Science of the Total Environment 502 (2015) 537–547

Contents lists available at ScienceDirect

Science of the Total Environment

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

On the feasibility of measuring urban air pollution by wireless distributed sensor networks

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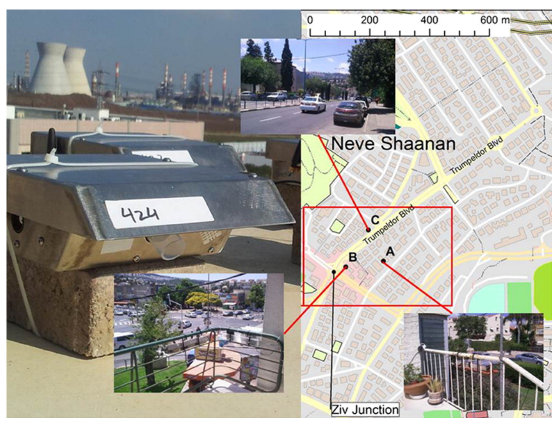
HIGHLIGHTS

- Air quality wireless distributed sensor network was deployed at a sub-neighborhood scale.
- High inter-nodal consistency was demonstrated.
- The nodes were sensitive to local microenvironment conditions and to “hot-spots”.
- In-situ calibration procedures for O_3 were demonstrated.
- This technology has a great potential for exposure assessment.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 9 April 2014
Received in revised form 17 September 2014
Accepted 19 September 2014
Available online xxxx

Editor: Lidia Morawska

Keywords:
Urban air pollution
Exposure
Air quality monitoring
Wireless distributed sensor network

ABSTRACT

Accurate evaluation of air pollution on human-wellbeing requires high-resolution measurements. Standard air quality monitoring stations provide accurate pollution levels but due to their sparse distribution they cannot capture the highly resolved spatial variations within cities. Similarly, dedicated field campaigns can use tens of measurement devices and obtain highly dense spatial coverage but normally deployment has been limited to short periods of no more than few weeks. Nowadays, advances in communication and sensory technologies enable the deployment of dense grids of wireless distributed air monitoring nodes, yet their sensor ability to capture the spatiotemporal pollutant variability at the sub-neighborhood scale has never been thoroughly tested. This study reports ambient measurements of gaseous air pollutants by a network of six wireless multi-sensor miniature nodes that have been deployed in three urban sites, about 150 m apart. We demonstrate the network's capability to capture spatiotemporal concentration variations at an exceptional fine resolution but highlight the need for a frequent in-situ calibration to maintain the consistency of some sensors. Accordingly, a procedure for a field calibration is proposed and shown to improve the system's performance. Overall, our results support the compatibility of wireless distributed sensor networks for measuring urban air pollution at a sub-neighborhood spatial resolution, which suits the requirement for highly spatiotemporal resolved measurements at the breathing-height when assessing exposure to urban air pollution.

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http://dx.doi.org/10.1016/j.scitotenv.2014.09.059

1. Introduction

Ambient air pollution results from emissions of diverse pollutants from different stationary and mobile sources, and from chemical reactions between primary pollutants that form secondary pollutants, such as tropospheric ozone. The dispersion and the generation of ambient pollutants are highly affected by local (micro-) meteorological conditions (wind speed, solar radiation, humidity, temperature). Accordingly, urban air quality is characterized by high spatial and temporal variability (Nazaroff and Alvarez-Cohen, 2001; Levy et al., 2014a,b).

Evidences of adverse health effects from exposure to ambient gaseous pollutants (e.g. ozone, O_3; nitrogen dioxide, NO_2; carbon monoxide, CO) and particulate matter (PM) have been widely reported (Kampa and Castanas, 2008; Peters et al., 1997). Typically, air pollution related exposure metrics used in environmental epidemiology studies are based either on short term sampling (Crouse et al., 2009) or on pollutant measurements by standard air quality monitoring (AQM) stations over extended time periods (Pope et al., 2002). Conventional AQM instruments provide accurate measurements but suffer from limited deployment due to their bulkiness, high cost and the professional maintenance requirements. This limits the AQM network capability to adequately capture the highly resolved air pollutant spatial variations. Intensive sampling campaigns use a large number of sensors deployed at high density but are limited to relatively short periods (~14 days), and oftentimes to integrative measurement over the whole period (Hoek et al., 2008). Consequently, accurate exposure assessment and the study of air pollution-health associations are still a challenging task (Rao et al., 2012). To tackle these limitations, recent environmental health studies incorporated proxy indicators of personal exposure to traffic related air pollution, such as distance of the residence to the nearby road (Pujades-Rodríguez et al., 2009) and other land use parameters (Hoek et al., 2008). Yet, the relationships between these surrogates and the individual's exposure are mostly stationary and depend on the choice of variables that are included in model (in part, based on data availability). Exposure estimation based on geospatial interpolation techniques that generate pollution maps from AQM data is also common (Whitworth et al., 2011; Eitan et al., 2010; Myers et al., 2013). However, these methods are dramatically affected by the stations' location (Yuval and Broday, 2006). Clearly, increasing the spatial density of the measurements will result in spatial interpolation with smaller uncertainty (Kanaroglou et al., 2005) but can be economically feasible only by deployment of low-cost instruments. Yet, such low-cost devices may suffer from poor accuracy, lack of robustness, and limited longevity, thus projecting on their deployment flexibility and on the network scaling up.

Recent advances in sensory and communications technologies have made the deployment of multi-sensor environmental wireless distributed sensor networks (WDSNs) feasible, and opened a new front in the air pollution and exposure assessment arena. Early studies that evaluated WDSN capabilities in a controlled lab environment (Lee, 2001; Becker et al., 2000) stressed the need for a calibration process in order to sustain reliable measurements. Field deployments of low-cost air quality sensor networks measuring ambient O_3 levels by metal-oxide micro-sensors (Williams et al., 2013) and CO, NO and NO_2 by electrochemical (Mead et al., 2013) or metal-oxide (Piedrahita et al., 2014) probes proposed calibration processes that are applicable for controlled lab environment but fell short in comparison to data collected at a collocated standard AQM station (even after an initial field calibration has been applied; Williams et al., 2013). Tsujita et al. (2005) suggested a field calibration approach where the metal-oxide NO_2 sensor baseline is adjusted to the average value of four surrounding AQM stations during time periods in which the NO_2 concentrations are low (<10 ppb) and homogeneous conditions apply. Yet, the method is designed to work on low NO_2 concentrations whereas the WDSN NO_2 detection limit is typically 10 ppb. This renders the method inapplicable. Moreover, this calibration method has been tested only on one sensor and has never been applied to a WDSN. To date, testing the operation of an air quality WDSN (AQ-WDSN) in the field has been reported only by Mead et al. (2013), who demonstrated the feasibility of deployment of an electrochemical sensor network. However, a detailed analysis of the network ability to capture the spatiotemporal pollutant variability, micro-environmental conditions (local sources and meteorology effects), and the unavoidable field calibration process has not been performed. Moreover, to the best of our knowledge field deployment of a metal-oxide micro-sensor network has not yet been reported.

This paper presents an analysis of measurements obtained by an AQ-WDSN. The network was deployed in an inner-city neighborhood, with a typical mixture of quiet residential areas, busy traffic routes, a neighborhood commercial area, education institutions, etc. Each node contained multiple sensors, however in this work we focus on measurements of O_3, NO_2, and total volatile organic compounds (TVOCs). The study aims were to examine the suitability of metal-oxide sensor network for measuring pollutant levels and capturing their spatiotemporal concentration variability, and to develop a reliable field calibration procedure for the sensors.

2. Materials and methods

2.1. Instrumentation

Air quality measurements were acquired using the CanarIT™ multi-sensor WDSN nodes (Airbase Systems LTD, Israel). Each CanarIT™ unit hosts in a compact housing ($20 \times 15 \times 7$ cm^3) three metal oxide (MO) chemoresistive sensors for O_3, NO_2 and TVOC, an optical (IR based) total suspended particulate matter (TSP) sensor, an electret microphone (noise sensor) and a dual semiconductor temperature and relative humidity (RH) sensor. In this study we discuss only measurements of NO_2 and TVOC (taken every 20 s) and O_3 (recorded once per minute). The data are sent by a GPRS communications channel to cloud storage.

The O_3 sensor (SM50, Aeroqual LTD, New Zealand) is pre-calibrated to the range of 0–150 ppb, and has a 1 ppb resolution and laboratory measurement uncertainty of less than ± 5 ppb. The NO_2 and TVOC sensors (iAQ-100, AppliedSensors GmbH, Germany) are pre-calibrated to 10–2000 ppb (NO_2, 5 ppb resolution) and 0–2000 ppm CO_2 equivalent (TVOC). Ambient pollutant concentrations (30 min resolution) were obtained from the Neve Shaanan AQM station (marked AQM in Fig. 1), ~750 m down the road from site C (see below) and operated by the Haifa District Municipalities Association for the Environment (HDMAE). The AQM is located on the roof of a school, 10 m above the ground level (a.g.l.) and 30 m from the road, and it is considered by the HDMAE to be unaffected by local microenvironmental conditions. Ozone concentration measurements at the AQM station (O342M analyzer, Environment S.A. LTD, France; precision $\pm$ 0.5 ppb) were used as reference values for field calibration of the WDSN O_3 sensors. Wind data (30 min resolution) were also obtained from the AQM station.

2.2. Study area

The study area is the coastal city of Haifa, located at the eastern Mediterranean Sea at the north of Israel (~295,000 residents). The city is built on and around the Carmel Ridge, from the shore at the foot of the ridge to its top at ~400 m above sea level (a.s.l.). The campaign was done at Neve Shaanan — a residential neighborhood on the Carmel Ridge, ~200 m a.s.l. The neighborhood is mostly planar and features mixed residential and commercial areas. A major road crosses the neighborhood and connects the north-east and south-west slopes of the Carmel Ridge, passing through the Ziv junction — a neighborhood busy commercial area (Fig. 1). The summer along the Israeli coast of the Mediterranean, from mid-May to mid-October, is dominated by a Persian trough at the surface that is capped by an Azorean high aloft. This synoptic pattern results in rather stable hot and humid