https://doi.org/10.1016/j.jweia.2017.06.014

On-site evaluation of pedestrian-level air quality at a U-type street canyon in an ancient city

D.J. Cui[a,b,c], C.M. Mak[b,*], Z.T. Ai[b], K.C.S. Kwok[d], X.Z. Meng[e] and J.L.Niu[b]
[a] School of architecture and urban planning,
Shenzhen University, Shenzhen, China
[b] Department of Building Services Engineering,
The Hong Kong Polytechnic University, Hong Kong, China
[c] Shenzhen Key Laboratory of Built Environment Optimization, Shenzhen , China
[d] Western Sydney University, Penrith 2751, Australia
[e] Xi'an Jiao Tong University, Xi'an, China
*Corresponding Author: E-mail: cheuk-ming.mak@polyu.edu.hk (C.M. Mak)
Tel.: +852 2766 5856 Fax: +852 2765 7198

Abstract: Urban building disposition plays an important role in determining local microclimate including air quality. Ancient cities normally have some special building dispositions to reduce the penetration of cold wind in winter, which, however, may impact adversely on air pollutant dilution today. This paper investigated the pedestrian-level air quality at a common building disposition in Chinese ancient cities, namely a U-type street canyon. On-site measurements were conducted comparatively at a U-type street canyon and a nearby open space in Xi'an China during January 2015. Three primary air pollutants (PM_{10}, $PM_{2.5}$ and NO_2) as well as wind speed and direction, air temperature and relative humidity were measured continuously from 8:00 a.m. to 8:00 p.m. for a six-day period that covered both clean and hazy days. Pedestrian-level wind condition at the U-type street canyon is mostly independent of that above the canyon, where adverse dilution condition is clearly evident for pollutants. $PM_{2.5}/PM_{10}$ ratio at the street canyon reached up to 0.9, which is nearly twice that at the nearby observatory. Overall, air quality index (AQI) in the street canyon is, on average, higher by 20% than that at the open space. These findings suggest that this ancient design should be discouraged.

Keywords: urban microclimate, pedestrian air quality, building disposition, on-site measurement

1. Introduction

Air pollution is a major environmental issue in urban areas today. It is known that many cities worldwide, especially in developing countries, frequently suffer from heavy air pollution, where the hazy days account for a large portion of a year. The major pollutants in urban environment produced by vehicles and industries are particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO) and Ozone (O_3) (Kaur et al, 2007; Rakowska et al, 2014; WHO, 2005). Chemical reactions between different pollutants, with the aid of catalysts such as solar radiation, generate secondary pollutants (Meng and Seinfeld, 1996; Kikumoto and Ooka, 2012). Among all contributors, particulate matter and NO_2 are the most common and detrimental urban pollutants that are normally the first batch to exceed safe exposure limits for human (HKEPD, 2015), particularly when emissions increase or adverse meteorological condition occur. In general, exposure to air pollution is closely associated with increased morbidity and mortality for not only outdoor pedestrians but also indoor occupants (Cao et al., 2005; EEA, 2014; Ai and Mak, 2015; Ai et al., 2015; Ai and Mak, 2014; Ai et al., 2013). Particularly, fine particulate matter is associated with a broad spectrum of acute and chronic illness, such as lung cancer, chronic obstructive pulmonary disease (COPD) and cardiovascular diseases. Worldwide, fine particles are estimated to be responsible for about 16% of lung cancer deaths, 11% of COPD deaths, and more than 20% of heart disease and stroke (WHO, 2005). Therefore, research effort devoted to increased understanding and improved control of air pollution is of great significance.

Building disposition is an important parameter that influences the local wind availability and pollutants dilution (Ng, 2009; Cui et al., 2016; Chavez et al., 2012). It has been reported that winds are increasingly stagnant inside deep street canyons, while air temperature inside a street canyon is lower by 3-5 ℃ than the corresponding air temperature above the canyon (Georgakis and Santamouris, 2006; Allegrini et al, 2012) and is higher by nearly 2 ℃ than that in a suburban location (Andreou. et al, 2012). In addition, owing to increased traffic emissions and adverse dispersion conditions including low wind speeds (Weber et al, 2006; Nazridoust and Ahmadi, 2006), pollutant concentration is relatively high in street canyons (Yim et al., 2009; Ji and Zhao, 2015). Eventually, pedestrian-level concentration of air pollutants in street canyons are normally 1.2-2 times higher than the background concentrations recorded in weather stations or city parks (Ai and Mak, 2015a). Findings of previous studies generally reveal the microclimate characteristics in urban street canyons. From the perspectives of building disposition, some solutions have been explored to improve the urban air quality. For example, staggered and low-high combined building disposition are recommended designs for increasing wind availability in urban environment, which would potentially enhance the dilution of air pollution (Wong et al., 2011) and increase the pressure differences around buildings to drive indoor natural ventilation (Oke, 1987).

Previous studies regarding urban microclimate focus mostly on typical building dispositions in modern urban environment, whereas those in ancient cities are rarely investigated. There are many ancient cities in China and the rest of the world which are located in places surrounded by mountains and rivers so as to prevent the incursion of outsiders and the penetration of cold wind in winter (Hong et al., 2007). Xi'an is a typical Chinese ancient city, where the streets are mostly along an east-to-west direction and the buildings face south. There are buildings located at the west or east ends of building communities, which form many street canyons like U-type; see for example Figure 1. While this kind of building disposition worked well for reducing cold wind penetration and thus heat loss, it is expected that these U-type street canyons may have negative effects on pollutant dilution. Since safety and heating are no longer primary concerns today, feeding the wind to ventilate the city sufficiently is critically important to dilute air pollutants.

This study investigates the pedestrian-level air quality in a U-type street canyon in the ancient city, Xi'an China. On-site measurements of some urban pollutants including (PM_{10}, $PM_{2.5}$ and NO_2; WHO, 2005) as well as other meteorological parameters (including air temperature, relative humidity, wind speed and wind direction) were conducted. As a comparison, an open space near the U-type street canyon was selected, where similar measurements were conducted. In order to examine the influence of building disposition on the penetration of ambient wind down to the pedestrian level, further measurements were conducted above the building roof at both the street canyon and the open space. Apart from the cross comparison of pedestrian-level air quality between the U-type street canyon and the open space, comparison of pollutant concentration between these pedestrian-level results and those measured at nearby governmental observatories is made. Considering that the weather forecasts and reports are made based on the observatory data, such a comparison is useful to indicate their accuracy in representing the pedestrian-level conditions. Particularly, the $PM_{2.5}/PM_{10}$ ratio at each location is determined, while its relationship with air quality (including clean air days and hazy days) is analyzed. In addition, Pearson correlation analysis is conducted to examine the correlation between pollutant concentration and other meteorological parameters, while air quality index (AQI) values at each location are calculated based on both Chinese and U.S. methods, which are described in Section 2. The findings of this study are expected to increase our understanding on the influence of building disposition on pedestrian-level air quality and raise public awareness of the environmental conditions in ancient cities.

2. Materials and methods

2.1 Measurement site

The on-site measurements were conducted in Xi'an city, the capital of Shaanxi province, China, which is located at 34°26′N, 108°94'E and 424 m above sea level. As the largest city in northwestern China, Xi'an occupies an area of about 9983 km^2, where there was a population of 8.5 million and more than 1.6 million vehicles. Geographically, it is located in the middle of the Yellow River Valley, in the center of the Guanzhong Plain, and is surrounded by the Loess Plateau and Qingling Mountain. Xi'an is regarded to be the borderline between a semi-arid climate (BSk) and humid subtropical climate (Cwa), with the prevailing wind from the northeast direction (Zhang and Gu, 2013).

Two locations with different building dispositions were selected for measurements (see Figure 2). The first building disposition was a U-type deep street canyon (SC), with the entrance of the 'U' facing the east direction. The second building disposition is an open space (OS). The width of the street canyon was 15 m, while the average height of buildings was 30 m on the north side of the canyon and 35 m on the south side. At the west end of the street canyon, there was a building 65 m in height, which together with the buildings at the north and south sides formed a U shape. According to the definition by Oke (1987), the aspect ratio (defined as the ratio of building height to street width) of this street canyon was between 2 and 2.3, which means that the street canyon was deep so that atmospheric flows could skim over the building tops. The area of the open space selected was 100×90 m^2 in area (see Figure 2). There was a nearby street that was parallel to the prevailing wind direction of the city and a building 35 m in height at the southeast end of the open space. The pedestrian-level measurements at the street canyon were conducted at a point at the center of the street canyon along north-south direction and 20 m away from the west end building. The measurements at the open space were conducted at the center of the space, between the nearby street and the building. Roof-level measurements were conducted above the west end building at the street canyon, and above the neighboring building at the open space. Note that the roof-level measurements were conducted above the highest buildings near the two locations.

The pollution sources in Xi'an city were traffic emissions, heating combustions and industrial pollutions. However, the heating and industrial emissions were far away from the two test locations (around the city center), which can be regarded to be uniformly distributed in the city center. In addition, the traffic flows (see Figure 2) near the two locations were close to each other (with a relative difference < 5%) during the test, although the peak traffic flow at the street canyon occurred 1 hour earlier in the morning and 1 hour later in the afternoon than those of the open space. However, the air sampler collections of gas pollutant measurements were not made during these peak hours. Therefore, it was believed that the source conditions at the two locations were approximately the same. The measured pollutants levels were normalized by the reference data recorded in the corresponding observatories, which further reduces the influence of the difference in background sources. The dominated difference between the two locations was thus the building disposition. Owing to the poor dilution conditions, traffic emissions would accumulate inside the street canyon, while it would be easy to dilute at the open space.

2.2 Data collection

All measurements were conducted in January, 2015 in winter, when the temperature varied from -4 ℃ to 5 ℃ with a mean value equal to 0 ℃, and the relative humidity was 60% on average. On average, January is the coldest and driest month in Xi'an, and is also the month with the most serious air pollution (EMS, 2013). Figure 3 shows the average daily air quality index (AQI) (China-MEP, 2012) for Xi'an in January, 2015. AQI is a parameter used by observatory to indicate the air quality; the scales of AQI and their health implications are presented in Table 1. Two time periods in January were selected to conduct the on-site measurements (see Table 2), namely January 8-10 and 13-15, where the air quality was relatively good and bad, respectively. Typically, AQI on January 8 was less than 100, meaning a clear day with good air quality. In contrast, AQI exceeded 250 on January 15, meaning a hazy day with heavy air pollution. An example of a clear day and a hazy day in Xi'an is illustrated in Figure 4. During the two periods, pedestrian-level measurements of concentrations of PM_{10}, $PM_{2.5}$ and NO_2 as well as wind speed and direction, temperature and relative humidity were conducted at the two locations. At the same time, roof-level measurements at the two locations were also conducted so as to examine the relationship of these parameters between the pedestrian level and the roof level. The height of pedestrian-level measurements was 1.6 m above the ground to represent the breathing level, while it was 2 m above the building roof for roof-level measurements. All the rest measurements were conducted continuously from 8:00 a.m. to 8:00 p.m. on each measurement day, except for NO_2 (see later explanation). These measurement results were compared with those retrieved from the nearby observatories (see Figure 2).

2.3 Measurement instrumentation

The mini weather station and equipment used in the measurements are illustrated in Figure 5, all of which was compliant with the ISO Standard 7726 (1998). The range and accuracy of the equipment for meteorological parameters were summarized in Table 3. This section describes in detail the measurement methods for pollutants PM_{10}, $PM_{2.5}$ and NO_2.

The PM_{10} and $PM_{2.5}$ samples were collected using sequential air sampler (MiniVol™ TAS, USA), which drew air at 5 liters/minute first through a particle size separator (impactor) and second through a 47 mm quartz fiber filters. The particulate samples were caught on the filters, which were baked at 800 ℃ for 3 hours to remove adsorbed organic vapors and then equilibrated in a desiccator before sampling. The quartz fiber filters must be weighed twice before and after exposure using a microbalance (Sartorius, Germany; Sensitivity ±1 μg, range 0 - 5100 mg). Prior to measurements, the flow rate of the sampler was calibrated. Filters were equilibrated in a desiccator for 48 hours at a temperature of 25 ± 1 ℃, humidity of 30%-40% to subtract any effect caused by possible contamination. During the whole test process, the filters were handled only with tweezers and cleaned with dry Kim wipes (Kimberly-Clar Corporation, USA) to reduce the possibility of contamination. These weighing methods were also successfully adopted by previous researchers (Cheng et al, 2015).

The level of NO_2 was quantified according to AQ Certification Scheme (China-MEP, 2012) by collecting air samples in Tedlar bags with subsequent analysis by a chemiluminescence based NO_2 analyzer that complies with USEPA designated methods. Alternatively, the level can be quantified by passive sampling and analyzed by spectrophotometric method or by real-time portable analyzers. These methods could also be used for general testing purpose. Tedlar air sample bags are made from classic DuPont® film with a good stability for NO_2 measurement. During the measurements, 9 sample bags were used to collect NO_2 samples using air sampler pump (SKC, USA) and sampling time for each bag was 5 minutes. The 9 NO_2 samples were then analyzed by a chemiluminescence gas analyzer (Thermo Scientific™ Model 42i, USA) to determine its concentration. Eventually, the NO_2 concentration was the average value of the 9 samples.

2.4 Data processing

Apart from the general data processing methods, correlation analysis was used to analyze the correlation between pollutant concentration and meteorological parameters, and AQI was used to indicate the air quality.

2.4.1 Correlation analysis

Pearson correlation coefficient was employed to test the correlations between concentration of pollutants (PM_{10}, $PM_{2.5}$ and NO_2) and meteorological parameters at pedestrian level in the urban environment. Pearson correlation coefficient is the covariance of two variables divided by the product of their standard deviations. This definition involves a "product moment", which is the mean value of the product of the mean-adjusted random variables. Pearson correlation coefficient, when applied to a sample, is commonly represented by the letter r defined in Equation (1) and may be referred to the sample correlation coefficient or the sample Pearson correlation coefficient.

$$r = r_{xy} = \frac{\sum x_i y_i - n\bar{x}\bar{y}}{\sqrt{(\sum x_i^2 - n\bar{x}^2)}\sqrt{(\sum y_i^2 - n\bar{y}^2)}} \quad (1)$$

where, x_i is one dataset $\{x_1, \ldots, x_n\}$ containing n values and another dataset, y_i and $\{y_1, \ldots, y_n\}$ containing also n values.

2.4.2 Air Quality Index (AQI)

There are two types of outdoor air quality standards stipulated in the context of 'Clean Air Act' of US-EPA (2013): primary standards to protect public health and secondary standards to protect the public against adverse environmental effects. In this context, a dimensionless number, AQI, is defined to indicate directly the air quality and the associated health effects (see Table 1). Six pollutants are considered in the calculation of AQI, which are $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO and O_3. For each pollutant, the AQI is calculated based on the measured concentrations using Equation (2). Eventually, six AQI values are obtained and the daily AQI is the maximum of the six values.

$$I = \frac{I_{high} - I_{low}}{C_{high} - C_{low}} (C - C_{low}) + I_{low} \quad (2)$$

where I is the AQI, C the pollutant concentration, C_low the concentration breakpoint being less than C, C_high the concentration breakpoint being larger than C， I_low the index breakpoint corresponding to C_low, I_high the index breakpoint corresponding to C_high. The breakpoint of pollutants and index is selected from the air quality standards (US-EAP, 2013; China-MEP, 2012; HK-EPD, 2014).

Different countries and regions use the same AQI calculation method but have different AQI breakpoints for pollutants and index. Such different AQI breakpoints may lead to different AQI values. Based on pollutants data in Beijing from October 2010 to October 2011, Andrews (2011) calculated the AQI of PM_{10} using four different guidelines including China (China-MEP, 2012), Hong Kong (HK-EPD, 2014), European Union (WHO-EU, 2005) and United State (US-EPA, 2013). The results show that the percentage days with AQI below the safe limit obtained based on the four guidelines were remarkably different, where the number of acceptable days calculated using Chinese guideline was the highest among others. In this study, the four guidelines are used to determine the AQI in Xi'an based on the measured results at pedestrian level and the data retrieved from the nearby governmental observatories.

3. Results and discussion

3.1 Thermal environment

Previous studies (Niachou et al., 2008; Bourbia et al., 2004) indicated that urban air temperature and relative humidity at pedestrian level is highly associated with urban morphology, building surface albedo, canyon AR, sky view factor and solar incidence angle. This section compares the air temperature and relative humidity measured at the two locations, in order to compare the thermal environment at the U-type street canyon and the open space.

Figure 6 shows the 6-day averaged value of air temperature and relative humidity at the two locations. From the results, two observations can be made. First, for both locations during daytime, owing to the difference in solar radiation, the air temperature at pedestrian level is lower and RH is higher than that at roof levels. For the street canyon, the average air temperature inside a street canyon is lower by up to 4 ℃ than that above the nearby building roof. For the open space, pedestrian level temperature is lower by up to 3 ℃ than that above the nearby building roof. Considering there was no shading effect by surrounding buildings, the difference in temperature between pedestrian level and roof level at the open space is smaller than that at the street canyon. Second, for both locations, the variation in air temperature is much smaller at pedestrian levels than that at roof levels. This can be attributed to the roof levels having a much higher exposure to solar radiation during daytime and sky radiation during night-time.

However, in general, the difference in thermal environment between the two locations is not significant. It is reported that the average air temperature is determined predominantly by large-scale regional factors rather than street-scale factors (Pearlmutter et al., 1999; Barring et al, 1985; Shashua-Bar and Hoffman, 2003). In addition, in winter, Xi'an has almost no green vegetation, hence solar radiation and wind are the main driving factors to control air temperature and relative humidity.

3.2 Wind environment

3.2.1 Pedestrian level

It is well-known that when wind flowing over an open area approaches the boundaries of a built up urban area, it encounters a higher 'roughness' of the surface created by the buildings. The increased resistance reduces the wind flow at the level of the urban canopy (Oke, 1987). Figure 7 presents the wind roses for 16 wind directions at pedestrian levels of the two measurement locations during the six-day measurement period. Figure 8 further provides the boxplots of wind speed for eight main wind directions at pedestrian levels of the two locations during the six-day period, where the percentage occurrence of each wind direction is also plotted. Evidently, wind speeds at the open space are mostly larger than those at street canyon. It is observed that 80% of wind speeds in street canyon are below 1 m/s and all of them are less than 2 m/s, while over 60% of wind speeds are large than 1 m/s at the open space. On average, pedestrian-level wind speed at open space is 22% higher than that at street canyon, while the standard deviation of wind speed at open space is nearly 93% higher than that at street canyon.

For almost 70% of the time, wind blows form east, northeast and southeast at pedestrian level, due to the absence of building in east end of the U-type street canyon. In comparison, at open space, wind comes from various directions. These findings indicate that variation in both wind speed and wind direction at open space is much stronger than that at street canyon. Moreover, it is important to note that the wind direction at pedestrian level inside the street canyon is mostly along the east or close-to-east direction, which suggests that the wind direction inside a street canyon is not necessarily associated with that above the street canyon.

3.2.2 Roof level vs. pedestrian level

Figure 7 (c, d) presents the wind roses at roof levels at the two measurement locations. Together with Figure 7 (a, b), Figure 7 (c, d) shows clearly that, at the street canyon, there is no perceivable relationship between the wind direction at pedestrian level and that at roof level, while obvious relationship exists at the open space. Previous studies show that, for a specific street canyon, there is a threshold ambient wind speed, above which the coupling between the airflow inside and outside the canyon can be achieved (Oke, 1987, Ai and Mak, 2015a). Such a threshold wind speed is dependent on the canyon aspect ratio. Some studies reported that the threshold wind speed ranges from 1.5 to 2.0 m/s for a canyon with aspect ratio equal to 1-1.5 (Nakamura and Oke, 1988; Arnfield and Mills, 1994; DePaul and Sheih, 1986; Yamartino and Wiegand, 1986), while it would be 4-5 m/s in a canyon with aspect ratio equal to 2.5 (Santamouris et al., 1999). The aspect ratio of the street canyon investigated in this study is 2-2.3, implying that the threshold wind speed could be close to 4-5 m/s. If the ambient wind speed is less than the threshold value, the wind above canyon would have no connection with the air inside canyon.

Figure 9 presents the boxplots of wind speed at both pedestrian and roof levels at the two measurement locations. Almost all wind speeds at roof level of the street canyon during the measurements are less than 2 m/s, meaning that no simple relationship between canyon interior and above the canyon is established and thus the wind speed and direction inside the street canyon is generally independent of those above the canyon. For the open space, no canyon effect existed to influence the pedestrian-level wind speeds.

Figure 10 shows average wind speeds at both pedestrian and roof level at the street canyon under various ambient wind direction above the canyon, where the total percentage occurrence probabilities of east, northeast and southeast wind directions at the pedestrian level are also plotted. From this figure, several observations can be made. First, the pedestrian-level wind speed at the street canyon is relatively stable, which does not vary obviously with the variation of ambient wind speed above the canyon. Second, under all eight ambient wind directions, wind at pedestrian level flows from the east and close-to-east directions for a significant percent of time. The lowest percentage occurrence occurs when the ambient wind approaches perpendicularly to the canyon from the south direction. These two observations again indicate that for a relatively low ambient wind speed the pedestrian-level wind environment is independent of the wind environment above the canyon (Nakamura and Oke, 1988; Santamouris et al., 1999).

FIgure 11 presents the relationship of wind direction at pedestrian and roof levels at the open space. As aforementioned, there is a building located at the southeast direction of the open space. According to ASHRAE (2007), the leeward cavity length of this neighboring building is 44 m. The measurement point is located at 50 m away from the building, which is outside of its leeward cavity. This implies that the presence of the building has a negligible influence on the wind environment around the measurement point. The prevailing wind direction at roof level is southwest (see FIgure 11 (a)). When the ambient wind comes from north, northwest and west directions (FIgure 11 (b), (i) and (h)), the pedestrian-level measurement point is located at the windward side of the neighboring building, while the pedestrian-level wind direction is very close to the ambient wind direction. When the ambient wind comes from the east, southeast and south directions (FIgure 11 (d), (e) and (f)), the pedestrian-level measurement point is located at the leeward side of the neighboring building. Under these circumstances, the pedestrian-level wind direction is still very close to the ambient wind direction. The similar wind directions between the pedestrian and roof levels suggest that the measurement location is sufficiently far away from the neighboring building, supporting the calculation by ASHRAE (2007). When the ambient wind comes from the northeast and southeast (FIgure 11 (c) and (g)), which is parallel to the neighboring building, the wind direction at pedestrian level is more scattered than under other ambient wind directions.

3.3 Pollutants

3.3.1 General results

In street canyon pedestrian level, average value is PM_{10} 415 ug/m^3, NO_2 114 ug/m^3. While, in the open space, average value is PM_{10} 432 ug/m^3, NO_2 109 ug/m^3. The pollutant concentration inside the street canyon is only slightly larger or even smaller than that in the open space. It is because that the background pollutant concentration of the open space test point is larger than that of the U-type street canyon. For example, at the observatory near the street canyon, average values for PM_{10} and NO_2 are 253 μg/m^3 and 81 μg/m^3, respectively. However, they are 292 μg/m^3 and 91 μg/m^3, respectively, at the observatory near the open space. Thus, we used the measured pollutants concentration data to compare with their corresponding observatory and obtain a dimensionless ratio to decrease the background source effect. FIgure 12 presents the ratio of pedestrian-level pollutant concentration to that recorded at the nearby governmental observatory. These ratios are useful to indicate the relative magnitude of the pedestrian-level concentration in comparison with the background concentration. It can be seen that the ratios are larger than 1, except for the NO_2 at open space on some days, which generally suggest that the pedestrian-level pollutant concentrations are much higher than corresponding background concentrations. In addition, the pedestrian-level pollutant concentration ratios at street canyon are on average higher than those at open space by 10-20%. This is attributable to the uncoupled phenomenon between the canyon interior and above the canyon, making the dilution of pollutants difficult and slow in the street canyon (Hunter et al, 1992).

As shown in Sections 3.1 and 3.2, the microclimates inside the street canyon are characterized by relatively stable temperature and relative humidity as well as more stagnant wind, when compared to those at the open space. Among these meteorological parameters, wind speed plays the most significant role in influencing the pollutants distribution (Clark et al, 1996; Vardoulakis et al, 2003). In the present study, for over 70% of time, wind blows along the U-type canyon from the east direction, which leads to the accumulation of pollutants inside the canyon and increases the pedestrian-level pollutant concentrations. Such canyon effects on pollutants accumulation were also reported in previous studies (DePaul, 1986; Qin and Kot, 1993; Jones et al, 2000).

3.3.2 $PM_{2.5}/PM_{10}$ ratio

The ratio of the concentration of $PM_{2.5}$ to that of PM_{10} is an important parameter to assess air quality, as fine particles $PM_{2.5}$ can penetrate deeply into human body and cause harmful effects. In addition, fine particles have a higher possibility to filtrate into the indoor environment when compared to larger particles (Jones et al., 2000). As an example, the average $PM_{2.5}/PM_{10}$ ratio in China is 0.56, ranging between 0.37 in the southwest and 0.62 in the northeast part of China (China-MEP, 2012). It has been known that the local pollutant sources, such as traffic emissions, become less important during dust storm (Cao et al., 2005), because the regional migration of pollutants dominates the pollutant concentration in the atmosphere. Similarly, the present measurements also show that the concentration of particulate pollutants at pedestrian level is closer to that at nearby observatory in hazy days when compared to that in clean days.

Figure 13 presents the $PM_{2.5}/PM_{10}$ ratio at the pedestrian levels of the two measurement locations and at their nearby observatories, where this ratio obtained in some previous cities is also plotted for reference. It can be seen that the $PM_{2.5}/PM_{10}$ ratio at pedestrian level can reach up to 0.8-0.9, which is usually higher than that at observatory, implying that the percentage composition of fine particles near pedestrian roads is much higher than that at relatively clean background locations. In addition, the pedestrian-level $PM_{2.5}/PM_{10}$ ratio at the street canyon is nearly 20% higher than that at the open space, which further suggests that a higher concentration of fine particles exists at an area with more serious pollution. Moreover, secondary fine particles would be formed at an area with more serious pollution, as chemical reactions between gaseous pollutants would be more likely to occur in this area. This observation is supported by some previous studies (Brook et al., 1997; Yang et al., 1998). Brook et al. (1997), which reported that the $PM_{2.5}/PM_{10}$ ratio is associated with human activities; the more human activities mean a higher $PM_{2.5}/PM_{10}$ ratio. In addition, Yang et al. (1998) found that the $PM_{2.5}/PM_{10}$ ratio in areas near heavy traffic roads is much higher than that at other areas.

3.3.3 Influence of meteorological parameters

In this study, Pearson correlation analysis method (see Section 2.4.1) is employed to investigate the correlations between pollutants (NO_2 and particles) and wind speed, standard deviation of wind speed, temperature and relative humidity. Based on the present measured data, there is no significant correlation between pollutant concentration and environmental parameters, except that negative correlation between NO_2 concentration and wind speed is found (see Figure 14), where the P value is 0.014. Note that P is a parameter used in correlation analysis to indicate the significance of a correlation. And Pearson coefficient r = -0.629. This indicates that wind speed is the most significant meteorological parameter influencing the traffic related NO_2 concentration in urban environment (Carslaw et al., 2005).

3.3.4 AQI

Figure 15 presents the AQI values of PM_{10} and $PM_{2.5}$ at pedestrian level at the two measurement locations as well as at the nearby observatories, which are calculated based on the method described in Section 2.4.2. Note that Figure 15 (a) presents only the AQI values of PM_{10} calculated by Chinese method, as similar values are obtained by using other methods. Figure 15 (b) presents the AQI values of $PM_{2.5}$ calculated by both Chinese method and U.S. method, as other methods produce similar values with those obtained by using the U.S. method. In general, Figure 15 (b) shows that the Chinese method predicts lower AQI values for $PM_{2.5}$ than those predicted by the U.S. method, particularly when the concentration of $PM_{2.5}$ is relatively small (based on data obtained from the observatories). This is attributable to the different breakpoints used in the two calculation methods.

It can be seen that the AQI values of both PM_{10} and $PM_{2.5}$ at pedestrian level are higher than those at observatories, while the difference between the two is higher at the street canyon than that at the open space. On average, the AQI values for PM_{10} and $PM_{2.5}$ at the street canyon are 1.9 and 2.2 times of those at their nearby observatories, respectively, while the corresponding values are 1.6 and 1.8 respectively for the open space. Taking January 8 and 9 as examples, the reported air quality was good, with AQI values for both PM_{10} and $PM_{2.5}$ ranging between 50 and 100. However, based on the measurements at pedestrian levels, the AQI values for both pollutants were higher than 100. Particularly, AQI for $PM_{2.5}$ on January 8 and 9 indicated that the air was heavily polluted (ranging between 200 and 300) and severely polluted (over 300), respectively. This difference in AQI between the observatories and the measurement locations in pedestrian level implies that the weather report based on observatory data tends to underestimate the air pollution condition at pedestrian level.

Comparison of the AQI values between the two measurement locations indicates that the AQI values for PM_{10} and $PM_{2.5}$ are generally higher at the street canyon when compared to those at open space. The reasons for this result should be the same as those explained in Section 3.3.2.

4. Conclusions

On-site measurements were conducted to investigate the urban air quality at a U-type street canyon and an open space in an ancient city Xi'an, China during 3 clean air days and 3 hazy days. The results of the short-term measurements may lead to the following conclusions.

For over 70% of time, the wind direction at pedestrian level in the U-type street canyon is from the opening of the ‘U’, namely from east or close-to-east, which is independent of the ambient wind direction above the canyon. In contrast, the wind direction at the open space varies constantly, which is mostly close to the ambient wind direction.

Owing to the adverse dilution condition, concentration of PM_{10}, $PM_{2.5}$ and NO_2 at the U-type street canyon are higher than that at the open space. The $PM_{2.5}/PM_{10}$ ratio at pedestrian level of the two measurement locations reaches 0.8-0.9, which is nearly twice that at the observatories. In general, the $PM_{2.5}/PM_{10}$ ratio is higher in areas with heavier air pollution, suggesting that the regional migration of pollutants dominates the pollutant concentration in the atmosphere in areas with heavier air pollution.

AQI values for pollutants at the street canyon are higher by nearly 20% than those at the open space. On average, PM_{10} and $PM_{2.5}$ at the street canyon are 1.9 and 2.2 times of those at their nearby observatories, respectively, while the corresponding values are 1.6 and 1.8 for the open space. Among others, wind speed is the most significant meteorological parameter influencing the traffic related NO_2 concentration in urban environment, it was found that a highly negative correlation (Pearson coefficient r = - 0.629) exists between NO_2 concentration and wind speed.

Overall, the U-type street canyon is characterized by low wind speed and stable wind direction (from opening of ‘U’ to the inside), where the dilution of pollutants is difficult. Urban designers should discourage adopting such ancient designs that place building(s) along main ventilation route; instead, designs feeding wind into street canyon by considering the prevailing wind directions should be encouraged.

Acknowledgements

The work described in this paper was supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. C5002-14G). The authors wish to thank Mr. Ye Zongqiang, Mrs. Wang Ni and Mr. Liu Fengrong in helping manning the weather stations and collecting the data and Prof. Cheng Yan in preparing and calibrating the instruments used.

Reference:

Ai Z.T., Mak C.M. 2015. From street canyon microclimate to indoor environmental quality in naturally ventilated urban buildings: Issues and possibilities for improvement. Build Environ. 94(2), 489-503

Ai Z.T., Mak C.M. 2014. A study of interunit dispersion around multistory buildings with single-sided ventilation under different wind directions. Atmos Environ. 88: 1-13.
Ai Z.T., Mak C.M., Niu J.L. 2013. Numerical investigation of wind-induced airflow and interunit dispersion characteristics in multistory residential buildings. Indoor Air. 23: 417-29.
Ai Z.T., Mak C.M., Cui D.J. 2015. On-site measurements of ventilation performance and indoor air quality in naturally ventilated high-rise residential buildings in Hong Kong. Indoor Built Environ. 24(2): 214-24.
Allegrini J., Dorer V., Carmeliet J. 2012. Analysis of convective heat transfer at building facades in street canyons and its influence on the predictions of space cooling demand in buildings. J Wind Eng Ind Aerodyn. 104-106: 464-473.
Andreou E., Axarli K. 2012. Investigation of urban canyon microclimate in traditional and contemporary environment: Experimental investigation and parametric analysis. Renew Energ. 43: 354-63.
Arnfield A.J., Mills G. 1994. An analysis of the circulation characteristics and energy budget of a dry, asymmetric, east-west urban canyon. I. Circulation characteristics. Int J Climatol. 14, 119-134.
ASHRAE. 2007. Building Air Intake and Exhaust Design. Chapter 44, ASHRAE Applications Handbook, Atlanta: American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., Atlanta, USA.
Barring L, Mattson JO, Lindovist S. 1985. Canyon geometry, street temperatures and urban heat island in Malmo Sweden. Int J Climatol. 5, 433-44.
Bourbia F, Awbi H. B. 2004. Building cluster and shading in urban canyon for hot dry climate Part 1: Air and surface temperature measurements. Renew Energ. 29, 249-262.
Brook, J. R., Dann, T. F. and Burnett, R. T. 1997. The relationship among TSP, PM_{10}, $PM_{2.5}$, and inorganic constituents of atmospheric particulate matter at multiple Canadian locations. J Air Waste Manag Assoc. 47(1), 2-19.
Cao J.J., Chow J.C., Lee, S.C., Li, Y., Chen S. W. et al. 2005. Characterization and source apportionment of atmospheric organic and elemental carbon during fall and winter of 2003 in Xi’an, China. Atmos. Chem. Phys. Discuss., European Geosciences Union. 5(3), 3561-3593.
Carslaw, D.C. 2005. Evidence of an increasing NO_2/NO_x emissions ratio from road traffic emissions. Atmos Environ. 39(26), 4793–4802.
Chavez M., Hajra B., Stathopoulos T., Bahloul A. 2012. Assessment of near-field pollutant dispersion: Effect of upstream buildings. J Wind Eng Ind Aerodyn. 104-106, 509-515.
Chen M.L., Mao I.F., Lin I. K. 1999. The $PM_{2.5}$ and PM_{10} particles in urban areas of Taiwan. Sci. Total Environ. 226, 227-235.
Cheng Y., Lee S.C., Gu Z.L., Ho K.F., Zhang Y.W., Huang Y., Chow J. C., Watson J.G., Cao J.J., Zhang R.J. 2015. $PM_{2.5}$ and $PM_{10-2.5}$ chemical composition and source apportionment near a Hong Kong roadway. Particuology. 18, 96–104.

China-MEP (Ministry of Environmental Protection). 2012. Technical Regulation on Ambient Air Quality Index, HJ 633-2012. The Ministry of Environmental Protection of People's Republic of China.

Clark A.G., Ko Y.H. 1996. The relative significance of vehicular emissions and other emissions of volatile organic compounds in the urban area of Leeds, UK. Sci. Total Environ. 189/190, 401-407.

Cui D.J., Mak C.M., Kwok K.C.S., Ai Z.T. 2016. CFD simulation of the effect of an upstream building on the interunit dispersion in a multistory building in two wind directions. J Wind Eng Ind Aerodyn. 150: 31-41.

DePaul F.T., Sheih C.M. 1986. Measurements of wind velocities in a street canyon. Atmos Environ. 20(3), 455-459.

EEA (European Environment Agency). 2014. Air quality in Europe – 2014 Report, European Environment Agency, Copenhagen, Denmark.

EEA (European Environment Agency). 2009. $PM_{2.5}/PM_{10}$ emissions ratios, total and for road transport, available at http://www.eea.europa.eu/data-and-maps/figures/pm2-5-pm10-emissions-ratios-total-and-for-road-transport. Accessed on November 8, 2015

EMS (Environmental Monitoring Station). 2013. Daily air quality data. Environmental Monitoring Station of Xi'an, available at: http://www.xianemc.gov.cn, accessed on 18 February 1 2015.

Georgakis C., Santamouris M. 2006. Experimental investigation of air flow and temperature distribution in deep urban canyons for natural ventilation purposes. Energ Buildings. 38, 367-76.

Ho K. F., Lee S.C., Chan C. K., Yu J. C., Chow, J. C., Yao X. H. 2003. Characterization of chemical species in $PM_{2.5}$ and PM_{10} aerosols in Hong Kong. Atmos Environ. 37(1), 31-39.

HK-EPD, 2015. An overview on air quality and air pollution control in Hong Kong, Environmental Protection Department, Hong Kong, available at:http://www.epd.gov.hk/epd/english/environmentinhk/air/air_maincontent.html, accessed on November 8, 2015.

Hunter L.J., Johnson G.T., Watson I.D. 1992. An investigation of three-dimensional characteristics of flow regimes within the urban canyon. Atmos Environ. 26B(4): 425-432.

ISO Standard 7726. 1998. Ergonomics of the thermal environment -Instruments for measuring physical quantities. Geneva: International Standard Organization.

Ji W.J., Zhao B. 2015. Contribution of outdoor-originating particles, indoor-emitted particles and indoor secondary organic aerosol (SOA) to residential indoor PM2.5 concentration: A model-based estimation. Build Environ. 90, 196-205.

Jones S.G., Fisher B.E.A., Gonzalez-Flesca N., Sokhi R. 2000. The use of measurement programmers and models to assess concentrations next to major roads in urban areas. Environ Monit Assess. 64, 531-547.

Kaur S., Nieuwenhuijsen M., Colvile R. 2007. Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. Atmos Environ. 41, 4781-4810.

Kikumoto H., Ooka R. 2012. A study on air pollutant dispersion with bimolecular reactions in urban street canyons using large-eddy simulations. J Wind Eng Ind Aerodyn. 104-106, 516-522.

Meng Z., and Seinfeld J.H. 1996. Time Scales to Achieve Atmospheric Gas-Aerosol Equilibrium for Volatile Species. Atmos Environ. 30, 2889-2900.

Nazridoust K., and Ahmadi G. 2006. Airflow and pollutant transport in street canyons. J Wind Eng Ind Aerodyn. 94: 491-522.

Nakamura Y., Oke T.R., 1988. Wind temperature and stability conditions in an east-west oriented urban canyon. Atmos Environ. 22(12), 2691-2700.

Ng E. 2009. Policies and Technical Guidelines for Urban Planning of High-density cities – Air Ventilation Assessment (AVA) of Hong Kong, Build Environ. 44(7), 1478-1488.

Niachou K, Livada I, Santamouris M. 2008. Experimental study of temperature and airflow distribution inside an urban street canyon during hot summer weather conditions-Part 1: Air and surface temperatures. Build Environ. 43, 1383-1392.

Oke T.R. 1987. Boundary layer climates. 2nd ed. New York: Routledge.

Pearlmutter D., Bitan A., Berliner P. 1999. Microclimatic analysis of 'compact' urban canyons in an arid zone. Atmos Environ. 33, 4143-4150.

Qin Y., Kot S.C. 1993. Dispersion of vehicular emission in street canyons, Guangzhou city, South China (P.R.C.). Atmos Environ. 27B, 283-291.

Rakowska A., Wong K.C., Townsend T., Chan K.L., Westerdahl D., Ng S., et al. 2014. Impact of traffic volume and composition on the air quality and pedestrian exposure in urban street canyon. Atmos Environ. 98, 260-270.

Santamouris, M., Papanikolaou, N., Koronakis, I., Livada, I. Asimakopoulos, D. 1999. Thermal and air flow characteristics in a deep pedestrian canyon under hot weather conditions. Atmospheric Environment, 33, 4503-4521.

Shashua-Bar L, Hoffman M.E. 2003. Geometry and orientation aspects in passive cooling of canyon streets with trees. Energ Buildings. 35, 61-68.

Hong S. K., Song I.J., Wu J.G. 2007. Fengshui theory in urban landscape planning. Urban Ecosyst. 10(3), 221–237.

US-EPA. 2013. Revised Air Quality Standards for Particle Pollution and Updates to The Air Quality Index (AQI) North Carolina, US EPA Office of Air Quality Planning and Standards, Environmental Protection Agency.

Vardoulakis S., Fisher B.E.A., Pericleous K., Gonzalez-Flesca N. 2003. Modelling air quality in street canyons: a review. Atmos. Environ. 37, 155-182.

Weber S, Kuttler W, Weber K. 2006. Flow characteristics and particle mass and number concentration variability within a busy urban street canyon. Atmos Environ. 40, 7565-78.

WHO, 2005. Air Quality Guidelines. World Health Organization.

WHO-EU, 2005. Air Quality Guidelines for Europe, second ed. WHO Regional Publications.

Wong M. S., Nichol, J.E., Ng, E. 2011. A Study of the “wall effect” caused by proliferation of high-rise buildings in Hong Kong, using GIS techniques. Landscape Urban Plan. 102, 245-253.

Yamartino R.J., Wiegand G. 1986. Development and evaluation of simple models for the flow, turbulence and pollution concentration fields within an urban street canyon. Atmos Environ. 20, 2137-2156.

Yang F., Kang Y., Gao Y., Zhong K. 2015. Numerical simulations of the effect of outdoor pollutants on indoor air quality of buildings next to a street canyon. Build Environ. 87, 10-22.

Yim S.H.L., Fung J.C.H., Lau A.K.H., Kot S.C. 2009. Air ventilation impacts of the “wall effect” resulting from the alignment of high-rise buildings. Atmos Environ. 43, 4982-4994.

Zhang Y.W., Gu Z.L. 2013. Air quality by urban design. Nature Geoscience. 6, 506

Table and Figure Captions

Table 1 (a) Breakpoints for the AQI (HJ 663-2012, 2012), (b) AQI and health implications (HJ 663-2012, 2012)

Table 2 Time schedule of on-site measurements.

Table 3 Equipment used in on-site measurements (except for equipment for pollutants)

Figure 1 U-type street canyons are common in ancient city Xi'an, China.

Figure 2 On-site measurement locations in Xi'an, China; (a) map of test locations and their corresponding observatories; (b) Test location of Street Canyon; (c) Test location of Open Space.

Figure 3 AQI of Xi'an in January, 2015.

Figure 4 Photos of a clean day and a hazy day at a same location in Xi'an, China. (a) Clean day (Taken on Jan 8th); (b) Hazy day (Taken on Jan 15th)

Figure 5 Mini weather stations and equipment used in on-site measurements.

Figure 6 Air temperature and Relative humidity during the measurement period, where SC-R represents roof level at street canyon, SC-P pedestrian level at street canyon, OS-R roof level at open space, OS-P pedestrian level on open space. (a) Air temperature; (b) Relative humidity

Figure 7 Wind roses at the street canyon and open space during the measurement period.

Figure 8 Boxplots of pedestrian-level wind speed at the street canyon and open space during the measurement period, where the percentage occurrence possibility of each wind direction is also plotted and scaled into the right axis: (a) street canyon and (b) open space;

Figure 9 Boxplots of wind speed at both pedestrian and roof levels at the two measurement locations; the reading method of this boxplots is same as that explained in the caption of Figure 6.

Figure 10 Wind speeds and percentage occurrence possibilities of three wind directions (east, northeast and southeast) at the street canyon. (U SC-P and U SC-R represent wind speed on pedestrian and roof level of street canyon respectively)

FIgure 11 Wind direction frequency at roof (a) and pedestrian (b-f) levels at the open space, where the ratio of wind speed at pedestrian level to that at roof level is also presented.

FIgure 12 Ratios of pollutant concentration at pedestrian level of measurement locations to that at nearby observatory stations.

Figure 13 $PM_{2.5}/PM_{10}$ ratios at measurement locations and nearby observatory stations or other background locations (Ho et al., 2003; Yang et al., 1998; EEA, 2009), where Xi'an (SC) and Xi'an (OS) represent the present measurements.

Figure 14 Hourly averaged wind speeds and NO_2 concentration ratios, where NO_2 ratio means the ratio of pedestrian-level concentration of NO_2 to roof-level concentration of NO_2.

Figure 15 AQI values for PM_{10} and $PM_{2.5}$ at pedestrian level of measurement locations and at the nearby observatory stations during the measurement period; SC-P represents pedestrian level at street canyon, SC-B background level at observatory.

Table 1(a) Breakpoints for the AQI (China-MEP, 2012; US-EPA, 2013)

IAQI	China-MEP(HJ633, 2012)		US-EPA (EPA-545/B-13-001)	
	PM_{10} (μg/m3)	$PM_{2.5}$ (μg/m3)	PM_{10} (μg/m3)	$PM_{2.5}$ (μg/m3)
0	0	0	0	0
50	50	35	55	12
100	150	75	155	35.5
150	250	115	255	55.5
200	350	150	355	150.5
300	420	250	425	250.5
400	500	350	505	350.5
500	600	500	600	500

Table 1(b) AQI and health implications (China-MEP, 2012; US-EPA, 2013)

AQI	Air Pollution Level	Health Implications
0–50	Excellent	No health implications.
51–100	Good	Few hypersensitive individuals should reduce outdoor exercise.
101–150	Lightly Polluted	Slight irritations may occur, individuals with breathing or heart problems should reduce outdoor exercise.
151–200	Moderately Polluted	Slight irritations may occur, individuals with breathing or heart problems should reduce outdoor exercise.
201–300	Heavily Polluted	Healthy people will be noticeably affected. People with breathing or heart problems will experience reduced endurance in activities. These individuals and elders should remain indoors and restrict activities.
300+	Severely Polluted	Healthy people will experience reduced endurance in activities. There may be strong irritations and symptoms and may trigger other illnesses. Elders and the sick should remain indoors and avoid exercise. Healthy individuals should avoid outdoor activities.

Table 2 Time schedule of on-site measurements, where RH relative humidity and T temperature.

	Street canyon		Open Space	
	Ground	Roof	Ground	Roof
Jan 8-10	Pollutants ($PM_{2.5}$/ PM_{10}/ NO_2) Wind (speed/direction) Thermal (RH/T)	*	Pollutants ($PM_{2.5}$/ PM_{10}/ NO_2) Wind (speed/direction) Thermal (RH/T)	*
Jan 13-15	Pollutants (PM_{10}/ NO_2) Wind (speed/direction) Thermal (RH/T)	Pollutants (PM_{10}) Wind (speed/direction) Thermal (RH/T)	Pollutants (PM_{10}/NO_2) Wind (speed/direction) Thermal (RH/T)	Pollutants (PM_{10}) Wind (speed/direction) Thermal (RH/T)

Table 3 Equipment used in on-site measurements (except for equipment for pollutants)

Environment parameter	Sensor	Range	Accuracy
Wind speed	Ultrasonic weather station	0-70m/s	± 0.25m/s
Wind direction	Ultrasonic weather station	0-359°	± 3°
Air temperature	Thermo-recorder	0-+55℃	± 0.5℃
Relative humidity	Thermo-recorder	10-95%	± 5%

Figure 1 U-type street canyons are common in ancient city Xi'an, China.

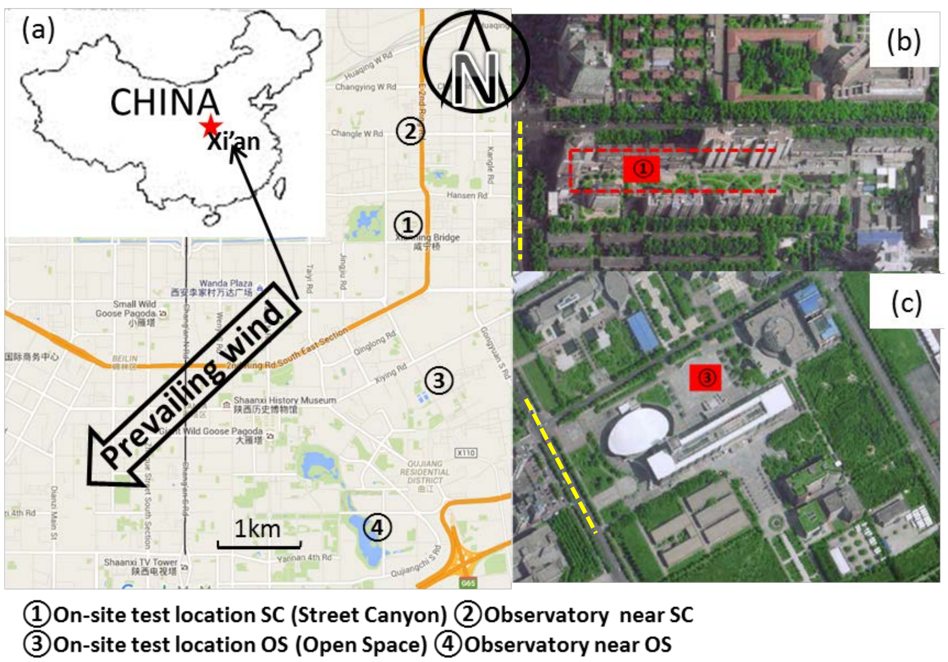


Figure 2 On-site measurement locations in Xi'an, China; (a) map of test locations and their corresponding observatories; (b) Test location of Street Canyon; (c) Test location of Open Space; the yellow lines on (b) and (c) indicate the main streets where the traffic flows were measured.

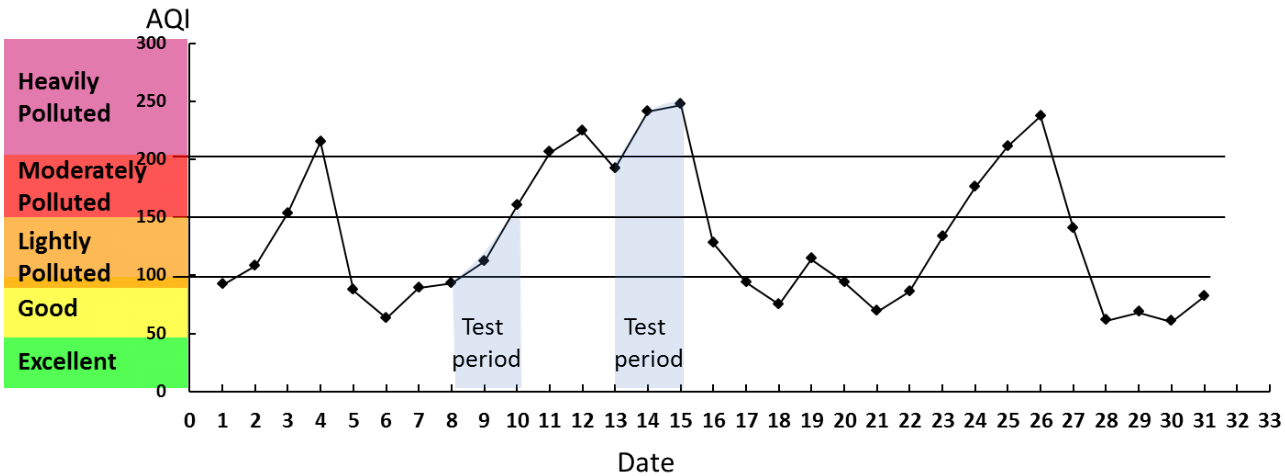


Figure 3 AQI of Xi'an in January, 2015.

(a) Clean day (Taken on Jan 8th) (b) Hazy day (Taken on Jan 15th)

Figure 4 Photos of a clean day and a hazy day at a same location in Xi'an, China.

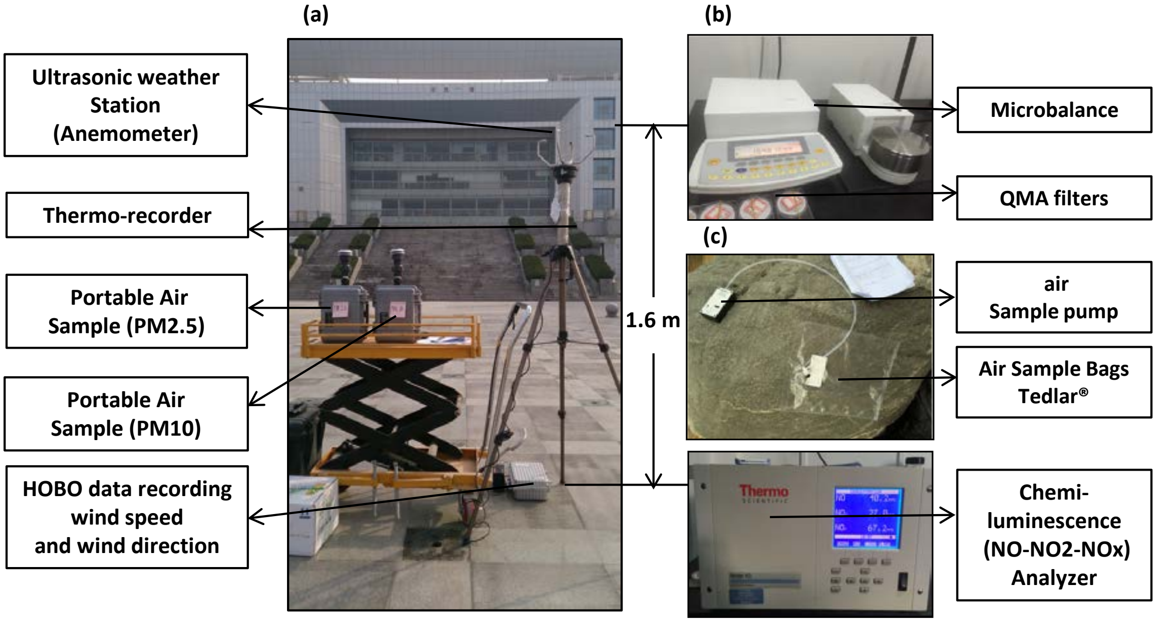
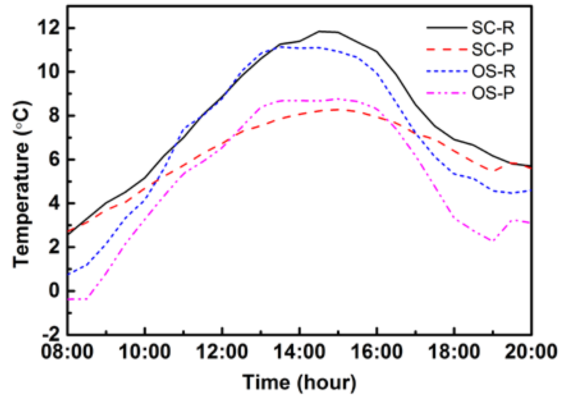
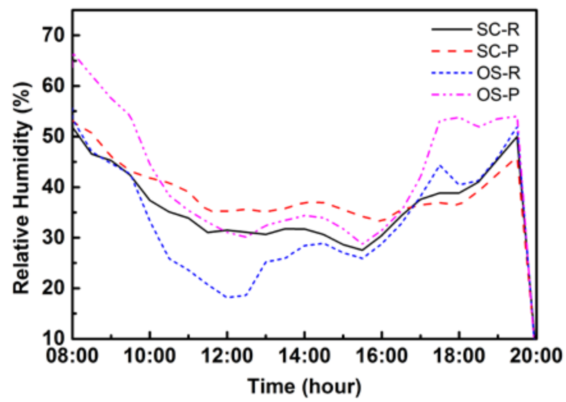


Figure 5 Mini weather stations and equipment used in on-site measurements.



(a) Air temperature



(b) Relative humidity

Figure 6 Air temperature and Relative humidity during the measurement period, where SC-R represents roof level at street canyon, SC-P pedestrian level at street canyon, OS-R roof level at open space, OS-P pedestrian level on open space

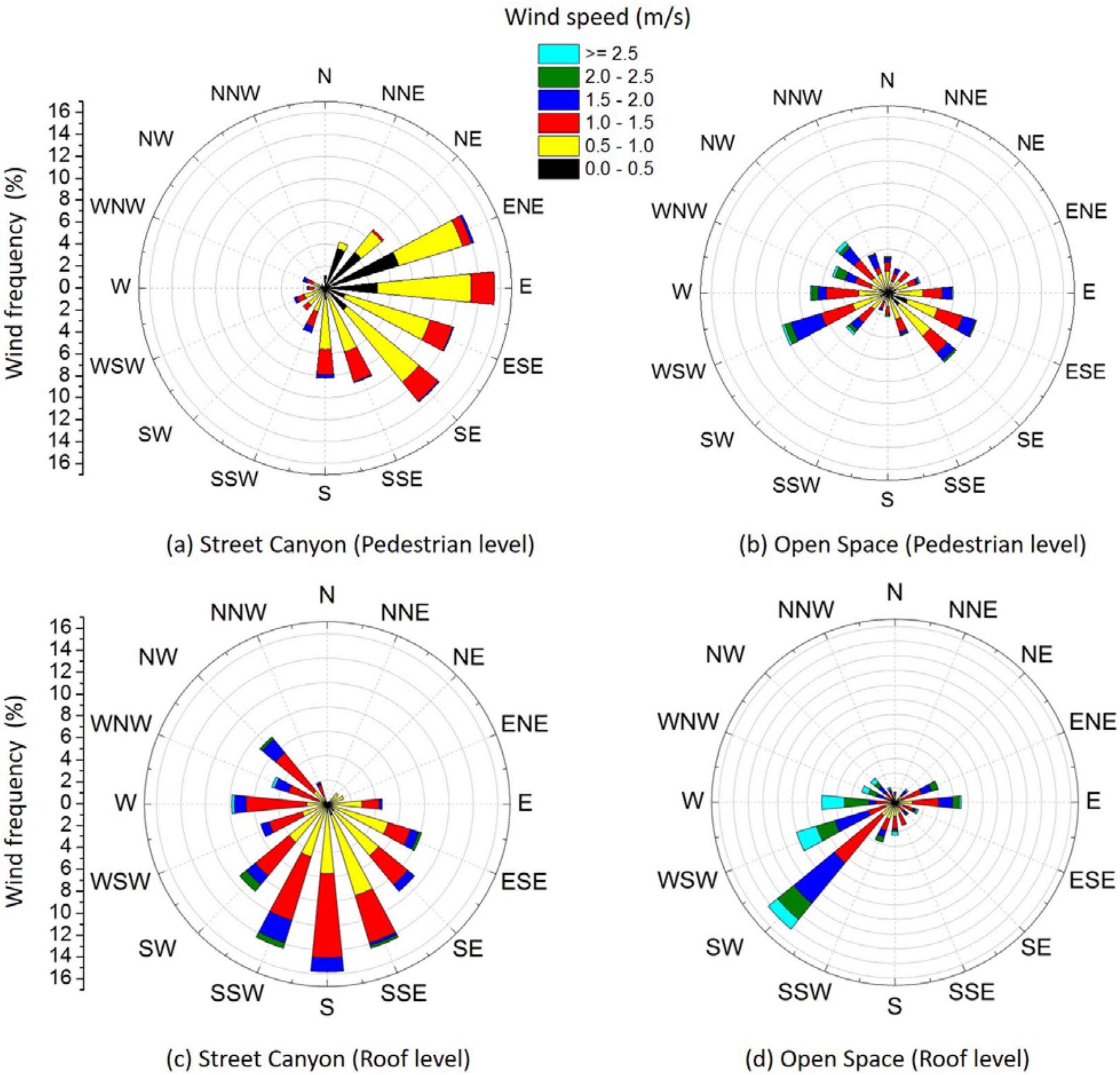
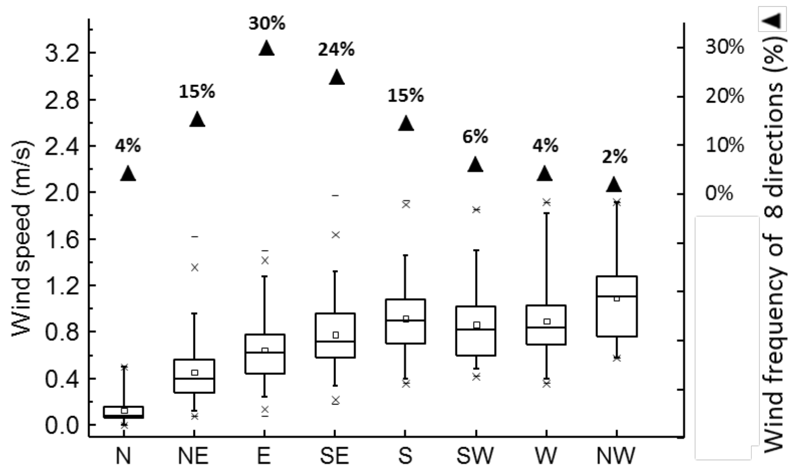
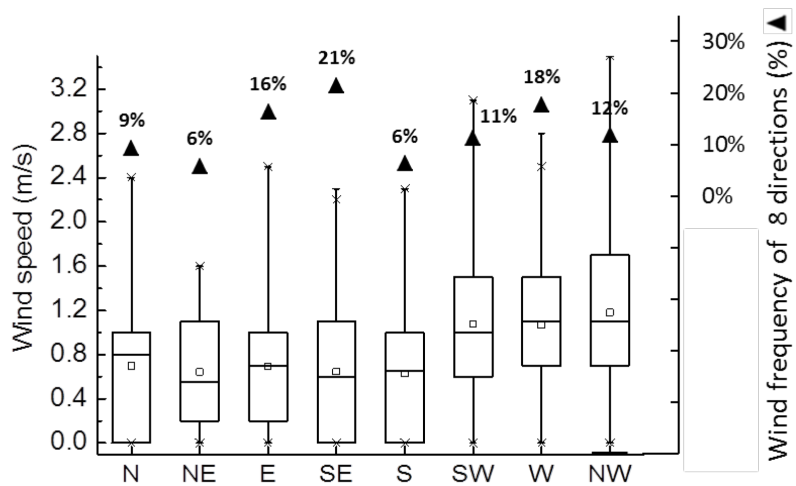


Figure 7 Wind roses at the street canyon and open space during the measurement period. (The measurements were conducted at a height of 2 m above the roof of the highest building around the two locations.)



(a) Street Canyon



(b) Open Space

Figure 8 Boxplots of pedestrian-level wind speed at the street canyon and open space during the measurement period, where the percentage occurrence possibility of each wind direction is also plotted and scaled into the right axis: (a) street canyon and (b) open space; the box edges represent the 25th and 75th percentiles, the whiskers for the 1th and 99th percentiles, the lines in the boxes for median values, and the symbols (Δ) for mean values.

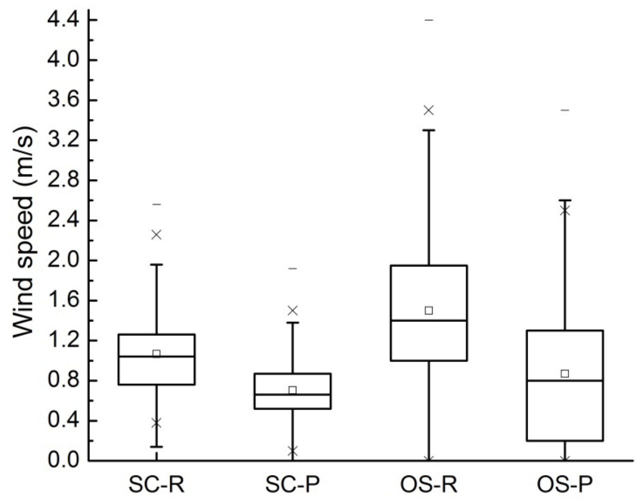


Figure 9 Boxplots of wind speed at both pedestrian and roof levels at the two measurement locations; the reading method of this boxplots is same as that explained in the caption of Figure 6.

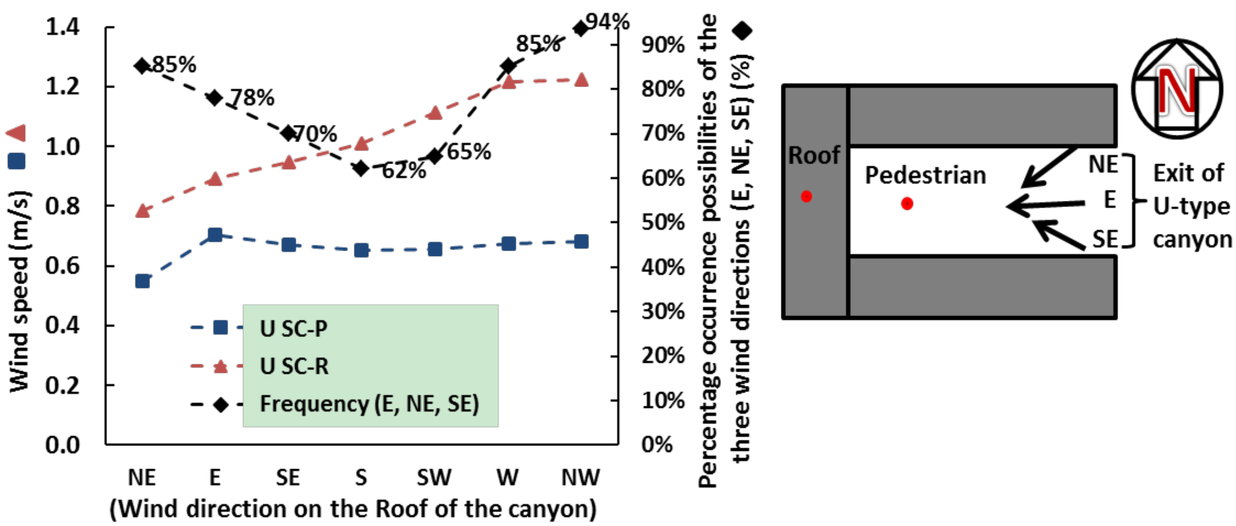


Figure 10 Wind speeds and percentage occurrence possibilities of three wind directions (east, northeast and southeast) at the street canyon. (U SC-P and U SC-R represent wind speed on pedestrian and roof level of street canyon respectively)

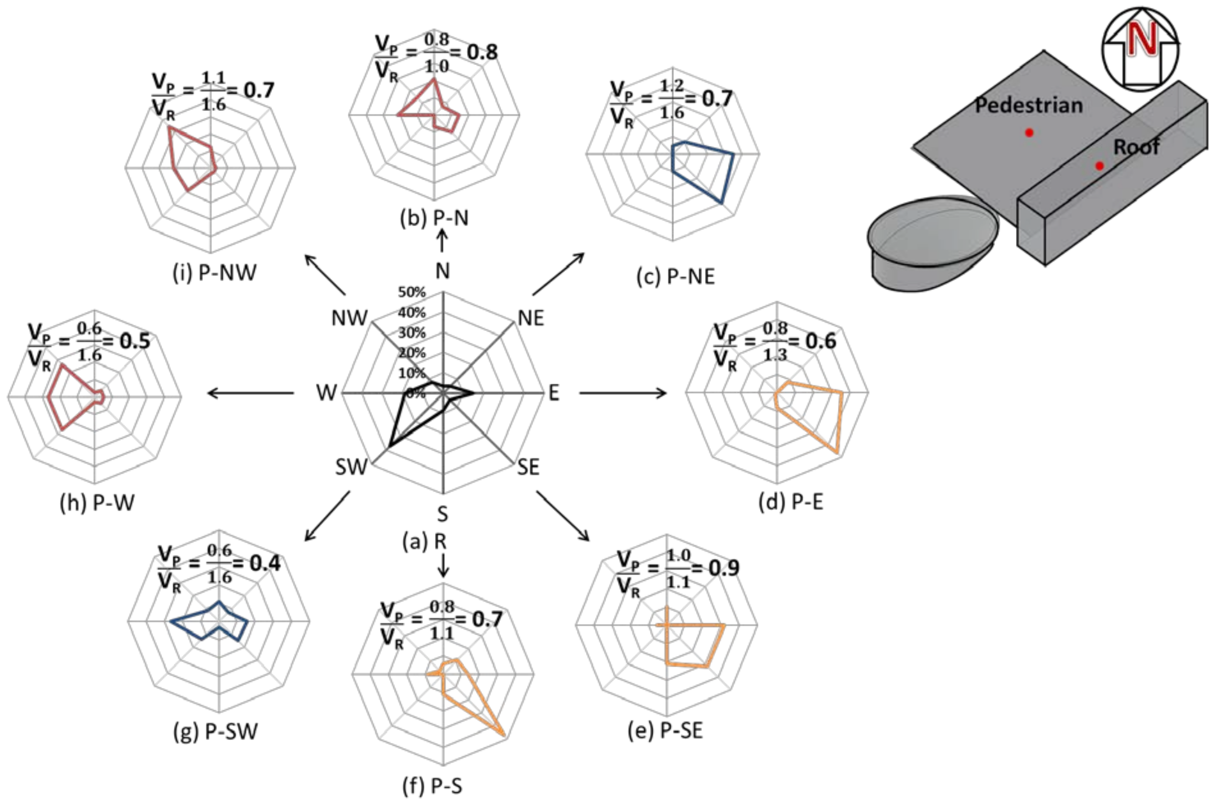


FIgure 11 Wind direction frequency at roof (a) and pedestrian (b-f) levels at the open space, where the ratio of wind speed at pedestrian level to that at roof level is also presented. (Red dots represent the test location)

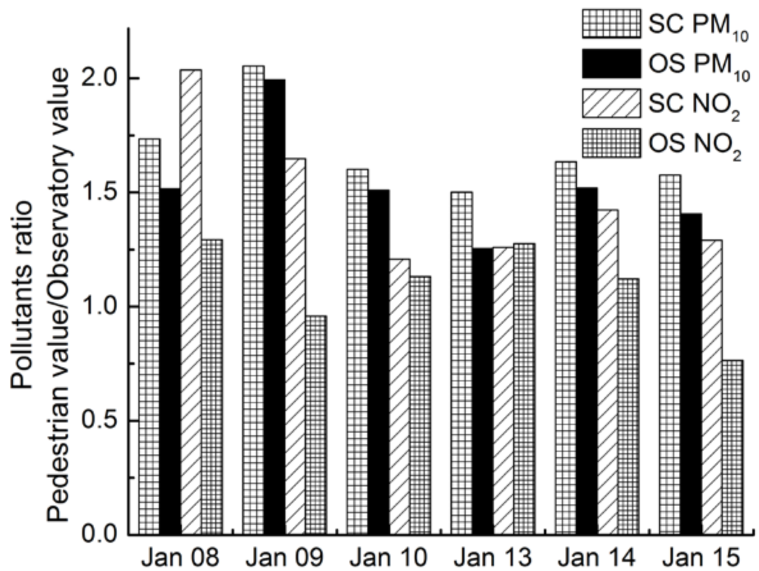


FIgure 12 Ratios of pollutant concentration at pedestrian level of measurement locations to that at nearby observatory stations.

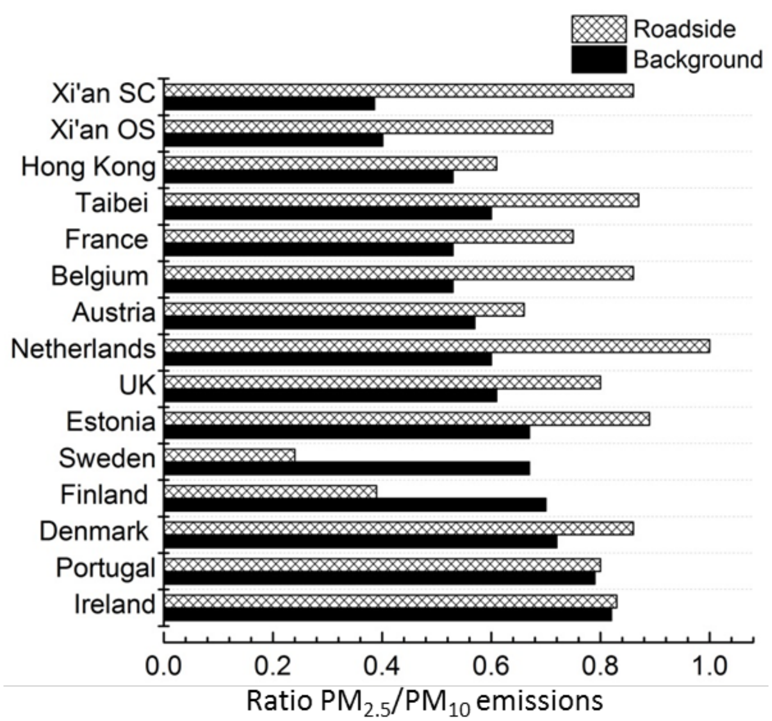


Figure 13 $PM_{2.5}/PM_{10}$ ratios at measurement locations and nearby observatory stations or other background locations (Ho et al., 2003; Chen et al., 1999; EEA, 2009), where Xi'an (SC) and Xi'an (OS) represent the present measurements.

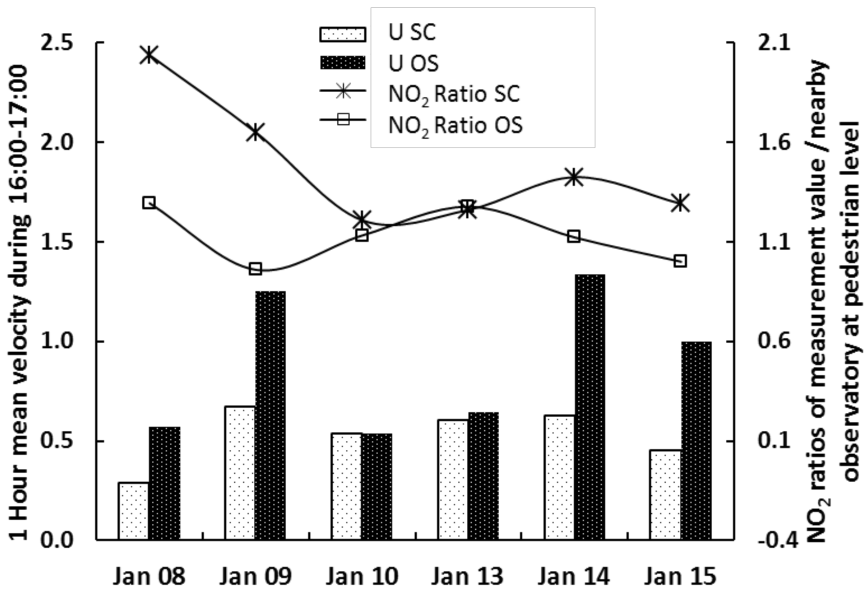
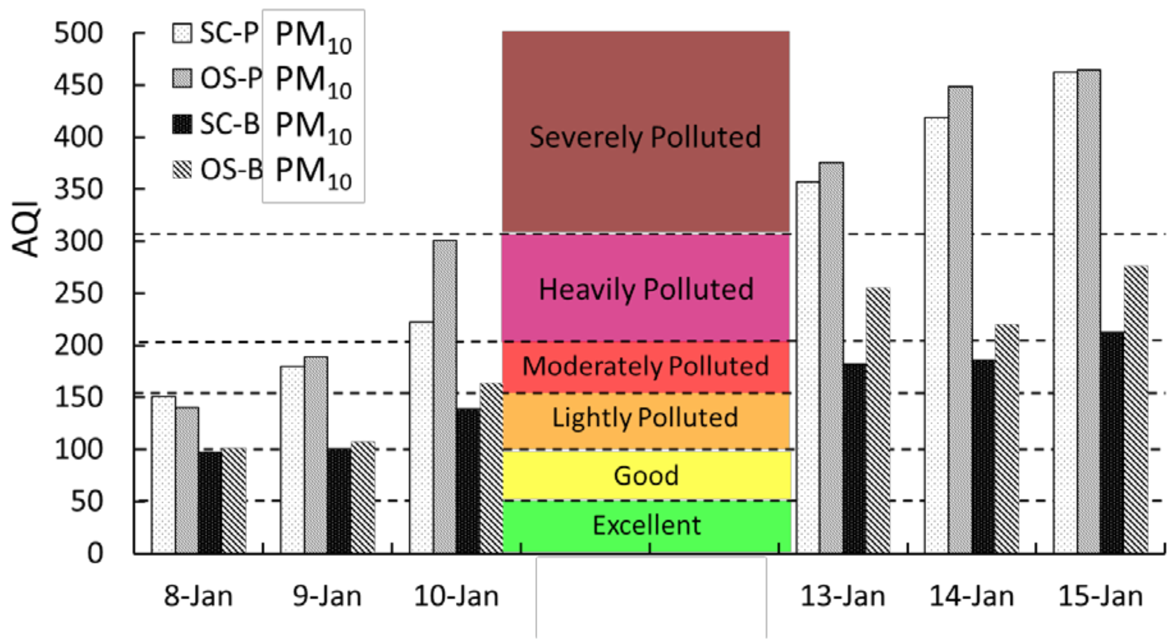
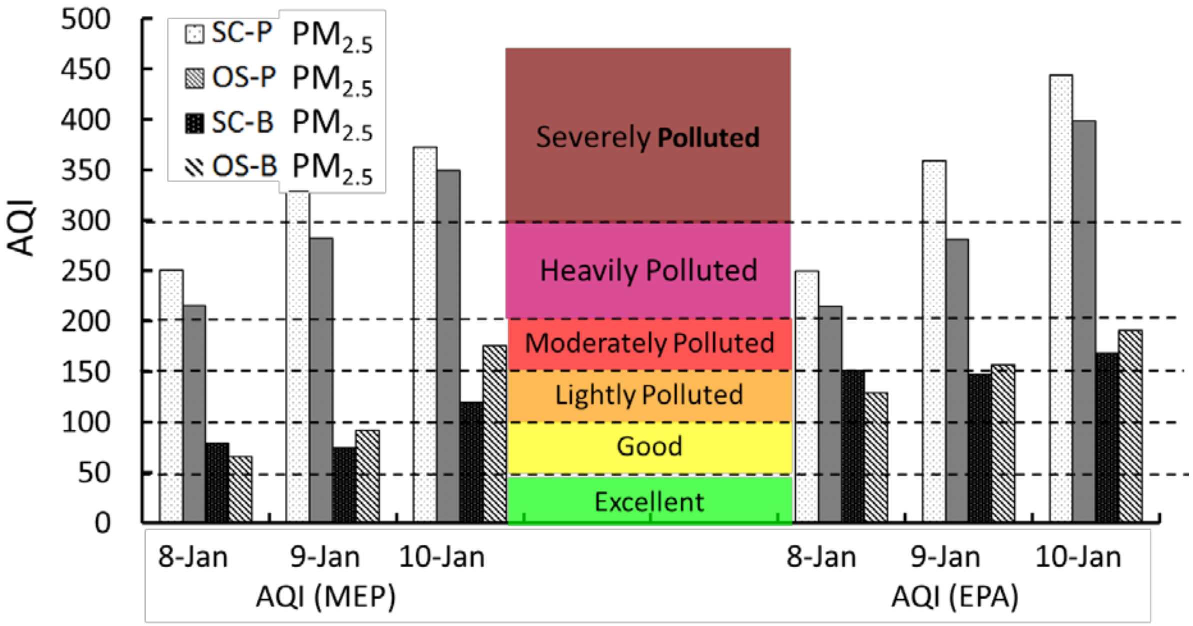


Figure 14 Hourly averaged wind speeds and NO_2 concentration ratios, where NO_2 ratio means the ratio of pedestrian-level concentration of NO_2 to roof-level concentration of NO_2.



(a) AQI of PM_{10}



(b) AQI of $PM_{2.5}$

Figure 15 AQI values for PM_{10} and $PM_{2.5}$ at pedestrian level of measurement locations and at the nearby observatory stations during the measurement period; SC-P represents pedestrian level at street canyon, SC-B background level at observatory.