A comparison of $PM_{2.5}$ concentrations during the COVID-19 lockdown phases and general trends in Ho Chi Minh City, Vietnam, under consideration of meteorological variables effects

Cong-Thanh TRAN[1,2], Tzong-Gang WU[1], Thi Hien TO[2], Chang-Fu WU[1], Kuo-Liong CHIEN[1,*]

[1]College of Public Health, National Taiwan University, Taiwan; [2]Vietnam National University Ho Chi Minh City, Vietnam

**Corresponding author: klchien@ntu.edu.tw*

INTRODUCTION

Ho Chi Minh City (HCMC) is one of the most air-polluted cities in Vietnam (Hien et al., 2019). However, a complicated situation of the coronavirus pandemic (COVID-19) during 2020-2021 may lead to changes of air quality in HCMC. The first Vietnamese case of the COVID-19 was reported on Jan 23, 2020 in HCMC (Nguyen and Vu, 2020). Consequently, the Vietnamese government initiated a series of policies to limit the spread of the COVID-19, including Directive 15 on social distancing measures (issued on Mar 27, 2020) and Directive 16 on quarantine measures (issued on Mar 31, 2020) (Huynh, 2020). Schools, businesses and all activities in HCMC, a city with the most heightened risk of the COVID-19 transmission in Vietnam, have been continuously cancelled or closed by Directives 15 and 16 during 2020-2021. Therefore, the air quality of HCMC during the COVID-19 lockdown phases was considerably affected, especially $PM_{2.5}$. This study was conducted to determine temporal variations of $PM_{2.5}$ concentrations in HCMC during the COVID-19 lockdown phases by using low-cost sensors. On the other hand, meteorological factors are important factors which affect changes of $PM_{2.5}$ concentrations. Therefore, this study also examined effects of meteorological factors on $PM_{2.5}$ concentrations during the COVID-19 lockdown phases.

METHODS

Data collection and Calibration

In this study, low-cost particulate matter sensors (LCPMS), Purple Air II-SD (PA) (**Fig 2**), were used to monitor ambient $PM_{2.5}$ concentrations at 5 fixed locations from January 01, 2020 to March 31, 2021. The five fixed sites were chosen to monitor $PM_{2.5}$ concentrations in five urban districts of HCMC, including District 5 (Q5), Binh Thanh District (BT), Phu Nhuan District (PN), Go Vap District (GV) and Tan Binh District (TB) (**Fig 1**). These locations were selected based on criteria for choosing monitoring locations of the Air Sensor Guidebook developed by the U.S. EPA (Williams et al., 2014). The set-up conditions of the locations are generally similar (about 4 m above ground level) but there is different with the location in District 5. The fixed site of District 5 was set up at the 11th floor of a building of University of Science, VNU-HCM, with 80 m above ground level. These locations are in a transition zone between central areas and suburbs of the city with similar characteristics. The total area of five districts is 72.08 km^2, approximately 26 percent of HCMC's urban district area. For calibration purpose, the PA sensors were set up side-by-side, in the same field conditions, with a reference instrument, a DustTrak II device (**Fig 2**), at the fixed site of Binh Thanh District during the first week of April 2023 (**Fig 2**).

The hourly $PM_{2.5}$ data of six years (2016-2021) were extracted from the US Consulate General Ho Chi Minh City (USCG-HCMC) to compare with the measured data by low-cost sensors. Meteorological measurements were collected from the U.S. National Oceanic and Atmospheric Administration during the same period time.

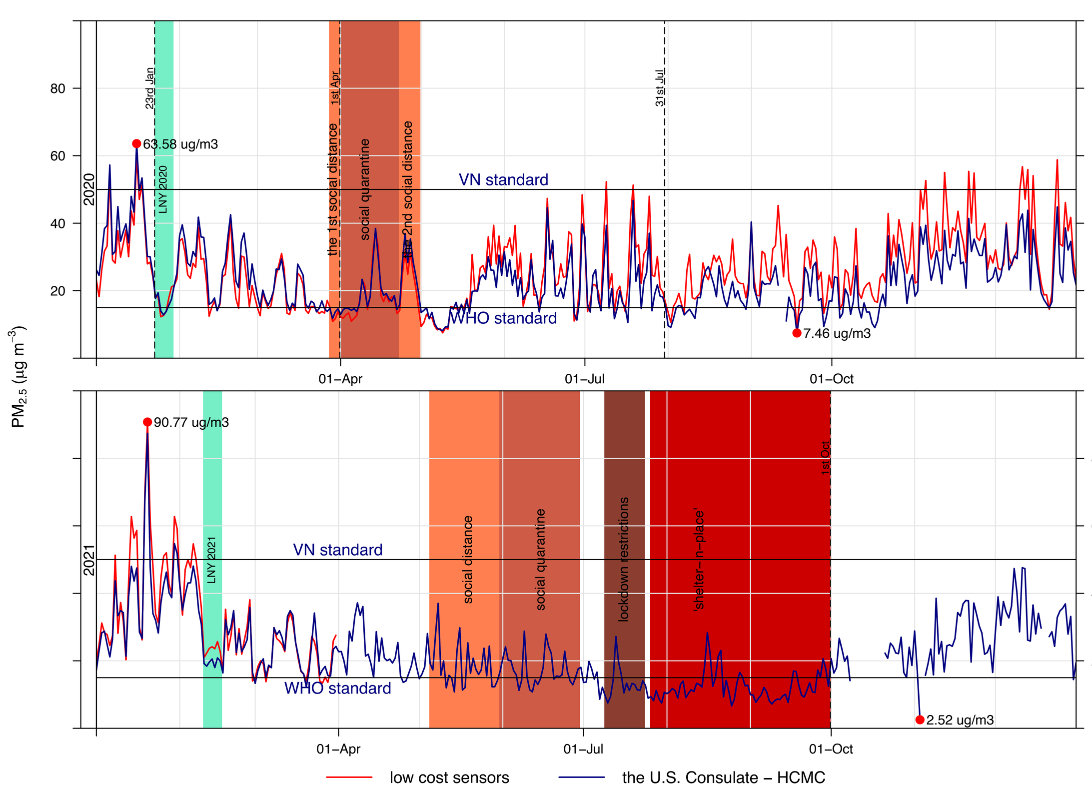

Figure 3. Daily average $PM_{2.5}$ concentrations during the COVID-19 lockdown phases of 2020 and 2021

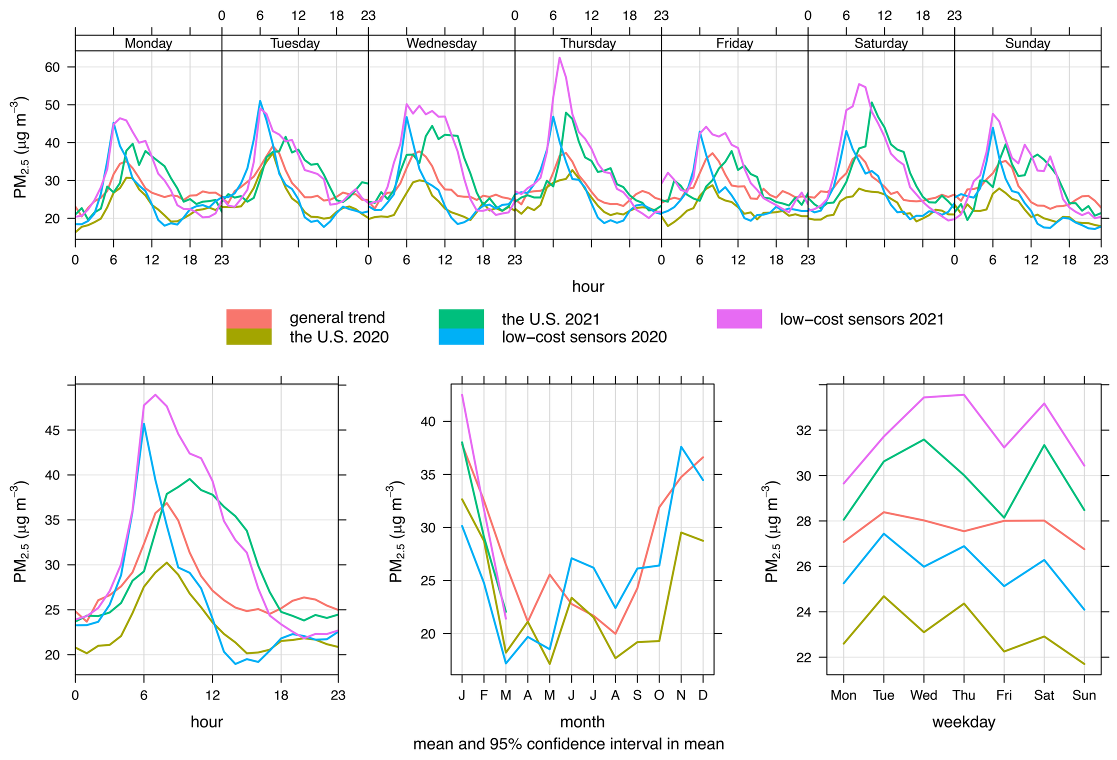

Figure 4. Variations of $PM_{2.5}$ concentrations by hour of day, day of week, and month of year in HCMC, 2016-2021

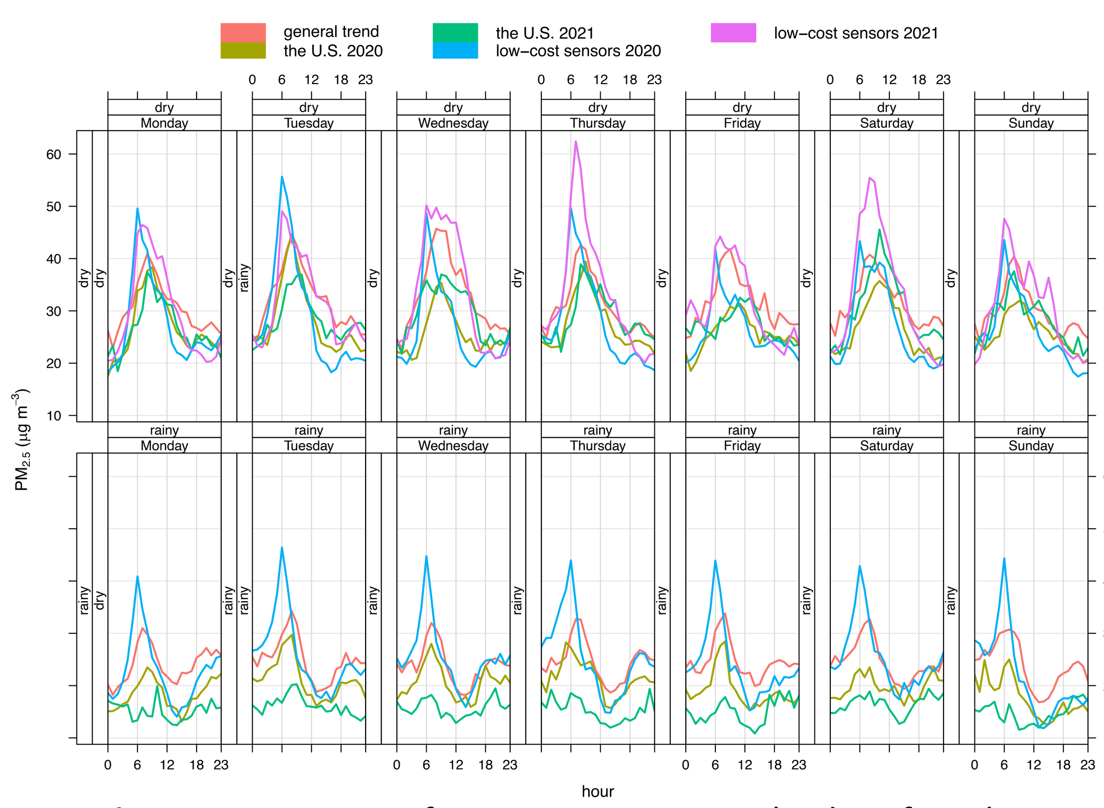

Figure 5. Variations of $PM_{2.5}$ concentrations by day of week in dry and rainy season in HCMC, 2016-2021

Data analysis

The $PM_{2.5}$ concentrations measuring by each PA sensor were calibrated with $PM_{2.5}$ measurements by the DustTrak II throughout using simple linear regression models. Then, the study evaluated data recovery of $PM_{2.5}$ concentrations. After data quality considerations, all data were tested for the normal distribution using Shapiro-Wilks test (p-value < 0.05). Next, to examine difference of $PM_{2.5}$ concentrations between the five fixed sites, the study used a one-way analysis of variance. The $PM_{2.5}$ concentrations were described temporal variations and assessed relationships with meteorological variables. Finally, the Bayesian Model Average approach was used to estimate regression model parameters in which daily average meteorological variables including wind speed, air temperature, and relative humidity act in independent variables and daily average $PM_{2.5}$ concentrations play a role in an independent variable. All statistical analyses were performed in R (version 4.0.2) by using the R stats package, the openair package (version 2.7-4), the BMA package (version 3.18.15), and the relaimpo package (version 2.2-6).

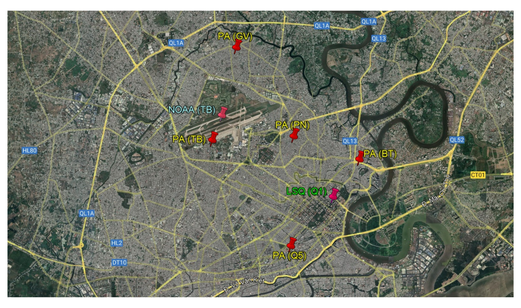

Figure 1. The study area

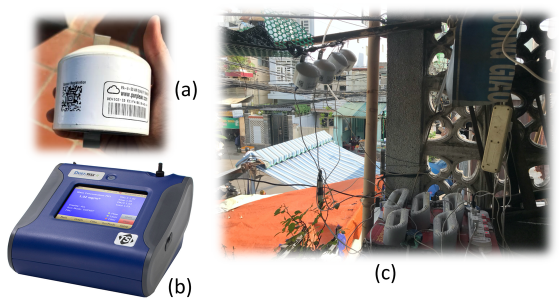

Figure 2. Instruments and calibration of low-cost sensors, (a) PurpleAir II-SD sensor, (b) DustTrak II 8530, (c) outdoor calibration at a household

RESULTS & DISCUSSION

All the calibration models are validated and R-squared values of the models are higher than 0.8 (p-value < 0.01). The results show that distributions of daily $PM_{2.5}$ concentrations of LCPMS were log-normal (p-value < 0.05). The results from the AVOVA analysis indicate that there is no observable difference in concentrations of $PM_{2.5}$ between the five fixed sites (p-value < 0.05). Thus, this study used average concentrations of the five sites as representative $PM_{2.5}$ concentrations of LCPMS measurements.

Table 1 shows the descriptive statistics of $PM_{2.5}$ concentrations measuring by LCPMS and collecting from the USCG-HCMC; wind speed; air temperature; and relative humidity. The $PM_{2.5}$ concentrations of the 2020 COVID-19 lockdown phases are lower than the general trend of 2016-2019 and the first quarter months of 2021. The daily average of meteorological variables is stable during 2016-2021.

There were sudden decreases in $PM_{2.5}$ concentrations during the COVID-19 lockdown phases of 2020 and 2021 (**Fig 3**). Indeed, daily $PM_{2.5}$ concentrations of the COVID-19 lockdown phases mostly reached the daily standards of Vietnam and the World Health Organization (May-Oct 2021). There were one-week cyclical fluctuations of $PM_{2.5}$ during the COVID-19 pandemic periods of both 2020 and 2021. The daily average $PM_{2.5}$ concentrations increased or decreased by week because the HCMC authorities also controlled or lifted the measures by the same period. For example, in Apr 2020, the concentrations enormously declined in couple days when the measures were applied very strictly; then, the concentrations moderately increased. The interesting reason for this increase was that the residents tried to go outside after having to stay at home and being limited in their social activities for so long. On the other hand, during May-Oct 2021, the concentrations suddenly rose in couple days before the measures were implemented because the residents went out to buy and hoard essential commodities and other items in these couple days.

In HCMC, the normal diurnal pattern of $PM_{2.5}$ is a two-peak pattern, a distinct peak in the morning rush hours (6-9 a.m.) and a sub peak around 6 p.m. With normal variations of $PM_{2.5}$ by day of week, the concentrations increase on weekdays and decrease on weekends. These trends were also obvious during the COVID-19 lockdown phases of 2020 and 2021 although the $PM_{2.5}$ concentrations during the periods are lower than the concentrations of general trends, 2016-2019 (**Fig 4**). In addition, the trend is similar between the two seasons in HCMC but $PM_{2.5}$ concentrations in rainy season are clearly lower than the ones in dry season (**Fig 5**).

Table 2 shows the results of multiple linear regression models using the Bayesian Model Average approach between $PM_{2.5}$ concentrations and wind speed, air temperature, and relative humidity. This study developed two models for $PM_{2.5}$ concentrations measuring by LCPMS and collecting from the USCG-HCMC. Both models have the best fit with the highest posterior probability (post prob = 100%). The intercepts and three independent variables (wind speed, air temperature, and relative humidity) are statistically significant in the two models (p-value < 0.001). All three meteorological variables negatively effect on $PM_{2.5}$ in which wind speed and air temperature quantifiably contribute on $PM_{2.5}$ changes. The adjusted R-squared values are 43% and 36% for $PM_{2.5}$ concentrations measuring by LCPMS and collecting from the USCG-HCMC, respectively (p-value < 0.001). In the context of wind speed and air temperature effects, **Fig 6** illustrates relationships between $PM_{2.5}$ concentrations and wind speed and air temperature by day.

In conclusion, using LCPMS gives us a chance to have a better understanding of temporal variations of $PM_{2.5}$ concentrations the COVID-19 lockdown phases of 2020 and 2021 in HCMC. The study pays much attention to air pollution in HCMC during the special periods because the air quality of the periods may be used as a worthy reference source to consider air quality management policies.

Table 1. Statistical summary of daily $PM_{2.5}$ concentrations and meteorological variables in HCMC, Jan 2016 – Mar 2021

	$PM_{2.5}$ measuring by LCPMS (μg/m³)		$PM_{2.5}$ collecting from the USCG-HCMC (μg/m³)			wind speed (m/s)			air temperature (°C)			relative humidity (%)		
	2020	2021	2016-2019	2020	2021	2016-2019	2020	2021	2016-2019	2020	2021	2016-2019	2020	2021
n (days)	366	90	1461	366	90	1461	366	365	1461	366	365	1461	366	365
missing data (days)	0	0	77	2	0	1	0	4	1	0	4	1	0	4
Mean	25.9	31.9	27.5	23.1	29.8	2.8	2.6	2.7	28.3	28.5	28.2	77.5	75.4	77.2
SD	10.7	15.0	11.7	9.3	12.6	1.0	0.9	1.0	1.4	1.4	1.5	9.9	11.0	9.6
Median	24.4	27.4	25.2	21.3	27.8	2.6	2.4	2.5	28.4	28.4	28.0	79.0	75.8	78.4
IQR	14.4	17.5	15.9	12.6	15.0	1.4	1.3	1.3	1.6	1.9	2.0	14.1	17.1	13.9
Minimum	7.5	13.4	3.6	7.5	12.3	0.9	1.1	1.0	21.7	25.0	23.6	48.5	48.2	45.2
Maximum	59.6	90.8	76.9	63.6	87.4	6.3	6.1	6.3	32.5	32.0	31.6	99.6	98.7	98.6

Table 2. Multiple linear regression models between $PM_{2.5}$ concentrations and wind speed, air temperature, and relative humidity by using the Bayesian Model Average approach

	Measuring by low-cost particulate matter sensors				Collecting from the US Consulate General Ho Chi Minh City			
Coefficients	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	128.36	11.20	11.46	<2e-16 ***	127.99	5.99	21.36	<2e-16 ***
wind speed (m/s)	-8.29	0.62	-13.41	<2e-16 ***	-5.70	0.24	-23.97	<2e-16 ***
air temperature (°C)	-2.17	0.34	-6.36	<2e-16 ***	-2.15	0.18	-12.04	<2e-16 ***
relative humidity (%)	-0.24	0.05	-4.79	<2e-16 ***	-0.33	0.02	-13.24	<2e-16 ***
Multiple R-squared			0.43					0.36
Adjusted R-squared			0.43					0.36
p-value			<2e-16 ***					<2e-16 ***
BIC				-232.69				-886.19
post prob				1				1

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

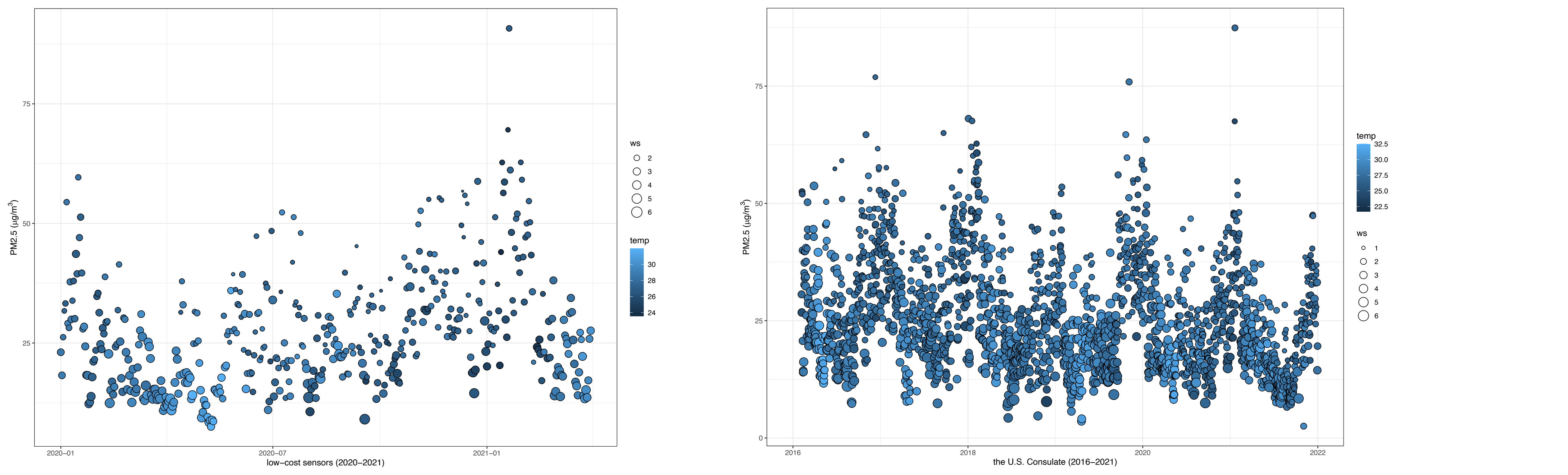

Figure 6. Scatterplots of $PM_{2.5}$ concentrations measuring by LCPMS and collecting from the USCG-HCMC with wind speed and air temperature by day in HCMC

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