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High spatiotemporal characterization of on-road $PM_{2.5}$ concentrations in high-density urban areas using mobile monitoring

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ABSTRACT

Mobile air quality monitoring reports air pollutant concentrations at a high spatiotemporal resolution, enabling the characterization of heterogeneous human exposure and localized pollution hotspots. In this study, on-road concentrations of fine particulate matter ($PM_{2.5}$) in a high-density urban area in Hong Kong were measured in December 2014 and January 2015 (winter) and June and July 2015 (summer) using a tramcar mobile monitoring platform. We developed a method of mapping the winter and summer on-road $PM_{2.5}$ concentrations along a tramcar route at a 50-m spatial resolution, using mobile measurements. In addition, the minimum number of days required to precisely estimate on-road $PM_{2.5}$ concentrations was estimated. The results showed that the on-road $PM_{2.5}$ concentrations were highly correlated with $PM_{2.5}$ concentrations measured at a nearby roadside air quality monitoring station (AQMS) in both winter and summer, with Pearson correlation coefficients of 0.89–0.93. The resulting maps of winter and summer on-road $PM_{2.5}$ concentrations revealed small-scale spatial patterns used to identify more polluted areas. In addition, approximately 12 and 4 days were required to precisely capture spatial patterns of $PM_{2.5}$ concentrations, with R^2 higher than 0.6 in winter and in summer. The findings of this study offer valuable information on air pollution control and exposure reduction by highlighting localized pollution hotspots, and provide insights into the minimum sampling duration for mobile sampling campaigns.

1. Introduction

Air pollution is a major environmental risk to human health [1,2]. For example, Lelieveld et al. [3] estimated that in 2010, global $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than or equal to 2.5 μm) related mortality reached 3.15 million people, with a 95% confidence interval of 1.52–4.60 million. In urban areas, emissions from roadway transport are a major source of air pollution, such as $PM_{2.5}$ and ultrafine particles, despite extensive emission control measures targeting motor vehicles [4–9]. Exposure to traffic-related pollutants in urban areas has various acute and chronic adverse health effects [10–12].

An effective approach to air quality monitoring can provide important information for exposure assessment, epidemiology, air quality management, and environmental equity [13,14], but the extent of fixed-site air pollution measurement is limited by the cost of equipping and maintaining fixed-site air quality monitoring stations (AQMSs) [1,15]. Air pollutant concentration in cities may vary sharply over short distances (~0.01–1 km) due to the uneven distribution of sources of emissions, dilution, and physicochemical transformation [1,16,17]. Thus, the measurements yielded by a network of several roadside AQMSs only poorly represent on-road air quality [1,17–19].

In recent years, air quality monitoring has been revolutionized by the increasing application of mobile platforms capable of reporting air pollutant concentrations in close to real time [1,4,7,16,20–23]. Platforms such as instrumented cars and vans [1,5,22,24–32], public transit trains and trams [33–36], bicycles [37–41], and backpacks [42–46], have increasingly been used to answer research questions relating to general air quality surveying, emissions characterization, and near-source assessment [20]. To sum up, mobile monitoring techniques offer a powerful supplement to the use of AQMSs to obtain air quality data, providing a more complete spatial picture of air pollution variability and population exposure in various microenvironments [16,30].

The primary downside of mobile sampling is that the sampling

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duration at a given measurement location is much shorter than that at a fixed-site monitor. Thus, previous studies have typically measured the investigated area or route repeatedly to provide a representative characterization of air pollution [1,24,26,32,36,37]. However, the aggregated sampling duration for each measurement location is still short, ranging from minutes to several hours over a sampling campaign [21,32,37]. The trade-offs between sampling duration and measurement precision/accuracy have been quantitatively explored [1,7,21,37,47]. In addition, mobile measurements are not made simultaneously at multiple sites. During mobile monitoring, ambient $PM_{2.5}$ concentrations change both temporally (e.g., between days and even within the period of measurement) and spatially (e.g., between locations) [1,48]. The direct comparison of $PM_{2.5}$ concentration between periods is questionable when ambient $PM_{2.5}$ concentrations differ significantly [49,50]. Therefore, the extent to which a mobile measurement data set can characterize the spatial patterns of and long-term trends in $PM_{2.5}$ concentrations remains unclear [48,50].

In Hong Kong, many tall commercial and residential buildings are located along narrow roads, forming deep street canyons with intensive traffic flow [35]. As a result, many Hong Kong people live and (or) work close to the main roads, and are thus subject to heavy traffic and toxic vehicle exhaust fumes. Hong Kong's dense urban construction has been reported to block ventilation and consequently retard the dispersion of vehicle exhaust emissions [36,51], which may result in higher $PM_{2.5}$ concentrations. In addition, $PM_{2.5}$ originating from traffic can easily penetrate the building envelope via open windows and doors and ventilation systems, reducing indoor air quality [52]. Therefore, on-road air pollution poses a potentially severe health risk to Hong Kong residents through both outdoor and indoor exposure. Gaining a better understanding of on-road $PM_{2.5}$ levels along major traffic corridors with high human activity level and pedestrian flow can offer insights for policy makers into air quality and exposure management.

The objectives of this study are 1) to characterize the spatiotemporal patterns of on-road $PM_{2.5}$ concentration and identify pollution hotspots using data from a tramcar mobile monitoring platform, and 2) to determine the minimum number of sampling days required to characterize the seasonal spatial patterns of on-road $PM_{2.5}$ concentration using a subsampling method with and without background correction.

2. Data and methods

This section describes the (1) sampling location and tramcar route, (2) mobile and fixed-site measurements, (3) processing of Global Positioning System (GPS) and $PM_{2.5}$ concentration data, (4) background concentration correction, and (5) determination of the minimum number of sampling days.

2.1. Sampling location and tramcar route

Hong Kong is a coastal city located in southern China. Hong Kong is one of the most densely populated cities in the world, with an average density of 6690 people per square kilometer as of mid-2014 [53]. Hong Kong is a representative example of a high-density, high-rise city with significant air quality issues. The effects of vehicular emissions on urban and street-level air quality have become one of the most pervasive air pollution issues in Hong Kong [54,55].

Hong Kong Tramway, Hong Kong's tram system, was one of the earliest forms of public transport in the metropolis. Trams on Hong Kong Island run between Kennedy Town (to the west of Hong Kong Island) and Shau Kei Wai (to the east of Hong Kong Island), with a branch circulating through Happy Valley (Fig. 1). This system, the world's largest operational double-deck tram fleet, provides a passenger transit service in a densely populated area that serves more than 200,000 passengers per day and operates a fleet of 163 tramcars across a network of 120 stations, 4 termini (two of which are depots), and 6 main route groups, resulting in several dozen routes. Powered by electricity via overhead cables, the tramcars run alongside vehicular traffic on rail-tracks laid on public roads in the central business district of the city [56]. It takes approximately 1 h to travel by tram from Kennedy Town to Shau Kei Wan.

2.2. Mobile and fixed-site measurements

An air quality monitoring unit composed mainly of an aerosol DustTrak monitor and a GPS locator was installed on one of the tramcars. DustTrak is an optical instrument based on a sheet of laser light formed by a laser diode and light scattering from a cloud of particles, which are detected in a chamber by a photodetector. The subsequent voltage is linearly proportional to the mass concentration [43]. The detection range of the DustTrak II 8530 was from 0.001 to 400 mg/m^3 for particles from 0.1 to 10 μm in diameter, with a resolution of ± 1% of reading or 0.001 mg/m^3 (whichever is greater) [57]. A $PM_{2.5}$ cutoff inlet was used, and the flow rate was adjusted to 3 L/min.

DustTrak was auto-zeroed every 3 h to minimize the impact of instrument drift on the measurement. Information on $PM_{2.5}$ concentrations and GPS location was collected every second. A preprogrammed data logger was used to control the operation of the system and archive $PM_{2.5}$ and GPS data with a high time resolution. The whole system was installed in metal casing underneath a seat at the rear end of the upper deck of the tram for two reasons. First, the monitoring unit is protected from potential damage (e.g., movement of passengers, and the rain). Second, the deployment of the monitoring unit should not disturb the operation of the tramcar. The system is powered by the direct current (DC) supply available on the tram. The system sampled ambient air from a water-drain hole for the upper deck (3 m from the ground), which was connected to DustTrak through a 0.3 m conductive tubing [35,36].

The measurement process began in August 2013 and continues to date. Measurements were taken every day after depot servicing from 07:00 a.m. to 19:00 p.m. to cover all of the normal hours of the day in which the tram was in service. On-road $PM_{2.5}$ measurements taken in December 2014 and January 2015 (winter) and June and July 2015 (summer) were used in the analysis. The completeness of $PM_{2.5}$ data collection was approximately 90% in both winter and summer. The entire data set was separated into two seasonal data sets (summertime and wintertime) to facilitate analysis of seasonal variability.

The Causeway Bay (CB) AQMS (Fig. 1), located at the roadside of No. 1 Yee Wo Street, is situated at a busy commercial area with very heavy traffic and surrounded by many high-rise buildings [58]. Hong Kong's marine background and air plumes transported from outside Hong Kong were monitored at Tap Mun (TM) AQMS (Fig. 1), located on a remote island in northeastern Hong Kong [59].

The Tapered Element Oscillating Microbalance Model (TEOM) 1405-DF monitor (ThermoFisher Scientific, Waltham, MA, USA) is used for the continuous measurement of $PM_{2.5}$ mass concentration at CB and TM AQMSs. The TEOM 1405-DF is dichotomous and is equipped with a Filter Dynamic Measurement System (FDMS) to quantify the mass of evaporated semi-volatile species such as ammonium nitrate and various organic molecules. Temperature is maintained at a constant value, typically 50 °C, to minimize thermal expansion of the tapered element. The ambient air sample stream first passes into the $PM_{2.5}$ inlet of the TEOM monitor at its design flow rate of 16.7 L/min, and the particles with an aerodynamic meter smaller than 2.5 μm are allowed to pass through the inlet. At the exit of the $PM_{2.5}$ inlet, the flow is isokinetically split into a 3 L/min sample stream that is sent to the instrument's mass transducer [60]. The TEOM measures $PM_{2.5}$ mass concentration by continuously sampling particles onto a TEOM TX-40 filter placed at the end of an oscillating glass tube (the tapered element). By monitoring changes in the oscillating frequency of the tapered element, the deposited mass can be calculated [61]. The measurement range of the TEOM monitor is from 0 to 1 g/m^3 with an accuracy of ± 0.75% of reading.