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Temporal Variation of Temperature Inversions and their Effect on Fine Particulate Matter ($PM_{2.5}$) Concentrations in a Vietnamese Metropolis

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Authors' contributions

This work was carried out in collaboration among all authors. Author TNTN designed the study, performed the data interpretation and wrote the manuscript. Author PTB managed the data pre-processing and analysis. Author MTTN performed the data visualization and managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

This study aims to investigate the temporal variation of temperature inversions, including inversion frequency and inversion strength, in Ho Chi Minh City (HCM), a metropolis of Vietnam. The effect of the temperature inversions on $PM_{2.5}$ concentrations in the dry and rainy seasons of HCM City was also identified. The results revealed that the surface inversions, which are temperature inversions below 300 m, were more frequent at 12Z (7 PM local time) in the rainy season. In addition, the

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stronger inversions were found in the dry season, when the higher $PM_{2.5}$ concentrations were also observed, suggesting an influence of the temperature inversions on an increase in $PM_{2.5}$ concentrations. This suggestion was also supported by the significantly positive correlation between $PM_{2.5}$ concentrations and inversion frequency in the dry season. However, the temperature inversions were believed to have a minor effect on the $PM_{2.5}$ concentrations in the rainy season since no significant correlation between the $PM_{2.5}$ concentrations and inversion frequency or strength was found for this season. The findings of this study contribute to understanding of the temperature inversions and their effect on $PM_{2.5}$ concentrations in a metropolis of Vietnam, a developing country in Southeast Asia. Based on these results, solutions for reducing the $PM_{2.5}$ pollution in the study area can be obtained.

Keywords: Temperature inversion; $PM_{2.5}$; Ho Chi Minh City; Vietnam.

1. INTRODUCTION

Temperature inversion is a phenomenon when atmospheric temperature increases with height in the troposphere [1]. The temperature inversions can be classified as radiation inversions and subsidence inversions. The radiation inversion, also known as surface temperature inversion, develops mostly at night when the ground becomes cooler due to emissions of longwave radiation [2]. Consequently, the air temperature in the lower planetary boundary layer is lower than that in the overlying layer. The subsidence inversion, which is also called an upper surface temperature inversion, forms when the air layer descend and then is compressed and heated due to an increase in atmospheric pressure [2], resulting in warmer air at higher altitudes.

The temperature inversions can act as a cap, preventing vertical dispersion of air pollutants [3], and thus, pollutant levels increase near the ground during the inversion. The relationship between temperature inversion and air pollution has been reported in several previous studies [4-9]. For instance, concentrations of several pollutants, including NO_2, SO_2, fine particulate matters ($PM_{2.5}$), were found to be higher when strong inversions occurred in Ha Noi City of Vietnam [4]. Of these pollutants, $PM_{2.5}$, which is a particle less than 2.5 micrometers in diameter, is a frequently monitored pollutant because of its harmful effect on human health. In particular, the components of $PM_{2.5}$ contain several chemicals, including metals, ions, and organic compounds (e.g., polycyclic aromatic hydrocarbons) that have high toxicities [10]. Added to this, $PM_{2.5}$ can penetrate deep into the human respiratory system through inhalation due to its small size, harm human health, and cause several diseases, such as lung diseases, asthma, and acute respiratory distress [10]. Therefore, it is essential to understand the factors governing the $PM_{2.5}$ levels. These factors include meteorological conditions (e.g., rainfall amount, wind speed, and air temperature), emission sources emitting air pollutants, and temperature inversions trapping the pollutants.

Ho Chi Minh City (HCM City), located in southeastern Vietnam, is a metropolis and economic center of the country. HCM City has a tropical monsoon climate with two distinct seasons, including dry and rainy seasons covering a period of November–April and May–October, respectively [11]. Air pollutants (e.g., $PM_{2.5}$, PM_{10}, SO_2, NO_x, and CO) in HCM City have been linked to vehicle exhaust, industrial emissions, and area sources (i.e., households and construction sites) [12,13]. Most previous studies on $PM_{2.5}$ pollution in HCM City have mainly focused on monitoring concentrations, investigating the correlation between concentrations and meteorological conditions, and calculating the emission inventory of $PM_{2.5.}$ The temperature inversions can contribute to $PM_{2.5}$ pollution [4-9]., however, there has been no information related to the temperature inversions in HCM City, such as frequency, strength, and seasonal variation of the inversions.

This study aims to investigate the temporal variation of the temperature inversions, considering inversion frequency and inversion strength, and determine the effects of the inversions on the $PM_{2.5}$ concentrations in HCM City, Vietnam. Results from this study help to increase understanding of the temperature inversions and their relation to the $PM_{2.5}$ pollution in a metropolis in Vietnam, a developing country in Southeast Asia. Based on these results, solutions for reducing the $PM_{2.5}$ pollution in the study area can be obtained.

2. METHODOLOGY

2.1 Study Area

Ho Chi Minh City (HCM City) is one of the municipal cities of Vietnam and this city covers approximately an area of 2,061 km^2 and is coordinated between latitude 10°46'32"N and longitude 106°42'07"E [11]. There are two seasons in this city, which are dry and rainy seasons. The average rainy day and rainfall amount in the dry season, lasting from November to April of the following year, are 5 days and 40.6 mm, respectively. The rainy season covers a period of May to October and tends to have more rainy days and greater rainfall amount, which are 21 days and 281.2 mm, respectively [14].

2.2 Data Collection

To determine the temperature inversion, radiosonde data of HCM City were downloaded via the Wyoming Weather website http://weather.uwyo.edu/upperair/sounding.html, operated by the Department of Atmospheric Science, College of Engineering, the University of Wyoming. The code and identifier of the station are 48900 and VVTS, respectively (Fig. 1). This station (latitude: 10°48'36"N, longitude:106°39'36"E) is 10 m above sea level and situated in northwestern HCM City. The radiosonde data were gathered twice per day at 00Z (7 AM local time) and 12Z (7 PM local time) from 1 January 2019 to 31 December 2020 and contained values of several meteorological parameters, including potential temperature, wind speed, and wind direction at different air layer heights.

To understand the effect of the temperature inversions on $PM_{2.5}$ pollution, data on $PM_{2.5}$ concentrations over the study period (i.e., 1 January 2019 to 31 December 2020) in HCM City were obtained from the AirNow monitoring network (https://airnow.com), operated by the U.S. Environmental Protection Agency. The technique used for $PM_{2.5}$ monitoring is a beta attenuation monitor, a detection technique of $PM_{2.5}$ based on the absorption of beta radiation by solid particles [15]. In addition, the $PM_{2.5}$ monitoring station is at the HCM City U.S Consultant (latitude: 10°46'58.76"N, longitude: 106°42'2.05"E), located in a downtown area of District 1, HCM City (Fig. 1). The hourly $PM_{2.5}$ concentrations obtained from the AirNow monitoring network, were pre-processed to remove missing and abnormal data (e.g., null and outliers). The processed data were then averaged into annual, seasonal, and monthly concentrations for further usage.

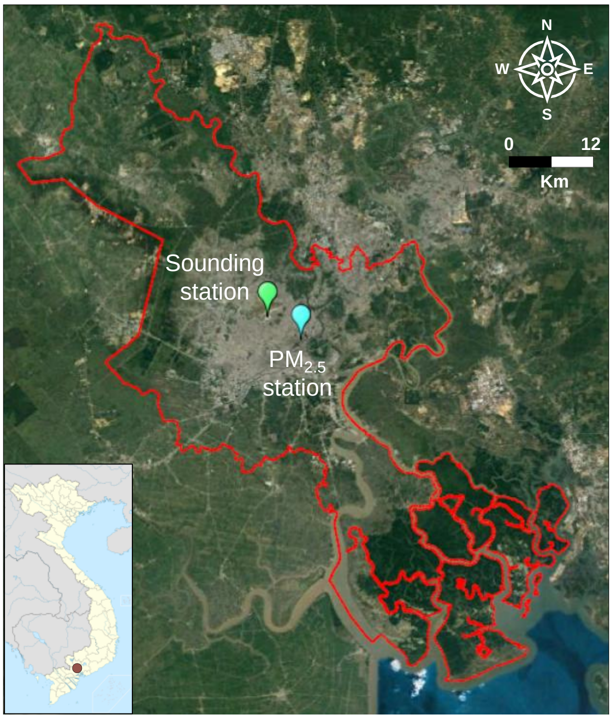

Fig. 1. Map of study area showing locations of the radiosonde and $PM_{2.5}$ monitoring stations in Ho Chi Minh City, Vietnam, The red line illustrates the city boundary

In addition, the monthly rainfall amount and the total of rainy days per month in HCM City were obtained from the Mac Dinh Chi station (latitude: 10°47'3.72"N, longitude: 106°42'1.04"E). This station is approximately 200 m from the $PM_{2.5}$ monitoring station and is operated by the Hydrometeorological Observatory-Southern region.

2.3 Determination of Temperature Inversion, Inversion Strength, and Inversion Frequency

The temperature inversion is identified based on a ratio of the difference in potential temperature, θT (K), and the height difference, θz (m) [16]. A positive value of $\theta T/\theta z$, meaning that potential temperature increases with increasing height, reflects a stable condition of the atmosphere or an occurrence of the temperature inversion [17]. Reversely, if $\theta T/\theta z$ is negative, the atmosphere is unstable. Additionally, if θT equals zero, the potential temperature un-changes with height, and this situation is defined as a neutral condition. In this study, the temperature inversions were checked at several atmospheric layers and were categorized into three types according to their bottom heights, namely surface inversion (SI), elevated inversion (EI), and lower-troposphere inversion (LTI). Particularly, the SIs has a bottom height of 10 to 300 m. The EIs and LTIs refer to the inversions with bottom heights in a range of 300–2,000 m and above 2,000 m, respectively.

The inversion strength was also calculated to understand the characteristics of the temperature inversion in HCM City. The inversion strength is defined as the change in atmospheric temperature over the first 100 m above from ground level [18] and is expressed as °C/m. Moreover, the inversion frequency was also computed as the percentage of inversion observation over the total events (i.e., inversion and non-inversion events) [16].

2.4 Data Analysis and Visualization

This study used Python programming language (https://www.python.org) with *numpy* [19] and *pandas* [20] libraries to pre-process the radiosonde and $PM_{2.5}$ concentration data, then compute the temperature inversion, inversion strength, and inversion frequency for the 2019 and 2020. The OriginPro version 2020 (OriginLab, USA) was used to visualize the calculation results. Moreover, the statistical analysis, such as a t-test for hypothesis testing, was performed using *scipy*, a Python library.

3. RESULTS AND DISCUSSION

3.1 Temporal Variation of $PM_{2.5}$ Concentrations

The $PM_{2.5}$ concentrations in HCM City from 2019 to 2020 are illustrated in Fig. 2. In general, the concentrations of $PM_{2.5}$ observed in 2019 (range: 15.1–42.6 μg/m^3, mean: 25.5 μg/m^3) were 1.3 times higher than those in 2020 (range: 17.2–32.7 μg/m^3, mean: 23.2 μg/m^3). Additionally, there was no statistically significant difference between the concentrations of 2019 and 2020 (Mann-Whitney rank-sum test, P = 0.442). Noticeably, the mean $PM_{2.5}$ concentrations of HCM City in 2019 and 2020 were 1.5–5.0 times higher than the WHO and Vietnamese air quality guidelines for annual $PM_{2.5}$ levels, which are 5 [21] and 25 [22] μg/m^3, respectively. Previous studies on monitoring $PM_{2.5}$ in HCM City also reported an exceedance of the monitored concentrations over the Vietnamese criteria level [13,23,24].

Regarding seasonal variation, the $PM_{2.5}$ concentrations in the dry season (range: 17.2–42.6 μg/m^3, mean: 25.1 μg/m^3) were 1.1–1.9 times higher than those in the rainy season (range: 15.1–36.7 μg/m^3, mean: 22.1 μg/m^3). A similar observation was also reported in previous studies [23,25]. The lower concentrations in the rainy season would be contributed by wet deposition removing particulate matters in the atmosphere. The greater rainfall amount and more rainy days in the rainy season (May–October) (Fig. 3) would support this interpretation. For monthly variation, the $PM_{2.5}$ concentrations in several months, including October, November, December, and January (27.9 ± 12.4, 36.1 ± 9.2, 31.0 ± 3.2, and 32.7 ± 1.6 μg/m^3, respectively) were 1.4–2.0 times higher than those in the other months (20.5±2.5 μg/m^3). The period of October to January exhibited lower rainfall amount (Fig. 3a) and rainy days (Fig. 3b), therefore, the removal ability of $PM_{2.5}$ through wet deposition declined and led to an increase of $PM_{2.5}$ concentrations in the atmosphere. In addition, the lower wind speed in this period (1.9–2.5 m/s) (Fig. 3c) would reduce the dispersion of air pollutants and contribute to the higher $PM_{2.5}$

concentrations in HCM City from October to January. The temperature inversion might also cause an elevation of $PM_{2.5}$ concentrations in this period (i.e., October to January) and this issue is more discussed in Section 3.3.

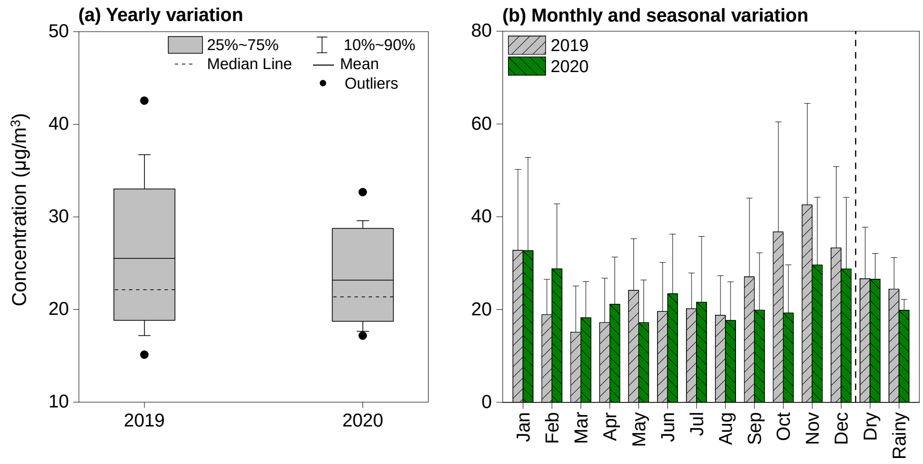

Fig. 2. Concentrations of $PM_{2.5}$ in Ho Chi Minh City of Vietnam shown in (a) yearly variation and (b) monthly and seasonal variation

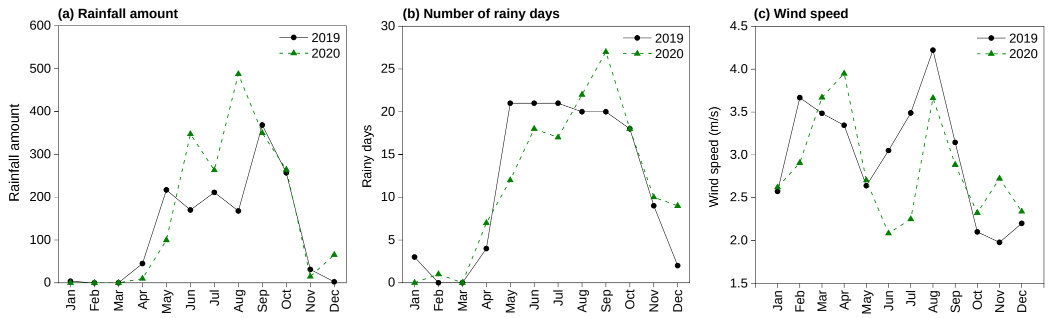

Fig. 3. Rainfall amount (a), number of rainy days (b), and wind speed (c) of Ho Chi Minh City shown as monthly averages

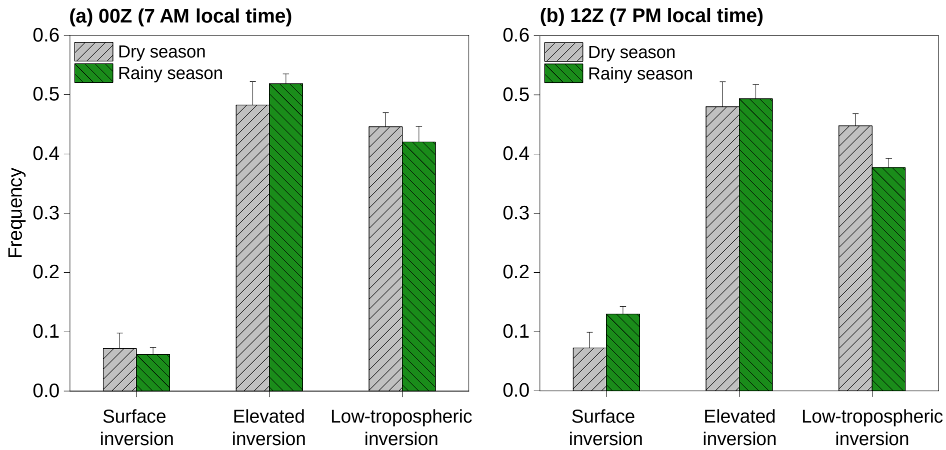

Fig. 4. Frequency of the surface inversions, elevated inversions, and low-tropospheric inversions at (a) 00Z (7 AM local time) and (b) 12Z (7 PM local time) in the dry and rainy seasons of Ho Chi Minh City

3.2 Characteristics of Temperature Inversions

The frequency and strength of the temperature inversions at 00Z (7 AM local time) and 12Z (7 PM local time) in the dry and rainy seasons of HCM City were determined. In addition, the inversions observed over the study period were classified as surface inversions (SIs), elevated inversions (EIs), and lower-troposphere inversions (LTIs) to understand the temperature inversions at several atmospheric layers. In general, the inversions in HCM City showed the highest frequency at the air layers between 300–2,000 m (i.e., the EIs), followed by the lower tropospheric layer above 2,000 m (i.e., the LTIs) and the surface layer lower than 300 m (i.e., the SIs). The annual frequencies of the SI, EI, and LTI were 8%, 49%, and 42%, respectively. Regarding hourly variation, mean frequencies of the SI, EI, and LTI at 00Z (7 AM local time) were 7%, 50%, and 43%, respectively. Those at 12Z (7 PM local time) were 10%, 49%, and 41%, respectively. The statistically significant difference in the inversion frequency at two-time points (i.e., 00Z and 12Z) was only observed for the SIs (i.e., near surface inversions) (t-test, P = 0.008).

Noticeably, the SIs at 12Z (7 PM local time) were more frequent in the rainy season (Fig. 4b). This observation would be because rain events in the rainy season of HCM City tend to occur from the afternoon until the evening [26]. After the rain events, the air near the ground is cooler than the air in the higher atmospheric layer, causing a high frequency of SIs (i.e., surface inversions) at 12Z (7 PM local time) in the rainy season. Our finding on the occurrence of surface inversions after the rain events is supported by the similar observations in Kolkata of India [25] which has the similar climate to HCM City. However, these SI tends to disappear in the morning when the ground is heated by solar radiation [3], resulting in a low frequency of the SIs at 00Z (7 AM local time) in the rainy season (Fig. 4a).

The inversion strengths, referred to as the change in atmospheric temperature over the first 100 m height from ground level [18], in the dry and rainy seasons of HCM City is shown in Fig. 5. In general, hourly and seasonal variations were observed for the temperature strength. Particularly, at 00Z (7 AM local time), the temperature inversions of the dry season (0.011 ± 0.005 °C/m) were 2.3 times stronger than those of the rainy season (0.005 ± 0.002 °C/m). The greater inversion strength in the dry season would possibly prevent the vertical mixing of air pollutants [27], leading to a trap of pollutants, such as $PM_{2.5}$, near the ground surface. The relationship between the temperature inversions and $PM_{2.5}$ concentrations in HCM City is more discussed in Section 3.3.

A reverse trend was observed for the inversion strength at 12Z (7 PM local time), in particular, the rainy season showed a stronger inversion (0.013 ± 0.001 °C/m) compared to the dry season (0.009 ± 0.001 °C/m). As mentioned, rain events in the rainy season of HCM city tend to last from the afternoon to the evening [26]. The occurrence of rain could cause the air near the surface to be cooler than the air in the above layers, expanding the temperature difference between the air layers and resulting in a stronger inversion at 12Z in the rainy season (Fig. 5).

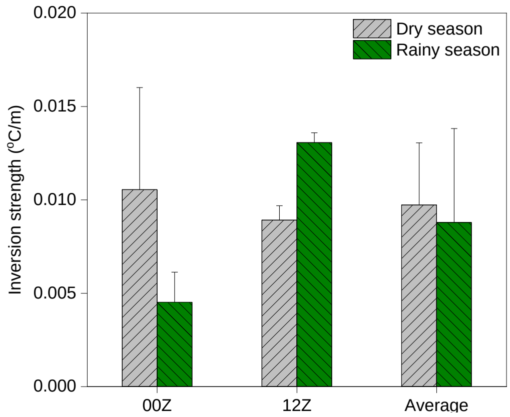

Fig. 5. Inversion strength observed at 00Z (7 AM local time) and 12Z (7 PM local time) in the dry and rainy seasons of Ho Chi Minh City, Vietnam

3.3 Effect of Temperature Inversion on $PM_{2.5}$ Concentrations

To identify the effect of the temperature inversion on $PM_{2.5}$ concentrations, the study period was classified into inversion and non-inversion days depending on the occurrence of the temperature inversion on a given day. To evaluate the effect of the temperature inversions on the $PM_{2.5}$ concentrations, only the inversions below 300 m height (i.e., the SIs) were considered because the $PM_{2.5}$ concentrations were monitored near the surface layer. The $PM_{2.5}$ concentrations on the inversion and non-inversion days in the dry and rainy seasons are illustrated in Fig. 6. As shown in this figure, the mean $PM_{2.5}$ concentration on the inversion days (dry season: 27.2 ± 9.1 μg/m^3, rainy season: 22.2 ± 4.9 μg/m^3) were 1.2 times higher than those on the non-inversion days (dry season: 23.0 ± 8.9 μg/m^3, rainy season: 18.4 ± 4.2 μg/m^3), reflecting a contribution of the temperature inversion to an increase of $PM_{2.5}$ concentrations in HCM City. This suggestion is supported by the significantly positive correlation between $PM_{2.5}$ concentrations and inversion frequency, especially in the dry season (Table 1).

Additionally, the monthly $PM_{2.5}$ concentrations on the inversion and non-inversion days and the monthly inversion frequency are shown in Fig. 6. The higher inversion frequencies were observed in several months of the dry season, including November, December, January, and February. Added to this, the concentrations of PM2.5 on the inversion days of these months increased markedly and exceeded the WHO and Vietnamese air quality guidelines for annual $PM_{2.5}$ levels (5 and 25 μg/m^3, respectively) (Fig. 7). This finding suggests that the temperature inversions would affect the concentrations of PM2.5 in HCM City and this influence could be more considerable in the dry season when the inversions were stronger and more frequent (Figs. 3 and 4).

Table 1. Spearman correlation between $PM_{2.5}$ concentrations and inversion frequency in the dry and rainy seasons

	$PM_{2.5}$ (dry season)	$PM_{2.5}$ (rainy season)
Inversion strength	0.2507	-0.3859
Inversion frequency	0.7004*	0.2362
Pressure	0.5718	0.4750
Wind speed	-0.8186*	-0.7960
Potential temperature	-0.3657	-0.4737

**: correlation is significant at the 0.05 level.*

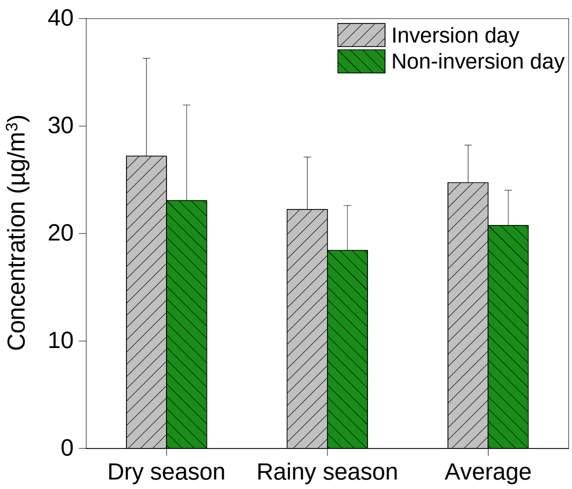

Fig. 6. Concentrations of $PM_{2.5}$ on the inversion and non-inversion days in the dry and rainy seasons of Ho Chi Minh City

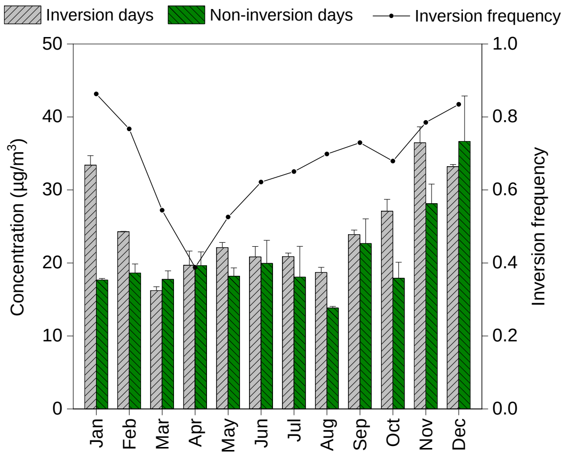

Fig. 7. Monthly concentrations of $PM_{2.5}$ on the inversion and non-inversion days. The solid line illustrates the inversion frequency in each month

In addition, the temperature inversions discourage the vertical mixing of $PM_{2.5}$ [5], causing this pollutant to be horizontal dispersed in the air [28] and resulting in an increase of $PM_{2.5}$ concentrations near the ground surface. Thus, the disappearance of temperature inversions promoted the vertical dispersion of $PM_{2.5}$ and led to a decrease in $PM_{2.5}$ concentrations on the non-inversion days. Regarding the rainy season, the $PM_{2.5}$ concentrations did not show a significant correlation to the inversion frequency and strength (Table 1), suggesting that other meteorological parameters, such as rainfall amount and rainfall frequency, rather than the temperature inversions could importantly impact the $PM_{2.5}$ concentrations in the rainy season. The wet deposition during the rain events would possibly remove particles in the air [25] and would mainly lower the $PM_{2.5}$ concentrations in the rainy season. In addition, the stronger wind speed in the rainy season (e.g., August to October) (Fig. 3) would enhance the dispersion of air pollutants and reduce the $PM_{2.5}$ concentrations.

4. CONCLUSION

In this study, temporal variation of the temperature inversions and their effect on the $PM_{2.5}$ concentrations in a metropolis having a tropical monsoon climate in Vietnam were investigated. For the $PM_{2.5}$ concentrations, the dry season (i.e., November to April of the following year) showed higher concentrations compared to the rainy season (i.e., May to October). The surface inversions, which are temperature inversions below 300 m, were more frequent at 12Z (7 PM local time) in the rainy season. This observation could be stemmed from the cooler air near the ground after rain events, which tend to last from the afternoon to the evening in the rainy season of HCM City.

The results also revealed a stronger inversion in the morning of the dry season, which could prevent the vertical mixing of air pollutants and lead to air pollution. This suggestion was supported by the higher $PM_{2.5}$ concentrations observed on inversion days and the significantly positive correlation between $PM_{2.5}$ concentrations and inversion frequency, especially in the dry season. For the rainy season, the temperature inversions were believed to have a minor effect on the $PM_{2.5}$ concentrations since no significant correlation between the $PM_{2.5}$ concentrations and inversion frequency and strength was found for this season. Based on the results of this study, solutions for reducing the $PM_{2.5}$ pollution in the study area can be obtained, such as the development of public transport to reduce the vehicle density and a limitation of private vehicles in the dry season when the stronger temperature inversions were observed.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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