are useful for understanding the general distribution of anthropogenic NO_2 production, more detailed information is required to understand the levels of exposure to NO_2 pollution by specific individuals in a given population. It is well known that individual exposure to NO_2 gas can vary greatly, even within the same city. Individual behavior such as one's house and work locations, route to work and mode of transportation, and other daily activities can lead to significant variability in an individual's exposure. The ideal monitoring scenario for short lived chemical pollutants such as NO_2 is to monitor air quality on a scale smaller than individual neighborhoods or communities.[13-15] The advent of inexpensive sensors for monitoring NO_2 could allow this level of detail to be obtained. Citizen science experiments have potential to provide health experts with a more detailed pollution distribution for epidemiological studies.

II B. Devices and sensors: In recent years numerous small handheld devices[16] for monitoring air quality have become available at relatively low cost. Examples include the Air Quality Egg ($240 USD)[17] and the Aircasting Airbeam ($249 USD) (Figure 3).[18] These devices are often linked to online databases designed to map out pollutant levels based on citizen measurements. Other efforts have focused on interfacing inexpensive sensors with Arduino computer boards.[14,19] While these represent great steps forward for citizen science initiatives, these devices are still too expensive to be deployed en masse in areas outside North America and Europe. In order to be truly deployable around the world, devices need to cost about tens of USD. In addition, while these devices contribute to two of the goals of this project, data collection and mapping of the data, the educational component of the science being done is not prioritized.

Figure 3 – Aircasting Airbeam $PM_{2.5}$ Sensor

II C. Database and visualization: The collection, sharing and evaluation of data obtained from citizen science projects has always been a challenge. Many projects start with a bang, getting many people and groups involved in collecting data but then disappear as resources and interest fade. This OPCW project endeavors to build a lasting database that can be used by multiple groups to bring many different types of chemical data together. The goal is to produce a database that can compare citizen measurements using small sensors, municipal air quality monitoring, and large governmental monitoring projects like NASA's Aura satellite data. The resulting ability for citizen devices to record data that is time stamped and geolocation tagged, means that personal visualizations can be made that track individuals' daily exposure.[14,20] This individualized data can then be linked to global data collected from other sources in a user-friendly database to show individuals how their daily exposer fits into the long-term global picture.

In order to make such a database approach a meaningful tool for citizen science, it will be critical to create a low-barrier environment for those who are interested in using the database. This should include two types of online 'user services': 1) verified, machine-readable datasets for those who have a genuine interest in using the data in combination with other - often seemingly unrelated - datasets; 2) intuitive UX design for those who have an interest in the topic but limited knowledge about data analytics. For example, the project should provide an easy-to-use tool that allows investigative journalists to access, analyze, and present data without technical barriers. In addition, the tooling would need to incorporate recent developments in interactive online visualizations to capture the 'modern' online reader. Both elements are technically possible, but require an iterative process, as none of these tools are likely to work perfectly from the start. The project instead works with built-in feedback loops from user groups, applying a trial-and-error (agile) development philosophy.

II D. Education about the significance of measurements and the health effects of air pollutants: One of the most important primary goals of this sensor project is education. OPCW and the collaborating research teams believe that when citizens better understand the chemical world around them they are better equipped to stand up for their right to live in a safe, clean world. The same issues that are present when dealing with air pollution are present when dealing with trace chemical substances connected to chemical weapons. A necessary step towards changing how humanity views chemical problems is to train citizens to understand their molecular world.

To help fulfil this important educational goal, the collaborators will develop an interactive, electronic set of learning resources that will help citizen scientists understand what air pollution is, its sources, the ways that it is measured, and the health significance of the values they measure locally. These resources will be produced by the interdisciplinary undergraduate student research team at the King's Centre for Visualization in Science (www.kcvs.ca), and will be modelled after resources such as the International Year of Chemistry legacy resource on climate change (www.explainingclimatechange.com). Along with knowledge about how to collect and analyze data on local environmental air pollutants, the educational resources will help citizens understand ways in which they can make use of understanding in chemistry to improve the quality of life in their communities and countries.

II E. Chemical Analysis: There are also opportunities to use sensor based data collection as an educational tool, where important concepts in analytical chemical measurement and statistics in data analysis can be explored. Data sets from local and national environmental monitoring agencies are readily available on the internet. For example, many cities have air monitoring programs, such as the Capital Airshed program in Edmonton Alberta or the Unites States Environmental protection Agency's

AirData site.[21,22] This monitoring data can be combined with student measured data sets with matching time stamps and geolocation tags. Data comparisons across sensors and data sets can be used to demonstrate concepts of accuracy, precision, uncertainty, instrument to instrument (and method to method) variations. The data can also be used to introduce issues that arise in the use of data for decision making when there are differences between data sets and observations (an essential topic for those who will be moving into scientific career paths where decision making based on analytical data may be required).

II F. Science Collaboration: Remote data storage and online analytics tools allow access from any location with an internet connection. This provides opportunities for projects where data collection from different regions of the world can be compared, and further facilitates the collaborative development of analysis/visualization tools among students located in different regions of the world, thereby supporting the Chemical Weapons Convention goal of using chemistry to build international collaborations (a form of "science diplomacy").

III. Progress to date:

To demonstrate proof of concept, we have selected for the first phases of this project a $ 16 USD PM sensor (Shinyei PPD 42NS) and an $8 NO_2 sensor (MiCS 2710) (Figure 4), and interfaced them with a Raspberry Pi computer. We are currently testing and calibrating the sensors and assessing the durability and long term reliability. We also intend to explore other sensor options and hope that other teams around the world will be willing to collaborate on this international project.

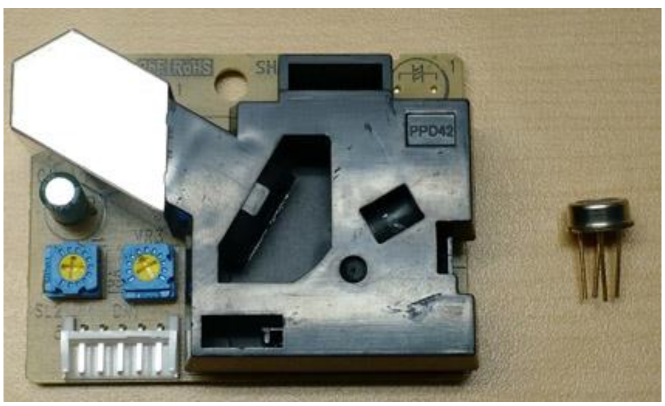

Figure 4 –Shinyei PPD42NS $PM_{2.5}$ Sensor (left) SGX MiCS 2710 NO_x Sensor (right)

We have also begun work on the educational resources that are key to this project. These resources will describe the sources of the priority air pollutants identified by the World Health Organization, what these priority air pollutants are, and their relationship to human and environmental health. Explanations of data quality and the importance of different global measurement techniques will also be discussed. Finally, specific resources to guide citizen scientist through device construction, utilization and data handling and analytics will be created.

IV. Creating synergies for long-term sustainability:

The project team hopes to build on the strengths of other initiatives that have used citizen science to collect environmental data. We believe the joint capacity of the project partners, OPCW, KCVS, and the Leiden University Centre have the potential to bring some unique synergies to efforts in this area. To that end, we seek feedback from the chemistry education community and this ConfChem on these questions:

- How might this OPCW project build synergy with other citizen science projects? What mechanisms can be used for the project to interact effectively?
- What is the best way to build low cost sensors for use in developing countries?
- Are NOx and PM the most reasonable starting point for priority pollutants that might be accessible with low cost mobile sensors and be of importance across the globe?
- How might other data streams (perhaps non-chemical) be integrated with sensor data to provide a more complete picture of the environmental chemical signatures?
- What are some creative ways low cost sensors and data analytics tools could be used as effective classroom tools?
- How can behavior design and gamification methodologies help to sustain citizen science efforts over time? What are best practices in this regard?
- What can we learn from volunteer networks in other sectors (open street map, wikipedia, wikileaks, etc)?

Acknowledgments:

We thank the King's University students Andrew Fox, Aaron Loset, and Aaron Yaremchuk for their work on this project as part of their senior thesis projects. KCVS undergraduate student researchers Mckenzie Oliver and Rachel Hislop-Hook of KCVS have given helpful input on this paper, and Dr. Brian Martin has served as a mentor. We thank the European Union for funding through Council Decision (CFSP) 2015/259 of 17 February 2015 in support of activities of the Organisation for the Prohibition of Chemical Weapons (OPCW) in the framework of the implementation of the EU Strategy against Proliferation of Weapons of Mass Destruction (project III, Chemical informatics for facilitating international collaboration, http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2015.043.01.0014.01.ENGEU)

References

1. Rockström, J.; Steffen, W.; Noone, K.; Persson, A.; Chapin, F. S.; Lambin, E. F.; Lenton, T. M.; Scheffer, M.; Folke, C.; Schellnhuber, H. J.; Nykvist, B.; de Wit, C. A.; Hughes, T.; van, d. L.; Rodhe, H.; Sorlin, S.; Snyder, P. K.; Costanza, R.; Svedin, U.; Falkenmark, M.; Karlberg, L.; Corell, R. W.; Fabry, V. J.; Hansen, J.; Walker, B.; Liverman, D.; Richardson, K.; Crutzen, P.; Foley, J. A. A safe operating space for humanity. *Nature* **2009**, *461*, 472-475.

2. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S. E.; Fetzer, I.; Bennett, E. M.; Biggs, R.; Carpenter, S. R.; de Vries, W.; de Wit, C. A.; Folke, C.; Gerten, D.; Heinke, J.; Mace, G. M.; Persson, L. M.; Ramanathan, V.; Reyers, B.; Sörlin, S. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, 736-747.

3. Mahaffy, P. G.; Martin, B. E.; Kirchhoff, M.; McKenzie, L.; Holme, T.; Versprille, A.; Towns, M. Infusing Sustainability Science Literacy through Chemistry Education: Climate Science as a Rich Context for Learning Chemistry. *ACS Sustainable Chem. Eng.* **2014**, *2*, 2488-2494.

4. Ballard, J.; Forman, J. E. Education, outreach and the OPCW: growing partnerships for a global ban. *2016 Spring ConfChem: Science, Disarmament, and Diplomacy in Chemical Education: The Example of the Organisation for the Prohibition of Chemical Weapons.* **2016**.

5. World Health Organization, Ambient (outdoor) air quality and health. http://www.who.int/mediacentre/factsheets/fs313/en/ (accessed May 24, 2016).

6. Pelucchi, C.; Negri, E.; Gallus, S.; Boffetta, P.; Tramacere, I.; La, V. C. Long-term particulate matter exposure and mortality: a review of European epidemiological studies. *BMC Public Health* **2009**, *9*, 453.

7. Laden, F.; Schwartz, J.; Speizer, F. E.; Dockery, D. W. Reduction in fine particulate air pollution and mortality: extended follow-up of the Harvard Six Cities Study. *Am. J. Respir. Crit. Care Med.* **2006**, *173*, 667-672.

8. Brunekreef, B.; Beelen, R.; Hoek, G.; Schouten, L.; Bausch-Goldbohm, S.; Fischer, P.; Armstrong, B.; Hughes, E.; Jerrett, M.; van, d. B. P. Effects of long-term exposure to traffic-related air pollution on respiratory and cardiovascular mortality in the Netherlands: the NLCS-AIR study. *Res. Rep. Health Eff. Inst.* **2009**, 5-71; discussion 73; 89.

9. World Health Organization, WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: Global Update 2005. **2006**.

10. Brauer, M.; Amann, M.; Burnett, R. T.; Cohen, A.; Dentener, F.; Ezzati, M.; Henderson, S. B.; Krzyzanowski, M.; Martin, R. V.; Van Dingenen, R.; van Donkelaar, A.; Thurston, G. D. Exposure Assessment for Estimation of the Global Burden of Disease Attributable to Outdoor Air Pollution. *Environ. Sci. Technol.* **2012**, *46*, 652-660.

11. Austen, K. Environmental science: Pollution patrol. *Nature (London, U. K.)* **2015**, *517*, 136-138.

12. Cole, S.; Gray, E. New NASA Satellite Maps Show Human Fingerprint on Global Air Quality. http://www.nasa.gov/press-release/new-nasa-satellite-maps-show-human-fingerprint-on-global-air-quality (accessed May 24, 2016).

13. Antonel, J.; Chowdhury, Z. Measuring ambient particulate matter in three cities in Cameroon, Africa. *Atmos. Environ.* **2014**, *95*, 344-354.

14. Sirbu, A.; Becker, M.; Caminiti, S.; De Baets, B.; Elen, B.; Francis, L.; Gravino, P.; Hotho, A.; Ingarra, S.; Loreto, V.; Molino, A.; Mueller, J.; Peters, J.; Ricchiuti, F.; Saracino, F.; Servedio, V. D. P.; Stumme, G.; Theunis, J.; Tria, F.; Van, d. B. Participatory patterns in an international air quality monitoring initiative. *PLoS One* **2015**, *10*, 1-19.

15. Bassok, A.; Hurvitz, P. M.; Bae, C. -. C.; Larson, T. Measuring neighbourhood air pollution: the case of Seattle's international district. *J. Environ. Plann. Manage.* **2010**, *53*, 23-39.

16. Yi, W. Y.; Lo, K. M.; Mak, T.; Leung, K. S.; Leung, Y.; Meng, M. L. A Survey of Wireless Sensor Network Based Air Pollution Monitoring Systems. *Sensors (Basel, Switzerland)* **2015**, *15*, 31392-31427.

17. Air Quality Egg. *http://airqualityegg.com/* (accessed May 24, 2016).

18. Air Casting Home. *http://aircasting.org/* (accessed May 24, 2016).

19. Gao, M.; Cao, J.; Seto, E. A distributed network of low-cost continuous reading sensors to measure spatiotemporal variations of PM2.5 in Xi'an, China. *Environ. Pollut. (Oxford, U. K.)* **2015**, *199*, 56-65.

20. Hasenfratz, D.; Saukh, O.; Sturzenegger, S.; Thiele, L. Participatory Air Pollution Monitoring Using Smartphones. *2nd International Workshop on Mobile Sensing*, **2012**.

21. City of Edmonton, Alberta Capital Airshed. *http://capitalairshed.ca/* (accessed May 26, 2016).

22. United States Environmental Protection Agency, AirData. *https://www3.epa.gov/airdata/* (accessed May 26, 2016).