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Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates?

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ABSTRACT

The emergence of low-cost, user-friendly and very compact air pollution platforms enable observations at high spatial resolution in near-real-time and provide new opportunities to simultaneously enhance existing monitoring systems, as well as engage citizens in active environmental monitoring. This provides a whole new set of capabilities in the assessment of human exposure to air pollution. However, the data generated by these platforms are often of questionable quality.

We have conducted an exhaustive evaluation of 24 identical units of a commercial low-cost sensor platform against CEN (European Standardization Organization) reference analyzers, evaluating their measurement capability over time and a range of environmental conditions. Our results show that their performance varies spatially and temporally, as it depends on the atmospheric composition and the meteorological conditions. Our results show that the performance varies from unit to unit, which makes it necessary to examine the data quality of each node before its use.

In general, guidance is lacking on how to test such sensor nodes and ensure adequate performance prior to marketing these platforms. We have implemented and tested diverse metrics in order to assess if the sensor can be employed for applications that require high accuracy (i.e., to meet the Data Quality Objectives defined in air quality legislation, epidemiological studies) or lower accuracy (i.e., to represent the pollution level on a coarse scale, for purposes such as awareness raising).

Data quality is a pertinent concern, especially in citizen science applications, where citizens are collecting and interpreting the data. In general, while low-cost platforms present low accuracy for regulatory or health purposes they can provide relative and aggregated information about the observed air quality.

1. Introduction

Urban air quality represents a major public health burden and is a long-standing concern to citizens. Air pollution is associated with a range of diseases, symptoms and conditions that impair health and quality of life (e.g., Bentayeb et al., 2015; Pascal et al., 2013; Raaschou-Nielsen et al., 2016; Wu et al., 2016). European cities, as with many other cities worldwide, are facing challenges in their fight against air pollution. Many efforts have been carried out to combat air pollution. However, levels of air pollution are still a problem in some cities. For instance, many European cities do not meet the requirements set out in air quality regulations (EEA, 2013, 2015).

1.1. Current monitoring systems

Historically, air quality monitoring has been conducted for two main purposes: legislation surveillance and scientific research. Currently air pollution concentrations are monitored by professional personnel (i.e., government authorities, scientists, health experts) using static monitoring stations equipped with certified reference instruments for measuring regulatory pollutants, such as carbon monoxide (CO), nitrogen oxides (NO_x, NO, NO_2), ozone (O_3) and particulate matter (PM_{10}, $PM_{2.5}$). The air pollutant analyzers are relatively large, heavy and expensive, with prices ranging between €5000 and €30,000 per device. Traditional fixed-site air quality monitoring stations are also subject to strict routines of maintenance and calibration of their instruments, to ensure high quality data and comparability between different stations and regions.

Large cities in developed countries are usually dotted with a network of reference monitoring stations that monitor air quality in real-time. However, the high costs of installation and maintenance of

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reference monitoring stations results in a relatively sparse monitoring, which provides accurate data but only in few locations, satisfying the legislative requirements but not providing information about localized gradients of potential importance to health protection. Moreover, in smaller cities or in underdeveloped regions, such air quality monitoring (AQM) stations may not exist. The fixed monitoring network is sometimes complemented by mobile air quality monitoring stations. These units usually have the same line of instrumentation as the fixed monitoring stations, mounted on vehicles, and the instruments have the same maintenance and calibration routines. Often, mobile monitoring stations are used for stationary measurements over a fixed period of time (e.g., a measurement campaign) in certain locations not covered by the fixed monitoring network (Glasius, 2006; Röösli et al., 2000). However, due to their high cost, mobile AQM vehicles cannot significantly increase spatial sampling density. The major limitation of mobile AQM data from the perspective of health protection is that their temporal coverage is incomplete.

Air quality monitoring may also be based on passive samplers. Such devices have the advantage in that they are inexpensive to deploy and operate (excluding laboratory analysis), easy to use and do not require electricity. The limitation of passive samplers is that they only allow the quantification of cumulative air pollutant levels, and therefore cannot identify short-term pollutant episodes or even track common temporal patterns (e.g., diurnal variability). Moreover, passive samplers are not as accurate as reference instrumentation, suffer from chemical interference, and are also affected by the atmospheric conditions (Krupa and Legge, 2000; Plaisance et al., 2004).

Finally, air quality models are an effective tool to supplement air quality monitoring. Models can also be used for tasks that cannot be conducted by monitoring alone, (e.g., scenario analysis, forecasting). However, the use of models requires a highly specialized knowledge and input data that is not available in all places. Moreover, in most cases air quality models do not run in an operational mode but rather in a prospective mode. Modelled concentrations may also suffer from systematic errors, including bias, depending on the input data and on the modeller parametrization choices (Pannullo et al., 2016).

1.2. Low-cost air quality platforms

There is a current trend worldwide to increase the collection of air quality data beyond reference monitoring stations. However, legislation to regulate the usability of these data is not in place yet (Castell et al., 2013; Kumar et al., 2015; Lewis and Edwards, 2016).

Several research projects are exploring the possibility of collecting air quality data using low-cost sensor platforms. Examples include OpenSense (www.opensense.ethz.ch) and Citi-Sense-MOB (Castell et al., 2015) that use mobile platforms to monitor air pollution variation in cities, Everyaware (www.everyaware.eu) that helps citizens collect and share noise and air pollution data and Citi-Sense (www.citi-sense.eu) that empowers people to use low-cost air quality platforms in 8 cities across Europe.

Sensor platforms are currently available to monitor a range of air pollutants and new devices are continually being introduced (Aleixandre and Gerboles, 2012; Snyder et al., 2013; Piedrahita et al., 2014). Air pollution sensors can be classified into two groups; those that measure gas phase species and those that measure particulate matter.

Commercially available gas sensors operate by measuring either the electrochemical interaction between the sensing material and the pollutant (i.e., electrochemical or metal oxide technologies) or the absorption of light at the visible range (Aleixandre and Gerboles, 2012). Particulate matter is measured by light scattering or absorption, using algorithms to relate the attenuated signal to the particle size and/or composition.

These individual sensors need to be integrated into a sensor platform or node. The sensor node contains a sensor board, the sensors, and a control board that integrates all the required electronics (e.g., signal conditioning, GPS, communication ports, data storage). The number and type of commercially available sensor platforms is increasing at a rapid pace. Whereas the price of individual gas sensors ranges from €20 to €100, the cost of a commercial sensor node that includes several sensors can reach €500–€5000.

1.3. New opportunities for ubiquitous monitoring

All European countries are required to comply with the EU Directives. The framework and legal requirements for assessment and management of ambient air quality are described in the Air Quality Directive 2008/50/EC (EU, 2008). The Air Quality Directive (AQD) establishes the criteria for air quality monitoring. It defines the reference measurement methods that Member States shall apply when monitoring air quality. These methods are currently applied in the fixed monitoring station networks in European cities. However, the AQD also opens the door for the use of other supplementary techniques, such as air quality models and indicative measurements.

Low cost sensor platforms can play an important role in air quality monitoring. Sensor nodes can be deployed as dense networks (ubiquitous monitoring) or mounted on vehicles, facilitating the elaboration of high-resolution air quality maps (Hasenfratz et al., 2015; Schneider et al., 2016). The reduced size of the low-cost platforms also allows new research in personal exposure. 'Wearable' platforms are able to consider changes in exposure due to changes in location and activities and provide new capabilities to evaluate health risk from air pollution (Bossche et al., 2016; Nazelle et al., 2013).

Legislation requires measuring of PM_{10} and $PM_{2.5}$. However, there is a growing concern on whether mass-based measurements are indeed relevant for assessing health effects of particulate pollution, or number-based measurements should be eventually promoted (Kumar et al., 2010). Several toxicological and panel studies present significant associations between elevated nanoparticle number concentrations (10–100 nm) and daily total as well as cardio-respiratory mortality using time-series epidemiological analysis (Stölzel et al., 2007), promoting number concentrations measurements as an appropriate metric for assessing health effects (Nel et al., 2006; Peters et al., 1997 and Xia et al., 2009).

We are experiencing now a paradigm shift in how and who is monitoring air quality (Castell et al., 2013; Lewis and Edwards, 2016). Attributes of sensor platforms are relatively lower in cost, easier to use and less bulky than traditional equipment, and provide the possibility for citizens and communities to monitor their local air quality that may affect their health (Snyder et al., 2013). Indeed, interest in low cost sensors is on the rise even before the sensor performance has been evaluated, and widespread data collection and data sharing using these sensor technologies is already occurring (Snyder et al., 2013; Lewis and Edwards, 2016). Examples are AirVisual, a crowdsourced community that has developed a home air quality monitor (https://www.indiegogo.com/projects/airvisual-node-the-world-s-smartest-air-monitor#/) and AirCasting - an open-source solution for collecting, displaying and sharing air pollution data (http://aircasting.org/). However, in order to employ low-cost platforms for air quality management and health studies, it is necessary to ensure their measurement reproducibility and assess any associated uncertainty. For example, it is known that low-cost sensors suffer from chemical interference and are affected by environmental conditions (Aleixandre and Gerboles, 2012).

The main challenge that low cost sensor technology faces in relation to legally based monitoring is to reach data quality requirements set by the AQD. Namely, to supplement air quality monitoring networks for scientific research, these data need to meet an acceptable level of quality. However, for many other applications, such as citizen awareness or community monitoring, it may be not crucial to have sensor platforms