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Characterizing $PM_{2.5}$ in Hanoi with New High Temporal Resolution Sensor

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ABSTRACT

A year-long observation of $PM_{2.5}$ concentrations was conducted in Hanoi from July 2016 to June 2017 using newly developed highly sensitive sensors. The hourly concentration data of $PM_{2.5}$ agreed well with corresponding data obtained with a beta attenuation monitor located 3 km away, with $R^2 = 0.73$. The monthly variation showed that levels of $PM_{2.5}$ were high during the dry season, particularly in December (median = 62 μg m^{-3}) and low during the rainy season, particularly in June and July (medians = 19 μg m^{-3}). Haze episodes of $PM_{2.5}$ with levels higher than 100 μg m^{-3} were observed 13 times during the dry season (October 2016–March 2017). These episodes may be linked to the East Asian winter monsoon, as the daily levels of $PM_{2.5}$ and CO increased several days after most of the cold surge events. Two events were investigated further at a higher temporal resolution. For both events, peaks of $PM_{2.5}$ appeared at midnight for some days after a cold surge, while CO levels often increased during rush hours. For the first event, brief peaks of $PM_{2.5}$ with a high rate of increase (~5 μg m^{-3} min^{-1}) were observed, highlighting the importance of a high temporal resolution for $PM_{2.5}$ sensors in assessing health effects. For the second event, a broad peak of $PM_{2.5}$ with a gradual increase was observed along with high CO levels. This research reveals the characteristics of $PM_{2.5}$ haze episodes in Hanoi, which should be studied further to effectively manage air pollution.

Keywords: $PM_{2.5}$ measurement; Compact sensor; Megacity; Southeast Asia.

INTRODUCTION

Particulate matter (PM), especially $PM_{2.5}$ poses a serious air pollution problem in several cities in South East and South Asia (Kim Oanh *et al*., 2006; Hopke *et al*., 2008; Cohen *et al*., 2009; Dey *et al*., 2012; Shen *et al*., 2014; Balasubramanian *et al*., 2017). A high level of $PM_{2.5}$ is proven to adversely affect health in many regions (Lelieveld *et al*., 2015; Ghude *et al*., 2016; Zhang *et al*., 2017; Landrigan *et al*., 2018). Research published in the last two decades reported the levels of $PM_{2.5}$ in Hanoi can be some folds higher than the WHO recommendation: a maximum of 10 μg m^{-3} for an annual average and 25 μg m^{-3} for a 24-hour average (Table 1).

Hanoi is the capital city of Vietnam and is located about 100 km west of the East Sea of Vietnam. As other areas in the region, the meteorology of Hanoi is dominated by the Asian monsoon circulation (Lawrence and Lelieveld, 2010). The monsoon meteorology is divided into three basic periods: the summer or southwest monsoon, the winter or northeast monsoon, and the monsoon transition periods (Lawrence and Lelieveld, 2010). Previous research in Hanoi has defined the winter period to be from October to March/April by Hien *et al.* (2002). During the first half of the winter period, the weather is dry, while moisture-laden air is observed from January as the air from the north and northeast passes the ocean before approaching Hanoi (Hien *et al*., 2002). Meteorological conditions largely affect the air quality in Hanoi. Levels of air pollutants were high in winter and low in summer (Kim Oanh *et al*., 2006; Cohen *et al*., 2010; Hien *et al*., 2011). Monthly variations in

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Table 1. $PM_{2.5}$ levels in Hanoi in the literature.

Place	Period	Season or air mass origin	$PM_{2.5}$ level ($\mu g\ m^{-3}$)	Sources
Hanoi	2001–2008	Year-round	54 ± 33	(Cohen *et al.*, 2010)
Industrial zone, Hanoi	12/2006–2/2007	Dry season	76 ± 32	(Hai and Kim Oanh, 2013)
Hanoi	2002–2005	Year-round	35.84	(Hopke *et al.*, 2008)
Hanoi	2001–2006	Dry season	186	(Kim Oanh *et al.*, 2006)
		Rainy season	33	
Hanoi	1999–2001	Air from mainland China (dry season)	49.5	(Hien *et al.*, 2002)
		Air from East Sea (rainy season)	44.3	
		Air from Indochina (transition period)	20.4	

concentration of $PM_{2.5}$ were reported for the period 2001–2008 (Cohen *et al*., 2010). However, diurnal variation in concentration of $PM_{2.5}$ was not available in the literature up to now. Several haze episodes were observed in Hanoi during the winter. An episode with the daily level of $PM_{2.5}$ higher than 250 $\mu g\ m^{-3}$, another in the range of 200–250 $\mu g\ m^{-3}$, and dozen episodes in the range of 150–200 $\mu g\ m^{-3}$ were reported in 24-hour concentration of $PM_{2.5}$ collected in every Sunday and Wednesday in the period 2001–2008 (Cohen *et al*., 2010). High levels of air pollutants including CO, SO_2, NO_2, and PM_{10} in winter due to prolonged anticyclonic conditions after northeast monsoon surges were reported by Hien *et al.* (2011). No published studies have reported hourly and higher temporal resolution data on concentration of $PM_{2.5}$ during haze periods in Hanoi. Recently, several studies on rapid increases of $PM_{2.5}$ in hazy period especially in China were reported (Wang *et al*., 2014; Zhang *et al*., 2017). Rapid increases in $PM_{2.5}$ can significantly affect health, and acute exposure to elevated levels of $PM_{2.5}$ has been linked to multiple adverse health outcomes (Barrett *et al*., 2006).

Hanoi was expanded in 2008. The city has an area of 3344.70 km^2 and a population of 6.2 million people during the first year of its expansion in 2008. Hanoi is now struggling to find suitable management measures to solve its air quality problem. In order to manage $PM_{2.5}$, the most serious pollutant, the level of $PM_{2.5}$ with respect to time and space must be measured. Even though, research about $PM_{2.5}$ levels in Hanoi has been performed over about two decades (Hien *et al*., 2002), the data are still sparse with respect to both time and space. A larger area than before of the city because of its expanding also require more measurement sites. Low-cost sensors are considered to be a good approach beside standard measurement instruments in Hanoi, as well as several other places in South East Asia. This research aims to i) investigate of the potential applicability of the Panasonic $PM_{2.5}$ sensor in tropical humid areas; ii) determine the monthly, weekly, and diurnal variation in concentration of $PM_{2.5}$; iii) determine the daily and hourly variation in $PM_{2.5}$ in accordance with meteorological conditions; and iv) determine the characteristics of $PM_{2.5}$ haze with 5-min resolution data of concentration of $PM_{2.5}$.

METHODS

Monitoring Sites, Instruments and Monitoring Data

Monitoring was conducted at Hanoi University of Science and Technology (HUST) (21°0′19″N, 105°50′43″E) in Hanoi, Vietnam, from July 2016 to June 2017 (Fig. 1). HUST is located in the Hai Ba Trung district, in the inner area of Hanoi, and is adjacent to two main roads and a minor road. The distance to the nearest road (the minor one) is 100 meters. Two Panasonic $PM_{2.5}$ sensors were hung outside the third floor of a four-story-building. CO was monitored by non-dispersive infrared spectroscopy (APMA-370, 115 HORIBA), and NO was measured by a chemiluminescence technique (Model 42i, Thermo Electron).

Hourly data from a beta attenuation monitor (BAM) at the US Embassy were obtained from the AirNow website (https://airnow.gov/index.cfm?action=airnow.global_summary#Vietnam$Hanoi). The BAM was installed on the rooftop of the US Embassy on Lang Ha Street (3.1 km northwest of the HUST site).

Thirty-minute averaged temperature, wind speed, and relative humidity (RH) data at 7 meter-height, as well as sounding data, of Lang station in Hanoi were also used. Radio sounding measurements were performed twice a day at 7:00 and 19:00 (local standard time). These data were obtained from Wyoming Weather Web (http://weather.uwyo.edu).

Surface synoptic charts were obtained at the website of the Hong Kong Observatory (http://www.hko.gov.hk/contente.htm)

Details of $PM_{2.5}$ Sensor

Characteristics of the Panasonic $PM_{2.5}$ sensors are reported elsewhere (Nakayama *et al*., 2018). Briefly, the particle size distribution was estimated by measuring the scattering intensities of single particles. The output of the $PM_{2.5}$ sensors was calibrated using nearly monodisperse polystyrene latex (PSL) particles. $PM_{2.5}$ levels in ambient air must be calculated by multiplying the output of the sensor by a correction factor. The correction factor can be calculated as the ratio of the density of ambient particles (1.2–1.8 $g\ cm^{-3}$) to that of PSL (1.03 $g\ cm^{-3}$) (Nakayama *et al*., 2018). However, the differences in refractive index, shape, and morphology between PSL and sample particles may also affect this correction factors. Therefore, determining the correction factor from the correlation between concentrations of $PM_{2.5}$ observed at collocated or near station with the output data of the sensors is more practical. Nakayama *et al.* (2018) showed that a factor of 1.3 worked well for Japanese sites with slope of 1.07–1.16 and R of 0.90–0.91 for collocated standard instrument and

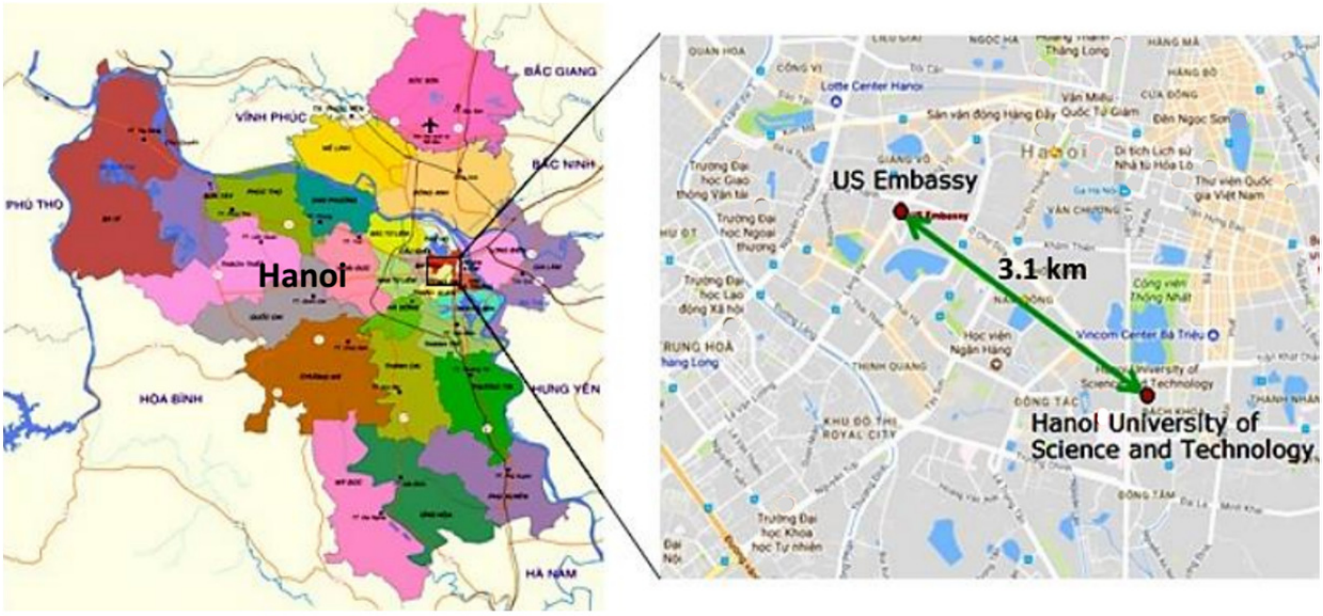

Fig. 1. Observation sites.

with slope of 0.97–1.23 and R of 0.89–0.95 with AEROS data of four sites 1.7–4.1 km away. In this study, we applied a factor of 1.4. This correction factor was determined by drawing the correlation curve between output of two Panasonic sensors (hourly average) and hourly $PM_{2.5}$ data obtained from BAM 3.1 km away with slope of 1.38 and R^2 of 0.73 (Fig. S1). The advantage of Panasonic sensor is its relatively low detectable particle size. Besides, the air flow was directed with a small heat source, which allowed the sensor to be operated without a fan. These features allow lower investigation and operation costs compared with other systems. Another advantage of this sensor is its ability to operate without a cyclone or impactor to separate bigger particles. To prevent possible artifacts resulting from wind, the sensor was installed in a box with louver windows.

RESULTS AND DISCUSSION

Correlation between $PM_{2.5}$ Sensor Data and Nearby Beta-attenuation Monitor Data

Fig. 2 demonstrates the correlation between average hourly $PM_{2.5}$ data obtained from two Panasonic sensors and hourly $PM_{2.5}$ data obtained from BAM. The level of $PM_{2.5}$ sensor mentioned in this research is the average value of two $PM_{2.5}$ sensors. As mentioned above, the $PM_{2.5}$ level is calculated by multiply the output data of Panasonic sensors with a density correction factor of 1.4. Hourly concentration data of $PM_{2.5}$ obtained from the sensors in HUST had good correlation with near BAM data (3.1 km away) with $R^2 = 0.73$ and a slope of 0.99. This correction factor is slightly higher than 1.3 used in previous study in Japan (Nakayama *et al*., 2018) reflecting the difference in density and/or other characteristics such as refractive index, shape, and morphology of PM between the two countries. It is also important to note that the investigated data in this study had a wider range of $PM_{2.5}$ (up to 400 μg m^{-3}) than in Japan (within 60 μg m^{-3}). Besides, the fact that Hanoi has humid tropical climate demonstrated the potential of the sensors in high humid conditions. The relative humidity (RH) of Hanoi during the study period is shown in Table 2. The good correlation between the two measurements also suggests that the effect of nearby site sources of $PM_{2.5}$ at both monitoring sites is insignificant. It is noted that the BAM sometimes gave negative and zero levels of $PM_{2.5}$, which was probably due to the relatively low precision of hourly averaged data. On the other hand, Panasonic sensor with a low detection limit did not meet this problem.

Seasonal, Weekly, and Diurnal Variations

Seasonal variation in concentration of $PM_{2.5}$ is presented in Fig. 3 and Table 3. Low levels of $PM_{2.5}$ were found in summer (particularly, June and July with a median of 19 μg m^{-3}). The 75th percentile of concentrations of $PM_{2.5}$ in June was within 50 μg m^{-3} and the value in July was slightly higher. Median values of concentrations of $PM_{2.5}$ in the other months in summer (May and August) were 28 and 24 μg m^{-3}, respectively. Both the transition period to the winter monsoon (September) and that to the summer monsoon (April) had higher levels of $PM_{2.5}$ than in the summer period (around 40 μg m^{-3}). High median levels of $PM_{2.5}$ were observed in dry season, particularly in December (62 μg m^{-3}) and January (59 μg m^{-3}). The levels of $PM_{2.5}$ in December and January were about three times higher than in July. This monthly variation was similar to that in previous research on the levels of $PM_{2.5}$ in the period 2001–2008 by Cohen *et al.* (2010). This seasonal variation was also similar to that in many areas in South East and East Asia, indicating the regional contribution to $PM_{2.5}$ (Cohen *et al*., 2004; Cohen *et al*., 2009; Chuang *et al*., 2015).

A box-and-whisker plot of variation in weekly concentrations of $PM_{2.5}$ is presented in Fig 4. The median

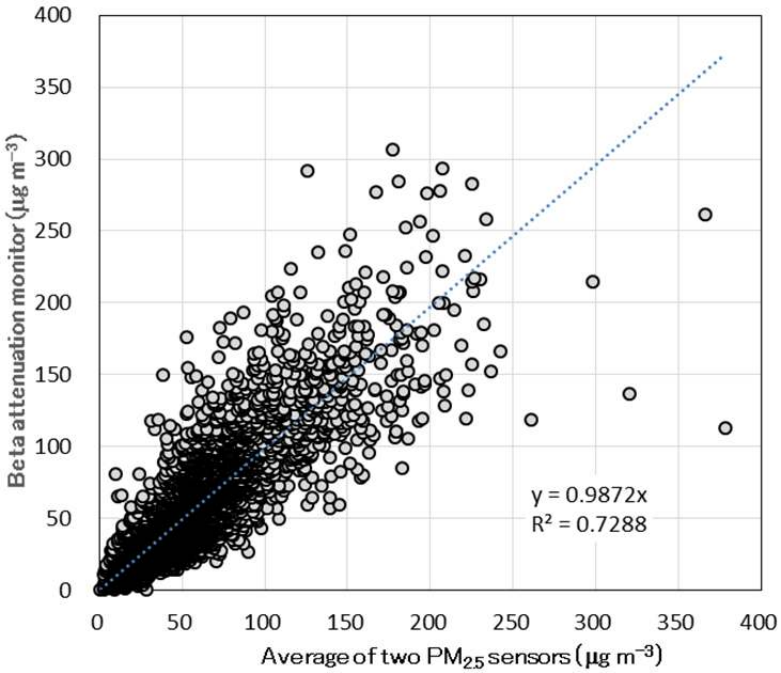

Fig. 2. Correlation between average hourly $PM_{2.5}$ mass concentrations measured with two Panasonic $PM_{2.5}$ sensors and $PM_{2.5}$ mass concentrations measured with a beta attenuation monitor.

Table 2. Meteorological data and $PM_{2.5}$ levels.

	Temp	Pressure	RH[a]	DWPC[b]	Wind speed	$PM_{2.5}$ level
	°C	mbar	%	°C	m s^{-1}	μg m^{-3}
July, August 2016						
Min	24	986	42	19	0	2
Median	29	1003	84	26	3	22
Mean	30	1003	81	26	3	26
Max	37	1011	100	29	14	99
Oct 2016–Mar 2017						
Min	12	1002	18	1	0	1
Median	22	1016	79	18	3	52
Mean	22	1016	76	17	3	61
Max	34	1030	100	28	9	459
May, June 2017						
Min	20	995	32	11	0	4
Median	28	1006	89	26	3	26
Mean	29	1006	84	25	3	27
Max	41	1015	100	30	13	170

[a] Relative humidity, [b] Dew point temperature.

levels of $PM_{2.5}$ varied around 40 μg m^{-3} for all days of the week. No clear difference between levels of $PM_{2.5}$ on weekdays and weekends was observed, except for slightly higher levels of $PM_{2.5}$ on Mondays and Tuesdays. This result may be partly because that total vehicle numbers in weekdays and weekends in Hanoi are not greatly different (Truc and Kim Oanh, 2007; Phuc and Kim Oanh, 2018).

Fig. 5 shows diurnal variations in the concentration of $PM_{2.5}$ for selected months. The results for even-numbered months are not shown because the variations were similar to those for neighboring months. There was no clear peak of $PM_{2.5}$ at transportation rush hours (around 8 a.m. and 6 p.m.), in contrast to CO and NO, which were also measured at the same sampling site (Sakamoto *et al*., 2018). These results suggest that the effect of direct emission from local transportation on the level of $PM_{2.5}$ is not dominant at the measurement site, other local sources and regional-scale background may be the main contributors to the average $PM_{2.5}$ level. This result is further support by the research of Hai and Kim Oanh (2013) that the main sources of $PM_{2.5}$ were: secondary mixed PM (40%), diesel traffic (10%), residential/commercial cooking (16%), secondary sulfate rich (16%), aged seasalt mixed (11%), industry/incinerator (6%), and construction/soil (1%). On the other hand,

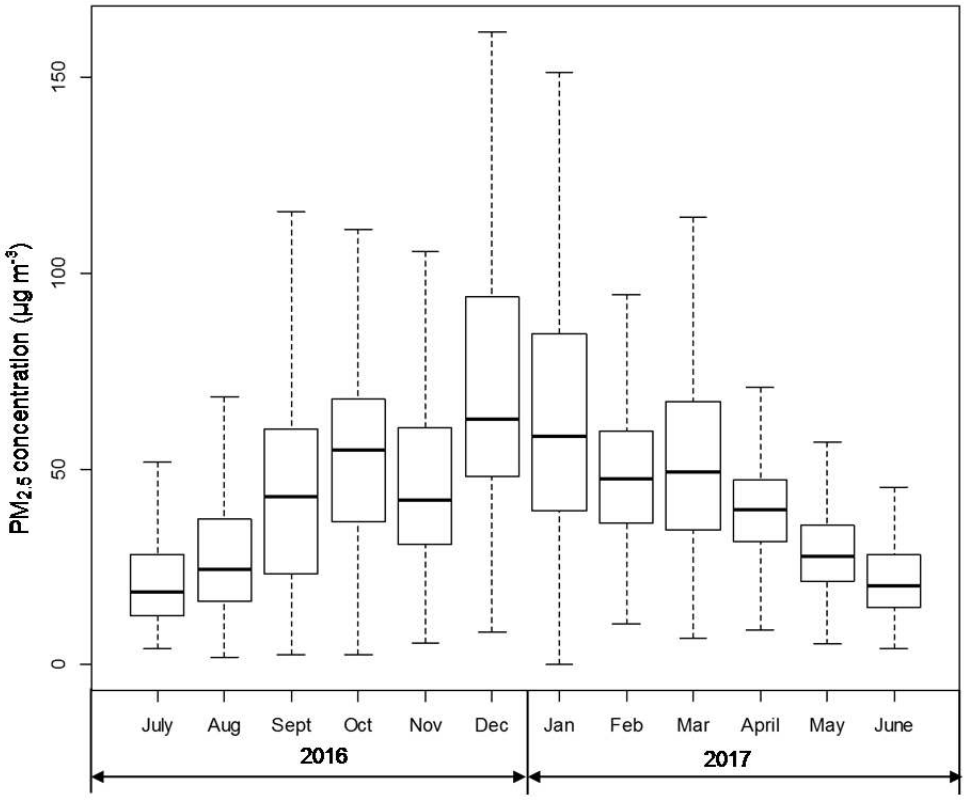

Fig. 3. Seasonal variation in $PM_{2.5}$ mass concentrations.

Table 3. Seasonal variation in $PM_{2.5}$ (µg m^{-3}).

Month	Min	Median	Mean	Max	Month	Min	Median	Mean	Max
January	40	59	70	243	July	4	19	22	82
February	11	45	50	235	August	2	24	28	91
March	7	49	54	192	September	3	44	46	142
April	10	40	42	126	October	3	54	58	293
May	6	28	30	149	November	6	42	51	225
June	4	19	22	94	December	8	62	76	459

Cohen *et al.* (2010) noted that the main sources of $PM_{2.5}$ were: automobile (40 ± 10%), soil (3.4 ± 2%), secondary sulfates (7.8 ± 10%), smoke (13 ± 6%), industry (19 ± 8%), and coal (17 ± 7%).

It should be noted that variation of relative contributions of several types of particles with different properties (such as density, refractive index, and morphology) possibly contributes to the sensitivity of the $PM_{2.5}$ sensors. However, the contribution of this factor to the above discussions on the variations of $PM_{2.5}$ should be limited because similar trends were observed even when the data obtained by the BAM instrument were used for analyses, as shown examples of monthly averaged diurnal variations in the supplemental information (Fig. S2).

Characteristics of Levels of $PM_{2.5}$ in Haze Episodes

Variations in Concentrations of $PM_{2.5}$ and Surface Meteorological Parameters in Winter 2016–2017

Daily time series were generated for levels of $PM_{2.5}$, temperature, wind speed, and RH during the dry season from October 2016 to March 2017 (Fig. 6). There were two periods in October 2016 in which data from the $PM_{2.5}$ sensor were missed. Beside $PM_{2.5}$, a time series of CO, a typical gaseous pollutant from transportation, industrial production, and biomass burning, is also shown in Fig. 6. Timings of cold surges, which were proposed as an indicator for haze episodes in previous research (Hien *et al*., 2011), are presented. Whereas Hien *et al.* (2011) used daily temperature drop of 2°C or more within 2 days and an hourly temperature drop of at least 2°C as criteria for a cold surge, we used a 2°C or more daily temperature drop as a criterion. When cold surges happened in two or three days continuously, it is still counted as an event. The reason why is we do not use hourly temperature drop of 2°C as cold surge criterion is hourly temperature data used in this study were rounded to 1 digit. This meant that errors could be made in calculating a 2°C drop in the hourly temperature and a cold surge could be misrecognized. A daily temperature drop of 2°C or more, however, served well as the indicator, as shown later.

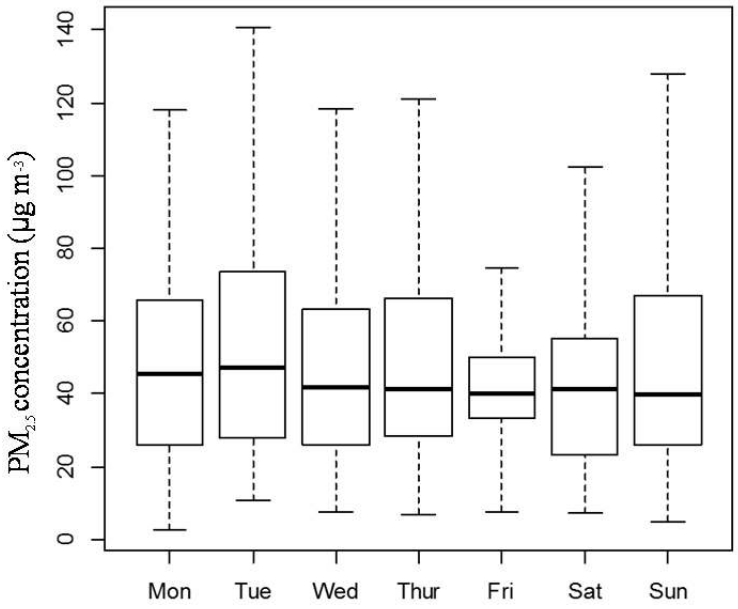

Fig. 4. Weekly variation in $PM_{2.5}$ mass concentrations.

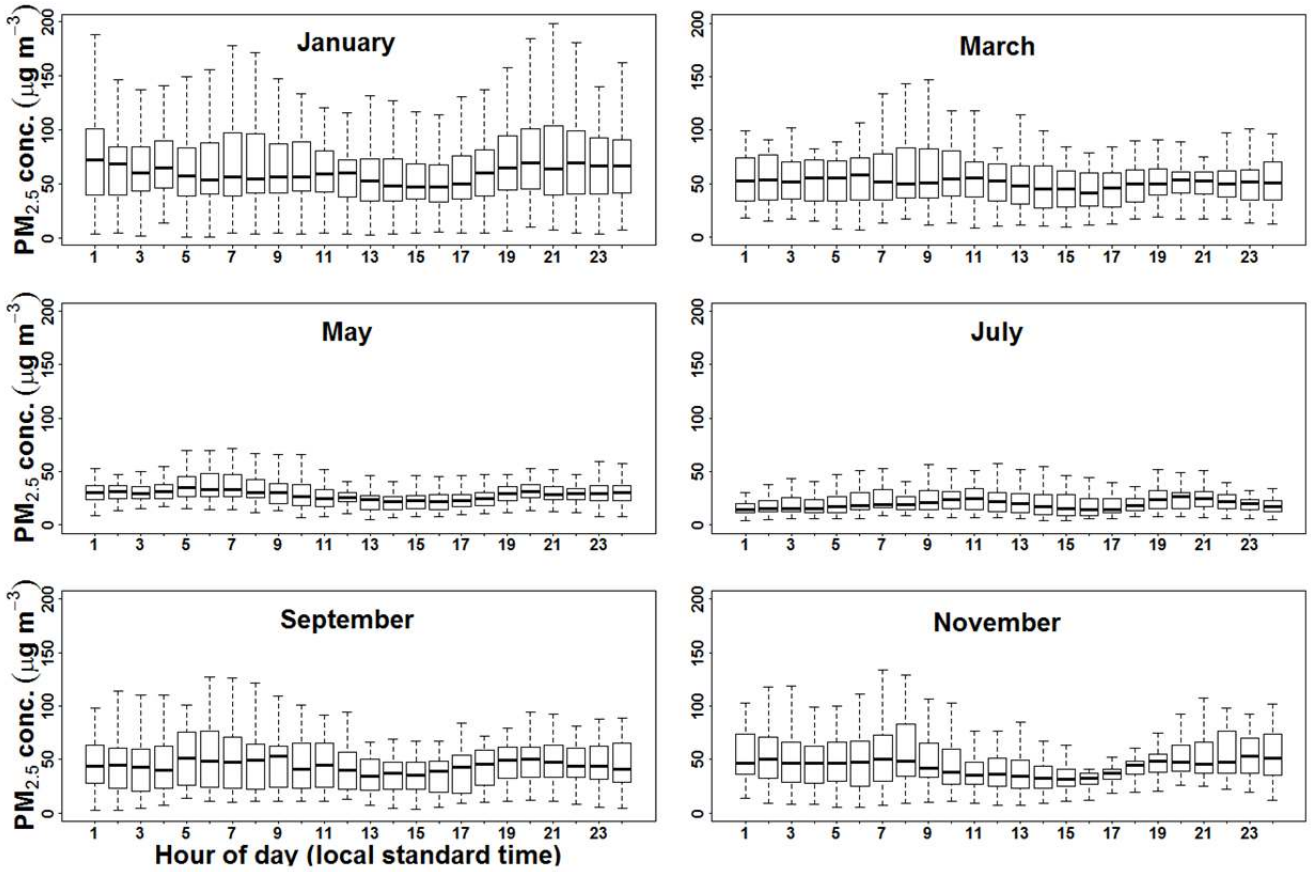

Fig. 5. Diurnal variations in $PM_{2.5}$ mass concentrations for selected months.

Two $PM_{2.5}$ episodes with 24-hour averages of 150–200 μg m^{-3} were observed, and 11 episodes with $PM_{2.5}$ levels of 100–150 μg m^{-3} were detected. Large increases in both $PM_{2.5}$ and CO were frequently observed several days after cold surges. These phenomena were observed 14 times during the dry season. The observed frequency of the high PM episodes after cold surges was similar to that quoted in previous research on PM_{10} (Hien *et al.*, 2011). These phenomena were explained in the research of Hien *et al.* (2011) as follows. A cold surge, which is caused by an air

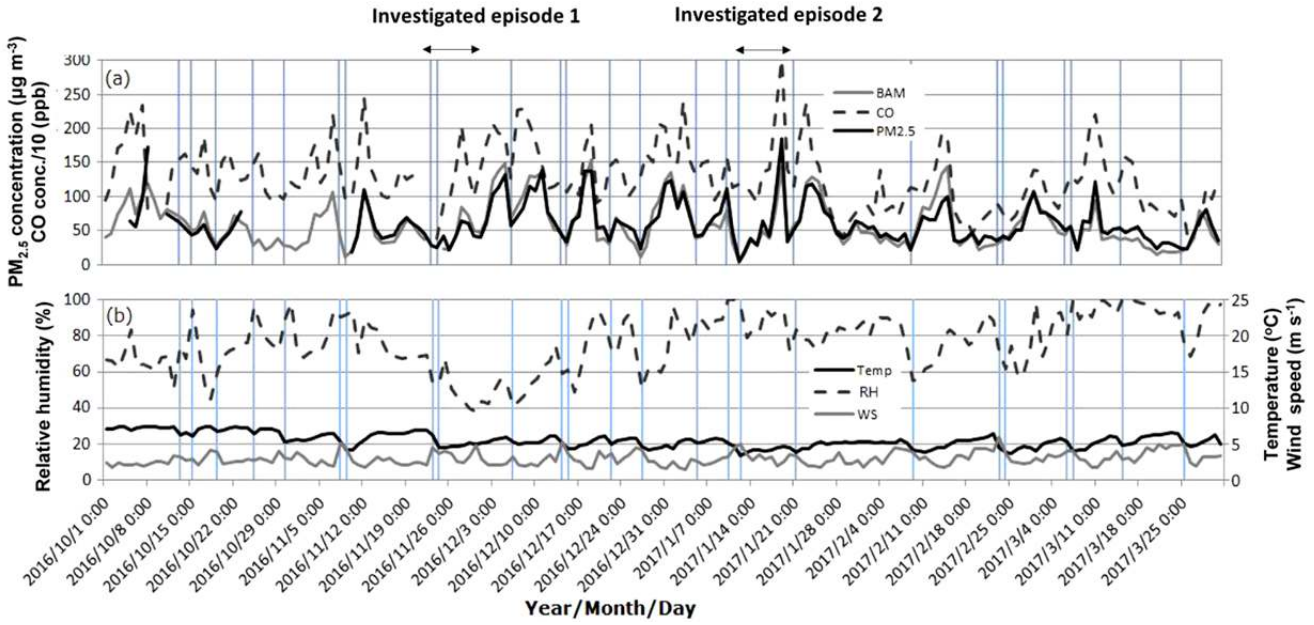

Fig. 6. Time series of (a) daily $PM_{2.5}$ concentrations measured with the $PM_{2.5}$ sensor ($PM_{2.5}$) and BAM, and daily CO concentration and (b) daily relative humidity (RH), temperature (Temp), and wind speed (WS) at a height of 7 m. Vertical bars represent a cold surge event.

parcel being moved from the north and northeast due to the outflow from a high-pressure system in Siberia or the Pacific, is often followed by stagnant conditions. The stagnant conditions then caused a temperature inversion, trapping pollutants near the surface (Hien *et al*., 2011; Wang *et al*., 2014). Several research studies in this region (China, Taiwan) also demonstrated that haze episodes were linked to regional cyclonic and meteorological conditions (Wang *et al*., 2014; Chuang *et al*., 2015; Chou *et al*., 2017). Other research in this area demonstrated that haze episodes were also linked to the outflow of air pollutants from Asia (Lee *et al*., 2006; Hsu *et al*., 2010; Chuang *et al*., 2017). The formation of secondary PM because of increases in precursor gaseous species were also demonstrated in this region (Huang *et al*., 2014; Wang *et al*., 2014; Chuang *et al*., 2017). In this research, the link between high level of $PM_{2.5}$ and meteorological conditions was discussed. The other potential formation mechanisms of increasing PM including trans-boundary and formation of secondary PM must be investigated in other research.

Characteristics of Selected Haze Episodes

To obtain further insight into these above mentioned haze episodes, we investigated the higher time resolution of $PM_{2.5}$ in relation with CO, RH, wind speed, temperature and synoptic chart. Two episodes, one is in early winter (dry winter, from 23 to 30 Nov. 2016) and the other is from late winter (wet winter, from 12 to 20 Jan. 2017) were chosen for further investigation.

Hourly and 5-min time resolution of $PM_{2.5}$ along with hourly CO, RH, wind speed, temperature of episode 1 are presented in Fig. 7. Cold surges occurred continuously on 23 and 24 November. Those two days were count as one cold surge event. Surface synoptic chart in 23 November (Fig. S3) showed a cold front passed near Hanoi during 14–20 UTC giving rise to a cold surge during this time. During five days after the cold surges, peaks of $PM_{2.5}$ were appeared at night. High hourly levels of $PM_{2.5}$ (higher than 120 µg m^{-3}) appeared at the fourth day after the cold surge and a level higher than 160 µg m^{-3} were observed at the firth day after the cold surge. The $PM_{2.5}$ level then returned to below 60 µg m^{-3}. It is also important to note that these peaks appeared within a short time and that daily values were in the range of 50–100 µg m^{-3}. Five-minute resolution concentration of $PM_{2.5}$ showed that at the fifth day after the cold surge the level of $PM_{2.5}$ abruptly increased to 240 µg m^{-3} from a level around 119 µg m^{-3} within 25 min at around 3 a.m. and then quickly decreased to 113 µg m^{-3} within 30 min (Fig. 7(c)). The rate of increase of concentration of $PM_{2.5}$ was ~5 µg m^{-3} min^{-1}. This extremely rapid increase in the level of $PM_{2.5}$ cannot be detected by hourly temporal resolution measurements. This highlights the importance of high temporal resolution of $PM_{2.5}$ sensors in assessing of health effect as acute exposure to elevated levels of $PM_{2.5}$ can lead to adverse health effects (Barrett *et al*., 2006). The RH was not high during the time that this peaks appeared. The contribution of the RH to the increases in the $PM_{2.5}$ mass should not be large. Peaks of $PM_{2.5}$ appeared (at night) several hours after the time of the peak of CO and NO (around rush hours) (Fig. 7(c)). The $PM_{2.5}$ peak, which often appeared at night after a cold surge, may be the result of secondary particle formation under stagnant conditions. Further detailed explanation is outside the scope of this research.

Hourly and 5-min time resolution of $PM_{2.5}$ along with hourly CO, RH, wind speed, temperature of episode 2 are presented in Fig. 8. The cold surge was happened in 12 January. The surface synoptic chart showed a strong pressure

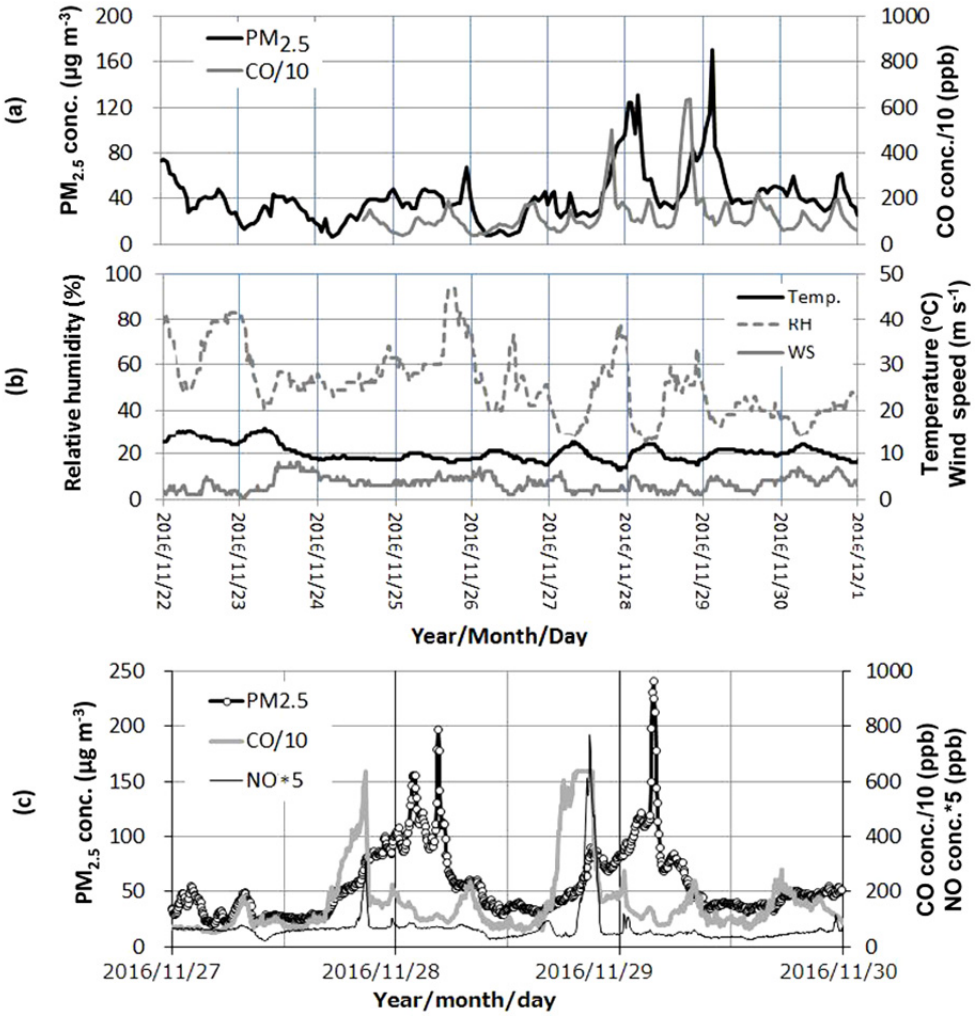

Fig. 7. Time series of: (a) hourly $PM_{2.5}$ level measured with the $PM_{2.5}$ sensor and CO level; (b) hourly temperature (Temp.), relative humidity (RH), and wind speed (WS) at a height of 7 m from 22 to 30 November 2016; and (c) 5 min resolution $PM_{2.5}$, CO and NO levels from 27 to 29 November 2016.

system over Northern Vietnam at this time (Fig. S4). Gradually increasing $PM_{2.5}$ peaks appeared at nights several days after the cold surge on 12 January 2017 (Figs. 8(a) and 8(b)). Unlike the haze period in November that peaks with $PM_{2.5}$ level higher than 100 µg m^{-3} only appeared in the night, in this event, a broad peak started on January 18, reached a plateau at ~200 µg m^{-3} in the evening (~8 p.m.) on the same day and fluctuated between 150 and 250 µg m^{-3} for over a day (Fig. 8(c)). The $PM_{2.5}$ level then decreased sharply in the evening on January 19 to 50 µg m^{-3}. Two smaller peaks appeared again that night (~11 p.m. and ~2 a.m.), and then the level settled at a low value of ~30 µg m^{-3}. Unlike the high $PM_{2.5}$ episodes in November, the CO level increased at the same time as the $PM_{2.5}$. The mechanism of $PM_{2.5}$ haze formation in this period is probably different from November period. Almost saturated water vapor condition was observed beyond the first half of the high $PM_{2.5}$ period from the evening of January 18 to the evening of January 19 (Fig. 8(b)). High humid may partly contribute to the high levels of $PM_{2.5}$ in addition to the stagnant condition or contributions of direct anthropogenic emissions (considering the simultaneous enhancement of CO).

CONCLUSIONS

The Panasonic sensor can provide reasonable $PM_{2.5}$ mass concentration data in a polluted tropical area such as Hanoi. Year-round data showed that measurements from the $PM_{2.5}$ sensor were well correlated with those from a nearby beta attenuation monitor (3.1 km away), with $R^2 = 0.73$.

The monthly variation in the $PM_{2.5}$ concentration in Hanoi reflected the effects of regional meteorological conditions. The maximum medians of $PM_{2.5}$ were observed in December (median = 62 µg m^{-3}) and January (median = 59 µg m^{-3}) and were about threefold higher than in July. There was no clear difference between the levels of $PM_{2.5}$ on weekdays and weekends. The diurnal variation showed no clear rush hour peaks for any month. These results suggest that the effect of direct emissions from transportation on $PM_{2.5}$ at the observation site is not dominant.

During the dry season from October 2016 to March 2017,

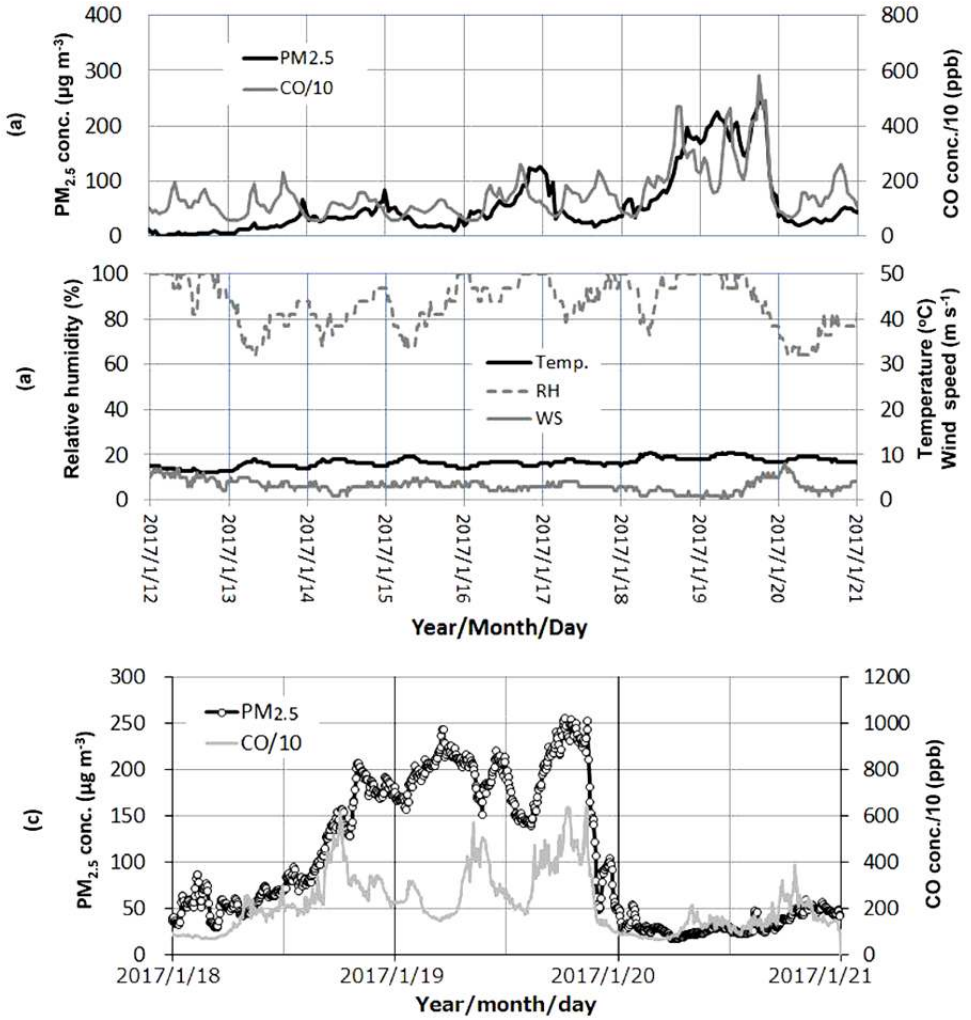

Fig. 8. Time series of: (a) hourly $PM_{2.5}$ level measured with the $PM_{2.5}$ sensor, and CO level; (b) hourly temperature (Temp.), relative humidity (RH), and wind speed (WS) at a height of 7 m from 12 to 20 January 2017; and (c) 5 min resolution $PM_{2.5}$ and CO levels from 18 to 20 January 2017.

two high $PM_{2.5}$ episodes with 24-hour concentrations above 150 µg m^{-3} were observed. Eleven episodes with $PM_{2.5}$ levels between 100 and 150 µg m^{-3} were also detected. Increases in the daily $PM_{2.5}$ and CO were often observed several days after cold surges, which can be considered as good indicators of high $PM_{2.5}$ episodes. Hourly data showed that peaks in the $PM_{2.5}$ levels appeared at night and the peak intensities increased in the days following cold surges. Two types of haze formation were revealed by $PM_{2.5}$ data with a 5-min resolution: A very short haze episode (duration of ~1 h) with a rate of increase of 5 µg m^{-3} min^{-1} in the $PM_{2.5}$ level was observed at around 3 a.m. in November. A broader peak (duration of > 1 day) with a gradual increase was observed in January. Further studies on the formation mechanisms of $PM_{2.5}$, especially those contributing to high $PM_{2.5}$ episodes, are needed to reduce the health effects of $PM_{2.5}$ in Hanoi.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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