Big Data Analysis for Effects of the COVID-19 Outbreak on Ambient PM_{2.5} in Areas that Were Not Locked Down

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ABSTRACT

COVID-19, which is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), first broke out at the end of 2019. Despite rapidly spreading around the world during the first half of 2020, it remained well controlled in Taiwan without the implementation of a nationwide lockdown. This study aimed to evaluate the PM_{2.5} concentrations in this country during the 2020 COVID-19 pandemic and compare them with those during the corresponding period from 2019. We obtained measurements (taken every minute or every 3 minutes) from approximately 1,500 PM_{2.5} sensors deployed in industrial areas of northern and southern Taiwan for the first quarters (January–March) of both years. Our big data analysis revealed that the median hourly PM_{2.5} levels decreased by 3.70% (from 16.3 to 15.7 $\mu\text{g m}^{-3}$) and 10.6% (from 32.4 to 29.3 $\mu\text{g m}^{-3}$) in the north and south, respectively, between these periods owing to lower domestic emissions of PM_{2.5} precursors (viz., nitrogen dioxide and sulfur dioxide) and, to a lesser degree, smaller transported emissions of PM_{2.5}, e.g., from China. Additionally, the spatial patterns of the PM_{2.5} in both northern

and southern Taiwan during 2020 resembled those from the previous year. Finally, controlling local PM_{2.5} emission sources critically contributes to reducing the number of COVID-19 cases.

Keywords: COVID-19, SARS-CoV-2, PM_{2.5}, Low-cost sensors, Domestic emission, Big data

1 INTRODUCTION

Since the sudden outbreak of the COVID-19 airborne disease, which is caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) virus that initially emerged in December 2019, the World Health Organization (WHO) has reported approximately 142,057,939 confirmed cases and 3,034,210 deaths worldwide as of April 19, 2021 (Li *et al.*, 2020d; WHO, 2021). Taiwan has experienced two waves of COVID-19 cases. The Taiwan Center for Disease Control (TCDC) announced 1,076 confirmed cases and 11 deaths by April 19, 2021 (TCDC, 2020). At that time, the TCDC announced guidelines, including wearing a mask and social distancing to help stop the spread of SARS-CoV-2 virus and cellular broadcast services to advise threat-risk population and reduce potential exposure to SARS-CoV-2 virus in densely populated areas starting in early February 2020. Even though the highly infectious SARS-CoV-2 virus continues to spread around the world, Taiwan has successfully controlled the pandemic and minimized the impact on Taiwanese daily life through a policy of transparency and honesty about COVID-19. Unlike other regions, Taiwan is available for human activities, including industrial production without any lockdown process excluding overseas visitors.

Several reports indicated that during normal talking and breathing, individuals infected with COVID-19 could easily generate small droplets of SARS-CoV-2, which are possibly transported by aerosol and remain on suspended particulate matter (PM) including PM_{2.5} in the air for hours and travel over social distancing (1.5 or 2 m or 6 feet) (Anderson *et al.*, 2020; Banik and Ulrich, 2020; Doremalen *et al.*, 2020; Setti *et al.*, 2020a, c; Wang and Du, 2020). Experimental results supported the existing evidence of accelerated transmission of the SARS-CoV-2 virus by PM_{2.5}, particularly in northern Italy and in Wuhan in China (Sharma and Balyan, 2020). These small particulates carry the SARS-CoV-2 virus in indoor environments and diffuse it more than 10 m from the source (Setti *et al.*, 2020b). Especially in poor indoor environments with habitual indoor burning of incense, such as in Middle Eastern countries (Amoatey *et al.*, 2020), it is possible to spread the COVID-19 disease through heavy PM_{2.5} and PM₁₀ pollution. Based on the current global data, air pollution, such as that caused by PM_{2.5} and PM₁₀, may be associated with COVID-19 mortality rates or incidence if population density, racial segregation, socioeconomic position, and meteorological variables, such as temperature and humidity, are not considered (Brandt *et al.*, 2020; Jiang *et al.*, 2020). Wu *et al.* (2020) revealed the positive association of PM_{2.5} with COVID-19 deaths based on a 1 µg m⁻³ increase in PM_{2.5}, leading to a 15% increase in mortality in the United States. Sharma and Balyan (2020) indicated that high PM_{2.5} might accelerate COVID-19-related mortality based on experience with increases in air-pollution-related comorbidities after humans were exposed to high levels of PM_{2.5}. Scientists have warned that future works need to consider whether air pollution, such as PM_{2.5}, directly affects COVID-19 mortality independent of population density, racial and socioeconomic segregation, cardiopulmonary disease, and meteorological conditions (Brandt *et al.*, 2020; Jiang *et al.*, 2020; Saadat *et al.*, 2020).

Several reports have indicated that air quality was improved after lockdown related to COVID-19 (Bao and Zhang, 2020; Collivignarelli *et al.*, 2020; Dantas *et al.*, 2020; Dutheil *et al.*, 2020; Kerimray *et al.*, 2020; Li *et al.*, 2020a; Li and Tartarini, 2020; Mahato *et al.*, 2020; Nakada and Urban, 2020; Otmani *et al.*, 2020; Saadat *et al.*, 2020; Sharma *et al.*, 2020; Tobias *et al.*, 2020; Wang and Su, 2020; Wang *et al.*, 2020a, c). Notable reductions in PM_{2.5}, PM₁₀, SO₂, NO₂, NO, and CO were observed. A study from Ecuador showed that a large drop in NO₂ (68%), SO₂ (48%), CO (38%), and PM_{2.5} (19%) was found in Quito during the first month of quarantine after COVID-19 outbreak compared with pre-COVID-19 period (Zalakeviciute *et al.*, 2020). Ma and Kang (2020) indicated that levels of PM_{2.5} and NO₂ were obviously reduced in Wuhan by 29.9% and 53.2%, respectively, after lockdown and decreased in Daegu by 20.9% and 19.0%, respectively, and Tokyo by 3.6% and 10.4%, respectively, after self-quarantine between January 23 and April 30 in 2020. Agarwal *et al.* (2020) revealed the average drop of PM_{2.5} and NO₂ in six cities (Xiangyang, Jingzhou, Huanggang,

Xiaogan, Wuhan, and Yichang) in Hubei Province, China, and six megacities (Delhi, Lucknow, Kolkata, Mumbai, Chennai, and Jaipur) in India by 11.3% and 48.6% for PM_{2.5} and NO₂ in China as well as by 20.2% and 59.3% in India after a week of lockdown for COVID-19 issues. The Singaporean report showed the large reduction of PM_{2.5}, PM₁₀, SO₂, NO₂, and CO by 29%, 23%, 52%, 54%, and 6%, respectively, while the increment fold of ozone (O₃) was 1.18 times after lockdown compared with pre-lockdown periods from April 2016 to May 2020 (Li and Tartarini, 2020). The decline of O₃ in the ambient air after lockdown implementation might be mainly due to lower titration O₃ by NO_x (Bedi *et al.*, 2020; Brimblecombe *et al.*, 2020; Kumari *et al.*, 2020b). At the same time, O₃ was significantly increased due to reductions in human and economic activities, traffic restrictions, and decreases in energy consumption during lockdowns for COVID-19 in various countries in comparison to the pre-lockdown period (Collivignarelli *et al.*, 2020; Dantas *et al.*, 2020; Kerimray *et al.*, 2020; Li *et al.*, 2020a, b; Mahato *et al.*, 2020; Nakada and Urban, 2020; Otmani *et al.*, 2020; Sharma *et al.*, 2020; Wang *et al.*, 2020c). The improvement of air quality may be associated with the reduced emissions from transportation, which is related to NO₂ reductions, and the manufacturing industry, which has been linked to reductions of PM_{2.5} and CO in China during the COVID-19 outbreak (Wang *et al.*, 2020c). The effects of lockdowns due to COVID-19 on O₃ production in southern European cities (Turin, Valencia, Rome and Nice), as well as in Wuhan, China, may be a reasonable explanation for the unpredicted decrease in NO_x emissions due to lowering ozone generation by NO (Sicard *et al.*, 2020). Generally, the mechanism of ground-level O₃ formation and depletion is complicated to be associated with the secondary pollutants which are formed by photochemical reaction of NO_x and volatile organic compounds (VOCs) due to natural sources or human activities (Bedi *et al.*, 2020). The possible explanation for the generation of O₃ related to COVID-19 is the lower PM_{2.5} loading, which decreases the sink for hydroperoxy radicals (HO₂) (Wang *et al.*, 2020b). Meteorological interference or variations should also be taken into account in terms of their air quality impacts during this outbreak (Dantas *et al.*, 2020; Kerimray *et al.*, 2020; Li *et al.*, 2020b). Kerimray *et al.* (2020) indicated that benzene and toluene levels in the COVID-19 period had 2–3-fold higher magnitudes compared with those in the same seasons from 2015 to 2019. These sources contribute substantially from various non-traffic-related sources, such as combined coal-fired heat and power plants and household heating systems (Kerimray *et al.*, 2020). Long-range transport aerosols contribute to air pollution, particularly in the case of PM_{2.5} and PM₁₀ in receptor areas, and in turn decrease the benefits of local emission reductions related to COVID-19 (Li *et al.*, 2020a; Otmani *et al.*, 2020). Obvious reductions in PM, such as emission reductions in transportation and slight reductions in industrial sources, in cities in central or southern China, did not lead to avoiding the PM loadings due to severe air pollution in northern China via long-range transport during the lockdown period (Griffith *et al.*, 2020; Li *et al.*, 2020a). To summarize the current global data, lockdowns or quarantining for COVID-19 have contributed to a positive impact on improvements in air quality (Nakada and Urban, 2020; Wang *et al.*, 2020c), recovery from climate change (Rosenbloom and Markard, 2020), and attenuation of environmental impacts (Saadat *et al.*, 2020).

The present study was focused on changes in PM_{2.5} from January to March in 2019 and 2020 in selected industrial areas in northern and southern Taiwan, where no lockdown or quarantine was implemented during the COVID-19 outbreak. A huge amount of data on PM_{2.5} was recorded and provided by the PM_{2.5} sensors in the selected areas to further examine PM_{2.5} concentrations in the first quarter (from January to March) of 2019 and 2020 and evaluate the effects of PM_{2.5} loading from domestic sources and transboundary transportation during the COVID-19 outbreak.

2 METHODS

2.1 Data Collection from PM_{2.5} Sensors

The Taiwanese Environmental Protection Administration (TEPA) established 10,200 air quality sensors in Taiwan before 2020. More than 3,200 air quality micro-stations are located in northern and southern Taiwan (Fig. 1; Civil IoT Taiwan, 2020). An air quality micro-station to assess PM_{2.5} is set up at the height of 3 m from the ground in industrial areas to gather data following the TEPA standard. The PM_{2.5} data from PM_{2.5} sensors were freely announced to the public on the Civil IoT Taiwan Data Service Platform website. PM_{2.5} data from air quality micro-stations are

Fig. 1. The location and distribution of $PM_{2.5}$ sensors in the industrial areas from north and south Taiwan (DY: Dayuan, GS: Guishan, KI: Kuangin, KD: Kaohsiung downtown, LK: Linkou, NK: north Kaohsiung, PZ: Pingzhen, PN: Pingnan (southern Pingtung)).

generated every 1 or 3 minutes. The $PM_{2.5}$ from the network for air quality micro-stations developed by the TEPA was aimed at investigating $PM_{2.5}$ emissions and levels in hotspot areas to identify and trace $PM_{2.5}$ emission sources in these regions. The hourly average $PM_{2.5}$ concentrations are calculated based on acceptable $PM_{2.5}$ data. More than 75% of all hourly average concentrations in a sensor are accepted as effective $PM_{2.5}$ data over an hour based on the TEPA standard. Based on the previous criteria, $PM_{2.5}$ micro-sensor stations were selected at 609 and 891 stations for northern and southern Taiwan, respectively, from January to March in 2019 and 549 and 872 stations for northern and southern Taiwan, respectively, from January to March in 2020 (Table 1). The hourly average $PM_{2.5}$ levels were collected between January and March in 2019 and 2020. For standardization of $PM_{2.5}$ data quality and assurance of the reliability of $PM_{2.5}$ sensors, the TEPA regulates whether the data meet the standard through certified laboratory certification, field certification, and parallel comparisons between a TEPA air pollution monitor site and an air sensor. The $PM_{2.5}$ data taken from air sensors were collected daily between January and March in 2019 and 2020 for further statistical analyses. The $PM_{2.5}$ data in the cloud system were gathered and transferred to statistical software, including Statistical Analysis System (SAS) and Microsoft Excel, based on time series before the big data analysis. More than 63,000,000 and 59,000,000 units of data on $PM_{2.5}$ from the air quality micro-stations were gathered in the first quarter of 2019 and 2020, respectively.

Table 1. Hourly average levels of PM_{2.5} from air quality micro stations between January and March in 2019 and 2020 located in the industrial areas from northern and southern Taiwan.

Year	2019		2020	
Region	North (2019N)	South (2019S)	North (2020N)	South (2020S)
PM _{2.5} sensor stations (number) ^a	609	891	549	872
Effective data for hourly average PM _{2.5} concentration (%) ^b	97.7%	99.5%	95.6%	97.3%
Median PM _{2.5} levels (μg m ⁻³)	16.3	32.4	15.7	29.3

^a PM_{2.5} sensor stations were selected based on the standard of Taiwanese Environmental Protection Administration. The hourly average PM_{2.5} concentrations in a sensor were included in the present study for at least 75% or higher of acceptable effective data for hourly average PM_{2.5} concentrations. Stations which effective data for hourly average PM_{2.5} concentrations were lower than 75% were excluded.

^b Effective data for hourly average PM_{2.5} concentration meant the hourly average PM_{2.5} concentration was followed by the regulation from Taiwanese Environmental Protection Administration, indicating that the data from a sensor in an hour (PM_{2.5} level was generated each 1 or 3 minutes) at least was provided for 75% or higher of acceptable measured data before the calculation.

2.2 Statistical Analysis

A descriptive analysis, including mean, standard deviation (SD), median, mode, and standard error (SE), was used on the PM_{2.5} data in the first stage. The probability density distribution of PM_{2.5} in the first quarter of 2019 and 2020 and the difference between the probability density distribution in 2019 and 2020 were compared, where the median PM_{2.5} in 2019 minus the median PM_{2.5} in the corresponding period of 2020 (PM_{2.5/2019}–PM_{2.5/2020}) were calculated. An unrotated principal component analysis (PCA) was used to determine the initial PM_{2.5} conditions by replacing the original complex variables with linear combinations of major components. The unrotated PCA maximizes the sums of the root mean square (RMS) of the correlation coefficient (CV), whereas the PCA (varimax method) maximizes the variance of the squared correlation coefficients in the rotated principal components (RPCs) (Kaiser, 1958; Horel, 1981). In order to interpret PM_{2.5} dependence or independence of RPCs between 2019 (pre-COVID-19 periods) and 2020 (COVID-19 outbreak), thousands of PM_{2.5} data from the sensors in the industrial areas from northern and southern Taiwan were used. The maximum of the CV second-order moment causes the CVs to generate a wide distribution of RPCs and measurable variables. However, the factor loadings of most measurable variables were zero, and few of them presented the high loading magnitudes among the RPCs that would easily simplify the explanation of the relationship between the RPCs and the measurable variables. A time series normalization for the PM_{2.5} data was thus needed before the RPCs could be determined (Eq. (1)).

$$Z_{ik} = \frac{C_{ik} - \mu_i}{S_i} \quad (1)$$

where Z_{ik} represents the Z score of k^{th} time series PM_{2.5} value from air quality micro-station i ; C_{ik} represents the k^{th} time series PM_{2.5} concentrations from air quality micro-station i ; μ_i represents the mean PM_{2.5} concentrations at air quality micro-station i ; and S_i represents the standard deviation of PM_{2.5} concentrations at air quality micro-station i . The association of the RPCs and Z scores could be expressed as in Eq. (2):

$$Z_{ik} = \sum_{j=1}^n L_{ij} P_{jk} \quad (2)$$

where L_{ij} represents the factor loadings of the j^{th} RPCs from air quality micro-station i , and P_{jk} represents the k^{th} observation value of the j^{th} RPC.

All statistical analyses were tested using SAS JMP (NC, USA). The figures were drawn using SigmaPlot 14.0 software (Systat Software Inc., CA, USA).

3 RESULTS

3.1 Hourly PM_{2.5} in Air Quality Micro-stations Located in Northern and Southern Taiwan

As shown in Table 1, the median hourly PM_{2.5} concentrations from the air quality micro-stations (air sensors) in the industrial areas were 16.3 and 32.4 $\mu\text{g m}^{-3}$ between January and March of 2019 in northern (2019N) and southern (2019S) Taiwan, respectively, and were 15.7 and 29.3 $\mu\text{g m}^{-3}$ in 2020 in northern (2020N) and southern (2020S) Taiwan, respectively. Compared with the corresponding period in 2019, the median PM_{2.5} was reduced by 3.70% and 10.6% in northern and southern Taiwan, respectively, in 2020 during the pre- and post-COVID-19 outbreak. When considering the total hourly average PM_{2.5} data in the big data comprising more than 5,000,000 measurements, the reduction in PM_{2.5} from 2019N to 2020N was 1.70%, and that from 2019S to 2020S was 4.42%, respectively.

3.2 Probability Density Distribution of Hourly PM_{2.5} in Northern and Southern Taiwan

The changes in the probability density distribution for hourly PM_{2.5} data in the industrial areas of northern and southern Taiwan from January to March in 2019 and 2020 are shown in Fig. 2. A unimodal distribution was found in these four probability density distribution modes, including 2019N, 2019S, 2020N, and 2020S (Fig. 2(A)). The median and CV of the hourly PM_{2.5} values in northern Taiwan were lower than those in southern Taiwan. The mode for hourly PM_{2.5} decreased from 14 $\mu\text{g m}^{-3}$ in 2019N to 12 $\mu\text{g m}^{-3}$ in 2020N, and from 34 $\mu\text{g m}^{-3}$ in 2019S to 26 $\mu\text{g m}^{-3}$ in 2020S, respectively. The modes were consistent: 9.2% (2019N) and 10.2% (2020N) of the total PM_{2.5} in northern Taiwan, and 4.2% (2019S) and 5.1% (2020S) of the total PM_{2.5} in southern Taiwan. According to the air quality guidelines of PM_{2.5} established by the WHO, PM_{2.5} was not to exceed 10 and 25 $\mu\text{g m}^{-3}$ for the annual and 24-hour means, respectively. If WHO's guideline for PM_{2.5} 24-hour mean was used as the cutoff point in the hourly PM_{2.5} data in the present study,

Fig. 2. (A) Distribution of probability density from hourly average PM_{2.5} concentrations in PM_{2.5} sensors of industrial areas was shown. The 2020S and 2019S was presented as PM_{2.5} data from southern Taiwan between January and March in 2020 and 2019, respectively. The 2020N and 2019N was expressed as PM_{2.5} data from northern Taiwan between January and March in 2020 and 2019, respectively. (B) Probability density distribution for difference of median PM_{2.5} from January to March between 2019 and 2020 (median PM_{2.5} in 2019 minus median PM_{2.5} in 2020 in the corresponding period).

the 25.1% (2019N), 23.7% (2020N), 65.3% (2019S), and 60.6% (2020S) PM_{2.5} data exceeded the WHO's guideline. Evaluating the impact of COVID-19 on outdoor air, the differences in the median for hourly PM_{2.5} between 2019 and 2020 (e.g., PM_{2.5} on January 22, 2019, minus PM_{2.5} on January 22, 2020) are shown in Fig. 2(B). Although the differences in the median for hourly PM_{2.5} between 2019 and 2020 (2019N–2020N and 2019S–2020S) were not consistently either positive or negative, most figures were positive and ranged from 0.0 to 5.0 $\mu\text{g m}^{-3}$ (2019N–2020N) in northern Taiwan and between 1.0 and 9.0 $\mu\text{g m}^{-3}$ (2019S–2020S) in southern Taiwan (Fig. 3).

Fig. 3. Hourly PM_{2.5} concentrations in northern and southern Taiwan (A) median hourly PM_{2.5} from northern Taiwan in 2019 (2019N); (B) difference of median hourly PM_{2.5} between 2019 and 2020 from northern Taiwan (2019N–2020N); (C) median hourly PM_{2.5} from southern Taiwan in 2019 (2019S); (D) difference of median hourly PM_{2.5} between 2019 and 2020 from southern Taiwan (2019S–2020S).

3.3 Rate at Which Hourly PM_{2.5} Levels Exceeded the PM_{2.5} Daily Standard

Three ambient air quality standards for daily PM_{2.5} (24-hour mean), 35 $\mu\text{g m}^{-3}$ for Taiwan, 25 $\mu\text{g m}^{-3}$ for the WHO, and 55.5 $\mu\text{g m}^{-3}$ for sensitive groups (air quality index [AQI] = 150) on the U.S. Environmental Protection Agency (U.S. EPA), were chosen as the evaluation and comparison criteria to demonstrate the hourly PM_{2.5} concentrations. A Pareto analysis (Cao *et al.*, 2019) is a technique used for decision making based on the 80/20 rule, which statistically indicates that a limited number of input factors (counted hours) have the most significant impact on an outcome (exceedance rate for PM_{2.5} daily standard). If the proportion of limited hours can capture the proportion of most hours during which PM_{2.5} concentrations are higher than the legal standard, decision makers can capture the majority of high PM_{2.5} pollution events with a few hours or days. This study was concerned with the cumulative ratios for the number of effective hours as the input, with the cumulative ratios for the numbers of hours exceeding the daily PM_{2.5} standards.

For the hourly average PM_{2.5} levels in 2019N (Fig. 4(A)), the top 10% of the hours with high concentration values explained 16.8%, 25.5%, and 37.1% of the total hours exceeding the PM_{2.5} standards of 25, 35, and 55.5 $\mu\text{g m}^{-3}$, respectively, and the top 20% of the hours explained 30.6%, 38.7%, and 56.7% of the total hours, respectively. The top 20% hours in 2020N explained 31.5%, 38.2%, and 53.6% of the total hours exceeding the PM_{2.5} standards of 25, 35, and 55.5 $\mu\text{g m}^{-3}$, respectively. The top 20% hours explained 56.7% and 53.6% of the total hours exceeding the PM_{2.5} standards of 55.5 $\mu\text{g m}^{-3}$ in 2019N and 2020N, where the cumulative rate exceeding the standard in northern Taiwan decreased by 3.10% during the first quarter of 2020.

For the hourly PM_{2.5} levels in 2019S (Fig. 4(B)), the top 10% hours explained 11.8%, 14.4%, and 25.8% of the total hours exceeding the PM_{2.5} standards of 25, 35, and 55.5 $\mu\text{g m}^{-3}$, respectively, and the top 20% hours explained 23.1%, 27.1%, and 44.4% of the total hours exceeding that standard, respectively. The top 20% hours in 2020 explained 25.8%, 33.6%, and 55.7% of the total hours exceeding the PM_{2.5} standards of 25, 35, and 55.5 $\mu\text{g m}^{-3}$, respectively. The top 20% hours explained 44.4% and 55.7% of the total hours higher than the PM_{2.5} standards at 55.5 $\mu\text{g m}^{-3}$ in 2019S and 2020S, where the cumulative rate at which the standards were exceeded in southern Taiwan decreased by 11.3% during the first quarter of 2020.

The rates at which the hourly PM_{2.5} levels exceeded distinct standards demonstrated the concentration profiles of high PM_{2.5} levels over northern and southern Taiwan. The rates at which the standards of 25.0, 35.0, and 55.5 $\mu\text{g m}^{-3}$ were exceeded in northern Taiwan (Table 2) were 25.8%, 9.45%, and 1.05% in 2019 and 23.6%, 9.79% and 1.56% in 2020, respectively. The rates at which the standards of 25.0, 35.0 and 55.5 $\mu\text{g m}^{-3}$ were exceeded in southern Taiwan were 64.5%, 40.2%, and 13.6% in 2019 and 60.6% and 36.9%, and 11.7% in 2020, respectively. Compared to 2019, there was a decreasing trend at which the PM_{2.5} concentrations exceeded the standards for most stations during the COVID-19 period in northern Taiwan; however, sporadic stations experienced an upward trend and resulted in the rates beyond the standard increasing 0.34% and 0.51% for the standard of 35 and 55.5 $\mu\text{g m}^{-3}$. The PM_{2.5} concentrations showed a decreasing trend for most stations during COVID-19 period in southern Taiwan, where the rate at which the standards of 25.0, 35.0 and 55.5 $\mu\text{g m}^{-3}$ were exceeded decreased by 3.88%, 3.34%, and 1.91%.

3.4 Spatial Changes in PM_{2.5} between January and March in 2019 and 2020

The descriptive statistics for PM_{2.5} and the regional changes in PM_{2.5} based on the geographical statistics could not be used in the present study due to collection from more than 2,000 air quality micro-stations that generate thousands of units of PM_{2.5} data in each station. Therefore, the RPCs were used to explain the spatial characteristics of the median hourly average PM_{2.5} in our selected areas. Three factors, including eigenvalues, explained variances, and factor loadings, were mainly used to determine the number of principal components. The RPCs of the hourly average PM_{2.5} data were determined as shown in Table 3. The number of principal components was first determined, based on having an eigenvalue over 1.00, to be 28 and 19 RPCs in 2019 and 2020, respectively, from PM_{2.5} data of northern Taiwan as well as 34 and 37 RPCs in 2019 and 2020 from southern Taiwan. Secondly, the number of principal components was chosen based on the explained variances being over 1% and was reduced to 7 and 8 RPCs in 2019 and 2020, respectively, from southern Taiwan. In northern Taiwan, both had 6 RPCs in the two years under consideration. Therefore, the number of principal components was finally determined to

be 6 $\text{PM}_{2.5}$ RPCs in northern Taiwan. For the hourly average $\text{PM}_{2.5}$ data in southern Taiwan, the station numbers for the 7th, 8th, and 9th RPCs were 11, 11, and 2 in 2019 and 0, 12, and 0 in 2020, respectively, based on factor loadings over 0.5 (data not shown). The 7th $\text{PM}_{2.5}$ RPC in 2020 from the $\text{PM}_{2.5}$ data for southern Taiwan did not reveal better correlations between the principal

Fig. 4. Pareto analysis for exceeding rates of $\text{PM}_{2.5}$ daily standards in TEPA ($35 \mu\text{g m}^{-3}$; L35), WHO guideline ($25 \mu\text{g m}^{-3}$; L25), and the sensitive groups ($55.5 \mu\text{g m}^{-3}$; L55.5) were performed (A) in north Taiwan; (B) in south Taiwan.

Table 2. Exceeding rate (%) for varied PM_{2.5} daily standards.

Region	North Taiwan			South Taiwan		
PM _{2.5} standard	2019N	2020N	2020N–2019N	2019S	2020S	2020S–2019S
25 µg m ⁻³	25.77	23.60	–2.17	64.49	60.61	–3.88
35 µg m ⁻³	9.45	9.79	0.34	40.23	36.89	–3.34
55.5 µg m ⁻³	1.05	1.56	0.51	13.56	11.65	–1.91

Sampling time is during Jan to Mar 2019 and Jan to Mar 2020.

Table 3. Eigenvalues and explained variance of rotated components for hourly average PM_{2.5} levels in PM_{2.5} sensors from January to March in 2019 and 2020.

Year	2019				2020			
Region	2019N		2019S		2020N		2020S	
RPC ^a	λ ^b	σ (%)	λ	σ (%)	λ	σ (%)	λ	σ (%)
1	207.08	34.23	314.3	35.27	192.8	35.19	294.8	33.80
2	122.26	20.21	214.8	24.11	116.2	21.21	210.7	24.16
3	88.56	14.64	121.2	13.60	85.1	15.53	113.0	12.96
4	46.71	7.72	49.4	5.54	75.2	13.73	55.1	6.32
5	34.10	5.64	21.2	2.38	6.3	1.14	14.5	1.66
6	11.10	1.84	15.0	1.68	5.9	1.07	10.4	1.20
7	5.71	0.94	9.3	1.04	3.3	0.61	10.2	1.17
8	3.03	0.50	8.3	0.93	2.8	0.50	9.6	1.11
9	2.97	0.49	7.2	0.80	2.4	0.44	7.4	0.85
Sum (%)		86.20		85.36		89.42		83.23

^a RPC: Rotated Principal Components.

^b λ: eigenvalues, σ: Explained variances (%).

components and the air quality micro-stations as compared with the other RPCs from the 1st to 9th RPCs. Finally, the predominant number of RPCs in the present study was determined to be 6 in the PM_{2.5} stations in both northern and southern Taiwan after the eigenvalues, explained variances, and factor loadings were taken into consideration (Figs. 5 and 6).

Fig. 5 shows the contour maps of factor loadings for distinct RPCs in 2019 and 2020 from northern Taiwan, and those from southern Taiwan are shown in Fig. 6 to present the main PM_{2.5} contour maps. In Fig. 5(A), the main PM_{2.5} factor loadings in the industrial areas in 2019 were as follows: (1) The 1st RPC was in Dayuan (DY) and Kuangin (KI), (2) the 2nd RPC was focused on Taipei City and New Taipei City, (3) the 3rd RPC was located at Pingzhen (PZ), (4) the 4th RPC was in Linkou (LK), and (5) the 5th and 6th RPCs were in Guishan (GS). The PM_{2.5} factor-loading map of the 6 main RPCs in 2020 was consistent with those in 2019 except for the 5th RPC in GS due to a lower factor loading in 2020 compared with that in 2019 (Fig. 5(B)). As shown in Fig. 6(A), the 1st RPC of the hourly average PM_{2.5} factor loading in 2019 was located at downtown Kaohsiung City, the 2nd RPC was distributed in the industrial areas of Pingtung County, the 3rd RPC was in the northern part of Kaohsiung City, the 4th RPC was focused on the Pingnan (PN) industrial area, and the 5th and 6th RPCs were scattered in sporadic points in industrial areas in Kaohsiung City. For the duration of the COVID-19 outbreak in 2020, the main factor loadings for the PM_{2.5} for the 1st to 4th RPCs are shown to be consistent in terms of the factor-loading map with those in 2019 from the industrial areas of southern Taiwan (Fig. 6(B)). Various PM_{2.5} factor loadings were found in the 5th and 6th RPCs between 2019 and 2020 in southern Taiwan.

4 DISCUSSION

Compared with the global pandemic outbreak of COVID-19, the spread of the SARS-CoV-2 virus was prevented and controlled effectively in Taiwan by the TCDC due to encouraging the Taiwanese population to wear masks in public, practice social distancing, reduce outdoor activities, and stay away from crowded areas. Taiwan was one of the few countries in the world without a lockdown

Fig. 5. Loading values of 6 rotated principal components in $\text{PM}_{2.5}$ levels from $\text{PM}_{2.5}$ sensors of the industrial areas from northern Taiwan between January and March in 2019 and 2020.

required during the COVID-19 outbreak. Even with the absence of a lockdown in Taiwan during the COVID-19 outbreak, anthropogenic activity was limited, which led to a reduction in air pollution based on the results of the present study. In Table 1, it can be seen that the median hourly average $\text{PM}_{2.5}$ levels were slightly decreased from 16.3 (2019N) to 15.7 (2020N) $\mu\text{g m}^{-3}$ in northern Taiwan and from 32.4 (2019S) to 29.3 (2020S) $\mu\text{g m}^{-3}$ in southern Taiwan. The reduction in $\text{PM}_{2.5}$ between January and March of 2019 and the corresponding duration in 2020 was 1.70%

Fig. 6. Loading values of 6 rotated principal components in PM_{2.5} levels from PM_{2.5} sensors of the industrial areas from southern Taiwan between January and March in 2019 and 2020.

and 4.42% in northern and southern Taiwan, respectively. Our findings were consistent with those from the previous report announced by the TEPA (Liang and Tsai, 2020) indicating that nationwide average $PM_{2.5}$ collected at the national-scale air pollution monitoring sites was reduced from $21.4 \mu g m^{-3}$ between October 2018 and March 2019 to $19.8 \mu g m^{-3}$ in the corresponding period from 2019–2020 ($PM_{2.5}$ attenuated by 7.1%) in Taiwan. Han *et al.* (2020) assessed improvements in the $PM_{2.5}$ pollution in Seoul, Korea, which did not execute a lockdown, before and after implementing social distancing during the COVID-19 outbreak and found a 10.4% reduction. Ma and Kang (2020) also revealed that the decline in daily $PM_{2.5}$ in the month before and after social distancing implementation without a lockdown was 20.9% in Daegu and 3.6% in Tokyo, respectively. According to the two previous reports for Korea and the results of the present study (Han *et al.*, 2020; Ma and Kang, 2020), implementation of social distancing and self-quarantining by the government legislation resulted in significantly obvious $PM_{2.5}$ decline in the regions and cities being investigated, including Taiwan, Korea, and Japan, without a mandatory lockdown. This was probably due to lower $PM_{2.5}$ emissions in lockdown-free regions due to limited anthropogenic activities, such as industrial production, transportation, and economic activities. The reduction could also have been related to the meteorological conditions discussed earlier (Lolli *et al.*, 2020). Due to the global spread of the SARS-CoV-2 virus, most countries were under mandatory lockdown conditions to introduce precautionary measures including limitations on travel, public gatherings, and a mandatory 14-day quarantine period for suspected or confirmed patients and overseas travelers, to help prevent the spread of COVID-19. The precautionary measures taken during lockdown facilitated temporary improvements in air quality particularly in highly polluted countries (e.g., China, India, and Italy), where $PM_{2.5}$ levels were significantly and dramatically decreased by at least 25% (Bedi *et al.*, 2020; Li *et al.*, 2020a; Li *et al.*, 2020c; Kumar *et al.*, 2020a; Şahin, 2020; Shakoor *et al.*, 2020; Srivastava *et al.*, 2020; Zoran *et al.*, 2020).

According to Figs. 5 and 6, the spatial patterns of 6 main PCs in 2019 and 2020 were overlapped. The intensity of PCs in 2019 was slightly higher than in 2020 from northern and southern Taiwan, as shown in Table 1 and Figs. 2 and 3, indicating that $PM_{2.5}$ levels between January and March in 2019 had significantly and slightly higher magnitudes than those in the corresponding periods of 2020 in northern and southern Taiwan. Liang and Tsai (2020) revealed that $PM_{2.5}$ in Taiwan is associated with transboundary transportation of $PM_{2.5}$, weather type, meteorological conditions, and precursors of $PM_{2.5}$, but $PM_{2.5}$ levels from transboundary transportation in 2020 were reduced by $0.31 \mu g m^{-3}$ compared with those in the corresponding period in 2019 (Fig. S1). This finding indicated that the main reason for the improvement in air quality due to $PM_{2.5}$ in 2020 was related to the decline of $PM_{2.5}$ precursors, nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), probably due to limitations on artificial and economic activities, but the improvement was slightly linked to transboundary transportation of $PM_{2.5}$, weather type, and meteorological conditions (Figs. S2 and S3; Liang and Tsai, 2020). Therefore, the long-range $PM_{2.5}$ transport from China (transboundary transportation) had minor effects on reductions in $PM_{2.5}$ during the COVID-19 outbreak in Taiwan. Reductions in $PM_{2.5}$ from local emissions were mainly associated with the decline in $PM_{2.5}$ during the COVID-19 situation (Figs. S1–S3). Inversely, Han *et al.* (2020) indicated that synoptic conditions and the decline in aerosol optical depth from eastern China to the Korean Peninsula led to improvements in air quality, including decreased $PM_{2.5}$, in Seoul during the COVID-19 outbreak, which might have been due to declines in domestic emissions and reductions in long-range transboundary transportation of air pollutants. According to our findings, $PM_{2.5}$ -related air quality was temporarily improved during the COVID-19 outbreak mainly from reduced levels of NO_2 and SO_2 from local emissions via limitations placed on human activities. $PM_{2.5}$ levels have a significantly positive association with the number of cases and mortalities associated with the SARS-CoV-2 virus. It is reiterated that $PM_{2.5}$ control and reductions in $PM_{2.5}$ emissions, especially those from local sources, are very important to reducing COVID-19 case numbers.

5 CONCLUSIONS

By implementing a multifaceted policy that includes community mitigation, border restrictions, travel quarantines, and a coordinated medical response, the TCDC has effectively limited the spread of COVID-19 in Taiwan from January 20, 2020, through the present without mandating a

lockdown. Based on our big data analysis, the PM_{2.5} concentrations in the industrial areas of northern and southern Taiwan decreased by 1.70% and 4.42%, respectively, between the first quarter of 2019 and the corresponding period in 2020. Furthermore, this pollutant exhibited similar spatial patterns during both years, indicating that social distancing and other COVID-19-related restrictions drove the observed changes. Although lower domestic emissions were primarily responsible for the decline in PM_{2.5} during the outbreak, reduced transported emissions also played a minor role.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest including financial interests and personal relationships.

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SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at <https://doi.org/10.4209/aaqr.210020>

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