Co-effects of COVID-19 and Meteorology on PM$_{2.5}$ Decrease in Ho Chi Minh City, Vietnam: A Comparison of 2016–2019 and 2020–2021

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ABSTRACT

The coronavirus disease 2019 (COVID-19) measures during 2020–2021 may lead to a downward trend of fine particulate matter (PM$_{2.5}$) concentrations in Ho Chi Minh City (HCMC), which is one of the most air-polluted cities in Vietnam. This study aimed to compare PM$_{2.5}$ variations during the COVID-19 period (2020–2021) with a short-term trend of PM$_{2.5}$ (2016–2019) in HCMC in conjunction with meteorological conditions. Five fixed-site locations were chosen to monitor PM$_{2.5}$ concentrations by using low-cost particulate matter sensors (Purple Air II SD) in five urban districts of HCMC from December 2019 to March 2021. This study also collected hourly PM$_{2.5}$ concentrations from the United States Consulate General HCMC and meteorological variables (i.e., wind speed, wind direction, air temperature, and relative humidity) from the weather station at Tan Son Nhat International Airport, 2016–2021. PM$_{2.5}$ concentrations of the COVID-19 period in HCMC were notably less than those of the 2016–2019 period by 18%. However, about half of the days during this period still had daily PM$_{2.5}$ concentrations exceeding the World Health Organization’s standard of 15 $\mu$g m$^{-3}$. Besides the impacts of COVID-19 restrictions on the PM$_{2.5}$ decrease, noticeable co-effects of meteorological variables on the decline of PM$_{2.5}$ in HCMC were also observed in the rainy season and with the west-south-west monsoon wind direction. Wind speed and air temperature substantially contributed to PM$_{2.5}$ reductions in Bayesian multiple linear regression models. In conclusion, the large decrease of PM$_{2.5}$ concentrations during the unprecedented period of COVID-19 pandemic gave us a better chance to more fully comprehend the PM$_{2.5}$ pollution status in HCMC for future reference.

Keywords: Air pollution, Coronavirus, Weather conditions, Low-cost sensors, Bayesian

1 INTRODUCTION

Ho Chi Minh City (HCMC) is one of the most PM$_{2.5}$-polluted cities in Vietnam, which greatly affects economic as well as health-related issues (Bui and Nguyen, 2023). A study in 2019 reported that the PM$_{2.5}$ pollution level in HCMC was larger than that in other cities in Vietnam, specifically, the annual average concentration of PM$_{2.5}$ in HCMC in 2019 was 36.3 ± 13.7 $\mu$g m$^{-3}$ (Hien et al., 2019), exceeding both the World Health Organization (WHO) and Vietnam annual standards of 5 $\mu$g m$^{-3}$ and 25 $\mu$g m$^{-3}$, respectively (WHO, 2021; MoNRE, 2023). In the context of PM$_{2.5}$ pollution, public health measures in controlling the spread of coronavirus disease 2019 (COVID-19) may lead to abnormal variations of PM$_{2.5}$ during the implementation period. As a result, much attention has also been paid to the PM$_{2.5}$ pollution during this unprecedented period by many investigators.
around the world because the air quality of this period may be used as a worthy reference source to consider air quality management policies (Chauhan and Singh, 2020; Kanniah et al., 2020; Rodriguez-Urrego and Rodriguez-Urrego, 2020; Gkatzelis et al., 2021; Khan et al., 2021).

In Vietnam, the first case of COVID-19 was reported in HCMC on 23 January 2020, which was also the first day of the 2020 Lunar New Year (LNY) holidays (Nguyen and Vu, 2020). Since then, the Vietnamese government initiated activities for prevention and control measures for COVID-19 (Tran et al., 2020). Directive 15 on social distancing measures (issued on 27 March 2020) and Directive 16 on quarantine measures (issued on 31 March 2020) were released by the Vietnamese Prime Minister. Notably, HCMC was one of the cities with the most heightened risk of the COVID-19 transmission in Vietnam. In 2020, schools, businesses, and all activities for large crowds in HCMC were continuously cancelled or closed by Directives 15 and 16 during March to April 2020 (Table 1). In 2021, the social distancing and quarantine measures were implemented from May to June. Then, HCMC was in lockdown from 09 July to 15 September 2021; especially during 26 July to 15 August 2021, HCMC was under a militarily enforced lockdown, “shelter-in-place” (Table 1). During this period, all activities were suspended except medical emergencies, and the residents of HCMC were not allowed to go outside from 6 p.m. until 6 a.m. The militarily enforced lockdown in HCMC was extended until 15 September 2021. Next, the HCMC authorities lifted measures in a phased, step-by-step manner. Finally, the HCMC authorities ended lockdown restrictions on 01 October 2021.

Table 1. Different COVID-19 periods in Ho Chi Minh City, Vietnam during 2020–2021.

<table>
<thead>
<tr>
<th>Event</th>
<th>Start date</th>
<th>End date</th>
<th>Description</th>
<th>Event length (days)</th>
<th>PM$_{2.5}$ pollution days$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar New Year 2020</td>
<td>23/01/2020</td>
<td>29/01/2020</td>
<td>Economic activities to temporarily shut down due to lunar new year</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>1$^{st}$ COVID-19 case</td>
<td>23/01/2020</td>
<td>–</td>
<td>The first COVID-19 case in Vietnam</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Social distance I</td>
<td>28/03/2020</td>
<td>31/03/2020</td>
<td>According to the Prime Minister’s Directive 15, schools and non-essential retail were closed, 10-person limit on public gatherings</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Declaration of COVID-19 as a national epidemic</td>
<td>01/04/2020</td>
<td>–</td>
<td>Prime Minister Nguyen Xuan Phuc officially declared COVID-19 as a national epidemic on April 1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Social quarantine I</td>
<td>01/04/2020</td>
<td>22/04/2020</td>
<td>According to the Prime Minister’s Directive 16, work from home, 2-person limit on public gatherings</td>
<td>21</td>
<td>14</td>
</tr>
<tr>
<td>Social distance II</td>
<td>23/04/2020</td>
<td>30/04/2020</td>
<td>Social distance measures according to the Prime Minister’s Directive 15</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>1$^{st}$ COVID-19 death</td>
<td>31/07/2020</td>
<td>–</td>
<td>The first COVID-19 death in Vietnam</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Lunar New Year 2021</td>
<td>10/02/2021</td>
<td>16/02/2021</td>
<td>Economic activities to temporarily shut down due to lunar new year</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Social distance III</td>
<td>05/05/2021</td>
<td>30/05/2021</td>
<td>Social distance measures according to the Prime Minister’s Directive 15</td>
<td>25</td>
<td>17</td>
</tr>
<tr>
<td>Social quarantine II</td>
<td>31/05/2021</td>
<td>29/06/2021</td>
<td>High alert measures according to the Prime Minister’s Directive 15</td>
<td>29</td>
<td>19</td>
</tr>
<tr>
<td>Lockdown I</td>
<td>09/07/2021</td>
<td>23/07/2021</td>
<td>Lockdown, stay at home</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>Shelter-in-place</td>
<td>26/07/2021</td>
<td>15/08/2021</td>
<td>Very strict contain measures, all activities shut down, 6 p.m. to 6 a.m.</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Lockdown II</td>
<td>16/08/2021</td>
<td>15/09/2021</td>
<td>Back to lockdown, stay at home</td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>Social quarantine III</td>
<td>16/09/2021</td>
<td>30/09/2021</td>
<td>Back to high alert measures according to the Prime Minister’s Directive 16</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>Out of social quarantine Total (days)</td>
<td>01/10/2021</td>
<td>–</td>
<td>Most restrictions lifted</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

$^a$ Number of days exceeding the World Health Organization daily standard for PM$_{2.5}$ of 15 µg m$^{-3}$.

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2021. Overall, the COVID-19 prevention and control measures in HCMC in 2021 were obviously stricter than those in 2020, and the implementation duration in 2021 was also longer than this in 2020.

As in many countries around the world, Vietnam in fact witnessed authoritarian measures at degrees of strictness and durations at different periods of the event. Hence, comprehension on PM$_{2.5}$ changes in the country under the circumstances of COVID-19 could benefit from studies and observations throughout the COVID-19 period. Some studies reported that the COVID-19 measures caused reductions of PM$_{2.5}$ concentrations in HCMC (Tran et al., 2023), Hanoi (Rodriguez-Urregro and Rodriguez-Urregro, 2020), and some provinces and cities of Vietnam (Nguyen et al., 2023a). However, the previous studies mainly observed the period of late 2019 to early 2021, and none had been conducted on behalf of the period from May to Sep. 2021; while the COVID-19 conditions were more severe during the latter, especially in HCMC. Therefore, it should be necessary to investigate PM$_{2.5}$ variations in HCMC during the whole COVID-19 period (2020 and 2021) and compare the changes between this period with the same period of previous years.

On the other hand, meteorological variables have been consistently considered as among important factors affecting PM$_{2.5}$ variations (Khan et al., 2018; Yang et al., 2018; Nogarotto and Pozza, 2020). As a typical representative of the southern climate of Vietnam, HCMC is also affected by the annual tropical monsoon climate (Hoang et al., 2022). There are two main seasons in HCMC: the dry season (November–April) and the rainy season (May–October). Due to effects of monsoons, there are three prevailing wind directions in different seasons in HCMC, i.e., the south-south-east (SSE) wind direction from March to May (pre-monsoon), the west-south-west (WSW) wind direction from June to October (monsoon), and the north-north-east (NNE) wind direction from November to February (post-monsoon). Several researchers have investigated that PM$_{2.5}$ concentrations in HCMC were greatly affected by weather conditions (Hien et al., 2019; Phan et al., 2020; Nguyen et al., 2023b). Hence, it is also needed to examine meteorological impacts in terms of the relationship between COVID-19 measures and PM$_{2.5}$ in HCMC.

In general, this study aimed to explore impacts of both COVID-19 restrictions and meteorological factors on PM$_{2.5}$ variations in HCMC. The main issues addressed in this paper are: (1) to observe temporal variations of meteorological variables and PM$_{2.5}$ concentrations in HCMC by using data between 2016 and 2021; (2) to determine simultaneous effects of COVID-19 measures and meteorological factors on PM$_{2.5}$ concentrations by dividing the study period into two sub-periods of 2016–2019 (a short-term trend) and 2020–2021 (the COVID-19 period).

2 MATERIALS AND METHODS

2.1 Data Collection

2.1.1 Meteorological variables

Hourly meteorological variables, including wind speed (m s$^{-1}$), wind direction, air temperature (°C), and relative humidity (%) were used in this study. These meteorological variables were obtained from the weather station at Tan Son Nhat International Airport from 01 January 2016 to 31 December 2021 (NOAA, 2022).

2.1.2 PM$_{2.5}$ data from the United States Consulate General Ho Chi Minh City

The United States Consulate General Ho Chi Minh City (USCG-HCMC) has installed an air quality monitor to measure PM$_{2.5}$ concentrations at number 4 Le Duan Street, District 1, HCMC, Vietnam (Fig. S1, Supplementary) (AirNow, 2022). The BAM-1020 Met One Instrument, which using beta attenuation technology, was used to monitor PM$_{2.5}$ concentrations. We collected hourly PM$_{2.5}$ concentrations from the USCG-HCMC between 01 January 2016 and 31 December 2021 (AirNow, 2022). For convenience, we will use US-PM$_{2.5}$ or us_pm2.5 as a representative of PM$_{2.5}$ concentrations collected from the USCG-HCMC.

2.1.3 Monitoring PM$_{2.5}$ concentrations by low-cost particulate matter sensors

Five fixed-site locations were chosen to monitor PM$_{2.5}$ concentrations in five urban districts of HCMC, i.e., Binh Thanh District (binh_thanh_dist), Phu Nhuan District (phu_nhuan_dist), Go Vap
District (go_vap_dist), Tan Binh District (tan_binh_dist), and District 5 (dist_5) (Fig. S1, Supplementary). According to the Air Sensor Guidebook developed by the United States Environmental Protection Agency (U.S. EPA), we selected these locations based on criteria for selecting a fixed-site location to monitor PM$_{2.5}$ (Williams et al., 2014). These locations were in a transition zone between central areas and suburbs of the city with similar characteristics. Total area of the five districts was 72.08 km$^2$, covering approximately 26% of the urban district area of HCMC. The average population of the study area in 2021 was 1,728,457 persons, about 33% of the urban district population of HCMC (HCMC Statistical Office, 2021).

In this study, low-cost particulate matter sensors (LCPMs), Purple Air II-SD (PA), were used to monitor ambient PM$_{2.5}$ concentrations (Table S2 and Fig. S2(a), Supplementary). The working principle of PA sensors was based on optical principles (Morawska et al., 2018). Each PA sensor had a small fan to provide uniform air flow through a measured chamber and dual sensors to measure particles simultaneously (PurpleAir, 2023). Previous studies reported that PA sensors had sufficient capability to provide good performance (Baron and Saffell, 2017; Morawska et al., 2018).

DustTrak II Aerosol Monitor 8530 (DustTrak II) was used as a reference device to calibrate LCPMs in our study (Table S2 and Fig. S2(b), Supplementary). The DustTrak II device was a real-time aerosol mass measurement instrument which also based on optical methods (TSI, 2023). It could measure concentration of aerosols corresponding to PM$_1$, PM$_{2.5}$, and PM$_{10}$. The device recorded single-channel data and operated on internal batteries or used a direct power supply. The data was stored with internal memory and downloaded in text format (.txt).

For calibration purpose, we set up all the PA sensors side by side, in the same field conditions, with the DustTrak II device at the fixed-site location in Binh Thanh District during the first week of April 2021 (Fig. S2(c), Supplementary). For monitoring set up, the PA sensors were set up to allow free air flow through the sensors. According to the Air Sensor Guidebook from U.S. EPA, the locations were at least 4 m above ground level and separated from other building surfaces by a distance of not less than 1 m (Williams et al., 2014). Four PA sensors were used to monitor PM$_{2.5}$ concentrations in the five districts during different durations (between 14 December 2019 and 31 March 2021). Detailed descriptions of the five fixed-site locations are shown in Table S1, Supplementary. Set-up conditions were generally similar in all locations except the location in District 5. The location of District 5 was set up at the 11th floor of a building (80 m above ground level) of the University of Science, Vietnam National University Ho Chi Minh City. The sensors were continuously operated with electricity 24/7 during the study period. Also, the sensors were maintained by regular on-site examination to ensure that the measure conditions were stable. The data were weekly collected by both downloading online data and extracting data from SD cards. In this study, the error and missing values were examined. The missing values due to power outages during the study period were also checked.

2.2 Data Analysis

2.2.1 Data calibration and data completeness

Using simple linear regression models, 5-minute average PM$_{2.5}$ concentrations measured by the PA sensors were calibrated with those measured by the DustTrak II device. After calibration with the DustTrak II device, the PM$_{2.5}$ concentrations measured by the PA sensors were adjusted for effects of relative humidity according to the methods from our previous publications (Wu et al., 2005; Wu et al., 2022). The detailed calibration methods are described in Table S3 of Supplementary. Three model evaluation statistics, i.e., root mean squared error, coefficient of efficiency, and index of agreement were used to evaluate data quality. Also, missing values and error values of meteorological variables and PM$_{2.5}$ concentrations were checked by data recovery metrics (Williams et al., 2014) (Table S4, Supplementary).

2.2.2 Descriptive analysis and testing hypothesis

Hourly and daily PM$_{2.5}$ concentrations were tested for the normal distribution by using Shapiro–Wilk test and Kolmogorov–Smirnov test. For PM$_{2.5}$ concentrations measured by the PA sensors, to examine differences in mean concentrations between the five fixed-site locations, we
used a one-way analysis of variance (ANOVA) with Tukey’s honest significant difference test as well as intra-model variability metrics (Williams et al., 2014) (Table S4, Supplementary). We used average concentrations of all the locations as representatives of PM$_{2.5}$ concentrations of LCPMSs in order to compare with PM$_{2.5}$ concentrations collected from the USCG-HCMC. For convenience, we also used PA-PM$_{2.5}$ or pa_pm2.5 as a representative of average PM$_{2.5}$ concentrations measured by the PA sensors. Next, Pearson correlation coefficients were used to test correlations of meteorological variables, US-PM$_{2.5}$, and PA-PM$_{2.5}$ concentrations. Meteorological variables and PM$_{2.5}$ concentrations were performed by using the OpenAir package (version 2.7-4). All statistical analyses were performed in R (version 4.0.2). A p-value < 0.05 was considered statistically significant.

2.2.3 Bayesian multiple linear regression models

We examined associations between meteorological variables and US-PM$_{2.5}$ concentrations (Model 1) and PA-PM$_{2.5}$ concentrations (Model 2) by multiple linear regression models. The Bayesian Model Average approach (BMA) was used to build the models (Fragoso et al., 2018). In the models, the average daily PM$_{2.5}$ concentration was used as a dependent variable, and daily meteorological variables (i.e., wind speed, air temperature, and relative humidity) and two binary variables related to days of LNY holidays and COVID-19 periods (0 = no event, 1 = event) were used as independent variables. The importance of independent variables in the models was evaluated by relative importance metrics. The validation of models was tested by using adjusted R-squared values, root mean squared error (RMSE), and mean absolute error (MAE). All statistical analyses were performed in R (version 4.0.2) by using the BMA package (version 3.18.15) and the relaimpo package (version 2.2-6).

3 RESULTS AND DISCUSSION

3.1 Data Descriptions

3.1.1 Meteorological variables

Hourly wind speed, wind direction, air temperature, and relative humidity were gathered from 2016 to 2021 with a total of 2,190 days. Both hourly and daily meteorological variables were used in this study. During 2016–2021, the daily average of wind speed was 2.8 ± 1.0 m s$^{-1}$, air temperature was 28.3 ± 1.4°C, and relative humidity was 77.1 ± 10.0% (Table 2). The correlations of meteorological variables are shown in Fig. 1. There was a strong negative correlation between air temperature and relative humidity ($R = -0.78$, p-value < 0.05). Air temperature was positively correlated with wind speed but relative humidity had a negative correlation with wind speed. Overall, daily meteorological variables in HCMC during 2016–2021 remained stable year by year, in dry and rainy season, and in three prevailing wind directions (Supplementary, Tables S5–S7).

3.1.2 PM$_{2.5}$ concentrations collected from the USCG-HCMC

Of the 2,191 days during the study period, PM$_{2.5}$ concentrations of 2,099 days (96%) were collected from the USCG-HCMC. The hourly US-PM$_{2.5}$ concentrations were log-normally distributed while the daily concentrations were normally distributed. The daily mean of US-PM$_{2.5}$ concentrations during 2016–2021 was 25.8 ± 11.4 µg m$^{-3}$ (Table 2). For annual means of US-PM$_{2.5}$ concentrations, Fig. 2(a) shows that the annual means decreased year by year from 2016 to 2021 (from approximately 30 to 20 µg m$^{-3}$). There were three groups of daily PM$_{2.5}$ concentrations in descending order, including: 2016–2017, 2018–2019, and 2020–2021 (Fig. 2(a)). Except for the COVID-19 period, PM$_{2.5}$ concentrations during 2016–2019 exceeded the Vietnam annual standard of 25 µg m$^{-3}$ (MoNRE, 2023).

3.1.3 PM$_{2.5}$ concentrations measured by LCPMSs

All the calibration models of LCPMSs were validated. The R-squared values of the models were between 0.91 and 0.93 (p-value < 0.01) (Supplementary, Table S3). The model evaluation statistics were within acceptable ranges, e.g., root mean squared error (7.00–7.76 µg m$^{-3}$), coefficient of
Table 2. Descriptive statistics of daily PM$_{2.5}$ concentrations and meteorological variables in Ho Chi Minh City during the study period (2016–2021), a short-term trend (2016–2019), and the COVID-19 period (2020–2021) (Unit of PM$_{2.5}$: µg m$^{-3}$).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (days)</td>
<td>Min</td>
<td>Max</td>
<td>Median (IQR)</td>
<td>Mean ± SD</td>
<td></td>
</tr>
<tr>
<td>PM$_{2.5}$ in Binh Thanh Dist</td>
<td>473</td>
<td>9.8</td>
<td>95.0</td>
<td>26.6 (15.9)</td>
<td>29.0 ± 12.3</td>
<td>N/A</td>
</tr>
<tr>
<td>PM$_{2.5}$ in Phu Nhuan Dist</td>
<td>473</td>
<td>6.0</td>
<td>80.5</td>
<td>23.8 (15.8)</td>
<td>25.3 ± 11.6</td>
<td>N/A</td>
</tr>
<tr>
<td>PM$_{2.5}$ in Go Vap Dist</td>
<td>473</td>
<td>9.4</td>
<td>96.8</td>
<td>29.9 (15.9)</td>
<td>33.1 ± 13.4</td>
<td>N/A</td>
</tr>
<tr>
<td>PM$_{2.5}$ in Tan Binh Dist</td>
<td>313</td>
<td>7.2</td>
<td>68.1</td>
<td>24.3 (13.2)</td>
<td>25.7 ± 10.9</td>
<td>N/A</td>
</tr>
<tr>
<td>PM$_{2.5}$ in Dist 5</td>
<td>150</td>
<td>4.5</td>
<td>46.0</td>
<td>14.1 (11.6)</td>
<td>15.9 ± 8.5</td>
<td>N/A</td>
</tr>
<tr>
<td>PA-PM$_{2.5}$ $^a$</td>
<td>473</td>
<td>7.5</td>
<td>90.8</td>
<td>25.4 (14.7)</td>
<td>27.3 ± 11.9</td>
<td>N/A</td>
</tr>
<tr>
<td>US-PM$_{2.5}$ $^b$</td>
<td>2,099</td>
<td>2.5</td>
<td>87.4</td>
<td>23.7 (15.6)</td>
<td>25.8 ± 11.4</td>
<td>27.5 ± 11.7</td>
</tr>
<tr>
<td>Wind speed (m s$^{-1}$)</td>
<td>2,190</td>
<td>0.8</td>
<td>6.3</td>
<td>2.6 (1.4)</td>
<td>2.8 ± 1.0</td>
<td>2.8 ± 1.0</td>
</tr>
<tr>
<td>Air temperature ($°$C)</td>
<td>2,190</td>
<td>21.7</td>
<td>32.5</td>
<td>28.3 (1.8)</td>
<td>28.3 ± 1.4</td>
<td>28.3 ± 1.5</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>2,190</td>
<td>45.2</td>
<td>99.6</td>
<td>78.3 (14.9)</td>
<td>77.1 ± 10.0</td>
<td>77.5 ± 9.9</td>
</tr>
</tbody>
</table>

$^a$ PA-PM$_{2.5}$ as a representative of average PM$_{2.5}$ concentrations measured by all PurpleAir sensors in five locations.

$^b$ US-PM$_{2.5}$ as a representative of PM$_{2.5}$ concentrations collected from the United States Consulate General Ho Chi Minh City.

N/A: not applicable.

Fig. 1. Correlations between hourly meteorological variables and PM$_{2.5}$ concentrations measured by low-cost particulate matter sensors and collected from the United States Consulate General Ho Chi Minh City in Ho Chi Minh City during 2016–2021. Notes: ws: wind speed (m s$^{-1}$); temp: air temperature ($°$C); rh: relative humidity (%); bnh_thanh_dist: PM$_{2.5}$ concentrations measured by a PurpleAir sensor in Binh Thanh District ($µg$ m$^{-3}$); phu_nhuan_dist: PM$_{2.5}$ concentrations measured by a PurpleAir sensor in Phu Nhuan District ($µg$ m$^{-3}$); tan_bin_dist: PM$_{2.5}$ concentrations measured by a PurpleAir sensor in Tan Binh District ($µg$ m$^{-3}$); go_vap_dist: PM$_{2.5}$ concentrations measured by a PurpleAir sensor in Go Vap District ($µg$ m$^{-3}$); dist_5: PM$_{2.5}$ concentrations measured by a PurpleAir sensor in District 5 ($µg$ m$^{-3}$); pa_hour_ave: average PM$_{2.5}$ concentrations measured by all PurpleAir sensors in five locations ($µg$ m$^{-3}$); us_pm2.5: PM$_{2.5}$ concentrations collected from the United States Consulate General Ho Chi Minh City ($µg$ m$^{-3}$).
Fig. 2. (a) Annual means of PM$_{2.5}$ concentrations collected from the USCG-HCMC in 2016–2021 and (b) daily means of PM$_{2.5}$ concentrations measured by LCPMSs at fixed-site locations during 2020–2021 and collected from the USCG-HCMC during 2016–2021. Notes: pa_hour_ave: average PM$_{2.5}$ concentrations measured by all PurpleAir sensors in five locations; us_16_19: PM$_{2.5}$ concentrations collected from the USCG-HCMC during 2016–2019, a short-term trend; us_20_21: PM$_{2.5}$ concentrations collected from the USCG-HCMC during 2020–2021, the COVID-19 period.

efficiency (0.75–0.77), and index of agreement (0.87–0.89) (Supplementary, Table S3). These results indicated that PM$_{2.5}$ concentrations measured by LCPMSs may ensure sufficient reliability for the following analysis.

PM$_{2.5}$ concentrations were monitored by PA sensors at the five fixed-site locations during different durations with a total of 473 days (14 December 2019–31 March 2021). For data completeness, Table 2 shows that there were full data at three locations, i.e., Binh Thanh, Phu Nhuan, and Go Vap District. The measurement durations were shorter in Tan Binh District and District 5. We used four sensors to monitor PM$_{2.5}$ in five locations; thus, three locations were simultaneously monitored with three sensors, including Binh Thanh, Phu Nhuan, and Go Vap District. With the last sensor, after we stopped monitoring in District 5 on 20 May 2020, we used it to monitor PM$_{2.5}$ in Tan Binh District from 22 May 2020 to 31 March 2021.
The hourly PA-PM$_{2.5}$ concentrations were log-normally distributed while the daily concentrations were normally distributed. There was a strong homogeneity of PM$_{2.5}$ among the five locations, which demonstrated by below 20% of intra-model variability values and statistical significance results from the ANOVA test (Supplementary, Table S8). Thus, the average concentrations of PM$_{2.5}$ of all the locations were used as representatives of PM$_{2.5}$ concentrations measured by the PA sensors (PA-PM$_{2.5}$ concentrations) to compare with US-PM$_{2.5}$ concentrations in the following analysis.

The daily mean of PA-PM$_{2.5}$ concentrations during 2016–2021 was $27.3 \pm 11.9$ µg m$^{-3}$ (Table 2). The PA-PM$_{2.5}$ concentrations were strongly correlated with the US-PM$_{2.5}$ concentrations ($R^2 = 0.78$, $p$-value < 0.05, Fig. 1). Also, there was a strong positive association between these two variables in a simple linear regression model (Supplementary, Fig. S3). These results demonstrated that LCPMSs may adequately capture variations of PM$_{2.5}$, e.g., hotspots and trends of PM$_{2.5}$.

For a comparison of PM$_{2.5}$ between the five fixed-site locations, Table 2 and Fig. 2(b) show that PM$_{2.5}$ concentrations were the largest in Binh Thanh and Go Vap District and the smallest in District 5 (at about 30 µg m$^{-3}$ compared with 15 µg m$^{-3}$). The greater concentrations in Binh Thanh and Go Vap District may be due to influences of traffic-related air pollution sources and construction activities around the monitoring sites. In contrast, the PM$_{2.5}$ concentrations in District 5 were less because this location was not affected by local sources as much as the others. Also, Fig. 1 shows that there were good correlations of PM$_{2.5}$ concentrations between the five locations ($R^2$, 0.74–0.90, $p$-value < 0.05). The PA-PM$_{2.5}$ concentrations measured in each district were also well correlated with the US-PM$_{2.5}$ concentrations ($R^2$, 0.52–0.91, $p$-value < 0.05).

3.2 Temporal Variations of Meteorology and PM$_{2.5}$ in Ho Chi Minh City

3.2.1 Meteorological variables

Fig. 3 displays deseasonalized monthly means of wind speed, air temperature, and relative humidity split by dry/rainy season and three prevailing wind directions in HCMC during the study period. The wind speed remained stable, the air temperature slightly increased, and the relative humidity moderately decreased (Figs. 3(a), 3(b), and 3(c), respectively). Short-term trends of air temperature in the dry and rainy season were $+0.1$ and $+0.3$ °C per year ($p$-value < 0.001) as an average over the entire period, respectively (Fig. 3(b)). The results provided an evidence that the air temperature in HCMC increased during 2016–2021. In contrast, there were decrease trends of relative humidity in both the dry/rainy season, about $-1$% per year ($p$-value < 0.1) (Fig. 3(c)).

Fig. 4 illustrates a clear pattern of the SSE prevailing wind direction in the dry season and the WSW prevailing wind direction in the rainy season in HCMC during 2016–2021. Besides the influence of the SSE wind direction, the NNE wind direction also blowed in the dry season in HCMC. During 2016–2021, the WSW monsoon wind direction in the rainy season had greater wind speed and direction frequency than the others. Notably, during the rainy seasons of 2018 and 2019, the WSW wind direction had the highest direction frequency of more than 50%.

3.2.2 PM$_{2.5}$ concentrations

PM$_{2.5}$ concentrations collected from the USCG-HCMC during 2016–2021 were mainly used to indicate a short-term trend of PM$_{2.5}$ in HCMC. Consistent with previous studies (Shi et al., 2018; Hien et al., 2019), Fig. 5(a) provides an evidence of a significant decreasing trend of PM$_{2.5}$ in HCMC during 2016–2021 with a reduction of 1.62 µg m$^{-3}$ per year over the entire period (95% CI, $-2.03$ to $-1.20$, $p$-value < 0.001). Particularly, besides the decrease of PM$_{2.5}$ during 2020–2021 due to effects of COVID-19 restrictions, the blue line with dots in Fig. 5(a) also reveals a dramatic drop of PM$_{2.5}$ from the latter half of 2018 to the beginning of 2019 as well as a spectacular rise during 2019. The substantial reduction in PM$_{2.5}$ in HCMC, a city in southern Vietnam, during 2016–2021 was consistent with the decrease in some places, e.g., southern Pakistan, southern India, Sri Lanka, and Oxford, UK (Shi et al., 2018; Bush et al., 2023). In contrast, there was a considerable increase of PM$_{2.5}$ in Bangladesh, India, Myanmar, North Laos, and Indonesia (Shi et al., 2018; Santos et al., 2020). The PM$_{2.5}$ reduction in HCMC during 2016–2021 may be caused by policies of the city authorities, e.g., relocating urban industrial activities to the suburbs and applying the European emission standards for vehicles and fuels (Hien et al., 2019).
Fig. 3. Short-term trends of (a) wind speed, (b) air temperature, and (c) relative humidity in Ho Chi Minh City during 2016–2021 split by dry/rainy season and three prevailing wind directions. Notes: the solid red line shows the trend estimate and the dashed red lines show the 95% confidence intervals for the trend based on resampling methods.
We continued to consider short-term trends of PM$_{2.5}$ split by dry/rainy season and three prevailing wind directions during 2016–2021 in Figs. 5(b) and 5(c). There were large downward trends of PM$_{2.5}$ of all the situations (p-value < 0.001). The decrease level of PM$_{2.5}$ in the dry season was $-1.3$ µg m$^{-3}$ per year and this in the rainy season was $-1.7$ µg m$^{-3}$ per year (Fig. 5(b)). The greater reductions of PM$_{2.5}$ were observed with the SSE wind direction (pre-monsoon) and the WSW wind direction (monsoon) (Fig. 5(c)). The results were consistent with the findings in Dhaka, Bangladesh where PM$_{2.5}$ concentrations were also influenced by monsoon wind directions and monsoon periods (Begum et al., 2006). On the other hand, the PM$_{2.5}$ variations in the dry season and with the NNE wind direction during 2016–2021 were not entirely linear, compared with the other situations in terms of using de-seasonalized monthly mean concentrations. Thus, we continued to deal with smooth trends in monthly mean concentrations of PM$_{2.5}$ in Fig. 6.

In Fig. 6(a), the smooth trend in raw PM$_{2.5}$ concentrations illustrated an apparent seasonal cycle. By removing the seasonal cycle of PM$_{2.5}$ in Fig. 6(b), we found that PM$_{2.5}$ concentrations firstly remained stable during 2016–2017. Then, the PM$_{2.5}$ dramatically declined in 2018. Next, the PM$_{2.5}$ climbed about 10 µg m$^{-3}$ during 2019, which approximated the concentrations of 2016–2017. Finally, the PM$_{2.5}$ continuously decreased during the COVID-19 period (2020–2021). The findings of de-seasonalizing PM$_{2.5}$ observations in this situation were useful for us to detect a dramatic abnormal reduction of PM$_{2.5}$ during 2018 besides the PM$_{2.5}$ decrease of the COVID-19 period. Furthermore, combining Figs. 4, 5(a), and 6(b) helps us to recognize a relation between the declining tendency of PM$_{2.5}$ and the abnormal changes of meteorological conditions in 2018. We will discuss more reasons in this regard in the Section 3.3.3.

### 3.3 Effects of COVID-19 Restrictions on PM$_{2.5}$ Decline in Ho Chi Minh City

#### 3.3.1 A decreasing trend of PM$_{2.5}$ during the COVID-19 period

Fig. 5(d) illustrates that the PM$_{2.5}$ decrease of the COVID-19 period (2020–2021) was more than 4 times higher than that of the short-term trend (2016–2019), $-2.7$ (95% CI, $-8.4$ to $2.9$) µg m$^{-3}$ per year during 2020–2021 compared with $-0.7$ (95% CI, $-2.3$ to $0.3$) µg m$^{-3}$ per year during 2016–2019. Moreover, a notable result in Fig. 5(e) reveals that PM$_{2.5}$ concentrations largely reduced in 2021 with $-16.8$ (95% CI, $-38.6$ to $19.1$) µg m$^{-3}$ per year, whereas a decline of PM$_{2.5}$ in 2020 was only $-0.6$ (95% CI, $-20.1$ to $14.3$) µg m$^{-3}$ per year. It means that the PM$_{2.5}$ decrease of 2021 was more than 17 times higher than this of 2020. The reasons for the larger reduction of PM$_{2.5}$ in 2021 were that the COVID-19 public health measures of this year were stricter than those of 2020 as well as the implementation duration in 2021 was also longer.

Fig. 7 shows more details of relative differences of PM$_{2.5}$ concentrations between the COVID-19 period (2020–2021) and the short-term trend (2016–2019) split by different conditions. This study
Fig. 5. Trends of PM$_{2.5}$ concentrations collected from the United States Consulate General Ho Chi Minh City (a) during 2016–2021, split by (b) dry/rainy season, (c) three prevailing wind directions, (d) a sort-term trend (2016–2019) and the COVID-19 period (2020–2021), and (e) 2020 and 2021. Note: the solid red line shows the trend estimate and the dashed red lines show the 95% confidence intervals for the trend based on resampling methods.
Fig. 6. Smooth trends of (a) raw PM$_{2.5}$ concentrations and (b) monthly mean concentrations of PM$_{2.5}$ concentrations in Ho Chi Minh City during 2016–2021. Note: the shading shows the estimated 95% confidence intervals.

Fig. 7. PM$_{2.5}$ concentrations of the COVID-19 period (2020–2021) compared with those of a short-term trend (2016–2019) by percentage reduction, separated by all time, dry/rainy season, daylight/nighttime, and three prevailing wind directions, including south-south-east (SSE), west-south-west (WSW), and north-north-east (NNE) wind direction.

indicated that PM$_{2.5}$ concentrations of the COVID-19 period in HCMC decreased by 18%, compared with those of the 2016–2019 period. Consistent with available studies, there has been a downward trend of PM$_{2.5}$ concentrations during COVID-19 periods in many countries in the world, such as Spain, Italy, the United States, Brazil, India, China, the United Arab Emirates, and Malaysia (Chauhan and Singh, 2020; Collivignarelli et al., 2020; Dantas et al., 2020; Kanniah et al., 2020; Kerimray et al., 2020; Mahato et al., 2020; Nakada and Urban, 2020; Xu et al., 2020). The decline in PM$_{2.5}$ concentrations across these places was from 20–50%. For example, PM$_{2.5}$ concentrations during COVID-19 periods significantly decreased by 12% in the Guanzhong Basin, China (Li et al., 2022); 12%–34% in main cities of North China Plain (Ding et al., 2021); 11% at the road sites in Bangkok, Thailand (Dejchanchaiwong and Tekasakul, 2021); 37% in Volos, Greece (Kotsiou et al., 2021); and a PM$_{2.5}$ reduction of 4.1 µg m$^{-3}$ (95% CI, −7.2 to −0.9) in Seoul, Korea (Han and Hong, 2020).

Although PM$_{2.5}$ concentrations greatly decreased during the COVID-19 period in HCMC, about half of the days during this period still had daily PM$_{2.5}$ concentrations exceeding the WHO daily standard of 15 µg m$^{-3}$ (Table 1). As the same findings of this study, the PM$_{2.5}$ pollution in five regions of Colombia and Volos, Greece was also severe even during lockdown situations (exceeding the standard with 41% of the days) (Arregoces et al., 2021; Kotsiou et al., 2021). Last but not least, in a comparison with the PM$_{2.5}$ level of the 2016–2019 period, we observed the highest decrease of PM$_{2.5}$ of the COVID-19 period was in the rainy season and with the WSW monsoon wind direction in HCMC (Fig. 7).
3.3.2 Temporal fluctuations of PM$_{2.5}$ during the COVID-19 period

Fig. 8 helps us to consider more details of PM$_{2.5}$ variations during the COVID-19 period, 2020–2021. The fluctuations of PA-PM$_{2.5}$ concentrations measured by LCPMSs were analogous to those of US-PM$_{2.5}$ concentrations collected from the USCG-HCMC during this period. Except for January of both the two years, PM$_{2.5}$ concentrations of the other months were lower than those of the 2016–2019 period in HCMC and totally met the Vietnam daily standard of 50 μg m$^{-3}$. With the WHO daily standard, PM$_{2.5}$ concentrations in 2020 mostly exceeded the standard while these in 2021 fluctuated near the standard during the months of implementing COVID-19 measures.

Compared with PM$_{2.5}$ concentrations of the 2016–2019 period, PM$_{2.5}$ variations of the COVID-19 period were considerably changed (Fig. 8). After the first case of COVID-19 was announced on 23 January 2020 in HCMC, there were many times that daily PM$_{2.5}$ concentrations bottomed out (below 20 μg m$^{-3}$). Notably, we found that there were one-week cyclical fluctuations of PM$_{2.5}$ during the social distance II–III and social quarantine I–II. Daily PM$_{2.5}$ concentrations increased or decreased by week because the HCMC authorities also controlled or lifted the measures with the same corresponding duration. For instance, during April 2020 and May–June 2021, the concentrations enormously declined in a couple of days when the measures were applied very strictly; then, the concentrations moderately increased (Fig. 8). The interesting reason for this increase was that the residents tried to go outside after having to stay at home for so long. Traffic activities immediately increased again when the measures were moderately relaxed. On the other hand, after the periods of COVID-19 measures, the PM$_{2.5}$ immediately

Fig. 8. Daily PM$_{2.5}$ fluctuations during the COVID-19 period, 2020–2021, including PA-PM$_{2.5}$ concentrations measured by LCPMSs (LCPMS 20–21) and US-PM$_{2.5}$ concentrations collected from the USCG-HCMC split by two periods, 2016–2019 (us_16_19) and 2020–2021 (us_20_21).
recovered in the first week of October 2021 but there was a three-week lag of PM$_{2.5}$ recovery in May 2020 (Fig. 8). The recovery lag of PM$_{2.5}$ in 2020 in our study was consistent with the findings of a study in HCMC by (Tran et al., 2023). The two-month lag of PM$_{2.5}$ recovery was also found in a study in Park City, Utah, USA (Mendoza et al., 2021).

In addition, Fig. 8 also illustrates PM$_{2.5}$ concentrations during LNY holidays of the two years in HCMC. PM$_{2.5}$ concentrations usually increase before a couple weeks of the holidays when preparation activities for the event are the most heightened and then decline during the holidays. As in other Asian cities, the LNY holidays in HCMC are generally a period of time that migrant workers head to their hometowns and the residents often travel. These behaviors cause economic activities to temporarily shut down, which is the same situation of the COVID-19 period. As a result, the air quality of the city is usually improved in this period. In this study, the decrease trends of PM$_{2.5}$ during LNY holidays were observed in HCMC, which consistent with the findings in some cities of China such as Hubei, Wuhan, Jingmen, and Enshi (Almond et al., 2020; Xu et al., 2020).

3.3.3 Rationale of PM$_{2.5}$ reductions during the COVID-19 period

Besides the effects of COVID-19 measures on PM$_{2.5}$ decrease in HCMC, there was another reason from impacts of meteorological factors. We may see these effects in Figs. 4, 7, and 9. First, the highest decrease of PM$_{2.5}$ during the COVID-19 period was in the rainy season and with the WSW wind direction (Fig. 7). Then, Fig. 4 illustrates a clearer impact of wind on the PM$_{2.5}$ decrease. In the rainy season, the relative frequency of the WSW monsoon wind direction in 2021 was greater than this in 2020. As a result, the PM$_{2.5}$ concentrations during the rainy season of 2021 were less than those of 2020. Next, in Fig. 9, PM$_{2.5}$ concentrations dramatically fell during the COVID-19 period in 2021 (May–October), which also corresponding to the lower PM$_{2.5}$ concentrations in

Fig. 9. Two-week average of PM$_{2.5}$ concentrations collected from the USCG-HCMC (us_PM$_{2.5}$), wind speed (wind spd.), air temperature (temp), and relative humidity in Ho Chi Minh City during 2016–2021. Notes: normalizing time series data to fix values to equal 100 at the beginning of 2016 and shaded areas are the rainy season of each year.
the rainy season and with the WSW monsoon wind direction in 2021. In this period of 2021, the lowest PM$_{2.5}$ concentrations were matched with a peak of wind speed, a large increase of relative humidity, and a slight decrease of air temperature. However, we did not observe the same results in 2020 (Fig. 9). This indicated that the increase of wind speed did not cause a PM$_{2.5}$ increase during the 2020 rainy season. Finally, we may draw a brief conclusion here, the PM$_{2.5}$ decline of 2020 was caused by effects of behavior changes due to COVID-19 restrictions while the PM$_{2.5}$ reduce of 2021 could be affected by not only COVID-19 measures but perhaps also meteorological factors.

3.4 Effects of Meteorological Factors on PM$_{2.5}$ Concentrations

Fig. 1 demonstrates weak correlations between meteorological variables and PM$_{2.5}$ concentrations, in which correlation coefficients of relative humidity with PM$_{2.5}$ were higher than those of wind speed and air temperature with PM$_{2.5}$. In general, wind speed and relative humidity had inverse correlations with PM$_{2.5}$ concentrations while air temperature had positive correlations with PM$_{2.5}$.

3.4.1 Rationale of a dramatic decrease of PM$_{2.5}$ during 2018

We may begin by dealing with Figs. 5(a) and 6(b) to recognize a dramatic decline of PM$_{2.5}$ from the latter half of 2018 to the beginning of 2019. The decrease level of PM$_{2.5}$ during 2018 was approximately this of the COVID-19 period (compared with the 2016–2019 period, PM$_{2.5}$ decrease by 13% during 2018 and 18% during the COVID-19 period). Endeavoring to further understand reasons of the decrease trend of PM$_{2.5}$ during 2018, we examined relationships between PM$_{2.5}$ and meteorological factors in Figs. 4 and 9. In 2018, the winds blewed from the WSW wind direction with a probability of 30% (Fig. 4). The increase of wind speed of the WSW wind direction in the rainy season in 2018 may be correlated with the decrease trend of PM$_{2.5}$ in the same period. Moreover, PM$_{2.5}$ concentrations of the 2018 rainy season hit a low, at the same time, the wind speed of the same period also reached the peak, air temperature decreased, and relative humidity simultaneously increased (Fig. 9). We may observe the same relations during the rainy seasons of the other years but the more significant relationships were recognized in 2016, 2018, and 2021, which were three highest peak of wind speed during the rainy seasons. Additionally, we continue to look into the results in Tables S6 and S7 in Supplementary to reinforce more evidence that meteorological factors may affect the decrease of PM$_{2.5}$. Wind speed and relative humidity in the rainy season and with the WSW wind direction in 2018 were the highest while these two meteorological variables in 2021 were at the third rank. In contrast, air temperature in the rainy season and with the WSW wind direction in 2018 was the lowest, and the air temperature in 2021 was also at the third rank.

Finally, we concluded that meteorological factors in the rainy season and with the WSW monsoon wind direction may cause a significant decline of PM$_{2.5}$ in both 2018 and 2021. More specifically, the decrease of PM$_{2.5}$ during 2018 was completely affected by meteorological conditions, whereas the reduction of PM$_{2.5}$ during 2021 was correlated with co-effects of both COVID-19 restrictions and meteorological factors.

3.4.2 Bayesian multiple linear regression models of meteorological variables and PM$_{2.5}$ concentrations

We developed two Bayesian multiple linear regression models of relationships between meteorological factors and PM$_{2.5}$ concentrations which collected from the USCG-HCMC (Model 1) and measured by LCPMSs (Model 2). The results showed that meteorological variables were correlated with PM$_{2.5}$ concentrations (Table 3), whereas two binary variables related days of LNY holidays and COVID-19 periods were not (Table S9 in Supplementary). Both the two models with three meteorological variables had the best fit with the highest posterior probability (post prob = 100%). The intercepts and regression coefficients were statistically significant in both of the two models (p-value < 0.001).

All the three meteorological variables negatively affected PM$_{2.5}$ concentrations. Specifically, wind speed and air temperature substantially contributed to PM$_{2.5}$ changes (see lmg values, relative importance metrics, in Table 3). The inverse effects of meteorological variables on PM$_{2.5}$
Table 3. The results of Bayesian multiple linear regression models between daily wind speed, air temperature, and relative humidity with PM$_{2.5}$ concentrations in Ho Chi Minh City during 2020–2021.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>US-PM$_{2.5}$ concentrations (Model 1)</th>
<th>PA-PM$_{2.5}$ concentrations (Model 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate</td>
<td>Std. Error</td>
</tr>
<tr>
<td>(Intercept)</td>
<td>127.99</td>
<td>5.99</td>
</tr>
<tr>
<td>Wind speed</td>
<td>-5.70</td>
<td>0.24</td>
</tr>
<tr>
<td>Air temperature</td>
<td>-2.15</td>
<td>0.18</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>-0.33</td>
<td>0.02</td>
</tr>
<tr>
<td>R-squared</td>
<td>Multiple R-squared: 0.36</td>
<td>Multiple R-squared: 0.43</td>
</tr>
<tr>
<td></td>
<td>Adjusted R-squared: 0.36</td>
<td>Adjusted R-squared: 0.43</td>
</tr>
<tr>
<td>p-value</td>
<td>p-value &lt; 2.2e-16c</td>
<td>p-value &lt; 2.2e-16c</td>
</tr>
<tr>
<td>RMSE</td>
<td>9.31</td>
<td>9.69</td>
</tr>
<tr>
<td>MAE$^d$</td>
<td>7.29</td>
<td>7.88</td>
</tr>
</tbody>
</table>

$^a$US-PM$_{2.5}$ as a representative of PM$_{2.5}$ concentrations collected from the United States Consulate General Ho Chi Minh City.

$^b$PA-PM$_{2.5}$ as a representative of average PM$_{2.5}$ concentrations measured by all PurpleAir sensors in five locations.

$^c$p-value < 0.001.

$^d$Relative importance metrics.

$^e$Root mean squared error.

$^f$Mean absolute error.

were the same with the findings in a study in HCMC, which mentioned a negative effect of wind speed on PM$_{2.5}$ (Hien et al., 2019) and a previous study in Hanoi, which also reported inverse impacts of meteorological factors on PM$_{2.5}$ by using multiple linear regression models (Hien et al., 2002). On the other hand, Table 3 also shows that the performance of Model 2 was better than this of Model 1 (the adjusted R-squared value of Model 1 at 36% and Model 2 at 43%, p-value < 0.001). Although the performance of the two models in this study was relatively low, which was less than the performance of models in the study in Hanoi (Hien et al., 2002), both the models were valid in terms of considering assumption test results.

In addition, Table S9 in Supplementary provides more outcomes of models with the two binary variables related to days of LNY holidays and COVID-19 periods. The performance of the models with two binary variables was also poor but the models were still valid. In comparison, a study in Grenada, West Indies also pointed out that there was an association between a variable representing COVID-19 measures and PM$_{2.5}$ concentrations (Dirienzo et al., 2023). Therefore, we suggested that effects of COVID-19 restrictions as well as meteorological factors on PM$_{2.5}$ should be simultaneously examined in the future study.

4 CONCLUSIONS

To the best of our knowledge, we firstly compared PM$_{2.5}$ concentrations during the whole COVID-19 period (2020–2021) with a short-term trend of PM$_{2.5}$ (2016–2019) in HCMC in conjunction with meteorological conditions. There was a significant decreasing trend of PM$_{2.5}$ concentrations in HCMC during 2016–2021, in particular considerable reductions of PM$_{2.5}$ during the year of 2018 and the COVID-19 period. The PM$_{2.5}$ decline in 2018 was completely related with meteorological factors, whereas the decrease in 2020 was caused by behavior changes due to the COVID-19 pandemic. Even more noteworthy was that the reduction of PM$_{2.5}$ in 2021 was correlated with co-effects of both COVID-19 measures and meteorological factors. Therefore, it should be taken into account the simultaneous relationships between meteorological factors and COVID-19 measures with PM$_{2.5}$ concentrations. Finally, using LCPMSs in this study gave us a chance to have a better understanding of temporal variations of PM$_{2.5}$ in HCMC, especially during the COVID-19 period. The results from this study demonstrated that the utilization of LCPMSs may hold a promising resolution to capture both temporal and spatial variations of PM$_{2.5}$ for countries like Vietnam with modest resources.
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ADDITIONAL INFORMATION AND DECLARATIONS

Disclaimer

This article is a part of PhD research of the first author, Tran Cong-Thanh, in College of Public Health, National Taiwan University, Taipei, Taiwan (PhD student number: D05849016). The contents expressed in this article are solely those of the authors and do not necessarily reflect or represent the views or policies of the National Taiwan University and the Vietnam National University Ho Chi Minh City.

Supplementary Material

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.230186

REFERENCES

Dejchanachaiwong, R., Tekasakul, P. (2021). Effects of coronavirus induced city lockdown on PM2.5...


Ministry of Natural Resources and Environment (MoNRE) (2013). National Technical Regulation on Ambient Air Quality. Ministry of Natural Resources and Environment (MoNRE), Hanoi, Vietnam.


