



Current Status of Fine Particulate Matter (PM_{2.5}) in Vietnam's Most Populous City, Ho Chi Minh City

To Thi Hien^{1*}, Nguyen Doan Thien Chi¹, Nguyen Thao Nguyen¹, Le Xuan Vinh¹,
Norimichi Takenaka², Duong Huu Huy³

¹ Faculty of Environment, University of Science, Vietnam National University – Ho Chi Minh City, Ho Chi Minh City, Vietnam

² Graduate School of Humanities and Sustainable System Sciences, Osaka Prefecture University, Osaka 599-8531, Japan

³ Faculty of Food Science and Technology, Ho Chi Minh City University of Food Industry, Ho Chi Minh City, Vietnam

ABSTRACT

This paper provides insights into fine particulate matter pollution in the urban atmosphere of Ho Chi Minh City (HCMC), the most populous city in Vietnam. Fine particulate matter (PM_{2.5}) samples were collected daily at five exposed sites from March 2017 to March 2018. PM₁₀ data (daily) and real-time PM_{2.5} (hourly) data were recorded concurrently at a roadside site. Daily particulate pollutant levels (i.e., PM_{2.5} and PM₁₀) were determined using the gravimetric method using an impact sampler, and real-time PM_{2.5} data were measured using a continuous monitor. The measured PM_{2.5} concentrations varied from 10.4 to 110.8 $\mu\text{g m}^{-3}$, with an annual mean of $36.3 \pm 13.7 \mu\text{g m}^{-3}$. All annual mean concentrations at the exposed sites exceeded the value limits of the Vietnamese standard ($25 \mu\text{g m}^{-3}$) and World Health Organization air quality guideline ($10 \mu\text{g m}^{-3}$), indicating high health risk at these sites. Although the sampling sites varied in their exposure levels, they exhibited very strong correlations and low differences in PM_{2.5} levels. Diurnal variation with a pronounced peak 2 hours after the morning rush hour was observed. This peak is likely attributable to not only primary sources (e.g., traffic-related sources) but also secondary aerosol formation. The urban atmosphere of HCMC was affected by strong local emission sources, as evidenced by the pronounced peak during morning rush hour as well as the significant negative correlation between PM_{2.5} and wind speed. In addition, monthly PM_{2.5} levels exhibited remarkable seasonal variability, with the lowest and highest levels observed during the rainy and dry seasons, respectively. However, elevated PM_{2.5} levels were observed during the months with heavy rains, highlighting the influence of strong emission sources, likely the biomass burning of rice straw residues in the Mekong Delta area.

Keywords: Ho Chi Minh City; PM_{2.5}; Urban air pollution; Tropical climate.

INTRODUCTION

Fine particulate matter with an aerodynamic diameter $\leq 2.5 \mu\text{m}$ (called PM_{2.5}) has long been recognized as the main air pollutant associated with adverse human health (Dockery, 2001; Dominici *et al.*, 2006), environmental degradation, visibility reduction, and climate change (Solomon *et al.*, 2007; Tai *et al.*, 2012; Zhao *et al.*, 2013). PM_{2.5} can be directly emitted from sources and be produced by precursors through physical-chemical transformation processes in the atmosphere. The main anthropogenic sources of PM_{2.5} are motor vehicle exhaust, biomass burning, and combustion of fossil fuels. Given its minute particle size, PM_{2.5} has long

residence time lasting several days to weeks, and it easily disperses in the atmosphere. PM_{2.5} can be removed from the atmosphere mainly by washout through precipitation. Regional distribution of PM_{2.5} pollution has been observed in many locations (Gehrig and Buchmann, 2003; Harrison *et al.*, 2012). Moreover, the effects of long-range transport on air quality have been reported (Harrison *et al.*, 2012; Wang and Ogawa, 2015). In sum, PM_{2.5} pollution is both a regional and global concern and has adverse effects on human health.

Although many countries have developed air monitoring networks, including PM_{2.5} observation using standard measurement equipment and methods, routine measurement of PM_{2.5} is rarely conducted by the Government of Vietnam. The most reliable data of PM_{2.5} levels are from the US Embassy in Hanoi and Consulate in Ho Chi Minh City (HCMC), which apply beta attenuation monitoring (BAM) instruments, per which the annual average concentrations of PM_{2.5} in Hanoi and HCMC in 2016 were 50.5 and 42 $\mu\text{g m}^{-3}$,

* Corresponding author.

Tel.: 84-8-38304379; Fax: 84-8-38304379
E-mail address: tohien@hcmus.edu.vn

respectively (<https://airnow.gov/>). The $PM_{2.5}$ concentrations in Vietnam are considerably higher than those in other cities in Europe and the US (Gehrig and Buchmann, 2003; Levy and Hanna, 2011; Harrison *et al.*, 2012), implying that the Vietnamese population is breathing air with a high level of air pollutants. In April 2013, for the first time, the Vietnamese Ministry of Natural Resources and Environment added new limits of $PM_{2.5}$ concentration to the “National Technical Regulation on Ambient Air Quality (NAAQ)” (QCVN 05:2013/BTNMT). To measure the efficiency of policy development and its implications in reducing the $PM_{2.5}$ emission in the future, understanding the current status of ambient $PM_{2.5}$, especially the long-term observation data at populous cities such as Hanoi and HCMC, is crucial.

HCMC, located in southern Vietnam, is the largest and most populous city in Vietnam. Its registered population was 8.445 million in 2017, accounting for 9% of the total population of Vietnam; however, the area of the city, 2095.5 km², accounts for only 0.6% of the country. Every year, HCMC contributes up to 30% of the total national GDP. Because of rapid economic development, HCMC is affected by a complex pollution scenario, especially air pollution. Recent epidemiological studies have revealed the effects of air pollution on respiratory and cardiovascular hospitalizations in HCMC (Mehta *et al.*, 2013; Phung *et al.*, 2016). However, these studies investigated the effects of only PM_{10} and several common gases, and not $PM_{2.5}$, which is the most serious pollutant affecting human health. The lack of adequate studies on $PM_{2.5}$ is attributable to the lack of reliable $PM_{2.5}$ data. Although the air pollution in Hanoi City, the capital of Vietnam, has attracted considerable research attention recently (Hai and Kim Oanh, 2013; Sakamoto *et al.*, 2018; Thuy *et al.*, 2018), few studies have investigated the air pollution in HCMC, the largest city in Vietnam (Huong Giang and Kim Oanh, 2014). To our knowledge, no study has evaluated the long-term observation data and different exposure sites of $PM_{2.5}$ in this region. Moreover, the data published previously have become outdated because of rapid industrialization and urbanization (Hien *et al.*, 2001). To obtain an effective management strategy, investigating the current levels of $PM_{2.5}$ and its temporal and spatial variations in HCMC is essential.

In this study, one-year field measurements of $PM_{2.5}$ based on a filter-based measurement technique were recorded at five exposed sites, including urban background, residential, and roadside sites. Furthermore, this study captured the real-time $PM_{2.5}$ data (hourly) from the air monitoring station and the daily PM_{10} data at a roadside site. This study aims to: (1) to understand the present levels of $PM_{2.5}$ in the urban atmosphere of HCMC; (2) to analyze the temporal and spatial $PM_{2.5}$ variation; (3) to investigate the effects of meteorological parameters on $PM_{2.5}$ levels; and (4) to identify possible emission sources of $PM_{2.5}$ in the HCMC metropolitan area. The results will provide useful insights for monitor siting, and relevant actions can be implemented to control aerosol pollution to meet the National Ambient Air Quality Standards of Vietnam if not the World Health Organization (WHO) standards.

EXPERIMENT

Site Descriptions

Samples were collected in HCMC from March 2017 to March 2018. Different exposed sites, including two roadside and two residential sites as well as one urban background site, were sampled. Additionally, a short sampling campaign was conducted at one rural site as a regional background site for HCMC. Twenty-four-hour samples were collected twice a week during weekdays at each site. Due to the “weekend effect”, the annual mean of $PM_{2.5}$ reported in this study could be higher than the actual annual value. The sampling locations are shown in Fig. 1, and a brief description is provided herein:

- a) Two roadside sites (Fig. 1, RO1 (10.7626°N, 106.6819°E) and RO2 (10.78°N, 106.6872°E)): The first roadside (RO1) site is at the air monitoring station at the campus of the University of Science, Vietnam National University, Ho Chi Minh City. This station is closed to Nguyen Van Cu Street (10 m from a busy road nearby and approximately 10 m above the ground level). The Nguyen Van Cu Street was a highly congested two-way street. The Street was 30 m wide with three lanes each way. There were sidewalks at both sides of the street of about 4 m wide. Several common gases and $PM_{2.5}$ were continuously measured using online instruments (Thermo suite). Hourly $PM_{2.5}$ data from FH62C14 Continuous Ambient Particulate Monitor (Thermo Fisher Scientific, USA) were averaged to 24-h filter $PM_{2.5}$ data to facilitate comparison. The temporal variation in the daily cycle was also reported for the first time in HCMC based on these continuous data. To understand the contribution of $PM_{2.5}$ to PM_{10} levels in ambient air, 24-h PM_{10} samples were concurrently collected at this site. The second roadside (RO2) site is located at the HCMC Department of Science and Technology, closed to Dien Bien Phu Street. The $PM_{2.5}$ collector was situated within the campus, approximately 10 m from a busy road. The Dien Bien Phu Street was a highly congested one-way street, with a width of 20 m. The pavement width on each street side was about 3 m. Both sides of the street were bordered by building with a height of 10 m. Both of the selected streets in this study are a typical urban street in HCMC with averaged vehicle speeds, traffic flows and traffic jam conditions. As it is common in HCMC, the composition of vehicles plying the roads was motorcycles (> 80%) followed by cars, busses and trucks (20%). A total of 90 and 91 $PM_{2.5}$ samples were collected at RO1 and RO2, respectively; 90 PM_{10} samples were collected at the RO1 site.
- b) Two residential sites (Fig. 1, RE1 (10.7717°N, 106.6839°E) and RE2 (10.7952°N, 106.7344°E)): We collected air samples at two representative residential areas. The first one (RE1) is in a downtown location (District 3), which is representative of an old district with very high population (40,000 inhabitants km⁻²) and traffic densities. The street is narrow and crowded, and traffic jams are frequent during rush hours. Many restaurants and commercial activities can be seen along the street. Sampling was conducted atop three-story



Fig. 1. Map of sampling locations.

building approximately 12 m high. The second site (RE2), located on Thu Thiem Island, is in a new urban area of HCMC. Currently, many construction activities are prevalent at this site, which is expected to become a modern urban area. The sampling device was situated in an open area approximately 1.5 m above the ground level. This site is mostly surrounded by residential districts with population density of approximately 3000 inhabitants km^{-2} . A total of 84 and 96 samples were collected at RE1 and RE2, respectively.

- c) Urban background site (Fig. 1, UB (10.7869°N, 106.7067°E)): This sampling site is located at Saigon Zoo, which is within the city centre of HCMC. Saigon Zoo, one of the oldest in the world, is the largest zoo and botanical garden in Vietnam. A total area of the zoo is 16.8 hectare, in which the green area of 13.6 hectare accounts for 81% the area of the zoo. Every year, the zoo has served approximately two million visitors. This site is in a historical area of HCMC (District 1) and is mostly surrounded by areas with residential activities, without any significant point sources of $\text{PM}_{2.5}$. The sample collection was conducted atop two-story building. This site therefore represents urban air; 90 $\text{PM}_{2.5}$ samples were collected.
- d) Rural site (Fig. 1, RU (10.615°N, 106.8156°E)): This sampling site is located at the Can Gio Mangrove Forest (Cần Giờ Biosphere Reserve), approximately 40 km southeast of HCMC. This site is populated by only a few sparsely populated, small villages; therefore, local anthropogenic emission sources are not significant. The sampler device was situated 1.5 m above the ground. Seven samples were collected for each season (i.e., dry and rainy seasons) for seven consecutive days.

Measurements

$\text{PM}_{2.5}$ samples were collected on pretreated quartz fiber

filters (Advantec, Japan) by using an IMPACT sampler (SKC, Inc., USA) at a flow rate of 10 L min^{-1} . The sampler contains two filters: a 37-mm filter for coarse particles ($> 2.5 \mu\text{m}$) and a 47-mm filter for fine particles ($\leq 2.5 \mu\text{m}$). First, air samples were drawn through the impactor for particle size separation at a cut-off size of $2.5 \mu\text{m}$. Then, the air sample bearing fine particles was continuously introduced through a 47-mm filter (second filter) for collecting the fine particles. A sampling flow rate of 10 L min^{-1} was maintained using a mass flow controller (MFC, Kojima Inc., Japan), and the total air volume was recorded using a dry gas meter (Shinagawa Corp., Japan). The MFC was periodically calibrated using a defender calibrator (SKC, Inc., USA). The air volume recorded using the dry gas meter was consistent with that calculated using the MFC (sampling time \times flow rate).

To determine $\text{PM}_{2.5}$ mass concentration, we weighed the filters before and after sampling by using a microbalance with a sensitivity of 10^{-6} g . Before weighing, the filters before and after sampling were equilibrated for 48 h in a desiccator with a temperature of $25 \pm 2^\circ\text{C}$ and relative humidity of $35 \pm 5\%$. Blank filters were also weighed similarly. To prevent an electrostatic charge during the weighting process, filter was passed through the U-electrode to neutralize static charge before it was placed on the weigh pan.

A similar procedure was adopted to collect PM_{10} samples at RO1 by using a sampling device equipped with a PM_{10} impactor (SKC, Inc., USA). In addition to 24-h $\text{PM}_{2.5}$ and PM_{10} data, real-time measurements of $\text{PM}_{2.5}$ and common gases (CO , NO_x , O_3 , CH_4 , and NMHCs) were obtained at the RO1 monitoring station. $\text{PM}_{2.5}$ was measured using a FH62C14 Continuous Ambient Particulate Monitor (Thermo Scientific) based on the principles of beta attenuation. This instrument was periodically calibrated using standard mass foils, as recommended by the manufacturer (Thermo Fisher Scientific, USA); the sampling flow rate was also checked

and calibrated. Meteorological data, namely temperature, relative humidity, wind speed, wind direction, solar radiation, and rainfall, were obtained from a nearby weather monitoring station, approximately 50 m from the monitoring station (RO1).

In this study, the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT4) model (<http://www.arl.noaa.gov/HYSPLIT.php>) was used to calculate the 72-h backward trajectories ending at RO1 at four times: 00:00, 06:00, 12:00, and 18:00 UTC daily in September, 2017 (Stein et al., 2015; Rolph et al., 2017). The arrival height of the incoming air masses was set at 100 m. The bivariate correlation and multiple linear regression analysis are conducted using SPSS software (Version 20). Some plots

noted in the footnote are generated by R (Version 3.3.3) and openair package (Carslaw and Ropkins, 2012).

RESULTS AND DISCUSSION

PM_{2.5} Levels at Specific Exposed Sites

Fig. 2 shows the daily (24-h) and monthly average mass concentrations of $PM_{2.5}$ at the five sampling sites. Table 1 summarizes the analysis results. The 1-year mean of $PM_{2.5}$ concentrations (\pm SD) at RO1, RO2, RE1, RE2, and UB were 39.1 ± 14.9 , 33.7 ± 10.9 , 31.4 ± 12.0 , 41.1 ± 15.0 , and $35.4 \pm 12.9 \mu\text{g m}^{-3}$, respectively, with a mean of $36.3 \pm 13.7 \mu\text{g m}^{-3}$. All annual values exceeded the NAAQ standards of Vietnam ($25 \mu\text{g m}^{-3}$) and WHO air quality

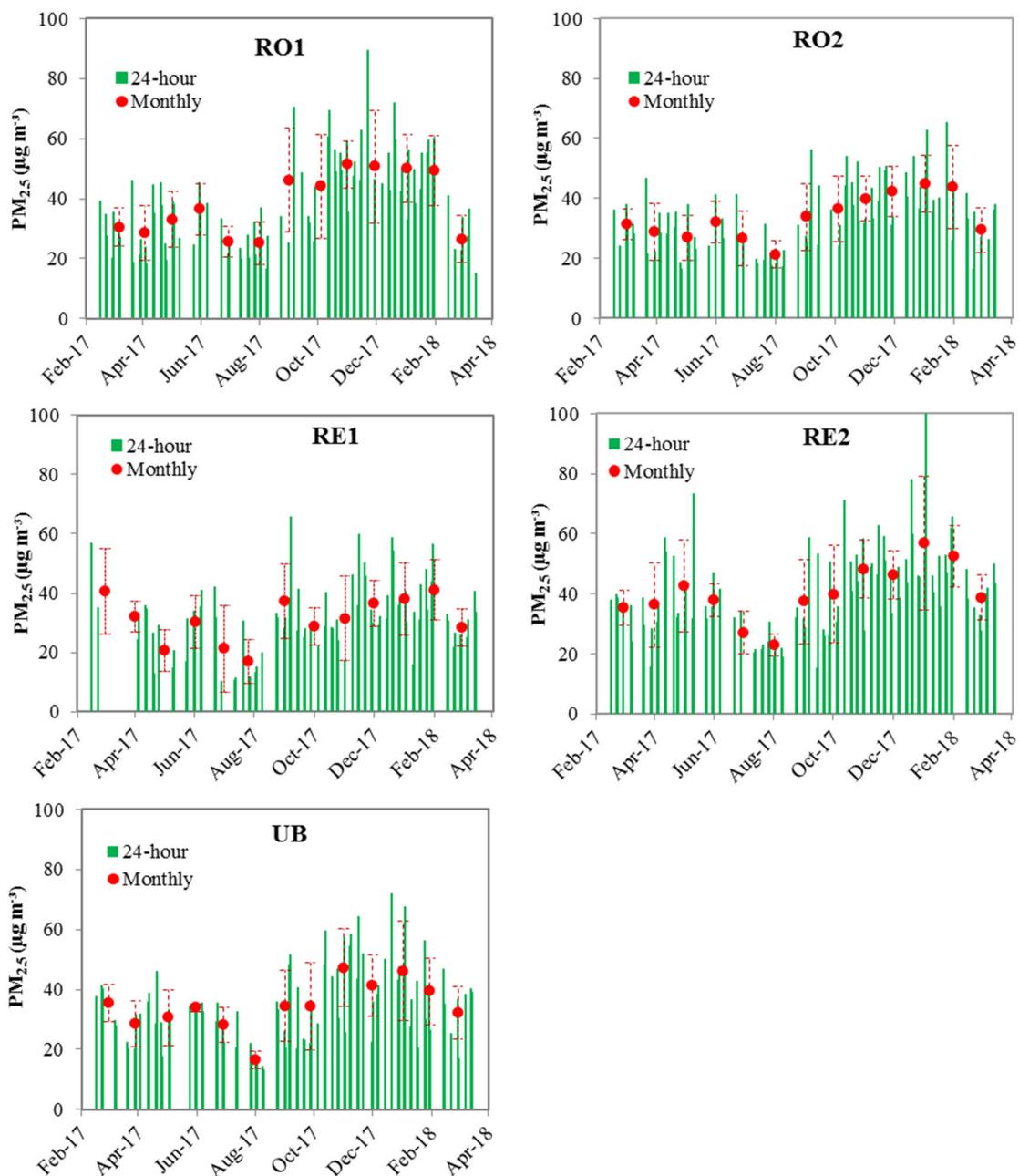


Fig. 2. Daily (24-h) average mass concentration of $PM_{2.5}$ at different exposed sites during 2017–2018.

Table 1. PM_{2.5} and PM₁₀ mass concentrations and meteorological parameters in HCMC during March 2017–March 2018.

Parameters (unit)	All data	Season	
		Dry (Dec.–Apr.)	Rainy (May–Nov.)
PM _{2.5} levels at sampling sites ($\mu\text{g m}^{-3}$)			
UB	35.4 ± 12.9 (13.3–72.0) ^a	37.7 ± 12.4 (16.8–72.0)	33.2 ± 13.1 (13.3–64.2)
RE1	31.4 ± 12.0 (10.4–65.8)	35.8 ± 10.1 (15.8–58.5)	27.7 ± 12.3 (10.4–65.8)
RE2	41.1 ± 15.0 (15.4–110.8)	45.0 ± 15.4 (15.6–110.8)	37.6 ± 13.7 (15.4–73.3)
RO1	39.1 ± 14.9 (15.1–89.2)	38.2 ± 14.3 (15.1–89.2)	40.0 ± 11.7 (16.4–70.35)
RO2	33.7 ± 10.9 (16.5–65.4)	36.7 ± 11.2 (16.5–65.4)	31.3 ± 10.2 (16.5–56.0)
Mean ^b	36.3 ± 13.7 (10.4–110.8)	39.2 ± 13.7 (15.1–110.8)	33.6 ± 13.3 (10.4–73.3)
PM ₁₀ and meteorological parameters at RO1 site			
PM ₁₀ ($\mu\text{g m}^{-3}$)	51.5 ± 18.2 (15.7–101.3)	58.2 ± 19.6 (21.8–101.3)	45.2 ± 14.3 (15.7–75.9)
PM _{2.5} /PM ₁₀ ratio	0.73 ± 0.13 (0.50–0.98)	0.68 ± 0.11 (0.50–0.84)	0.77 ± 0.15 (0.52–0.98)
Temp (°C)	28.3 ± 1.2 (24.2–31.2)	28.1 ± 1.2 (24.2–30.8)	28.5 ± 1.2 (25.6–31.2)
RH (%)	77.5 ± 6.7 (57.1–95.1)	73.7 ± 6.7 (57.7–95.1)	80.3 ± 5.2 (57.1–92.9)
WS (m s^{-1})	1.35 ± 0.45 (0.60–3.35)	1.20 ± 0.26 (0.60–2.05)	1.47 ± 0.53 (0.73–3.35)
Solar (W m^{-2})	165.4 ± 51.4 (11.9–324.1)	170.4 ± 57.0 (14.8–281.9)	161.6 ± 46.4 (48.2–324.1)
Pressure (mbar)	1007.0 ± 1.8 (1003.0–1013.9)	1008.3 ± 1.6 (1005.2–1013.9)	1006.0 ± 1.3 (1003.0–1010.0)

Note: ^a mean ± sd (min–max); ^b average concentration of all sites.

guideline ($10 \mu\text{g m}^{-3}$). The WHO updated the annual mean PM_{2.5} for more than 4000 cities in 108 countries in 2018 (<http://www.who.int/airpollution/data/cities/en/>). The annual PM_{2.5} mean in HCMC shown in WHO report was $42 \mu\text{g m}^{-3}$ during 2016, higher than the mean of $36.3 \mu\text{g m}^{-3}$ observed in this study during 2017–2018. It should be noted that the PM_{2.5} data used in WHO report was measured by the HCMC US Consulate. Therefore, this result may be because the air monitoring station at the US Consulate is located at the most crowded area of HCMC (District 1), whereas our measurements were conducted at five sites over the city. From this report, the world average PM_{2.5} concentration at city level ranges from 2 to $173 \mu\text{g m}^{-3}$, with a world mean of $18.9 \pm 18.4 \mu\text{g m}^{-3}$. The PM_{2.5} concentration in HCMC observed in this study was approximately two times higher than the world average. Thus, developing effective policies to control aerosol pollution in Vietnam is an imperative need in order to protect public health, especially in densely populated cities such as HCMC.

As can be seen in Table 1 and Fig. 2, the highest and lowest average concentrations were observed at RE2 and RE1, respectively. The sampling campaign in this study was designed to measure fine particle pollution at two representative residential sites. RE1 is located in the old district, which represents traditional residential activities, whereas RE2 is located in the new district, which has many ongoing construction activities. Our results indicate that construction activities are a crucial emission source contributing to aerosol pollution in HCMC. In the case of traffic sites, the average PM_{2.5} concentrations were relatively high. For example, a concentration of $39.1 \pm 14.9 \mu\text{g m}^{-3}$ observed at RO1 was comparable with that observed at RE2 ($41.1 \pm 14.9 \mu\text{g m}^{-3}$). With more than 7.6 million motorbikes and 0.7 million cars, traffic jams often occur within the city center during rush hour; consequently, vehicular exhaust is among the major contributors to air pollution in HCMC. The relationship between traffic pattern activity and the daily PM_{2.5} cycle at the roadside is discussed in detail in the

following section, based on the continuous and high-temporal resolution measurements. The PM_{2.5} concentration at UB was also high, with a mean of $35.4 \pm 12.9 \mu\text{g m}^{-3}$. UB is located at Saigon Zoo, and it has been used as an urban background site for a long time in the air quality network governed by the local government. For comparison, air samples were collected at a rural site of HCMC (located at the Can Gio Mangrove Forest approximately 40 km southeast of HCMC); the average concentration was $13.0 \pm 5.8 \mu\text{g m}^{-3}$. Although the sampling duration was short (1 week in each season), the PM_{2.5} concentrations were considerably lower than those within the city center because of the large number of local emission sources of PM_{2.5} within the urban area. During sampling, southeasterly (April) and southwesterly (October) winds were prevalent, but they do not pass through the city center to the rural sampling site. Therefore, emission from urban sources may not affect the aerosol levels, and this site can hence be used as a regional background site to study the effects of long-range transport. The low PM_{2.5} concentration at this site could be explained by the dilution effect of prevailing wind from the sea. Except for the rural site, surprisingly small differences were observed between these differently exposed sites within the city center of HCMC; this is discussed further later in this paper.

To understand the current status of aerosol pollution in the HCMC area, the PM_{2.5} levels observed in this study were compared with those reported in other published reports (Table 2). Few studies have investigated PM_{2.5} pollution in HCMC. A very high PM_{2.5} level of $97 \pm 31 \mu\text{g m}^{-3}$ was measured almost a decade ago (Huong Giang and Kim Oanh, 2014). However, this study was conducted over a short period, from December 2007 to January 2008, a period reported to have a very high PM_{2.5} concentration in the yearly cycle. A PM_{2.5} concentration of $21.4 \pm 24.5 \mu\text{g m}^{-3}$ was reported during May 2014, which is comparable with our current observations (Pant *et al.*, 2018). Since 2007, a significant reduction in the PM_{2.5} level could relate to

Table 2. Comparison of the measured PM_{2.5} mass concentrations ($\mu\text{g m}^{-3}$) with those reported in other studies.

Locations	Periods		PM _{2.5} ($\mu\text{g m}^{-3}$)	Refs
HCMC, Vietnam (5 sites over HCMC)	Mar 2017–Mar 2018	Yearly	36.3 ± 13.7	This study
HCMC, Vietnam (Roadside)	Dec 2007–Jan 2008	Short period	97 ± 31	(Huong Giang and Kim Oanh, 2014)
HCMC, Vietnam (Onroad)	May, 2014	Short period	21.4 ± 24.5	(Pant <i>et al.</i> , 2018)
Hanoi, Vietnam (Urban site)	Jul 2016–Jun 2017	Monthly	22–76	(Ly <i>et al.</i> , 2018)
Shanghai, China (10 sites over Shanghai)	2013–2015	Yearly	53.0	(Zhang and Cao, 2015)
Beijing, China (12 sites over Beijing)	2013–2015	Yearly	79.8	
Baoding, Hebei, China (6 sites over Baoding)	2013–2015	Yearly	118.8	
United Kingdom (urban background)	2009	Yearly	12–14	(Harrison <i>et al.</i> , 2012)

several actions such as removal of the industrial activities to outside of the city, application of new EURO standards for vehicles and fuels, and development of public transportation. Compared with other cities (e.g., Beijing or Shanghai) in China and Hanoi in Vietnam (Zhang and Cao, 2015; Ly *et al.*, 2018), the annual PM_{2.5} level is lower in HCMC but substantially higher than those reported in Europe (e.g., in the UK (Harrison *et al.*, 2012)).

PM₁₀ measurements were conducted earlier during 2003–2009 in HCMC, and high PM₁₀ concentrations were frequently observed in the urban atmosphere of HCMC (Phung *et al.*, 2016). A significant relationship between the PM₁₀ levels and hospital admissions for respiratory and cardiovascular diseases has been reported among the population in HCMC (Mehta *et al.*, 2013; Phung *et al.*, 2016). PM_{2.5} has more adverse health effects than PM₁₀, and the strong health impact of the high PM₁₀ levels in HCMC might be associated with the large contribution of PM_{2.5} to PM₁₀. In this study, reliable ratios of PM_{2.5} to PM₁₀ in the urban atmosphere of HCMC were obtained using the reference method (gravimetric method). In addition to PM_{2.5} measurement at RO1, we concurrently measured PM₁₀ by using the same sampling impactor. The PM_{2.5} to PM₁₀ ratios varied from 0.5 to 0.98, with a mean of 0.73 ± 0.13 (Table 1). These ratios are within the range (0.51–0.90) reported across Europe (Putaud *et al.*, 2010). The highest and lowest ratios occur in November and July, respectively. In the yearly cycle, the PM_{2.5} to PM₁₀ ratios have a tendency to be high at the end of the rainy season, when PM_{2.5} concentration increases.

TEMPORAL VARIATIONS

Monthly and Seasonal Variations

HCMC, located in southern Vietnam, has a tropical climate with two distinct seasons: dry (December–April) and rainy (May–November). High precipitation during the rainy season washes out the pollutant particles; therefore, precipitation plays a key role in reducing atmospheric particle loading. Generally, PM_{2.5} concentrations exhibit remarkable seasonal variability. The highest and lowest levels of PM_{2.5} are observed during the dry and rainy seasons, respectively, consistent with the clear seasonality of precipitation. The average PM_{2.5} concentrations during

the dry and rainy seasons were 39.2 ± 13.7 and $33.6 \pm 13.3 \mu\text{g m}^{-3}$, respectively.

Fig. 3 illustrates the monthly mean of PM_{2.5} concentrations at different sampling sites in HCMC from March 2017 to March 2018. Overall, the highest PM_{2.5} concentration was observed during the dry months from November through February, whereas the lowest values were observed during the rainy months of July and August. Numerous similarities in the monthly variation pattern of PM_{2.5} concentration were observed among the study sites, except for the RE2 site. The maximum PM_{2.5} concentration of $110.8 \mu\text{g m}^{-3}$ was also observed at this site. This result could be explained by many construction activities in this area. After reaching the minimum value during August, the PM_{2.5} level rapidly increased in September, and peaked from November through February, although very high precipitation occurs in September (see section “*Role of meteorological conditions on monthly PM_{2.5} distribution*” for details). Subsequently, the PM_{2.5} concentration rapidly declined from February through March up to April and then slightly increased in May and June. In contrast to September, rainfall in March and April is sparse. Therefore, we conclude that other influencing factors contribute to the monthly variation pattern of PM_{2.5} in HCMC, which are discussed later in this paper.

Diurnal Variation at the Roadside Site

This study is one of first analyses of diurnal variability of PM_{2.5} in HCMC. The study results can provide information about the time of day at which PM_{2.5} level reaches a maximum as well as about potential emission sources. In this analysis, we used the hourly PM_{2.5} data obtained using the continuous particulate monitor (FH62C14, Thermo Fisher Scientific, USA) at the roadside site (RO1). In addition to filter sampling, the air quality station at RO1 measures some core air quality pollutants (NO_x, CO, O₃, CH₄, NMHC, and PM_{2.5}) by using the Thermo suite since 2013. Therefore it is better to compare two datasets. First, the continuous PM_{2.5} data were extracted and averaged to the 24-h integrated filter measurement data. Then, the two data sets were subjected to linear regression analysis; the result revealed overall good agreement, with a slope of 1.01 and coefficient of determination of 0.84 (Fig. S1).

Fig. 4(a) shows the diurnal pattern of PM_{2.5} mass concentration during March 2017–March 2018; a pronounced

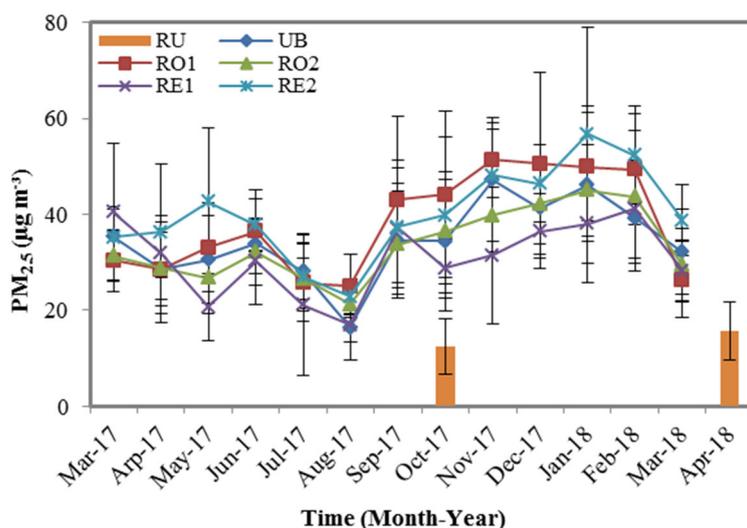


Fig. 3. Monthly average of PM_{2.5} mass concentration at six sampling sites during March 2017–March 2018. Whiskers represent ± 1 standard deviation.

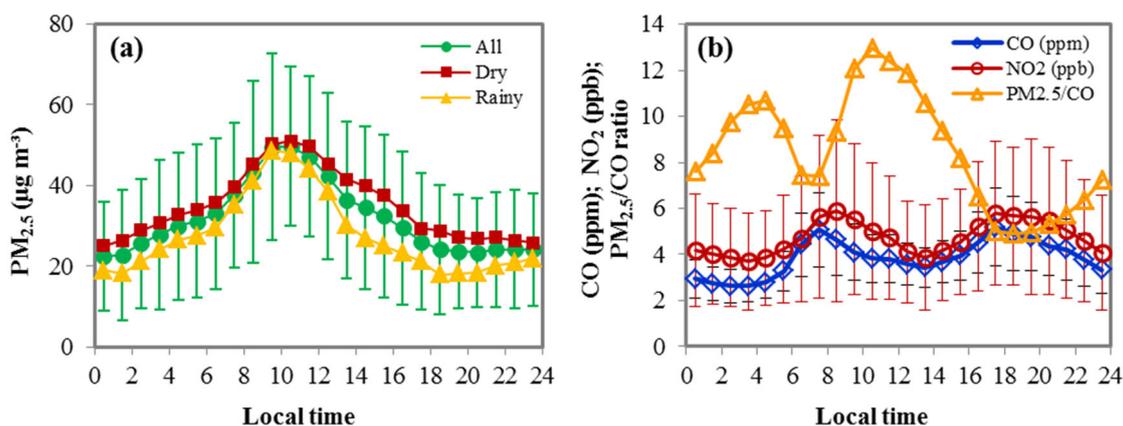


Fig. 4. Diurnal variation (a) in PM_{2.5} concentration ($\mu\text{g m}^{-3}$); (b) in CO (ppm), NO₂ (ppb) and PM_{2.5}/CO ratio ($\mu\text{g m}^{-3}/\text{ppm}$) at the roadside site (RO1) during March 2017–March 2018. Whiskers represent one standard deviation for all data.

diurnal variation in PM_{2.5} can be seen. During the daily cycle, the lowest concentration of $24.9 \pm 14.0 \mu\text{g m}^{-3}$ was noted at midnight (approximately 0:00 am), followed by an increase in the concentration until the peak was reached in the late morning. The maximum concentration of $50.9 \pm 21.6 \mu\text{g m}^{-3}$ was observed at approximately 9:00 am, one hour after rush hour (8:00 am); subsequently, the PM_{2.5} concentration decreased until midnight. Therefore, the diurnal variation in the PM_{2.5} concentration displays a unimodal pattern with a broad peak in the late morning, which is surprising because the sampling site is located near the roadside (10 m from the road and 10 m above the ground) within the urban area. Moreover, almost no significant difference in the diurnal pattern of PM_{2.5} was observed between the dry and rainy seasons; however, the PM_{2.5} level in the dry season was significantly higher than that in the rainy season (Fig. 4(a)). The peak could be explained by the contribution of the morning rush-hour traffic as well as the increase of domestic activities. The PM_{2.5} concentration decreased from the late morning due to

the greater turbulence during the day and the reduction of anthropogenic emissions. As also shown in Fig. 4(a), large contributions of local emission sources to PM_{2.5} levels were seen during the morning rush hour but not during the evening rush hour. Currently, no clear explanation is available for the absence of a peak in the PM_{2.5} levels during the evening, even though traffic flows are extremely high and traffic jams are frequent (Fig. S2).

To examine the contribution of vehicular exhaust to PM_{2.5} levels, we compared the diurnal pattern of PM_{2.5} with that of CO used as combustion tracer gas. Fig. 4(b) shows the diurnal patterns of CO and NO₂ as well as the PM_{2.5} to CO ratios. Two sharp peaks of CO concentrations were observed: one in the morning (7:00 am) and another in the late afternoon (17:00 pm). Both these peaks are consistent with those in the rush hours in the urban areas of HCMC. After peaking, the CO concentration rapidly decreased because of reduction in anthropogenic emission and increase in the dilution and dispersion effects. Similar to CO, PM_{2.5} concentrations increased in the morning due to

the increased vehicular emissions. However, the $PM_{2.5}$ concentration peaked almost 2 or 3 h later. This phenomenon has several explanations: (1) during the morning rush hour the emitted primary fine particles build up in the air at the low dispersion conditions due to their minute particle size; (2) automobiles including car, bus, light and heavy duties have a high emission of $PM_{2.5}$ and they tend to be reach at around 11:00 am (Fig. S2); (3) secondary aerosol formation from the precursor also contributes to the $PM_{2.5}$ peak. HCMC is characterized by a tropical climate with a high average temperature of 30°C throughout the year. The increase in solar radiation and temperature occurs sooner compared with other climatic zones (e.g., subtropical or temperate), thereby facilitating photochemical reactions that form secondary aerosols sooner. Very high and rapidly increasing O_3 concentrations observed in HCMC during the morning partially support this hypothesis (Fig. S3). A second significant peak in $PM_{2.5}$ consistent with the rush hour during the late afternoon was not observed in HCMC. This phenomenon implies that the $PM_{2.5}$ levels in HCMC are not only dependent on primary traffic emission but also on several other factors, such as meteorological parameters and secondary aerosol formation. Moreover, the diurnal pattern of the $PM_{2.5}$ to CO ratio ($PM_{2.5}/CO$) was compared with that of $PM_{2.5}$ in order to exclude the contribution of primary combustion emission of $PM_{2.5}$. As shown in Fig. 4(b), the diurnal variation in $PM_{2.5}/CO$ ratio shows two minimums during the two rush-hour periods, whereas a pronounced peak occurs at around 10:00 am, indicating the significant contribution of secondary aerosol.

Role of Meteorological Conditions on Monthly $PM_{2.5}$ Distribution

The monthly distribution of $PM_{2.5}$ levels over a year was similar at all sites. Therefore, we examined the influence of meteorological monthly variation on the average $PM_{2.5}$ concentrations. As reported in many locations, the highest $PM_{2.5}$ concentration was usually observed during winter months due to the greater emission of both primary particles and secondary aerosol precursors, which is mostly a result of the increased heating demands. However, the heating demand is not a practice in our tropical region (i.e., HCMC). Another reason is the reduced dispersion, which may facilitate the accumulation of air pollutants. We assume that the human activities, mainly traffic-related emissions and cooking activities do not vary significantly on a monthly basis in HCMC. The monthly variation in $PM_{2.5}$ could relate to the effect of meteorological factors. A clear understanding of atmospheric factors that influence air pollutant behavior is crucial for implementing effective policy management to improve air quality. Fig. 5 presents the monthly averaged $PM_{2.5}$ concentrations along with the meteorological parameters, including rainfall, wind direction (WD), wind speed (WS), temperature (Temp), relative humidity (RH), solar radiation (SR), and planetary boundary layer (PBL), during the study period. Table 3 presents the correlation coefficients of $PM_{2.5}$ concentrations at sites and between $PM_{2.5}$ concentrations and meteorological factors during the study period. Very high correlations of $PM_{2.5}$ (0.75–0.94)

were noted between different exposed sites. This result is consistent with data from Europe (Gehrig and Buchmann, 2003; Harrison *et al.*, 2012). The role of meteorological conditions in monthly distribution of $PM_{2.5}$ in HCMC is discussed in detail in the following paragraph.

Table 3 presents the correlation coefficients between $PM_{2.5}$ and the meteorological factors. The monthly distributions of these factors compared with the monthly $PM_{2.5}$ distributions are presented in Fig. 5. In general, only pressure exhibited a significantly positive correlation ($r = 0.50$), whereas the other parameters exhibited negative correlations (r from -0.34 to -0.79). A strong positive correlation between solar radiation and temperature ($r = 0.72$) was evident. Although high solar radiation and temperature is believed to accelerate the formation of new particles, both these parameters had a moderate negative correlation with $PM_{2.5}$ levels ($r = -0.53$ for temperature and $r = -0.48$ for solar radiation) in the present study. This result is consistent with those reported in the literature (Chen *et al.*, 2016; Li *et al.*, 2017). In addition to the acceleration of particle formation, high temperature can affect the vertical dispersion of $PM_{2.5}$ through the promotion of a higher PBL. A strong positive correlation between solar radiation and PBL ($r = 0.83$) further affirms this result. As seen in Fig. 5, the monthly patterns of temperature, solar radiation, and PBL are mostly similar. A moderate correlation was observed ($r = -0.36$) between PBL and $PM_{2.5}$. When relative humidity and rainfall were considered, a positive correlation was noted between the two elements ($r = 0.74$) with similar monthly patterns. Both these parameters exhibited a weak negative correlation with $PM_{2.5}$. Because of the wet scavenging effect induced by precipitation, the $PM_{2.5}$ levels in the rainy season were lower than those in the dry season, as previously mentioned. Among meteorological factors, the strongest correlation was obtained for wind speed and mean $PM_{2.5}$ concentration, with a correlation coefficient of -0.79 . Because of their importance, the effects of rainfall and wind on $PM_{2.5}$ levels are discussed in the following paragraphs.

Wet scavenging through precipitation is one of the main mechanisms of reducing aerosol pollution, especially $PM_{2.5}$ pollution. Fig. 5 illustrates the monthly rainfall along with the average $PM_{2.5}$ concentration. Overall, a lower $PM_{2.5}$ concentration was observed during the rainy season. The highest $PM_{2.5}$ concentration was observed during January, which coincided with the lowest rainfall (21 mm month⁻¹). The minimum $PM_{2.5}$ level was observed in August, with a rainfall of 211 mm month⁻¹. When the amount of rainfall rapidly increased from August to September (approximately two-fold higher), the $PM_{2.5}$ concentration also increased rapidly from 20.5 $\mu\text{g m}^{-3}$ in August to 37.2 $\mu\text{g m}^{-3}$ in September. Moreover, when the amount of rainfall peaked during October (462.5 mm month⁻¹), the $PM_{2.5}$ concentrations were still relatively high, suggesting that the enhanced washout by the rainfall could not offset the high contribution of several emission sources (e.g., biomass burning of crop residues). A similar result was observed from May to June. The rainfall rapidly increased from March (31.5 mm month⁻¹) to May (304 mm month⁻¹), and the $PM_{2.5}$ concentration

increased slightly (Fig. 5). Because of the fluctuation between rainfall and $\text{PM}_{2.5}$ concentrations, insignificant correlations were noted (Table 3). These results indicate that rainfall is a key meteorological factor that influences the monthly distribution of $\text{PM}_{2.5}$ in HCMC; however, other influencing factors also contribute concurrently to the monthly variation.

The HCMC metropolitan area is affected by winds along three directions: northerly-northeasterly, westerly-southwesterly, and southerly-southeasterly (Fig. S4). Fig. 6 depicts polar plots of $\text{PM}_{2.5}$ concentrations ($\mu\text{g m}^{-3}$) at the RO1 site as function of wind speed and wind direction. Overall, the local sources influencing the RO1 site are evident in higher concentrations with lower wind speeds. The polar plot also shows high concentration associated with winds from the southwest which have high wind speed (10–12 m s^{-1}), indicating possible sources elevated the $\text{PM}_{2.5}$ concentration. To explore the wind direction affecting the monthly $\text{PM}_{2.5}$ distribution, wind direction were grouped to monthly average. As also shown in Fig. 5, the $\text{PM}_{2.5}$ concentrations were generally higher than the annual average when winds blew from the northeast to the southeast. On the contrary, when winds blew from the southwest to the west, the $\text{PM}_{2.5}$ concentrations appeared to be lower than the annual mean, except in September and October (Fig. 5). The lowest average $\text{PM}_{2.5}$ concentration was observed when the winds blew from the south and southeast, originating from East Sea. In addition to wind direction, wind speed contributes to monthly $\text{PM}_{2.5}$ distributions; lower $\text{PM}_{2.5}$ concentrations

were observed during higher wind speed months and vice versa (Fig. 5). Compared with other meteorological factors, the correlations between wind speed and $\text{PM}_{2.5}$ concentrations were negatively significant, with correlation coefficients ranging from -0.69 to -0.80 , as seen in Table 3. The Mekong Delta located to the west of HCMC is the largest area for rice production in Vietnam, accounting for more than 50% of the country's total production. According to The Daily Record, Vietnam ranked fifth in the list of 10 largest rice producing countries in the world in 2017. Rice-cropping systems are divided to three systems which consist of single-, double- and triple- rice-cropping systems. The common system is triple-rice-cropping system including winter-spring (around November–February), spring-summer (around March–May) and summer-autumn (around June–September). Huge amount of straw was burned in March; however, during this period the prevailing wind blew from the southeast. Therefore biomass burning in this month does not affect to air quality of HCMC. On the other hand, June, September and October are the active months during which biomass burning of crop residues is performed in suburban areas surrounding HCMC and the Mekong Delta area, and the elevated $\text{PM}_{2.5}$ concentration during this period coincides with this activity. It is important to note during these months the prevailing winds blew from west and southwest, passing through HCMC. Furthermore backward trajectory analysis was used to assess the possible effects of regional transport on the $\text{PM}_{2.5}$ concentration in HCMC. Distance from Mekong

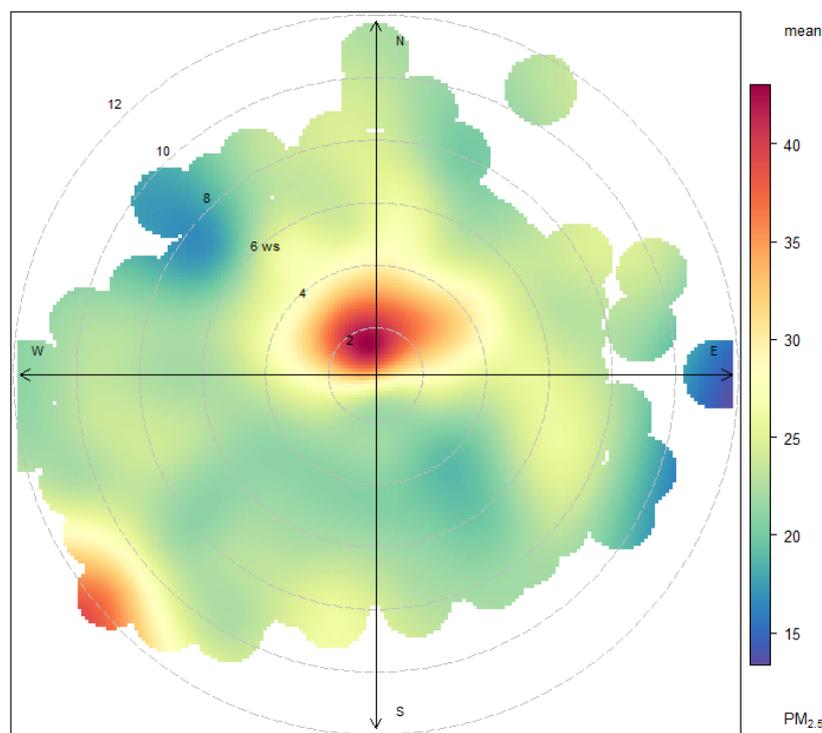


Fig. 6. Polar plot of $\text{PM}_{2.5}$ concentrations ($\mu\text{g m}^{-3}$) at the RO1 site as function of wind speed and wind direction. The wind speeds increase from 0 m s^{-1} at the centre to 12 m s^{-1} in the outer circle. High $\text{PM}_{2.5}$ concentration was observed when winds blew from the north (northwest to northeast) at low wind speed. The plot also shows the elevated $\text{PM}_{2.5}$ concentration when wind speed is high (10–12 m s^{-1}) from the southwest (Mekong Delta area). Figures plotted using the polarPlot function in Openair.

Delta area to HCMC ranges approximately from 50 to 250 km. The 72-h backward trajectories ending at RO1 were calculated using the HYSPLIT4 model at four times (0:00, 6:00, 12:00, and 18:00 UTC) daily during September in 2017. Fig. 7 shows the individual and cluster mean backward trajectories in September. Most of the trajectories passed through the Mekong Delta area before arriving at the measurement site in HCMC. This result supports our hypothesis regarding the contribution of open burning of crop residues to the enhanced PM_{2.5} levels in the downwind regions (i.e., HCMC). However, we suggest that future studies focus on chemical compositions as well as biomass burning tracers (e.g., levoglucosan) to identify this emission source.

In addition to bivariate analysis, we further carry out the relationship between PM_{2.5} and meteorological parameters using the multiple regression analysis. Because the significant correlation between the several meteorological variables was seen above, we adopted the stepwise multiple linear regression method to exclude multicollinearity. Table 4 shows the model results. There are five among seven meteorological factors included in the regression model.

Among the meteorological variables, wind speed (WS) and solar radiation (SR) are the most important determinants governing the PM_{2.5} variation. Inverse relationships are seen indicating that decrease in PM_{2.5} levels relate to the effect of dispersion and dilution. The results are in consistent with the correlation analysis. However, a relative low adjusted R² value of 0.31 is observed in the present analysis. In general, although the bivariate correlation analysis and multivariate linear regression have been used to screen the influence of the meteorological parameters on PM_{2.5} variation, more comprehensive multivariate studies are needed to figure out the complex relationship between PM_{2.5} and weather conditions in the urban area of HCMC. In the future study, we will pay more attention to analyze the PM_{2.5} variation in relation to other pollutants and meteorological factors at hourly (or daily) scale when our long-term continuous monitoring data will be generated.

CONCLUSIONS

This study investigated the ambient PM_{2.5} concentration

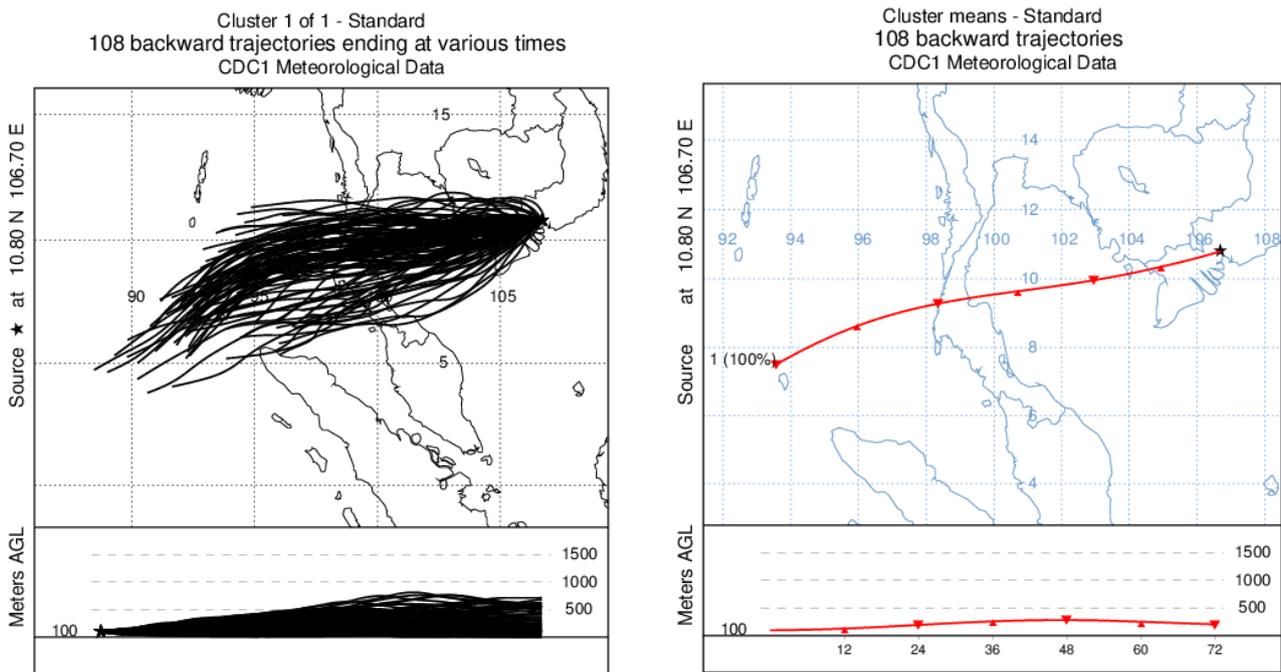


Fig. 7. Individual backward trajectories and cluster mean of backward trajectories ending at various times at the RO1 site in HCMC during September 2017.

Table 4. Result of regression analysis (*p* = 0.05).

Model variables	Intercept (± std. err.)	Estimated slope (± std. err.)	Significant value, <i>p</i>	Standardized coefficient
	35.71 (± 15.43)			
WS		-7.409 (± 1.051)	0.000	-0.399
SR		-0.041 (± 0.012)	0.009	-0.250
RH		-0.228 (± 0.082)	0.005	-0.182
Temp		1.299 (± 0.470)	0.001	0.182
PBL		-0.010 (± 0.004)	0.006	-0.165

Notes: WS wind speed, SR solar radiation, RH relative humidity, Temp ambient temperature, PBL planetary boundary layer. Model variables are in sort of decreasing the standardized regression coefficients.

measured at different exposed sites, namely urban background, roadside, and residential sites, in the urban atmosphere of the most populous city (i.e., HCMC) in Vietnam during March 2017–March 2018. The PM_{2.5} concentration varied from 10.4 to 110.8 µg m⁻³, with an annual mean concentration of 36.3 ± 13.7 µg m⁻³. This annual level exceeds the limit of the Vietnamese standard (25 µg m⁻³) and is considerably higher than that recommended by WHO air quality guideline (10 µg m⁻³). During the study period, 15.7% of the data exceeded the 24-h limit value recommended by the Vietnamese standard (50 µg m⁻³), but 79.4% of the data were higher than the WHO recommended value (25 µg m⁻³). The percent contribution of PM_{2.5} to PM₁₀ was also very high (approximately 75%).

An investigation of the daily PM_{2.5} cycle at the roadside site revealed a pronounced diurnal pattern, with a peak occurring for 2 h during the morning rush hour. A large difference between the lowest and highest PM_{2.5} concentrations during the daily cycle confirmed the presence of strong local emission sources within the urban atmosphere of HCMC. Significant negative correlations between the PM_{2.5} level and wind speed also supported this conclusion.

Monthly mean concentrations exhibited a remarkable seasonal variation, with a high concentration observed during the dry season. Because of the effect of precipitation during the rainy season, a lower PM_{2.5} concentration was observed. However, an exception was still noted from August to September when the rainfall increased while the PM_{2.5} concentration also increased. Rice straw biomass burning (from the Mekong Delta area) during this period is likely a possible emission source that causes an increase in the PM_{2.5} concentration in downwind regions. Furthermore, the similarity in monthly pattern distribution and high correlations between the different sampling sites in this study concluded that fine particulate matter pollution is a regional concern.

ACKNOWLEDGMENTS

The authors thank the Ho Chi Minh Department of Science and Technology for its support in this research under Grant No. 120/2017/HĐ-SKHCN and Japan Science and Technology Agency and Japan International Cooperation Agency, Science and Technology Research Partnership for Sustainable Development for the SATREPS project entitled “Multi-beneficial measure for mitigation of climate change in Vietnam and Indochina countries by development of biomass energy.” The authors gratefully acknowledge the NOAA Air Resources Laboratory for the provision of the HYSPLIT transport and dispersion model and READY website (<http://www.ready.noaa.gov>) used in this study.

DISCLAIMER

The authors declare no conflict of interest.

SUPPLEMENTARY MATERIAL

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

REFERENCES

- Carslaw, D.C. and Ropkins, K. (2012). *openair* — An R package for air quality data analysis. *Environ. Modell. Software* 27–28: 52–61.
- Chen, T., He, J., Lu, X., She, J. and Guan, Z. (2016). Spatial and temporal variations of PM_{2.5} and its relation to meteorological factors in the urban area of Nanjing, China. *Int. J. Environ. Res. Public Health* 13: 921.
- Dockery, D.W. (2001). Epidemiologic evidence of cardiovascular effects of particulate air pollution. *Environ. Health Perspect.* 109: 483–486.
- Dominici, F., Peng, R.D., Bell, M.L., Pham, L., McDermott, A., Zeger, S.L. and Samet, J.M. (2006). Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. *JAMA* 295: 1127–1134.
- Gehrig, R. and Buchmann, B. (2003). Characterising seasonal variations and spatial distribution of ambient PM₁₀ and PM_{2.5} concentrations based on long-term Swiss monitoring data. *Atmos. Environ.* 37: 2571–2580.
- Hai, C.D. and Kim Oanh, N.T. (2013). Effects of local, regional meteorology and emission sources on mass and compositions of particulate matter in Hanoi. *Atmos. Environ.* 78: 105–112.
- Harrison, R.M., Laxen, D., Moorcroft, S. and Laxen, K. (2012). Processes affecting concentrations of fine particulate matter (PM_{2.5}) in the UK atmosphere. *Atmos. Environ.* 46: 115–124.
- Hien, P.D., Binh, N.T., Truong, Y., Ngo, N.T. and Sieu, L.N. (2001). Comparative receptor modelling study of TSP, PM₂ and PM₂₋₁₀ in Ho Chi Minh City. *Atmos. Environ.* 35: 2669–2678.
- Huong Giang, N.T. and Kim Oanh, N.T. (2014). Roadside levels and traffic emission rates of PM_{2.5} and BTEX in Ho Chi Minh City, Vietnam. *Atmos. Environ.* 94: 806–816.
- Levy, J.I. and Hanna, S.R. (2011). Spatial and temporal variability in urban fine particulate matter concentrations. *Environ. Pollut.* 159: 2009–2015.
- Li, X., Chen, X., Yuan, X., Zeng, G., León, T., Liang, J., Chen, G. and Yuan, X. (2017). Characteristics of particulate pollution (PM_{2.5} and PM₁₀) and their space-scale-dependent relationships with meteorological elements in China. *Sustainability* 9: 2330.
- Ly, B.T., Matsumi, Y., Nakayama, T., Sakamoto, Y., Kajii, Y. and Trung Nghiem, D. (2018). Characterizing PM_{2.5} in Hanoi with new high temporal resolution sensor. *Aerosol Air Qual. Res.* 18: 2487–2497.
- Mehta, S., Ngo, L.H., Van Dzung, D., Cohen, A., Thach, T.Q., Dan, V.X., Tuan, N.D. and Giang, L.T. (2013). Air pollution and admissions for acute lower respiratory infections in young children of Ho Chi Minh City. *Air Qual. Atmos. Health* 6: 167–179.
- Pant, P., Huynh, W. and Peltier, R.E. (2018). Exposure to air pollutants in Vietnam: Assessing potential risk for tourists. *J. Environ. Sci.* 73: 147–154.
- Phung, D., Hien, T.T., Linh, H.N., Luong, L.M.T., Morawska, L., Chu, C., Binh, N.D. and Thai, P.K. (2016). Air pollution and risk of respiratory and cardiovascular

- hospitalizations in the most populous city in Vietnam. *Sci. Total Environ.* 557–558: 322–330.
- Putaud, J.P., Van Dingenen, R., Alastuey, A., Bauer, H., Birmili, W., Cyrys, J., Flentje, H., Fuzzi, S., Gehrig, R., Hansson, H.C., Harrison, R.M., Herrmann, H., Hitznerberger, R., Hüglin, C., Jones, A.M., Kasper-Giebl, A., Kiss, G., Kousa, A., Kuhlbusch, T.A.J., Löschau, G., Maenhaut, W., Molnar, A., Moreno, T., Pekkanen, J., Perrino, C., Pitz, M., Puxbaum, H., Querol, X., Rodriguez, S., Salma, I., Schwarz, J., Smolik, J., Schneider, J., Spindler, G., ten Brink, H., Tursic, J., Viana, M., Wiedensohler, A. and Raes, F. (2010). A European aerosol phenomenology – 3: Physical and chemical characteristics of particulate matter from 60 rural, urban, and kerbside sites across Europe. *Atmos. Environ.* 44: 1308–1320.
- Rolph, G., Stein, A. and Stunder, B. (2017). Real-time environmental applications and display system: Ready. *Environ. Modell. Software* 95: 210–228.
- Sakamoto, Y., Shoji, K., Bui, M.T., Phạm, T.H., Vu, T.A., Ly, B.T. and Kajii, Y. (2018). Air quality study in Hanoi, Vietnam in 2015–2016 based on a one-year observation of NO_x, O₃, CO and a one-week observation of VOCs. *Atmos. Pollut. Res.* 9: 544–551.
- Solomon, S., Qin, D., Manning, M., Averyt, K. and Marquis, M. (2007). *Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC*. Cambridge University Press.
- Stein, A., Draxler, R.R., Rolph, G.D., Stunder, B.J., Cohen, M. and Ngan, F. (2015). NOAA's HYSPLIT atmospheric transport and dispersion modeling. *Bull. Am. Meteorol. Soc.* 96: 2059–2077.
- Tai, A.P., Mickley, L.J., Jacob, D.J., Leibensperger, E., Zhang, L., Fisher, J.A. and Pye, H. (2012). Meteorological modes of variability for fine particulate matter (PM_{2.5}) air quality in the United States: Implications for PM_{2.5} sensitivity to climate change. *Atmos. Chem. Phys.* 12: 3131–3145.
- Thuy, N.T.T., Dung, N.T., Sekiguchi, K., Thuy, L.B., Hien, N.T.T. and Yamaguchi, R. (2018). Mass concentrations and carbonaceous compositions of PM_{0.1}, PM_{2.5}, and PM₁₀ at urban locations in Hanoi, Vietnam. *Aerosol Air Qual. Res.* 18: 1591–1605.
- Wang, J. and Ogawa, S. (2015). Effects of meteorological conditions on PM_{2.5} concentrations in Nagasaki, Japan. *Int. J. Environ. Res. Public Health* 12: 9089.
- Zhang, Y.L. and Cao, F. (2015). Fine particulate matter (PM_{2.5}) in China at a city level. 5: 14884.
- Zhao, H., Che, H., Zhang, X., Ma, Y., Wang, Y., Wang, H. and Wang, Y. (2013). Characteristics of visibility and particulate matter (PM) in an urban area of northeast China. *Atmos. Pollut. Res.* 4: 427–434.

Received for review, December 20, 2018

Revised, April 12, 2019

Accepted, August 26, 2019