Commentary

Opportunities for the application of low-cost sensors in epidemiological studies to advance evidence of air pollution impacts on human health

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Introduction

Every year, air pollution is associated with more than 7 million deaths globally (Forouzanfar et al., 2016). It is one of the top environmental health risks in low- and middle-income countries (LMICs) (Joubert et al., 2020). Ambient and household air pollution (HAP) threaten human health and well-being, particularly for vulnerable groups such as infants and children, women, people with pre-existing diseases and the elderly (Forouzanfar et al., 2016).

Annually, 3.8 million premature deaths caused by non-communicable diseases, including stroke, ischaemic heart disease, chronic obstructive pulmonary disease (COPD) and lung cancer, are attributed to HAP exposure (World Health Organisation 2021). While there is good international evidence of the health impacts and patterns of air pollution exposure, there is less evidence in African countries (Zhang and Smith 2007; Khilnani and Tiwari 2018). Constrained by various factors, such as cost, prioritisation and capacity, air pollution data in ambient and household settings are lacking in the African context (Wetsman 2018).

For policy- and decision-makers, and people advocating for clean air, including communities themselves, evidence is required to understand the severity of Africa's air pollution problem and the associated health burden. Data and evidence in a local context are called upon by government and civil society alike, for example, when air pollution is suddenly visible in the atmosphere or smelt in the air. A case of the latter occurred recently when the putrid smell of hydrogen sulphide permeated the air in parts of Gauteng and Mpumalanga, South Africa (eNCA 2021). These occurrences highlight the importance of hard evidence and data to understand, explain and call for action, and interventions to prevent air pollution and its harmful health impacts.

Until recently, air pollution data were primarily available from two sources: ground-based monitoring stations and satellites. Both have their strengths and limitations. Ground-based stations (183 officially listed stations in South Africa) are generally sparse and situated in ambient/ outdoor settings and do not capture HAP exposure. They typically monitor a variety of criteria / regulated pollutants (i.e., PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3, CO) in air pollution hot spots. Satellite air quality data cover a broader geographic area but do not necessarily measure the air people breathe on the ground. The integration of satellite data with atmospheric and/or statistical models along with surface monitored data is necessary to gain a more holistic understanding of air pollution exposure (van Donkelaar et al., 2016).

An exciting and relatively novel solution to air pollution monitoring in both ambient and household settings is the concept of low-cost air quality sensors. Drawing on technology, connectivity and big data, low-cost sensors have several benefits over ground-based stations and satellite-based instruments. They are (usually) relatively inexpensive so that one can create a high-density network in an area of interest, say, outdoor and indoor locations in an air pollution hotspot. Data can be collected frequently (as often as every few seconds) and sometimes in real-time, generating evidence at appropriate resolutions in space and time. The higher resolution temporal and spatial data 'fill in the gaps' between ground-based monitoring stations and can provide data for epidemiological studies such as indoor air quality data. Researchers can better understand the relationships between air pollution concentrations experienced by individuals rather than for an entire area/community, and human health impacts in micro-environments. In this commentary, we consider the current use of low-cost sensors in air quality assessment and management, including African examples. We discuss how data from low-cost sensors are useful for epidemiological studies to inform interventions and ultimately to prevent adverse health impacts. In addition, we describe a new project, the South African 'Low-Cost Sensor Inter-Comparison Campaign (LCS-SA)' to understand the advantages and limitations of using low-cost sensors in South African epidemiology.

Low-cost sensors in air quality management

The need to better assess and understand air pollution exposure where large air quality data gaps exist in developing countries has led to large-scale air quality measurement programmes. UNEP's "Global Environment Monitoring System for Air (GEMS Air)", for example, integrates data from satellites, air quality reference monitors and complements these measurements with data from low-cost sensors for maximum spatial and temporal coverage across the globe (UNEP 2021a, UNEP 2021b). The programme promotes global stakeholder engagement and collaboration between private and public sectors, academia, civil society, and local governments. It builds capacity for the use of low-cost sensors to develop evidence-based air quality management policies and supports actions for air quality management through the elevation of awareness levels in developed and developing countries alike (UNEP 2021a).

Another example is the World Air Quality Index project, which has been running since 2007, and provides air quality information for more than 130 countries, including South Africa (World Air Quality Index Project 2021).

Studies conducted within Sub-Saharan Africa using low-cost air quality sensors have demonstrated the feasibility and practicality of using in situ low-cost sensors, despite the challenges encountered (power outages, SD memory card issues, connectivity problems, device safety concerns, as well as sensitivity to chemical interference and environmental conditions) (Awokola et al., 2020). These data are being used to enhance coverage of air pollution-related human health and environmental concerns, and for advocacy purposes (Awokola et al., 2020; Amegah 2018). Sensors set up by universities, schools, and local media organizations are also being used to upskill civil society to better understand the quality of the air they breathe and to lobby for cleaner air when necessary (Desouza et al., 2017). Studies using low-cost sensors in Ghana and Nigeria have assessed relationships between air pollution exposure and adverse health outcomes, indicating the potential of such sensors for health research (Quinn et al., 2017; Alexander et al., 2018; Clark et al., 2020).

Though South Africa's ambient air quality monitoring network feeds real-time ground-based air quality data for various primary pollutants into UNEP's Live "Airvisual" tool (the largest real-time air quality databank), South Africa's air quality monitoring network is biased in location towards large industrial sources and their surrounding areas (UNEP 2021c). There is a need for air quality data collection beyond this monitoring network, which could be critical for health studies. Crucial gaps in air quality monitoring efforts exist, especially for HAP, representing a large health risk in low-income communities across the country where air pollution levels are high and where few ground-based monitoring stations are located. Low-cost sensors are a means to fill this gap.

Leveraging air quality data for epidemiological studies

In 2020, an international consortium embarked on a project to consider leveraging air quality data for high-grade epidemiological studies in LMICs. Entitled LEAP-Epi (Leveraging Environmental data for Air Pollution exposure assessment in Epidemiology), the project is a collaboration between the University of Leicester (UK), the South African Medical Research Council and the University of the Witwatersrand. To enrich the project with specific areas of expertise, additional partners have joined LEAP-Epi (e.g., North-West University (NWU) and University of the Free State (UFS)).

The aims of the project are to 1) Perform a comprehensive assessment of available global and local air pollution data across several study sites in South Africa; 2) Develop a sustainable sampling methodology for indoor and outdoor air quality data at different levels of exposure in low and middle-income contexts; and 3) Build local capacity for air quality research, involve local communities in developing sensor deployment and exposure mitigation strategies, and contribute evidence for national policies. Phase 1 of the project is currently underway and entails the LCS-SA Campaign. It is hoped that this study can show the value of low-cost sensors in collecting indoor and ambient air quality exposure data at an unprecedented scale and duration.

Low-cost sensor inter-comparison campaign

Over recent years, the low-cost sensor market has produced many instruments, making it difficult for end-users to evaluate the sensor's reliability for in-field monitoring. The LCS-SA Campaign is coordinated by the SAMRC and NWU in collaboration with several low-cost sensor developers and stakeholders. The collaboration is unique in that it sees researchers, experts and product developers work together to meet one end goal: to

Figure 1: *LCS-SA Campaign set-up at the North-West University Air Quality Monitoring Station at the Vanderbijlpark Campus (NWU-Climatology Research Group)*

evaluate and produce meaningful, user-friendly instruments which can be strategically deployed in areas of concern to generate credible, repeatable, and reproducible results for epidemiological work and effective air quality management. End-users range from researchers to civil society, where local communities can learn to use the sensors for their benefit and to improve local air quality.

Different low-cost sensors measuring a range of pollutants (e.g., PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3, CO) and meteorological data have been co-located and run parallel with reference method instruments. Low-cost sensors have been provided by scientific research groups, instrument suppliers and instrument manufacturers. The instruments have been deployed simultaneously at the North-West University Air Quality Monitoring Station at the Vanderbijlpark Campus, located in the Vaal Triangle Airshed Priority Area (Figures 1 & 2).

Instruments are being operated as per the manufacturer's specifications for six months, starting in May 2021. This period spans typical air pollution conditions ranging from periods of relatively low air pollution to extreme pollution events. The LCS-SA Campaign will provide data and information on each sensor's performance relative to each other and to the reference instruments in a field setting. Data recovery rates and data comparisons will help identify sensor issues such as bias, inaccuracies and imprecision, for which correction factors will be determined. Finally, user-friendliness will be evaluated.

In conclusion, the deployment of these low-cost sensors will supplement ground-based readings and contribute to verification exercises when considering satellite data or improve understanding of indoor personal exposure. Indicative air quality measurements provided by low-cost sensors would go a long way in identifying pollution hotspots in local communities, thereby empowering civil society.

Figure 2: *LCS-SA Campaign set-up – various low- and medium cost air quality sensors co-located at the same height on a custum-constructed sensor-stand.*

Conclusion

Despite the known impacts of air pollution on human health, research and data are essential to understand its impact on mortality and morbidity in South Africa. A narrative review of HAP exposure and respiratory health outcomes illustrated significant challenges in measuring the exposure variables, namely criteria pollutants, both outdoors and indoors (Shezi and Wright 2018). Instruments to measure exposure tend to be expensive, burdensome to wear in the case of personal monitors, and labour-intensive to manage. However, the data needed to assess the associations between personal air pollution exposure and health effects, such as lung function, inflammation, and chronic diseases (e.g., Chronic Obstructive Pulmonary Disorder), need to be at high resolution and take place where people breathe the polluted air (Cattaneo et al., 2010). Moreover, for comparative purposes, instruments applied in different studies need to be comparable in the data that they generate.

Finally, we aim to generate good quality data to understand the prevalence and distribution of air pollution-related health impacts in South Africa to inform the design of effective interventions that would decrease pollution associated morbidity and mortality at local, provincial, and national scales. Low-cost sensors have the potential to generate epidemiological evidence to inform policy decisions and evidence-based practice.

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