Environmental Pollution 223 (2017) 102–110

Contents lists available at ScienceDirect

Environmental Pollution

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

Characteristics and applications of small, portable gaseous air pollution monitors☆

Grant R. McKercher [a], Jennifer A. Salmond [b], Jennifer K. Vanos [a, c, *]

[a] Texas Tech University, Department of Geosciences, 3003 15th Street, Lubbock, TX 79409, USA
[b] University of Auckland, School of Environment, 10 Symonds St., Auckland 1010, NZ
[c] University of California San Diego, Scripps Institution of Oceanography, 9500 Gilman Dr, La Jolla, CA 92093, USA

A R T I C L E   I N F O

Article history:
Received 5 August 2016
Received in revised form
14 December 2016
Accepted 18 December 2016
Available online 3 February 2017

Keywords:
Air pollution
Monitoring
Low-cost sensors
Urban pollution
Ozone

A B S T R A C T

Background: Traditional approaches for measuring air quality based on fixed measurements are inadequate for personal exposure monitoring. To combat this issue, the use of small, portable gas-sensing air pollution monitoring technologies is increasing, with researchers and individuals employing portable and mobile methods to obtain more spatially and temporally representative air pollution data. However, many commercially available options are built for various applications and based on different technologies, assumptions, and limitations. A review of the monitor characteristics of small, gaseous monitors is missing from current scientific literature.

Purpose: A state-of-the-art review of small, portable monitors that measure ambient gaseous outdoor pollutants was developed to address broad trends during the last 5–10 years, and to help future experimenters interested in studying gaseous air pollutants choose monitors appropriate for their application and sampling needs.

Methods: Trends in small, portable gaseous air pollution monitor uses and technologies were first identified and discussed in a review of literature. Next, searches of online databases were performed for articles containing specific information related to performance, characteristics, and use of such monitors that measure one or more of three criteria gaseous air pollutants: ozone, nitrogen dioxide, and carbon monoxide. All data were summarized into reference tables for comparison between applications, physical features, sensing capabilities, and costs of the devices.

Results: Recent portable monitoring trends are strongly related to associated applications and audiences. Fundamental research requires monitors with the best individual performance, and thus the highest cost technology. Monitor networking favors real-time capabilities and moderate cost for greater reproduction. Citizen science and crowdsourcing applications allow for lower-cost components; however important strengths and limitations for each application must be addressed or acknowledged for the given use.

1. Background and objectives

The urban environment cannot be fully characterized using sparse, static networks of air pollution monitors (Mead et al., 2013). While established urban networks of fixed site monitors have spatial densities on the order of 1–10 km^2 (i.e. distance between monitors is generally 1–10 km), concentrations of regulated criteria air pollutants can vary significantly within 10–100 m from roadways (Snyder et al., 2013). To combat this issue, recent advancements in sensor technology have led to the development of small, portable monitors with various and dynamic uses, and in some instances at a very low-cost. Mobile monitors, which can be defined as small devices that are capable of obtaining measurements while in motion, as well as stationary portable monitors, which are designed to be easily moved between various locations for stationary monitoring, are well-suited to address the spatiotemporal variability in air pollution caused by changes in local meteorology, traffic density, street topology, distance from sources, and pollutant chemistry (Bereitschaft, 2015; Snyder et al., 2013; Van den Bossche et al., 2015). The word “monitor” is used synonymously with the

☆ This paper has been recommended for acceptance by Charles Wong.

* Corresponding author. Texas Tech University, Department of Geosciences, 3003 15th Street, Lubbock, TX 79409, USA; University of California San Diego, Scripps Institution of Oceanography, 9500 Gilman Dr, La Jolla, CA 92093, USA.
E-mail address: jkvanos@ucsd.edu (J.K. Vanos).

http://dx.doi.org/10.1016/j.envpol.2016.12.045
0269-7491/

phrase “instrument-system”. In other words, air pollution “monitors” are systems made up of many different parts that perform various functions (e.g. power supply, signal conversion, display screen, etc.), while “sensors” refer to the individual air pollution sensing component.

Improvements in portable air pollution technology are motivated by a widespread desire to create more accurate human air pollution exposure assessments. Quantifying evidence of human exposure is ultimately needed for legislative purposes (Mead et al., 2013) so that urban planning changes can be made. For example, off-road cycling paths can be created and/or maintained for safer and healthier non-motorized travel. In order to advance environmental and human health studies, mobile air pollution monitors are increasingly used to obtain more accurate personal exposure estimates. Studies show that personal sampling of air pollution is preferable when attempting to accurately measure human exposure (Good et al., 2015; Steinle et al., 2013; Weichenthal et al., 2011; Zartarian et al., 2007), and that a high spatiotemporal resolution is required to correct for misinterpretation of actual exposure (Baxter et al., 2013; Kumar et al., 2013). Although there is a lack of concrete information on the effective use of such sensors by individuals and communities, specific vulnerable populations in urban areas could benefit from these sensor systems (e.g. child exposure (Grineski, 2007; McConnell et al., 2010; Vanos, 2015), and environmental justice such as health inequity issues could be addressed (Grineski et al., 2007; Pope, 2014; Wakefield et al., 2001; Wheeler and Ben-Shlomo, 2005; White et al., 2012)). The rapid acceleration of technological innovations in environmental sensing offers vast opportunities to improve individual and collective decision-making, and the ability to pursue improved environmental equality.

However, the measurement accuracy of available monitoring devices vary greatly depending upon their intended applications. With continual and rapid advancements in small sensor technology, it can be difficult for different audiences (i.e. researchers, citizen scientists) to stay informed of the various options, cost, limitations, and benefits specific to their intended use. Furthermore, while numerous research studies and reviews have been published on the use of such mobile and personalized monitors for particulate matter, information on the use of mobile monitors for gaseous pollutants is scarce. Studies have distinguished the technologies of mobile monitors of gaseous pollutants from those of stationary monitors (Kumar et al., 2015; Aleixandre and Gerboles, 2012; Castell et al., 2013; Steinle et al., 2013; Snyder et al., 2013; Van Poppel et al., 2013) and evaluated mobile monitors in comparison to reference analyzers (Gerboles and Buzica, 2009; Lin et al., 2015; Williams et al., 2014b), yet no current study synthesizes these findings or promotes new research directions from the perspectives of specific audiences and intended applications. Therefore, this state-of-the-art review is the first to provide an exclusive assessment of small portable air pollution monitors that measure ambient gaseous outdoor pollutants.

The United States Environmental Protection Agency (EPA) *Air Sensor Guidebook* (Williams et al., 2014a) includes a table comparing the performance characteristics (e.g. accuracy and precision) of several mobile monitors, which is useful for researchers undertaking mobile studies, yet some of the monitors are outdated or discontinued. The format and utility of this EPA resource was a primary influence for the current paper.

This review aims to help future experimenters interested in studying gaseous air pollutants choose monitors appropriate for their application and sampling needs. Moreover, we highlight particular aspects of currently available sensor technologies used within the small monitors that may influence and motivate future portable/mobile monitor development, which will remain useful long after the current monitors are replaced. Further, a detailed examination of the components and characteristics of several handheld mobile devices is provided to address the relations between cost and data quality. Finally, the current review distinguishes the current technologies based upon different research areas (e.g. epidemiology/public health, atmospheric chemistry, urban planning) and different applications (e.g. government, citizen scientists, researchers) so that there is less confusion amongst groups. While there are many small monitors that measure particulate matter (PM) that have been widely used in mobile monitoring studies, these are not the focus of this review. For detailed reviews and further information on research and applications regarding PM spatial assessments and monitoring, the reader is referred to Jovašević-Stojanović et al. (2015) and Gozzi et al. (2015).

2. Methods

A “state-of-the-art review” addresses more current matters instead of focusing on the combined retrospective of an entire body of scientific literature (Grant and Booth, 2009). Therefore, this review first addresses the broad trends in portable monitor use during the last 5–10 years, further narrows its focus to gaseous monitor technologies, and finally highlights specific aspects of a select list of recently available small, portable gaseous monitors.

In order to select specific monitors for the review, online searches were performed on general and scientific databases (e.g. Google Scholar and Science Direct) using keywords: “portable/mobile air pollution monitor” and “handheld air quality monitoring”. These searches included articles from both commercial websites and peer-reviewed journals and were performed in 2015. Only monitors that measure one or more of three specific gaseous air pollutants (O_3, NO_2, and CO) were selected. These three gases are common criteria urban air pollutants that have been widely analyzed in the recent scientific literature and can be harmful to human health (e.g. Castell et al., 2013; Deville Cavellin et al., 2015; Good et al., 2015; Lin et al., 2015). The air pollution monitors were chosen based upon the availability and accessibility of the comparable information. For example, if a monitor was found on the online search that measured one of the selected gases, but specifics such as test results and the distinct components could not be found, then the monitor was excluded from this review. Only resources that provided specific information that was useful to the comparisons presented in Tables 1 and 2 (e.g. intended application, tested precision, sensing range, battery life) were included. The available information also helped establish the variables to be compared. For instance, many resources did not list monitor “accuracy”, but many sources listed the “precision”, therefore, the precisions were compared in this review and accuracies were not.

The search revealed seven small, portable air pollution monitors: the Personal Ozone Monitor (2B Technologies Inc.), the SENS-IT (Unitec), the CairClip (Cairpol), the Series 500 Portable Monitor (Aeroqual Inc.), the AGT Environmental Sensor (AGT International), The Smart Citizen Kit (Acrobotic Industries), and the AirCasting Air monitor (HabitatMap).

3. Review of literature

3.1. Applications of mobile air pollution monitors

Three of the most prevalent uses for mobile air pollution monitors include (1) personal exposure monitoring, (2) the supplementation of existing air pollution monitor networks, and (3) citizen science or education (Williams et al., 2014a). Mobile air pollution monitors can also be used for measurements of near point sources for safety reasons; however, this paper seeks to specifically address applications intended for monitoring general human