Environment International 75 (2015) 199–205

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Review

The rise of low-cost sensing for managing air pollution in cities

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ARTICLE INFO

Article history:
Received 28 August 2014
Received in revised form 24 November 2014
Accepted 28 November 2014
Available online 5 December 2014

Keywords:
Air pollution
Exposure assessment
Health risks
Cities and megacities
Sensors

ABSTRACT

Ever growing populations in cities are associated with a major increase in road vehicles and air pollution. The overall high levels of urban air pollution have been shown to be of a significant risk to city dwellers. However, the impacts of very high but temporally and spatially restricted pollution, and thus exposure, are still poorly understood. Conventional approaches to air quality monitoring are based on networks of static and sparse measurement stations. However, these are prohibitively expensive to capture tempo-spatial heterogeneity and identify pollution hotspots, which is required for the development of robust real-time strategies for exposure control. Current progress in developing low-cost micro-scale sensing technology is radically changing the conventional approach to allow real-time information in a capillary form. But the question remains whether there is value in the less accurate data they generate. This article illustrates the drivers behind current rises in the use of low-cost sensors for air pollution management in cities, while addressing the major challenges for their effective implementation.

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1. Introduction

Road vehicles are one of the major sources of outdoor air pollution in cities (Gurjar et al., 2010; Kumar et al., 2013; Molina et al., 2004). At present, air pollution concentrations are collected by environmental

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http://dx.doi.org/10.1016/j.envint.2014.11.019
0160-4120/

or government authorities using networks of fixed monitoring stations, equipped with instruments specialised for measuring a number of pollutants, such as carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), ozone (O_3) and particulate matter (PM). Reliability of the measured data is ensured by applying standard procedures for instrument calibration, data collection and post-processing. Typically, regulatory decisions are made based on long duration time-series data that allow for the construction of temporal trends and statistics, while specific conditions related to hotspots are assessed based on real-time data, when available.

In addition, many cities worldwide are adopting mobile laboratories to collect air quality data for specific purposes such as for testing the implementation of a mitigation plan, evaluating a traffic management plan, carrying out feasibility studies, or capturing high spatial and temporal variability in pollutant concentration (e.g. near road-site). A number of publications have reported the use of such mobile laboratories. For instance, Wang et al. (2009) reported the experience of collecting road-site air quality data for the 2008 Olympic Games in Beijing. Padró-Martínez et al. (2012) carried out measurements of air pollutant levels in a near-highway urban environment with a wide range of traffic and meteorological conditions using a mobile monitoring platform, which was equipped with rapid-response instruments. Currently, a few research projects are also exploring the other ways of collecting air quality data. An example of this is the OpenSense project (http://www.opensense.ethz.ch/trac/) dedicated to monitoring air quality in urban areas with mobile wireless sensor nodes to better understand the variation of main air pollutants in cities. Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ; http://www.nasa.gov/mission_pages/discover-aq/) is another five-year science project of the National Aeronautics and Space Administration (NASA), USA. This project involves two aircrafts, ground sites and mobile labs to understand air quality in Houston (Texas) in which mobile labs provide critical ground truth to complement information on surface conditions from column and vertically resolved observations relevant to air quality. There is a current trend worldwide to increase the collection of air quality data beyond fixed monitoring stations, although legislation to regulate the usability of these data is not in place yet.

Monitoring of air pollutants is primarily performed using analytical instruments, such as optical and chemical analysers. Gas chromatographs and mass spectrometers can also be used for monitoring, but these are typically used for research purposes due to their complexity and high cost (Clemitshaw, 2004). Usually air pollutant analysers are complicated, bulky and expensive, with each instrument costing anywhere from about £5000 to tens of thousands of pounds, together with a significant amount of resources required to routinely maintain and calibrate them (Chong and Kumar, 2003). Although recent developments in the field have resulted in compact and more mobile instruments, they still have many limitations for widespread use and multipoint sampling (Heard, 2006). Therefore, more solid and compact systems are needed to capture the spatio-temporal variation of air pollution (Peng et al., 2014).

Air quality management is based on an adopted monitoring paradigm (Kim et al., 2012), which is subject to continuous evolution due to technological progress and the development of portable, low-cost (~£100 s) air pollution monitoring devices (i.e. sensors) and wireless communication systems. The adoption of the latter, a key component of low-cost air pollution sensing (DoE, 2010), relative to wired communication systems has been shown to reduce initial investments and annual operating costs by 3- and 5-fold in the US, respectively (DoE, 2010). In Europe, all countries are required to comply with the EU Directives (e.g. the Council Directive 96/62/EC on ambient air quality assessment and management, commonly referred to as the Air Quality Framework Directive). Such directives describe the basic principles for assessing and managing air quality in the Member States, and list the pollutants for which air quality standards and objectives shall be developed and specified in the legislation. These also recommend specific numbers of monitoring stations for individual pollutants, on the basis of the number of inhabitants and geographic partitioning. Demonstration studies have applied mobile sensor networks in some cities, such as Cambridge (UK), Valencia (Spain) and Lagos (Nigeria) (Mead et al., 2013), but their widespread long-term application is yet to find a legislative purpose. Current legislation for criteria pollutants in Europe is set by the European Union (EU) Air Quality Directive 2008/50/EC, which clearly defines the minimum of fixed monitoring stations for each target pollutant. For example, a minimum of one station should be installed every 100,000 km^2, which may exceed the size of some European countries. In this case each country should have at least one station or may set up together one or several common measuring stations by agreement with adjoining Member States.

Given the benefits and concerns related to low-cost sensing, a number of questions remain. In particular: (i) Is there really a need for low-cost air pollution sensing, and if yes, why? (ii) What is the current state-of-the-art of available sensors? (iii) Does this low-cost sensing have the potential to alter the conventional way of monitoring in the future? (iv) Are current sensors sensitive, selective and robust enough for reliable long-term monitoring? (v) What are the major challenges in their production and large-scale deployment in city environments? (vi) Are there any implications of the full life cycle assessment of these sensors and what is the probable cost of dismantling waste?, and (vii) What are the associated gaps on which future research should focus? There are numerous other questions and areas (e.g. energy management) where the use of sensors is popular (Kim et al., 2012), but our focus here remains on the application of low-cost sensing for air pollution management in urban outdoor environments. A comprehensive overview of these questions, highlighting operational challenges and a way forward, is therefore presented.

2. The need

Urban air quality is currently a global concern, which can be attributed to the massive scale of urbanisation and population growth, together with their resultant increases in traffic, industrialisation and energy use (Kumar et al., 2013; Molina et al., 2004). It is understood that technological improvements in low emission motor engines have been offset by an exponential increase in vehicle numbers. Consequently, the release of pollutants into the atmosphere continues to increase (Akimoto, 2003), having adverse impacts on a local, regional and global scale, with significant associated health-effects (Lim et al., 2012). A recent 'Global Burden of Disease' study has provided new evidence of the significant role that air pollution plays globally, placing it among the top ten risks faced by human beings (Lim et al., 2012). Many of the world's cities are unable to comply with the prescribed concentration limits of air pollutants (Kumar et al., 2013; Sharma et al., 2013), and in many cases, reported measurements far exceed them, resulting in millions of premature deaths (Kumar et al., 2014a; Lim et al., 2012; White et al., 2012). At the forefront of pollutants which exceed concentration limits are coarse (PM_{10}) and fine particulate matter ($PM_{2.5}$), and unregulated ultrafine particles (<100 nm) (Kittelson et al., 2004), making this issue even more complex (Heal et al., 2012). For example, a recent World Health Organisation report on ambient air pollution suggests that the annual mean concentration of PM_{10} has increased by more than 5% between 2008 and 2013 in 720 cities across the world (WHO, 2014). A reduction in long-term exposure to PM_{10} by 5 μg per cubic meter in Europe has been reported to "prevent" between 3000 and 8000 early deaths annually (Medina et al., 2004). Similar estimates for $PM_{2.5}$ suggest an average loss of 7–8 months in life expectancy for UK residents and about £20 billion per year in corresponding health costs (Defra, 2008). An equivalent estimate for exposure to ultrafine particles, which have a greater potential for adverse health impacts compared to their larger counterparts (HEI, 2013; WHO, 2013), is currently