Vertical monitoring of traffic-related air pollution (TRAP) in urban street canyons of Hong Kong

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Abstract

Rapid urbanization has significantly increased air pollution especially in urban regions with high traffic volumes. Existing methods for estimating traffic-related air pollution (TRAP) and TRAP-related health impacts are based on two-dimensional modelling. This paper describes a point-based methodology to monitor vertical pollutant concentrations in typical street canyons of Hong Kong. It explains the conceptual design, monitoring strategy and selection criteria for a limited number of receptor locations in street canyons to undertake field measurements for both outdoor exposure and indoor infiltration. It also expounds on the limitations and complications associated with field instrumentation and retention of participating home units. The empirical results were applied on the building infiltration efficiencies assessment. It is concluded that the cost-effective field methodology developed in this paper expects to strike a balance between exposure error and limited data locations. These findings will have important implications in future monitoring design of vertical TRAP exposure to support health studies.

Keywords: Air pollution; vertical dispersion; canyon monitoring; spatial analysis; infiltration efficiencies;

1. Introduction

The United Nations (2014) suggested recently that urban regions have over 50% of the world's population and this proportion will increase to 70% by 2050. This rapid increase in urban activities has escalated air pollution problems in built-up areas (Gurjar et al., 2010; Cheng et al., 2016). As vehicular traffic is a major source of urban air pollution, densely packed high rises and limited open space that restrict natural air ventilation may further exacerbate air quality problems. Air pollutants have serious adverse impacts on human health and the environment. Long term exposure to air pollution can cause respiratory illnesses or trigger abnormal cardiovascular/heart conditions that can be fatal. Children, elderly, and people with asthma or other lung and heart diseases may be more susceptible to the harmful effects of air pollution (Gurjar et al., 2010; Gan et al., 2011; Shields et al., 2013). The adverse health effects of fine particulate matters, such as $PM_{2.5}$ and aerosols, have been gaining attention in recent years (Pope et al., 1995; Huang et al., 2014; Bereitschaft, 2015). Meanwhile, Black Carbon (BC), a short-lived climate pollutant, has been suggested as a stronger indicator of harmful particulate matter arising from combustion sources such as traffic (Dons et al., 2012; Dons et al., 2013; Brasseur et al., 2015; Chen et al., 2016), smoking, residential heating and cooking (Cao et al., 2009). In 2012, the World Health Organization (WHO) advocated the use of BC as an additional indicator for evaluating local action aimed to reduce combustion PM (WHO, 2012).

Much effort has been expended on understanding the concentration fluctuation and dispersion patterns of TRAP in relation to environmental conditions and street canyon design. There is also growing interest to understand TRAP exposure and dispersion in the increasingly vertical urban landscapes (Liu et al., 2013; Moltchanov et al., 2015; Yi et al., 2015). Recognizing that vulnerable groups of individuals spend most of their time indoor, recent studies have focused on examining building infiltration efficiency (F_{inf}), defined as the proportion of the outdoor PM concentration that penetrates indoors and remains suspended. Results have showed that F_{inf} varies between communities, between homes, and over time within homes (Chen and Zhao, 2011). Multi-ethnic studies of atherosclerosis and air pollution (MESA Air) further concluded that the frequencies of air conditioning usage and window opening had direct effects on F_{inf} (Bild et al., 2002; Allen et al., 2012).

Urban streets are generally defined either as open streets or street canyons. An open street has built structures on one side and unobstructed on the other, whereas a street canyon is confined by buildings on both sides but open to the sky. A street canyon is also described by its aspect ratio expressed as H/W, where H is the building height and W is the width of the street. Street and building geometries aside, pollutant concentration and dispersion in street canyons are affected by wind speed and direction (Taseiko et al., 2009; MacNaughton et al., 2014; Yuan et al., 2014; Lateb et al., 2016). Previous published studies have shown that the average PM concentration has a 3-fold increase when the wind direction turned from parallel to perpendicular (Longley et al., 2004). The results of field experiments in three typical street canyons in Guangzhou City (Qin and Kot, 1993) revealed an increased concentration of TRAP on the leeward side of a canyon and decreasing concentration with increasing distance from the ground level. Another study involving a wind tunnel experiment (Hoydysh and Dabberdt, 1988) indicated pollutant concentrations for a perpendicular wind direction were generally a factor of two greater for the leeward than for the windward side. It was also evident that people living on the leeward side were exposed to higher pollution levels than those living on the windward side when the prevailing wind direction was perpendicular or near-perpendicular to the street canyon (Vardoulakis et al., 2002). Discounting effects of wind direction, it was noticed that increasing street lengths and wind circulation near intersections in short canyons (known as corner vortices) would weaken ventilation effects (Theurer, 1999).

A number of published studies have also investigated pollutant behavior within street canyons in Asian cities. Studies about the vertical variation of pollutants have recognized pollutant concentrations to vary with heights from the ground level to around 35m (Chan and Kwok, 2000; Vardoulakis et al., 2002;

Janhäll et al., 2003; Wu et al., 2014). A field experiment in a street canyon in Shanghai (Li et al., 2007) that measured only CO and $PM_{2.5}$, reported pollutant concentration to drop with larger particle size when height ranged between 1.5m to 20m but with lesser effects with increasing height from 20m to 38m. Another study observed a significant decrease in concentration levels of PM_{10}, $PM_{2.5}$ and Pm_1 with increasing height from 2m to 79m (Wu et al., 2002). Unfortunately, each of these studies were performed only in one or two street canyons within the same region and under a short monitoring period which may not represent the diurnal and annual conditions. Other factors such as traffic pattern (Väkevä et al., 1999) and presence of vegetation (Salmond et al., 2013) within a street canyon were found to exert noticeable impact on the vertical concentration of pollutants although they might not be strong enough to relieve local air pollution (Vos et al., 2013).

A few vertical dispersion studies of air pollutants conducted in street canyons included also the open street setting for comparison. These results indicated significant differences between the two street configurations (Janhäll et al., 2003) confounded by competing effects from vertical mixing, local dilution and other local influences (Chan and Kwok, 2000). Ioana and Popescu (2010) evaluated the state of art for air quality mobile measurements. The significance of selecting sampling locations and different altitudes would influence the sampling quality and whether the sample is representative of the area. However, each of these studies was primarily interested in pollutant behavior and did not attempt to apply their results to health studies or population exposure estimates. Wu et al. (2014) investigated the impact of residential height above street level on population exposure in Boston, USA downwind of a highway using a mobile monitoring platform and hoist. They found very little variation in $PM_{2.5}$ concentration with height due to limitations of the study design. The data collection procedures were performed discontinuously on Friday at day time for 3 months during the winter season at one location.

Findings of empirical and numerical studies to date have indicated dispersions and concentrations of air pollutants do vary significantly according to street canyon configuration, prevailing wind direction and speed, as well as local vehicular traffic. Hong Kong is a distinctive example of a densely populated city with many street canyons and large amounts of traffic. The city suffers severe air pollution and degrading visibility that have exceeded the WHO guidelines (Leung et al., 2004). It has been speculated that rapid local development and uncontrollable regional impacts from China are major contributing sources of air pollution in Hong Kong (Huang et al., 2009). This paper describes a conceptual framework and methodology for a large project of continuous monitoring of vertical TRAP exposure in Hong Kong. It offers a set of criteria for selecting typical street canyons and documents the methodologies for vertical TRAP monitoring that includes outdoor exposure and indoor infiltration. The proposed methodologies were extended from previous smaller scale or site specific vertical monitoring studies in high-rise Asian cities of Hong Kong, Macao and Shanghai (Chan et al. 2000; Wu et al. 2002; Li, et al. 2007). Limitations and challenges encountered during field implementation are discussed. The development of a field methodology to collect vertical TRAP exposure, which balances exposure error with limited data locations, will advance on-going study of TRAP. The methodology can be applied to collect empirical data on pollution in other cities, notably in Asia and the developing world, as a first step towards recognizing the problem and fostering greater regional cooperation. Several publications have resulted from this field methodology (Lee et al., 2017; Tang et al., 2018; Yang et al., 2018).

2. Method

2.1 Study Area

Hong Kong Special Administrative Region (Hong Kong) (22°15'N, 114°10'E), located along the southeast coast of mainland China and facing the South China Sea, has a combination of mountainous terrain and tall urban structures. Hong Kong is one of the most densely populated megacities in the world with a high proportion of its 7.5 million people residing in just 265 square kilometers of its urban land (or 24% of the total land area), which is due to the clustering of developments and mountainous terrain. High rents and a shortage of livable space in Hong Kong have resulted in its densely-packed urban design. Many districts of Hong Kong have mixed land uses with compact and tall buildings for residential, commercial and industrial purposes. Road networks of Hong Kong are among the most heavily used in the world. There were over 728,000 vehicles running on 2,101 km of roads by the end of 2015 (Highways Department, 2016). The well-established public transport system was also being used by 98% of the local population. The air quality monitoring network operated by the Environmental Protection Department (EPD) comprises 16 fixed air quality monitoring stations (AQMS) in strategic locations of Hong Kong (Figure 1). Thirteen of the AQMS are general stations installed on rooftops whereas three AQMS are positioned on roadside next to roads with heavy traffic (EPD, 2016). In view of the above, Hong Kong represents an ideal development site for TRAP modelling in high-density, high-rise Asian cities.

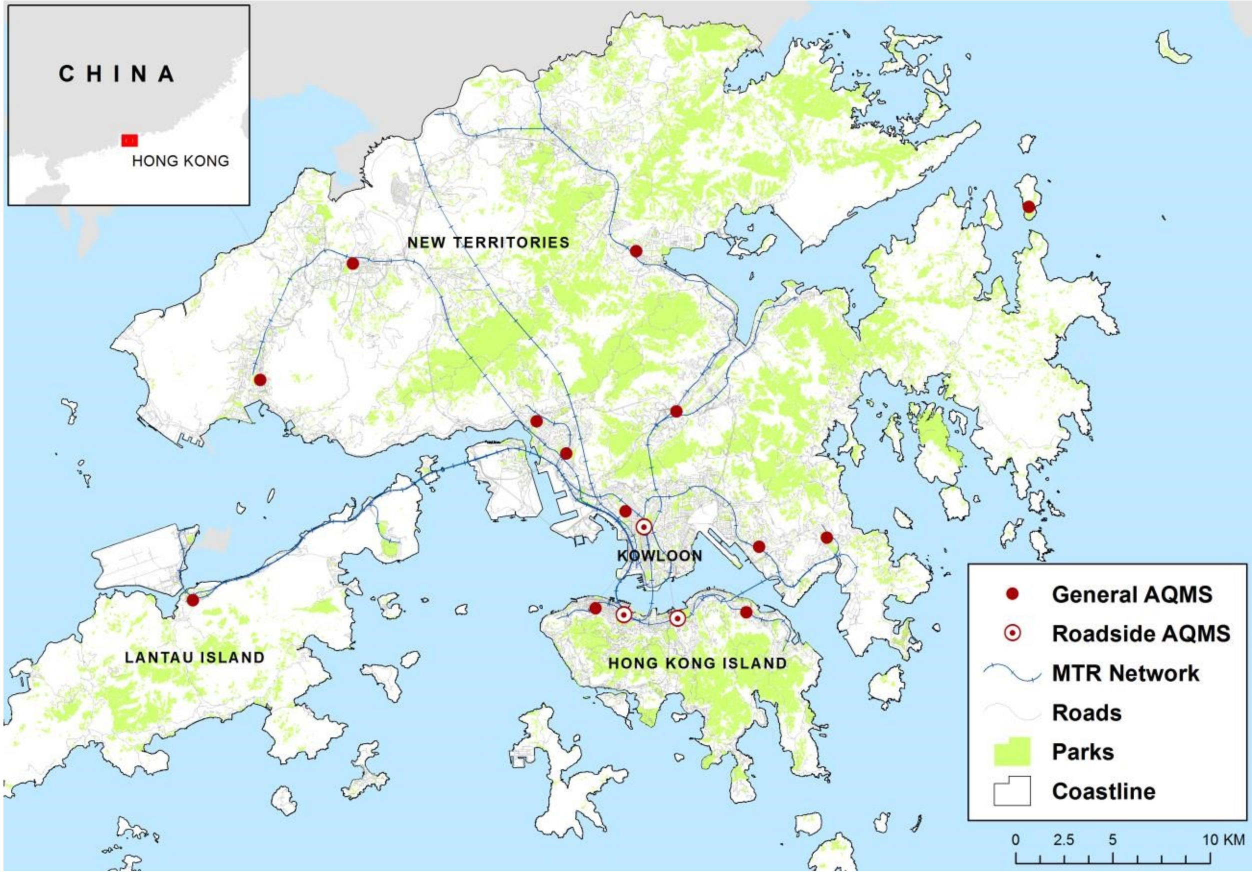


Figure 1: Locations of existing air quality monitoring stations managed by the Environmental Protection Department of Hong Kong, 2016.

2.2 Study Design

The study had pragmatic issues of budget constraints and the number of measuring instruments. These restrictions limited the number of survey sites. It was decided at the outset to conduct vertical air pollution monitoring at six strategic locations for two weeks in the summer (June-August) and repeated in the winter (December-February). Adopting past research practice, four of the six sites were typical street canyons and the remaining two were open streets. Continuous measurements were carried out at four different heights of a residential building and on both sides of a street canyon. The heights would range from 2-6m near the ground level (i.e., 1st or 2nd floor) up to a maximum of 50m (i.e., below 20th floors), as informed by published literature showing lesser effects with increasing heights (Li et al., 2007) as discussed in section 1. In addition, all measuring devices should ideally be positioned towards the center of a building slab or near the middle of a street canyon to avoid disturbance of corner vortices (Theurer, 1999). Priority would be given to measurement sites close to reference monitoring stations.

The selection of TRAP monitoring/sampling locations was accomplished in two steps. Step 1 involves identifying geographic districts known to suffer from poor air quality based on literature (Yim et al., 2009; Kao, 2015), AQMS record (EPD, 2016), or local knowledge. Normally, districts with a high population density and a compact urban design would qualify. Potential districts in Hong Kong would include Causeway Bay, MongKok, Tsuen Wan, Tsim Sha Tsui, and Kwun Tong. Step 2 involves classifying street canyons based on selected characteristics. Previous literatures have suggested the following as major factors commonly known to affect the variation of pollution concentration at different heights: street canyon configuration, wind direction, traffic volume, and building type.

Table 1 presents a list of factors and the corresponding selection criteria and data sources. The selection criteria are descriptive in nature and numerical values for the ordinal categories can be adjusted according to local situations and practical considerations. About two times the required number of monitoring/sampling locations should be identified for recruitment of participating home units to ensure survey requirements specified in the study design could be sufficiently met.

Table 1: Major factors and selection criteria for street canyons

Major Factors	Selection Criteria	Data Sources
Canyon Orientation	Perpendicular to the prevailing wind direction, preferably opposite prevailing wind direction for summer and winter	Road centerline (Lands Department); Prevailing wind direction (Hong Kong Observatory and Hong Kong University of Science & Technology)
Aspect Ratio	Medium to high	Building height (Lands Department); Road width (Lands Department)
Canyon Length	Medium to long	Roads (Lands Department)
Road Type	Major and minor	Roads (Lands Department)
Annual Average Daily Traffic (AADT)	Low to high	2014 Traffic data (Transport Department)

Population Density	High	2011 Census (Census & Statistics Department)
Building Type	Residential (preferable)	Buildings (Census & Statistics Department)

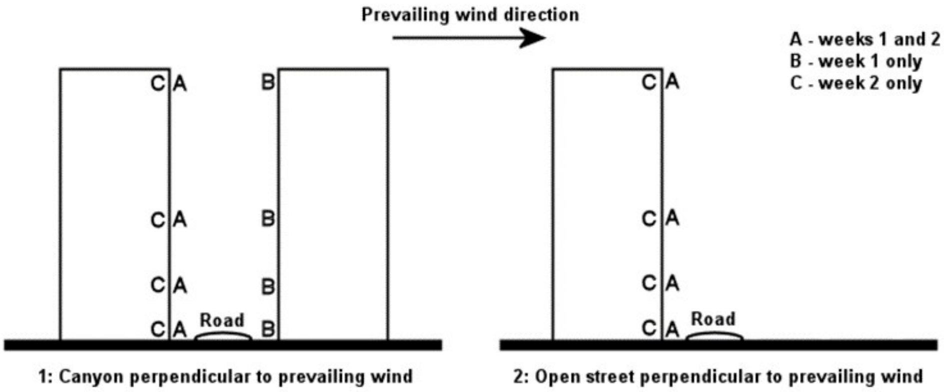
2.3 Instrumentation and Field Measurement

A complete set of monitoring unit comprises four active and passive sampling loggers to collect eight sets of air pollutant and meteorological data (i.e., $PM_{2.5}$, BC, CO, NO, NO_2, O_3, air temperature, and relative humidity). Table 2 lists the data to be collected and the corresponding measuring instruments.

Table 2: Pollutant and meteorological data with their measuring instruments

Data	Description	Sampling Instrument	Power Source	Unit	Frequency
$PM_{2.5}$	Particulate matter 2.5	TSI SidePak personal exposure monitor (AM510)	Electric	mg/m^3	1 min
BC	Black carbon	AethLabs microAeth (AE51)	Electric	mg/m^3	1 min
CO	Carbon monoxide	AQMesh air quality monitoring system	Battery	ppb	15 min
NO	Nitric oxide	AQMesh air quality monitoring system	Battery	ppb	15 min
NO_2	Nitrogen dioxide	AQMesh air quality monitoring system	Battery	ppb	15 min
O_3	Ozone	AQMesh air quality monitoring system	Battery	ppb	15 min
Temp	Air temperature	Maxim iButton (DS1923)	Battery	°C	15 min
RH	Relative humidity	Maxim iButton (DS1923)	Battery	%	15 min

The installation of the monitoring equipment involves a two-stage process. Firstly, it is necessary to determine the spatial distribution of monitoring units within a canyon site (Figure 2). The placement of measuring devices will change over the two-week period for a street canyon (Figure 2(i)) and an open street (Figure 2(ii)). Secondly, the monitoring devices must be physically installed onsite, i.e., inside a home unit. The equipment must be linked to a power supply and set near an open window facing the street, preferably away from the kitchen. The set of instruments shall measure the required data continuously at set time intervals, as detailed in Table 2, over the two-week period.



(i) (ii)

Figure 2: Spatial distribution of monitoring devices for (i) a street canyon and (ii) an open street. A = Leeward side (Outdoor), B= Windward side (Outdoor); C = Leeward side (Indoor)

Note: With perpendicular wind conditions, the up-wind side of the canyon is labelled as leeward and down-wind side windward.

2.4. Building infiltration efficiencies (F_{inf}) assessment

Infiltration efficiency (F_{inf}) for each residence where paired in/out sampling was undertaken was derived for $PM_{2.5}$ and BC following Allen et al. (2012). F_{inf} is a unitless quantity defined as the equilibrium concentration of outdoor pollution that penetrates indoors and remains suspended. The derivation model states that the average indoor concentration during time period t (C^{in}_{t}) is equal to the sum of a fraction of the average outdoor concentration during the same time period (C^{out}_{t}), a fraction of the average indoor concentration from the previous time period (C^{in}_{t-1}), and the contribution from indoor sources (S^{in}_{t}):

$$C^{in}_{t} = a_1(C^{out}_{t}) + a_2(C^{in}_{t-1}) + S^{in}_{t} \qquad (1)$$

Parameter a_1 describes the fate of ambient particles once they penetrate indoors, a_2 describes the decay of indoor particles. A censoring algorithm has been applied to identify periods impacted by indoor sources. Typically, only the “rising edge” (and not the decay) of the indoor peak was censored because at the time (t) when an indoor source was shut off and the indoor concentration begins to decay, the S^{in}_{t} term in eq. (2) becomes zero and the particles generated by the indoor source become part of the C^{in}_{t-1}

term (i.e. part of the indoor concentration during the previous time step). Retaining the decay of indoor peaks provides information from which to estimate the total particle loss rate, which is a key component of a building's infiltration efficiency.

The censoring method does not identify constant indoor sources. Unidentified (constant) indoor sources would be incorrectly considered to be outdoor particles that have infiltrated, thus causing an overestimation of F_{inf}. This is unlikely to cause a major bias in the estimates of infiltration efficiency because pollution resulting from indoor sources generally occurs as "spikes" relating to resident activities, displaying a rapid increase and subsequent decay (Abt et al. 2000). Thus, constant indoor sources may account for a very small percentage of the total indoor contribution in most residences.

Following censoring, F_{inf} was estimated using a linear regression (forcing the intercept to zero) of eq. (2) to solve for a_1 and a_2. F_{inf} was then calculated from:

$$F_{\mathrm{inf}} = \frac{a_1}{1-a_2} \qquad (2)$$

Basic diary cards were also kept by residents during the campaigns. Information on cooking, window opening and air conditioning use during the warm and cool seasons was used to investigate variations in F_{inf} and incidences of indoor "spikes" for censoring. Participants were not allowed to smoke inside.

3. Deployment Results and Discussions

3.1 Recruitment process and rates

As the study design required access to multiple residential homes, significant effort was required to recruit households to the study. Initial contact was by mail. At each potential sampling location, all flats and apartments below the 20th floor and with openable windows facing the target street side were sent recruitment letters. Recruitment of a total of 40 homes were required in the study design (approximately 1% recruitment rate), however, these homes had to be distributed on or close to specified floors. A total of 3,500 recruitment letters were mailed across eight potential sampling locations, with an overall response rate of 4%. Recruitment at lower floors was particularly challenging, resulting in the rejection of some potential sampling sites. Telephone interviews followed by flat visits were conducted with all respondents to assess compliance with recruitment criteria; (i) residents must be non-smokers, (ii) suitable space must be available facing the street for placement of monitoring equipment and (iii) at least one household member must be available during the daytime over the two-week period in both the summer and winter campaigns to allow researcher access into the flat to replace filters and check equipment. The participating home units were also asked to maintain a record of their daily activities inside the premises. Each participating home unit fully engaged in both campaigns was compensated an amount of HK$800 (~$100 US).

3.2 Implementation and Deployment

The study had a designated total of six monitoring sites comprising of four street canyons and two open streets (see Table 3 and Figure 3). These sites represented a range of physical canyon types of Hong Kong, biased towards locations with high AADT counts. All were in areas with high population density. A small number of residents withdrew from the study during or between seasonal campaigns. When this occurred, a replacement residence was recruited on a floor as close as possible. The ideal vertical distribution of monitoring units is shown in Figure 2. However, the screening process revealed that very few candidate sites had residences at ground floor. The typical layout of high rise buildings in Hong Kong is to have commercial, retail or restaurant concerns on the lower two or three floors. Consequently, the mean height above street level of the lowest monitoring point was 10.2 m across the six canyons.

Field deployment of limited instruments to fulfill monitoring requires careful coordination. A total of nine sets of monitoring units were first calibrated and corrected before deployment for indoor/outdoor (8 sets) and co-location (1 set) measurements. For each monitoring campaign lasting over two weeks, four sets of monitoring units were first installed on side A at one of four canyon sites (see Figure 2(i)). Another four sets of monitoring units were installed on side B for one week and then on side C in the following week at the same canyon site. Upon completion, the same deployment logistics were repeated in two-week succession at each of the three remaining canyon sites. Subsequently, eight sets of monitoring units were installed at an open site for continuous paired outdoor/indoor measurements (sides A and C in Figure 2(ii)). After one week, four sets of monitoring units on side C were shifted over to side A at the second open site for outdoor measurement of two weeks. When the four sets of monitoring units completed the two-week measurement on side A of the first open site, they were shifted over to side C of the second open site for the one-week of paired outdoor/indoor measurements. The design of the outdoor/indoor monitoring was added for the calculation of infiltration efficiencies for the Hong Kong housing stock. Throughout the measurement period of each monitoring campaign, one set of monitoring unit was used for concurrent co-location measurement at the respective official AQMS (MKAQMS and CWAQMS in Figure 3). These co-location measurements were compared against official or reference readings to control for variability measurement errors.

Table 3: Physical characteristics of and recruitment rates at monitoring sites.

	District	Road	Canyon Type	Aspect Ratio*	AADT	Description	Floors (A)	Floors (B)	Response Rate
Street Canyon	Jordan (JDC1)	Man Ying Street (Kowloon)	Symmetric	7.4	Low	Privately owned- Old residential slab	1, 3, 9, 15	3, 13	7% (24/360)
	Mong Kok (MKC1)	Hoi Wang Road (Kowloon)	Symmetric	3	Medium	Large estate with residential tower (1999)	2, 5, 12, 20	11, 14, 20	5% (17/321)
	Hung Hom (HHC1)	Hung Hom Road (Kowloon)	Symmetric	2.1	High	Privately owned - Large estate with residential tower (1991)	2, 3, 5, 11, 14	2, 6, 13	2% (10/585)
	North Point (NPC1)	Java Road (Hong Kong Island)	Asymmetric	3.6	High	Privately owned - Mixed age residential tower	3, 5, 9, 10, 16	2, 17	2% (12/532)
Open Street	Sai Wan (SWO1)	Des Voeux Road West (Hong Kong Island)	-	-	High	Privately owned - Residential slab	2, 4, 11, 15	N.A.	3% (7/260)
	Choi Hung (CHO1)	Lung Cheung Road (Kowloon)	-	-	High	Public Housing - Residential slab	1, 4, 6, 19	N.A.	2% (6/400)

* *A larger aspect ratio indicates more enclosed street canyon with tall buildings on both sides. Aspect ratio approaching a value of 2 is considered as a "deep" canyon (Vardoulakis et al., 2003).*

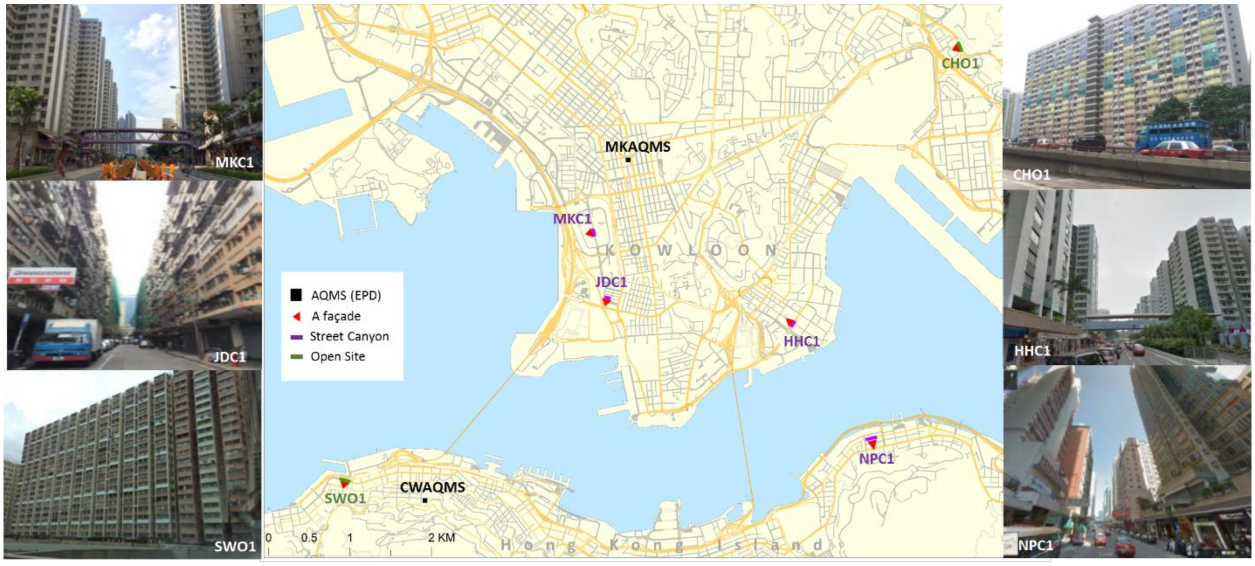


Figure 3: Physical locations and photographs of the monitoring sites (purple = street canyons; green = open streets; red triangles show side A). Two official air quality monitoring stations managed by the Environmental Protection Department (MKAQMS and CWAQMS) were used as co-locations to gauge data measurements in Kowloon and Hong Kong Island respectively throughout the monitoring campaigns.

It is not difficult to estimate that the air quality monitoring exercise for six sites with nine sets of measuring devices shall consume a total of eleven weeks (or a little short of three months) each for the summer and winter campaign, assuming no equipment failure and other hiccups. As local weather and urban activities can fluctuate within a three-month period, measurements taken at all six sites may not be entirely comparable or representative of the seasonal effects. Obviously, this issue can be resolved simply by purchasing more monitoring units but at the expense of high costs that may not be justifiable. Therefore, inter-unit precision was particularly important. Prior to and following each seasonal campaign, all monitoring units were operated for a period of at least 48 hours in the same location to test precision. Throughout the measurement period of each monitoring campaign, one set of monitoring equipment was co-located at the nearest AQMS reference monitoring site to allow reference scaling and subsequent temporal correction, however, no reference BC monitors were available for scaling of the *microAeth* units. Reference correction of *SidePak* and *AQMesh* monitors was calculated separately for each campaign to allow for variable atmospheric conditions. *SidePak* units were also flow checked and zero calibrated with HEPA filters prior to each canyon deployment.

3.3 Applied outcomes on Building infiltration efficiencies (F_{inf})

Table 4 shows the seasonal average infiltration rates at each monitoring sites (paired outdoor/indoor measurements). The results found that median F_{inf} values for both BC and $PM_{2.5}$ were especially high during the cool season (91%), indicating that residents were breathing only slightly lower levels of these pollutants indoors than ambient. F_{inf} values were comparatively lower during the warm season (81% and 88% for $PM_{2.5}$ and BC respectively) and we found a significant negative correlation between air conditioning use and F_{inf} of $PM_{2.5}$ and BC. The MESA-Air study reported a median F_{inf} for $PM_{2.5}$ across seven urban communities in North America of 62%, although the median for New York was 82% and therefore similar to that we found in Hong Kong (Allen et al., 2002).

Table 4: Seasonal residential infiltration efficiencies (F_{inf}) at monitoring sites

Site	**Summer**			**Winter**			**Number of flats**
	$PM_{2.5}$		**BC**	**$PM_{2.5}$**		**BC**	
JDC1	0.84	<	0.87	0.91	<	1.00*	5
MKC1	0.61	<	0.85	1.00*	≅	1.00*	4
HHC1	0.74	<	0.98	0.91	≅	0.91	5
NPC1	0.63	<	0.79	0.85	>	0.80	4
CHO1	0.78	<	0.97	0.88	>	0.53	5
SWO1	1.00*	>	0.86	0.92	<	0.97	4
Mean	0.75	<	0.87	0.90	>	0.85	
Median	**0.81**	<	**0.88**	**0.91**	≅	**0.91**	
SD	0.2		0.10	0.08		0.19	

* Infiltration rates > 1 are replaced by 1.00

Overall infiltration efficiencies in winter were higher than in summer due to increased use of windows to ventilate, rather than air conditioning systems used on hot summer days. In these closed window conditions, it is likely that BC infiltration factors would be higher than PM2.5 due to the smaller mean particle size. In winter, with open window conditions, size is unlikely to make a significant difference, thus the closer infiltration factors. This pattern is not followed in three out of 12 cases. The SWO1 summer PM2.5 factor and CHO1 BC factors were outliers. While it is not known what caused these unusual results, the most likely explanation is instrument drift in either the indoor or outdoor monitor not captured by the rigorous scaling process. In the case of NPC1 winter, the difference is only 5% and within the uncertainty of the methodology.

During the cool season, when $PM_{2.5}$ concentrations are typically far higher in Hong Kong, residents were more likely to open their windows, leading to a greater infiltration of outdoor air. Therefore, higher ambient concentrations and higher infiltration efficiencies acted together to increase population exposure.

For comparison, F_{inf} measurement has also been made in the mechanically ventilated office building. The F_{inf} result was 45% and 40% during the cool and warm seasons respectively. While we only measured F_{inf} in one such building, this is similar to those reported in other studies for occupied HVAC (heating, ventilation and air-conditioning systems) buildings (Chatoutsidou et al., 2015, Fisk et al., 2000). Only a very small proportion of high value residences have mechanical ventilation in Hong Kong, so few benefit from this protection. This finding has important socio-economic implications for developing sub-tropical cities; those who can afford higher specification homes are also more likely to have office jobs in similarly protected buildings. Conversely, these buildings have higher power requirements than naturally ventilated buildings and in many cases, will contribute further to regional sources of $PM_{2.5}$ through fossil fuel based electricity generation.

3.5 Method Challenges and Limitations

Various challenges in identifying suitable monitoring locations and securing sufficient participants have been addressed in sections 3.1. The key to selecting suitable sampling locations is to set clear selection criteria and pick locations that meet those criteria. The low response rate in subject recruitment was partially affected by the commitment of two sessions of two-week long participation and the requirement of frequent re-visits to the residence. Even though the two-week of continuous measurements could not be avoided, the number of re-visits could be reduced with better instruments that permit remote access to field equipment. It should be noted that many participants signed up for the monitoring campaign because they were genuinely concerned about TRAP in their living environment more than for the monetary compensation.

Some local adaptation and outfitting of instruments may be necessary to prevent participating home units from dropping out. For example, some instruments requiring the use of a pumping device to actively pass air through an air sample container can be quite noisy. Sound absorbing materials must be used to achieve noise reduction. Furthermore, inlets of the sampling instruments may need to be extended using a specialized sampler tube for outdoor measurement. Inlet tubes for indoor unit must be positioned away from kitchen and open windows. The monitoring unit for co-location measurement in an outdoor setting must be shielded to safeguard the instruments.

Difficulties in the logistic deployment of a limited number of measuring instruments and the necessity for local adaptation have also been discussed in section 2.3. There were a few unforeseen events including power outage, inclement weather, and religious functions involving incense burning that distorted the normal level of pollutant concentrations. Moreover, the monitoring instruments are not designed for operations in a sub-tropical location with relatively high humidity (i.e. 90-100%) like Hong Kong. Frequent failures of the measurement sensors interrupted the data collection and affected data quality and completeness. It is thus important to have co-location measurements at reference AQMS to enable validation and adjustment of variability in measurements. Unfortunately, scaling and correction methods applied in Hong Kong are not transferrable to other urban settings.

4. Implications for future monitoring of vertical TRAP exposure

In general, the development of a new generation of relatively low cost air pollution sensors has generated a great deal of interest both in the research community and public interest groups (USEPA 2016). This study has adopted relatively high cost (c. $4,000 per unit) active samplers for $PM_{2.5}$, BC and gaseous pollutants. While these samplers have advantages over passive samplers, several major shortcomings are further evaluated, which should be considered by others while designing spatial sampling campaigns in Asian cities and elsewhere across the world.

First, harsh sampling conditions – variously high temperatures, intense rainfall, wind storms, high humidity and high particulate levels – typical in tropical and sub-tropical climates take their toll on sensitive electronics. Every active sampling unit being deployed required maintenance at least once during the campaigns and several back up units are required while repairs are carried out. Second, active samplers are more visible, heavier and more expensive to replace than passive samplers. Safety and security is therefore a major concern, both to personnel and equipment. This spatial sampling campaign relied on collaboration with the HK EPD. Hong Kong is widely considered a very secure city and there are no losses being happened. In addition, no active samplers could be hung outside of buildings above floor level, necessitating the use of sampling tubing (for pumped PM samplers) and a manifold (for electrochemical samplers). Third, a high degree of inter-unit precision is necessary when deploying samplers in networks to detect spatial and vertical variations in TRAP. The development of refined methods of data scaling and ratification are required to achieve the necessary precision in each of the PM units. While all instruments suffer from some degree of bias, this has been well characterized in more established monitors and robust demonstrably consistent methods for correction can be developed. The strong influence of a range of factors (including temperature, humidity, cross-gas interference and signal noise), which combine to produce a complex pattern of interference in real-world conditions, make consistent correction methods challenging to develop. Unfortunately such correction methods may not be applicable or transferable to other cities for future studies.

4. Conclusion

This paper described a cost-effective field methodology for monitoring vertical TRAP that can be applied in other urban settings. An understanding of the vertical behavior of pollutants has become increasingly important as urbanization is unavoidable and tall buildings have become the norm in urban development. This study sets out a workable framework for monitoring TRAP in the vertical dimension. Applied outcome of seasonal average infiltration rates found in homes were close to one and residences provided little protection from ambient air pollution. This is particularly critical when considering regional pollutants, such as $PM_{2.5}$, where height above street level makes little difference. There are also socio-economic implications of this finding; those residents who can afford to live in mechanically ventilated buildings will have nearly half the exposure of those who cannot.

The proposed study is part of a larger project on the dynamic three-dimensional exposure model for Hong Kong. More work is underway to attest the feasibility of the proposed conceptual framework and field methodology by examining the vertical decay rate and dispersion profile of each monitoring site. The ambient results will be used to create the canyon decay 'typology' for TRAP, stratified by canyon aspect ratio, orientation and building type. The aforementioned outcome will be presented in a future publication. The results will also be applied to create a dynamic 3D land use regression model by incorporating population movements. It is hoped that the methodology described in this paper can be used to collect more empirical evidence on pollution in neighboring cities to raise awareness of the interconnected threat and to enhance regional cooperation.

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