

Research Article

Seasonal Variability of Air Pollutants and Their Relationships to Meteorological Parameters in an Urban Environment

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Air quality in urban areas is deteriorating over time with the increased pollutant distribution levels mainly caused due to anthropogenic activities. In addition, these pollutant distribution levels may relate to changing meteorological conditions. However, the relationships were not researched in-depth in the context of Sri Lanka, a country with a significant impact on climate change. The main objective of this study was to provide a broader perspective on the seasonal variation of tiny particles in air (PM2.5 and PM10), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), and sulfur dioxide (SO_2) in two urban cities (Colombo and Kandy) in Sri Lanka over 3 years period (2018–2021) and the possible relationships between air pollution and meteorological variables. Results show that all the aforementioned pollutants except O_3 consistently depict two peaks during the day, one in the morning (~07:00–09:00 local time) and the other in the evening (~18:00–20:00 local time). These peaks coincided with the traffic jams observed in both cities. The results further revealed that the concentration of all pollutants has significant seasonal variations. Compared to two monsoon seasons, the highest daily average PM2.5 ($31.2 \mu\text{g}/\text{m}^3$), PM10 ($49.5 \mu\text{g}/\text{m}^3$), NO_2 (18.9 ppb), CO (717.5 ppb), O_3 (18.5 ppb), and SO_2 (9.4 ppb) concentrations in Colombo are recorded during northeast monsoon (NEM) seasons while contrast pattern is observed in Kandy. In addition, it was found that wind speed with its direction is the most influencing factor for the pollutant concentration except for SO_2 and O_3 in two cities, and this is irrespective of the season. This study's findings contribute to understanding the seasonality of ambient air quality and the relationship between meteorological factors and air pollutants. These findings ultimately lead to designing and implementing season-specific control strategies to achieve air pollution reduction at a regional scale.

1. Introduction

High air pollution levels are experienced in a most urban environment [1] and exhibit substantial regional variation [2, 3]. More than 80% of the people who live in urban areas which are monitored for air quality have exceeded the air quality levels given under the WHO standards. Air pollution is one of the greatest environmental risks to individuals, public health, ecosystem, and economies [4–6]. The

mortality rate worldwide from respiratory and cardiovascular diseases related to air pollution is around 6.7% [7]. Many health-related problems are increasing due to adverse air quality. Therefore, the damage which can cause is significant. World Air Quality report in 2020 stated that out of the 50 most polluted cities in the world, 46 are located in Central Asia and South Asia. Highly important to note that around 40% of the world's deaths due to adverse ambient air pollution are found in South Asia [8].

Rapid urbanization and industrialization are increasingly being identified as the major factors for increasing air pollution in developing countries [2, 9, 10]. It is important to determine potential pollution sources and then, develop and implement well-designed and efficient long-term emission control measures to control and maintain the air quality in urban areas [11]. Therefore, understanding the air pollutant origin, seasonal variation, and characteristics even at a regional level is important [12]. Based on the previous studies, regional variation of air pollutants concentration depends on emissions, meteorology [10, 13], physicochemical transformations, urbanization process [4], long-term policies for air pollution, laws, and regulations [14].

Among them, meteorological driving factors largely contribute to variations in diurnal concentrations of air pollutants [2, 3, 13, 15] and aerosol composition [13, 16]. The meteorological driving factors are significant more than 70% of pollutant concentration variation in 31 cities in China [17]. However, the magnitude of the impact of meteorological divers, especially wind speed and direction on air pollution concentration, depends on the geographical location of the emission source and pollutants [2]. Nevertheless, the research studies to investigate the relationships between meteorological factors and air pollutants are inadequate [2]. Therefore, investigating the relationships between meteorological factors and air pollutants, and seasonal variation of pollutants are important to identify new policies for future and then to implement air pollution control strategies [18].

According to a recent study by Shaddick et al. [19], the SO₂ and PM2.5 concentrations over southern Asia have increased, resulting in high exposure to PM2.5 except for Sri Lanka [20]. Even though the air pollutant concentration in Sri Lanka is comparatively less than in other South Asian countries, air pollution in Sri Lanka is an emergent problem due to the rapid development in the industrial and commercial sectors, expansion of major urban centers, the rapid increase in the usage of motor vehicles [21], and power generation in thermal power plants [22]. For instance, vehicle emission in Colombo City alone contributes around 55–60% to air pollution [23]. As a result of continuous air pollutant emissions, indoor and outdoor air quality deterioration is responsible for 4,300 and 1,000 deaths (WHO), respectively, an emergent public health issue in Sri Lanka [24, 25].

The National Policy on Urban Air Quality Management was implemented in Sri Lanka in 2000. The national policy targets maintaining good air quality, preventing air pollutant-related disease, and reducing national health expenditures in Sri Lanka. Several measures have been adopted by the Sri Lankan government to increase the atmospheric conditions over time. Introduction of low-percentage sulfur diesel (in January 2003), prohibition of 2-stroke three-wheelers (in 2008), and initiation of vehicular emission tests (in 2008) are some of the measures taken by the government [21, 24]. These measures have further strengthened the National Environmental (Ambient Air Quality) Regulations of 1994 [26], which impose the permissible ambient air quality standards for selected air pollutants in Sri Lanka.

On the other hand, previous studies strongly suggest that pollutant concentrations are varied seasonally [1, 3, 11, 12, 27, 28], especially with monsoonal winds in tropical countries [1, 29]. For instance, the concentration of PM10, PM2.5, SO₂, and NO₂ in South India is higher during the southwest monsoon [27]. Though the importance of the seasonal variation of pollutant levels of a specific region or a country is understood [12], very few studies have worked on the seasonal variation of pollutants in Sri Lanka using long-term continuous data sets. Moreover, the relationship between air pollutant and meteorological variables is not well studied with the recently updated data sets. Most of the studies are focused on assessing the threat of air pollution to public health [24, 30, 31], and they have found that it is growing as a health issue, especially among children [25, 32]. Sly et al. [33] found that indoor air pollution remains a significant threat compared to outdoor air pollution in Southeast Asia and South Asia. Ranathunga et al. [34] found that CO and PM2.5 concentrations were significantly higher in households using biomass fuel for cooking and responsible for childhood respiratory diseases in a semiurban population. However, data is inadequately specific to Sri Lanka to conclude that indoor air pollution is more harmful to respiratory health than outdoor pollutants levels. To the best of the author's knowledge, a detailed study of the seasonal changes of air pollutants such as CO, O₃, NO₂, SO₂, PM10, and PM2.5 and the effect of meteorological factors on air pollutant concentrations during the COVID-19 lockdown has not been previously reported for urban cities in Sri Lanka.

The unavailability of adequate scientific knowledge on air quality management is a significant hindrance to the slow progress of setting the air quality management policy and its implementation. This study examines the seasonal variation of PM10, PM2.5, NO₂, SO₂, CO, and O₃, and the association of meteorological variables with pollutant concentration to accurately identify the characteristics of the air pollution changes. The findings can be used as scientific facts for controlling air pollution in Sri Lanka.

2. Materials and Methods

2.1. Air Quality Monitoring Stations in Sri Lanka. With financial support from the Vehicular Emission Testing Program (VETP) of the Department of Motor Traffic (DMT) in Sri Lanka, two ambient air quality monitoring stations were established in December 2018 (AQMS) at Battaramulla (6.90103°N: 79.9265°E), and Kandy (7.29262°N: 80.63564°E). The AQMS at Battaramulla (11 m ASL) is situated in the administrative capital of Sri Lanka and is characterized by a high degree of industrialization. In Colombo, ambient air pollution is contributed by traffic, industrial activities, power plants, and natural dust and salt [35]. The AQMS Kandy (500 m ASL) is located in a populated city in the middle of the country that lies on a plateau surrounded by the Knuckles and Hunnasgiriya Mountain Ranges (refer to Figure 1). It was understood that the road transport is the primary source of air pollution in Kandy due to high density of vehicles, narrow roads, and frequent traffic congestion

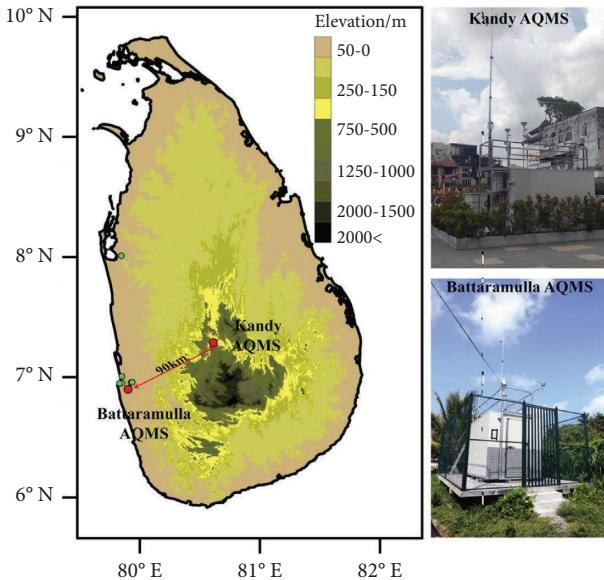


FIGURE 1: The location of the ambient air quality monitoring stations.

[36]. At present, both AQMS are operated under the Air Resource Management and Monitoring Unit (ARM&M Unit) Central Environmental Authority, Sri Lanka.

The red dots in Figure 1 showcase the two air quality monitoring stations, whereas the green colour dots show the locations of major fuel-based power stations near Colombo (Kelaniya, Yugadanavi, Sapugaskanda, Lakdhanavi, Colombo Port, and Heladhanavi).

2.2. Air Quality and Meteorological Data Measurements. AQMS at Battaramulla and Kandy (hereinafter AQMS_{Bat} and AQMS_{Kan}) has been fixed in places where unrestricted airflow is ensured, with a minimum influence from nearby buildings. Samples were collected to measure nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and particulate concentrations of PM2.5 and PM10 at both locations. These air samples were collected 5 m above the ground level to minimize the turbulent effects of air near the ground. They were collected in hourly intervals from January 2019 to May 2021 (for 30 months). All the gas samples were let go through several filters before the measurements to eliminate other aerosols that cause interferences.

The Serinus 40 Oxides of Nitrogen Analyser was used to measure the NO_2 concentration. This instrument uses gas-phase chemiluminescence detection to perform continuous analysis of nitric oxides. The Serinus 50 Sulfur Dioxide (SO_2) Analyser was used to measure the SO_2 concentrations at both locations. This instrument uses UV fluorescent radiation technology to detect sulfur dioxide in the range of 0–20 ppm (US-EPA designated range is 0–0.5 ppm, each instrument is maintained and calibrated as directed by the operational manual and in accordance with the general guidance). The CO in ambient air was measured using Ecotech Serinus 30 Carbon Monoxide

analyser with the nondispersive infrared spectrophotometry (NDIR) technology. In addition, the Serinus 10 Ozone Analyser, which adopts nondispersive ultraviolet (UV) absorption technology, was used to measure the O_3 concentration. However, the air samples are extracted from 6 meters above the ground level and automatically recorded for airborne particulate concentrations PM2.5 and PM10 using Ecotech Spirant BAM with the principle of beta ray attenuation.

In addition, rainfall, temperature, relative humidity, wind speed, and wind direction were recorded at both AQMS locations. These meteorological data were collected in hourly resolution for 30 months (from January 2019 to May 2021, about 21600 data points). Rain gauges, solar radiation sensors, ambient temperature sensors, barometers, and relative humidity sensors were located about 5 meters above the ground level to measure these meteorological data. In addition, the wind speed and wind directions were measured using sensors about 10 meters above the ground level. These data were stored in data loggers (WinAQMS) and sent to the client and report manager (Airodis) for further processing.

2.3. Rainfall Characteristics of Sri Lanka. Rainfall in Sri Lanka can be characterized by wind direction and circulation patterns over the country. Two major monsoon seasons based on the wind direction can be identified as northeastern monsoon (NEM) (from December to February) and southwestern monsoon (SWM) (from May to September). These two major monsoons bring rainfall to northern and southern Sri Lanka, respectively [37, 38]. In addition, Sri Lanka has two other intermonsoons in between the above two major monsoons to bring significant rainfall. The first intermonsoon (FIS) (from March to April) and the second intermonsoon (SIM) (from October to November) are the two intermonsoons.

2.4. Overall Methodology. This study adopted the aforementioned monthly groups to identify the seasonal distribution of air pollutant concentration in Battaramulla and Kandy. Pearson's correlation coefficient was used to analyse the relationship between pollutant concentrations and meteorological factors and visualized the correlation matrix. The corplot package in R was used to develop the correlation matrix. The wind speed, together with wind direction and pollutant concentration, is commonly used to distinguish different source types [39, 40]. Polar plots are widely used to showcase related research [27, 39, 41]. Wind directions are represented to 360° clockwise from the north and the wind speeds are showcased by the radius. Therefore, the pollutant concentrations and wind speed with directions were plotted in the polar plots. They were constructed by the “R” statistical software (<https://www.r-project.org/>) and the open air package (<http://www.openairproject.org/>).

3. Results and Discussion

3.1. Daytime and Nighttime Variations of Pollutant Concentration. Figure 2 illustrates the diurnal variation of PM10, PM2.5, CO, NO₂, O₃, and SO₂ concentrations in AQMS_{Bat} and AQMS_{Kan} for the FIM, NEM, SWM, and SIM seasons during the time January 2019 to May 2021. The left panel of Figure 2 showcases the plots for Battaramulla, whereas the right panel showcases the plots for Kandy. The nighttime (18:00 hrs to 06:00 hrs) is showcased in the grey shaded strips for each day.

In AQMS_{Bat}, the hourly average concentrations of PM10, PM2.5, CO, and NO₂ reached their maximum during the morning and evening hours. For instance, curves obtained for CO show two peaks, the morning peak from 06:00 to 09:00 LT, while the evening peak occurs from 18:00 to 21:00 LT for all the monsoon seasons (refer to Figure 2(c)). Similar to the diurnal variation of CO, PM10, PM2.5, and NO₂ concentrations for all the monsoon seasons follow a similar bimodal distribution pattern (refer to Figures 2(a)–2(d)). According to Figure 2(e), the diurnal variation of O₃ concentration in AQMS_{Bat} deviates from the above pattern and has only a single peak a day in each season, which occurs between 10:00 and 14:00 LT. Figure 2(f) shows that the diurnal variation of SO₂ concentration in AQMS_{Bat} follows diverse patterns in different climate/seasons and does not show prominent peaks except in the NEM season. During the NEM season, the mentioned graph shows two pronounced peaks from 6:00 to 9:00 LT and from 00:00 to 4:00 LT with corresponding maximum average hourly concentration values of 12 ppb and 11.5 ppb. However, during the SIM and FIM seasons, the variation of average hourly concentration of SO₂ during a day happens differently from the above pattern since only one small peak is visible in each graph from 8:00 to 12:00 LT with peak values of 7.5 ppb (SIM) and 6 ppb (FIM). Following a completely different pattern, the diurnal variation of SO₂ concentration does not show much fluctuation in the SWM season and maintains its level of around 4 ppb throughout the day.

Figures 2(g)–2(i) illustrate that the variation of average diurnal PM10, PM2.5, CO, and NO₂ concentration in Kandy also follows bimodal distribution patterns for all seasons except for the SWM period. For PM10, PM2.5, and CO, the peaks appeared in the morning (from 6:00 to 8:00 LT) and evening (from 16:00 to 20:00 LT). Even though the evening peaks were significantly broader than the morning peaks in all three graphs, the nighttime peaks for AQMS_{Kan} were less broad than those of Battaramulla. However, for NO₂ (Figure 2(j)), the morning and evening peaks appeared between 6:00 and 10:00 LT and 16:00 and 20:00 LT with similar peak breadths. The variation of hourly average O₃ concentration during a day for AQMS_{Kan} is given in Figure 2(k), and all of its graphs exhibit two broad peaks except the one drawn for the FIM season. The daytime peaks occurred between 10:00 and 17:00 LT, while the nighttime peaks appeared between 23:00 and 5:00 LT, reflecting a high level of O₃ concentrations throughout the day. Figure 2(l) shows that the diurnal variation of average SO₂

concentration in the AQMS_{Kan} does not fluctuate much in all four seasons. The graphs maintain their values at an almost constant level of 1.5 ppb throughout the day. However, the SO₂ level slightly drops from 00:00 to 06:00 LT in every graph. Furthermore, it can be observed that the nighttime peaks are broader than the morning peaks in all of the four graphs. These maximum pollutant concentrations might have occurred due to the heavy traffic of motor vehicles at these hours.

It can be further observed that the mentioned graphs drawn for the four seasons have nearly overlapped each other. Some of the day-to-night differences may have been caused by differing wind directions transporting air masses from different emission sources during the day and the night. The observed morning and evening peaks of pollutants are ascribed to the variations of mixing height, vertical turbulence, and horizontal wind velocity and emission characteristics.

3.2. Monthly Variation of Pollutant Concentration in the Daytime and Nighttime. Figure 3 shows the monthly maximum, minimum, and average daytime PM10, PM2.5, NO₂, O₃, and SO₂ concentrations in AQMS_{Bat} and AQMS_{Kan} from January 2019 to May 2021. The left panel showcases the plots for Battaramulla, whereas the right panel is for Kandy. The black dots show the long-term mean for average pollutant concentrations from December to November. The 10th and 95th percentile concentrations are given by lower and upper bounds in the box, whereas the whisker lines depict the maximum and minimum pollutant concentration in each month.

In AQMS_{Bat}, the highest average concentrations of trace pollutant gases and particulate matter are observed from December to March, while the lowest concentrations were observed from July to September (Figures 3(a)–3(f)). For Kandy, the pollutant levels get higher from February to April and reach their minimum from April to June (Figures 3(g)–3(i)). Even though the highest and lowest concentrations of all the pollutants occur during the same period, the exact months of peaks and troughs are different for pollutant types.

Figure 3(a) illustrates the average monthly variation of the daytime PM10 concentration, which reaches its maximum in February with a value around 60 μgm^{-3} and slopes downward until reaching a minimum of 20 μgm^{-3} in March. After March, the PM10 concentration again started to increase and forms another small peak around June (35 μgm^{-3}), which lowered until it reaches 20 μgm^{-3} in September. The whisker lines reveal that the highest recorded concentration and highest concentration variation occurred in April. As shown in Figure 3(b), the highest and lowest PM2.5 concentrations were recorded in November and May, respectively. Similar to PM10, the maximum monthly average concentration of PM2.5 was also recorded in February. A similar trend can be seen in the box plots created for CO, O₃, and SO₂ with slight changes in the months in which the highest and lowest average concentrations are recorded.

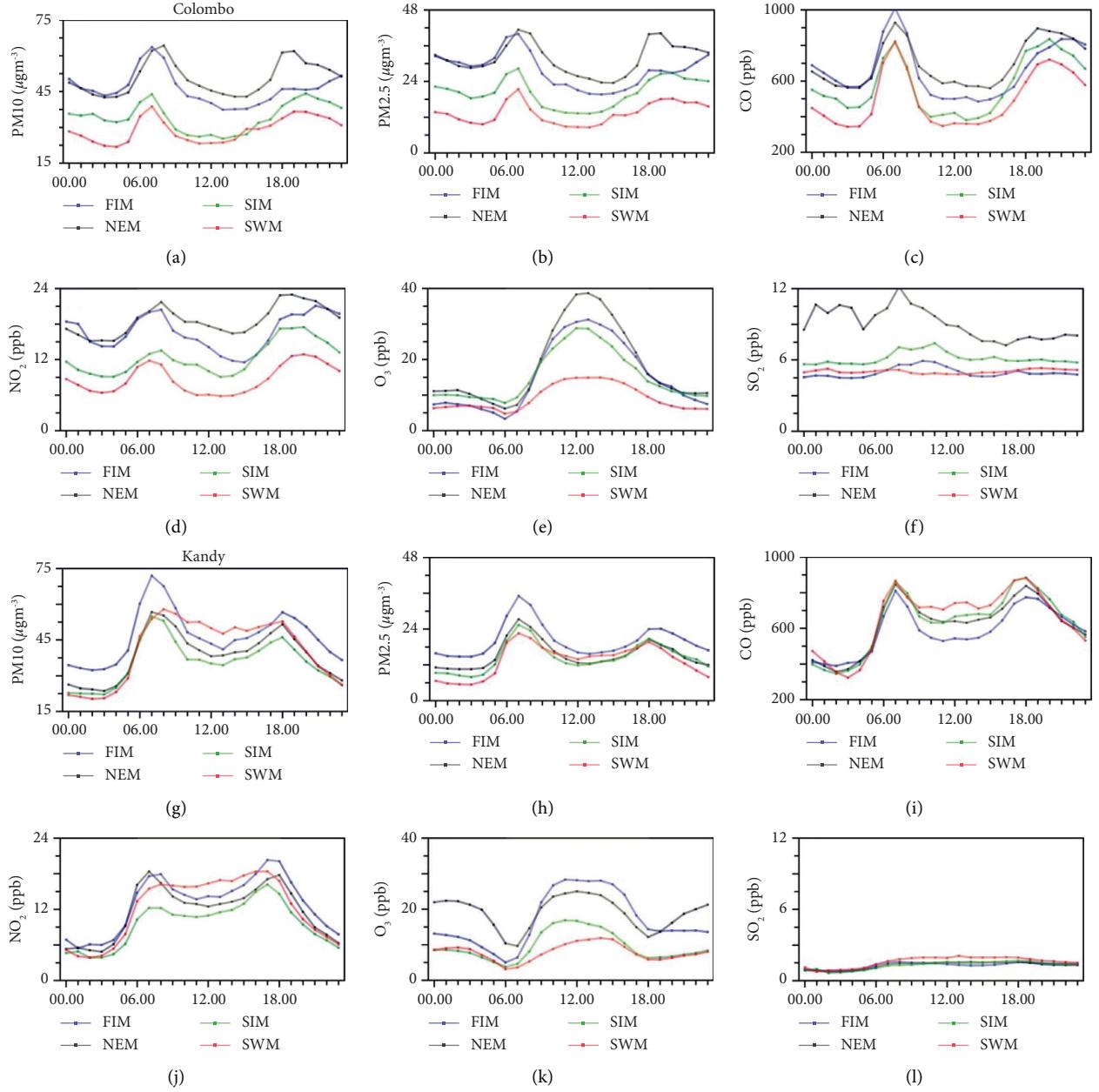


FIGURE 2: Seasonal variation of average hourly concentrations.

The maximum daytime average concentrations of CO, O_3 , and SO_2 were found in March (800 ppb), February (30 ppb), and June (10.5 ppb), respectively (refer to Figures 3(c), 3(e), and 3(f)). The lowest values of both CO (408 ppb) and O_3 (11 ppb) were found in August, while SO_2 reached its minimum in April (4.1 ppb). However, it was found that the difference between the first and second peaks was comparatively lower in the SO_2 plot than that of the other pollutants. The highest average daytime concentration of NO_2 (18.1 ppb) was found in February, and the respective minimum values (6.9 ppb) were found in June and August. When the concentration variation within a month is considered, the highest variation occurs for the pollutants CO, NO_2 , O_3 , and SO_2 in November, March, April, and January,

respectively. However, the lowest variations for PM10, PM2.5, and CO were recorded in August, while NO_2 and O_3 concentrations were less varied in July. In addition, September marked the month in which the SO_2 concentration is less fluctuated.

In Kandy, Figures 3(g)–3(i) show that the monthly variation of mean daytime concentrations of all pollutants except NO_2 and SO_2 follows similar trend in Battaramulla. However, except for SO_2 , all other pollutants demonstrated a bimodal pattern. The pollutants PM10, PM2.5, NO_2 , and O_3 showed two pronounced peaks, while one prominent peak and one small peak appeared for O_3 . Furthermore, the box plots depict that the highest monthly mean concentration for PM10, PM2.5, O_3 , and SO_2 occurred in May, while CO

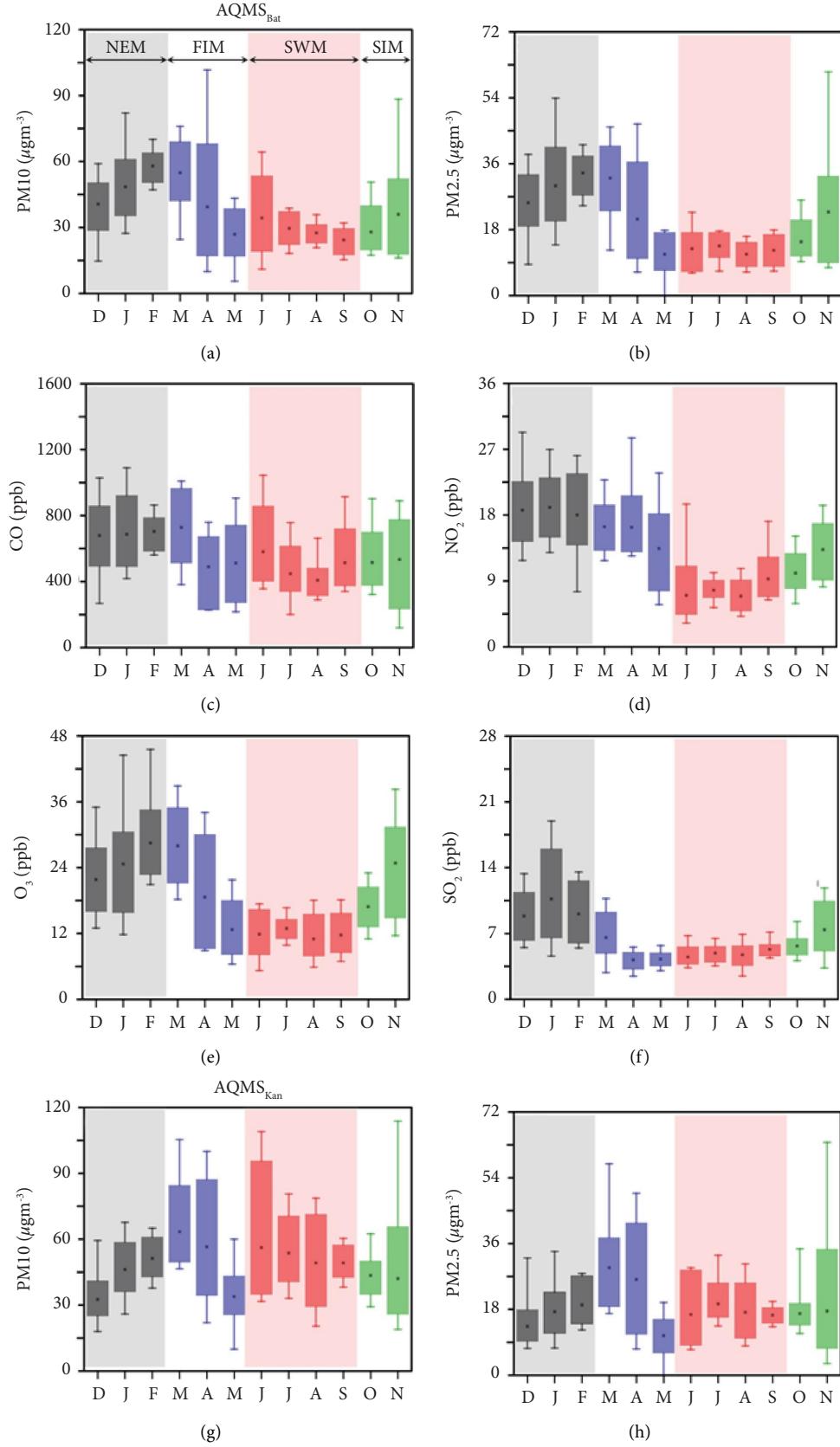


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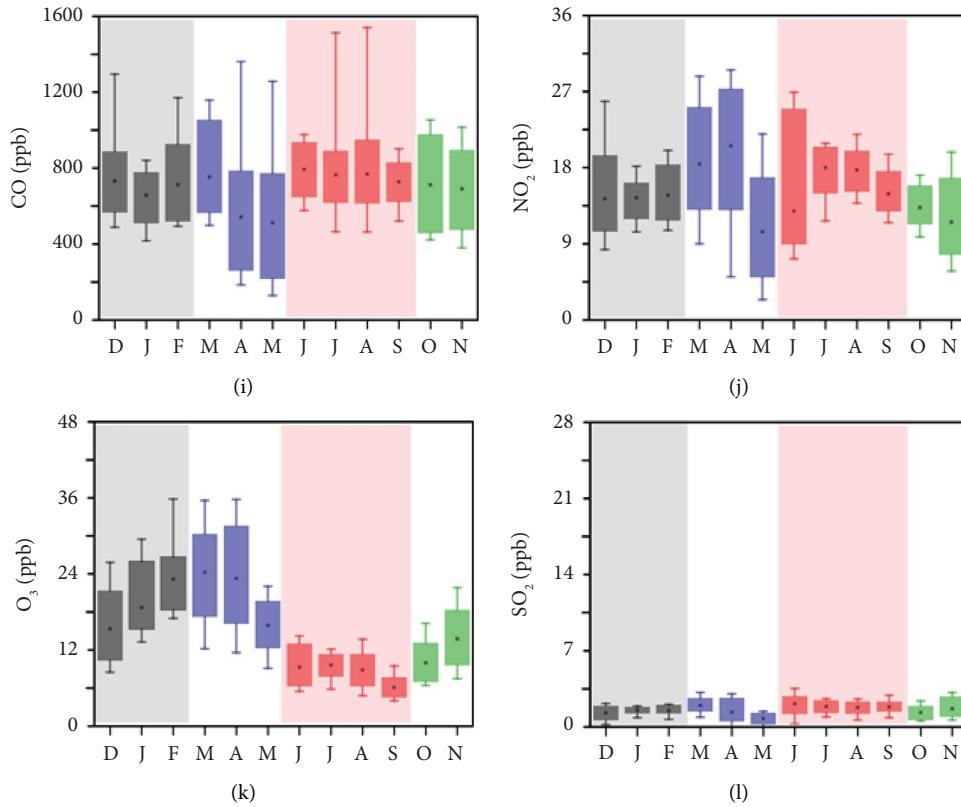


FIGURE 3: Boxplots of (a) PM10, (b) PM2.5, (c) CO, (d) NO₂, (e) O₃, and (f) SO₂ concentrations at daytime (06:00 hrs–18:00 hrs).

and NO₂ peak in June and April, respectively. For PM10 and SO₂, the second highest peak appeared in June, whereas PM2.5, NO₂, and O₃ reached their second peak during July. The lowest mean daytime concentrations of all pollutants occurred during May except for O₃, which shows its minimum in September. Furthermore, from April to June, the pollutant concentrations were highly varied, and the lowest variance in the concentrations was found in September.

When the mean daytime concentrations of the pollutants in the two cities were compared, it was observed that the PM10, CO, and NO₂ pollutant levels are higher in Kandy than in Battaramulla. However, the opposite is true for O₃ and SO₂, as Battaramulla displays higher mean concentrations in those two pollutants than Kandy. Moreover, in Kandy, the mean daytime concentration of SO₂ was much lower than in Battaramulla. The polluted air from power plants and industries can be transported to Battaramulla AQMS by the wind. In addition, the vehicle movements in Colombo are higher than Kandy contributing high SO₂ emissions.

Figure 4 illustrates the monthly maximum, minimum, and mean nighttime concentrations of PM10, PM2.5, CO, NO₂, O₃, and SO₂ in Battaramulla and Kandy from January 2019 to May 2021. The left panel showcases the plots for Battaramulla, whereas the right panel is for Kandy. The black dots show the long-term mean for average pollutant concentrations from December to November. The 10th and 95th percentile concentrations are given by lower and upper

bounds in the box, whereas the whisker lines depict the maximum and minimum pollutant concentration in each month.

It could be observed that for Battaramulla, the monthly variation of the mean concentrations of mentioned pollutants follows a similar pattern to that of daytime, which is displayed in Figure 3. Furthermore, it can be seen that the highest monthly concentration of each pollutant in Battaramulla displays approximately similar values in both daytime and nighttime only with a negligible small drop in the nighttime. However, in Kandy, the highest nighttime monthly mean concentrations of pollutants were lower than that of their daytime values, and the magnitude of the second peak, which usually appeared between May and August, has dropped in the nighttime compared to the daytime. When the mean nighttime concentrations of the pollutants of the two cities were compared, it can be observed that the PM10, PM2.5, CO, NO₂, and SO₂ pollutant levels were higher in Battaramulla than in Kandy. Deviating from the above pattern, the mean nighttime concentration of O₃ was higher in Kandy than that of Battaramulla from July to December.

3.3. Seasonal Variation of Pollutant Concentration.

Table 1 summarizes the seasonal average of O₃, CO, NO₂, SO₂, PM2.5, and PM10 in the daytime and nighttime for Battaramulla and Kandy. The daytime (06:00 hrs–18:00 hrs) are given without parentheses, whereas the nighttime (18:

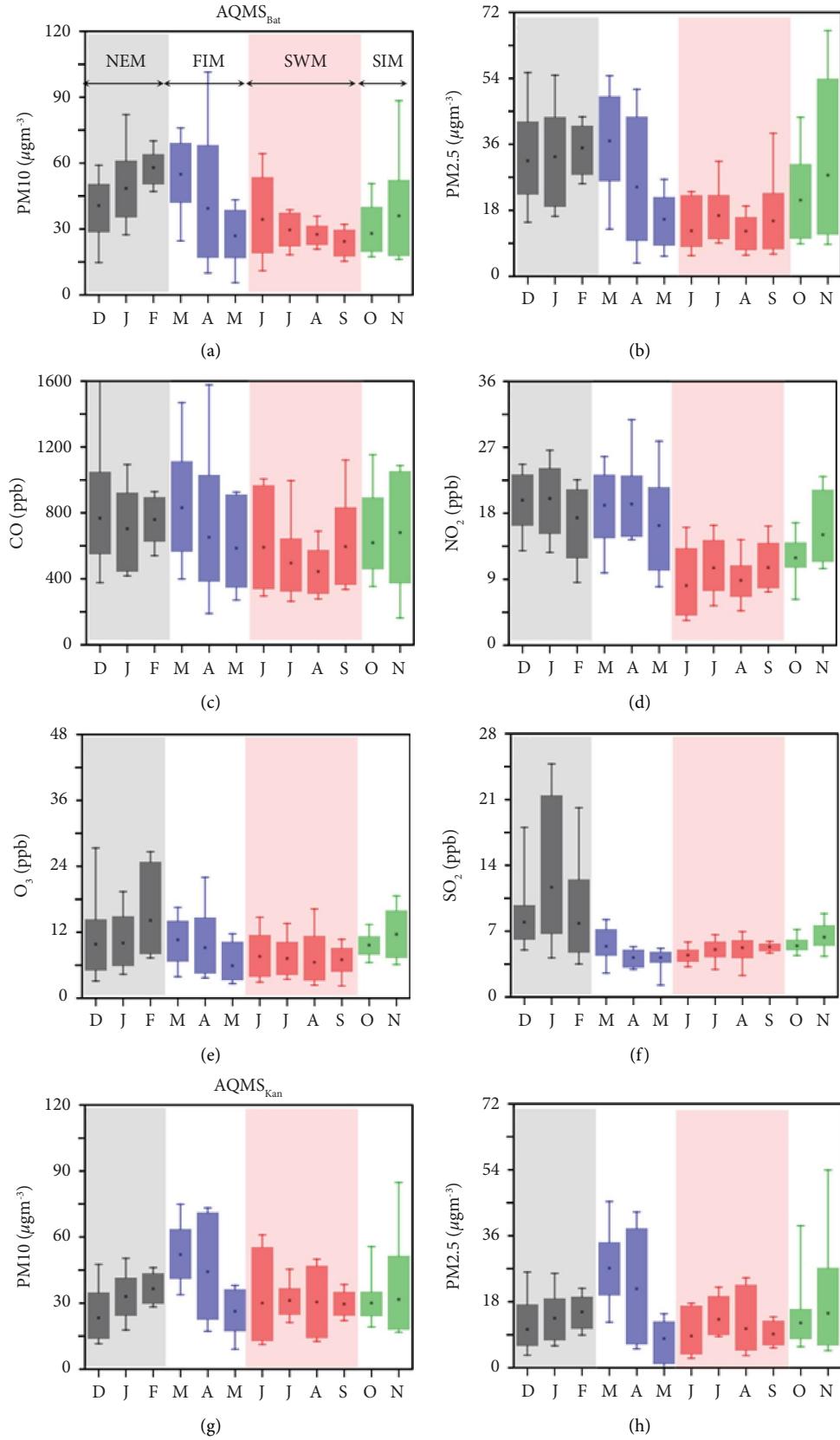


FIGURE 4: Continued.

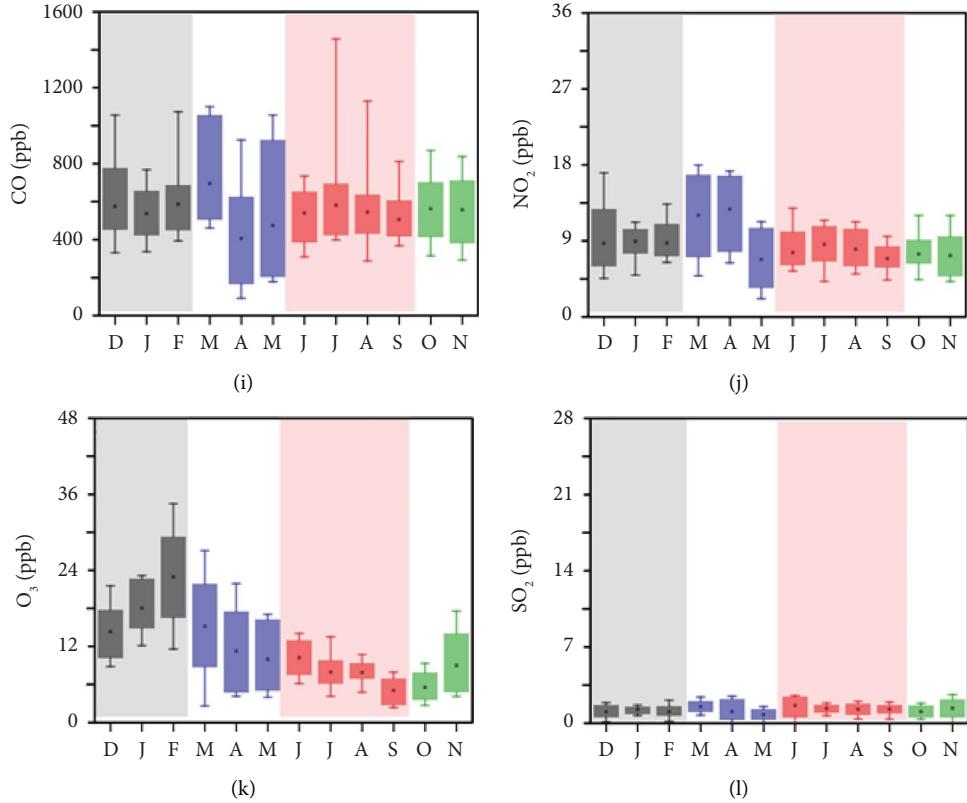
FIGURE 4: Boxplots of (a) PM10, (b) PM2.5, (c) CO, (d) NO₂, (e) O₃, and (f) SO₂ concentrations at nighttime (18:00 hrs–06:00 hrs).

TABLE 1: The seasonal average pollution concentrations.

Station	Season	PM2.5 ($\mu\text{g}/\text{m}^3$)	PM10 ($\mu\text{g}/\text{m}^3$)	O ₃ (ppb)	CO (ppb)	NO ₂ (ppb)	SO ₂ (ppb)
Colombo	FIM	22.0 (25.8)	41.2 (42.5)	19.7 (8.5)	618.3 (697.2)	15.4 (18.2)	5.0 (4.5)
	NEM	29.5 (33.0)	48.8 (50.1)	24.9 (11.2)	690.5 (744.6)	18.6 (19.1)	9.7 (9.1)
	SIM	18.5 (23.9)	31.7 (37.9)	20.6 (10.5)	524.2 (648.6)	11.6 (13.4)	6.4 (5.8)
	SWM	12.5 (14.1)	28.9 (30.2)	11.8 (7.0)	486.8 (530.8)	7.7 (9.5)	4.8 (5.0)
Kandy	FIM	21.9 (18.7)	51.1 (40.7)	21.1 (12.1)	606.3 (529.8)	16.4 (10.5)	1.3 (1.1)
	NEM	16.6 (13.0)	43.7 (31.2)	19.0 (18.3)	700.9 (566.5)	14.5 (8.7)	1.4 (1.1)
	SIM	17.2 (13.5)	42.8 (30.8)	11.8 (7.2)	702.0 (560.3)	12.4 (7.3)	1.4 (1.2)
	SWM	17.3 (10.3)	52.0 (30.3)	8.4 (7.7)	763.6 (543.9)	15.9 (7.8)	1.8 (1.4)

They are highlighted due to their maximum value.

00 hrs–06:00 hrs) are showcased inside the parentheses. The recorded maximum values per season are showcased in bold.

The maximum daytime and night concentrations of pollutants in the Battaramulla are recorded for the NEM season compared to other seasons, while the lowest pollutant concentration is observed in the SWM season. These findings are consistent with that of Grange et al. [39], who found that the average pollutant concentrations of CO, NO₂, SO₂, PM2.5, and PM10 reached their maximum during winter postmonsoon months as opposed to the lowest levels during the monsoon (June–August) season. This happens mainly due to the dilution of surface emissions into a deeper atmospheric boundary layer caused by the high temperature during the warm season. The strong winds also contributed to this effectively ventilating the area and causing lower

pollution in urban areas [42, 43]. However, in the wet season, the atmosphere is characterized by low mixing height, low wind speed, and low ventilation, resulting in less dispersion and rise in air pollutants [43, 44].

Interestingly, the concentration of NO₂, CO, PM2.5, and PM10 at nighttime was larger than the daytime concentration in Battaramulla for all seasons. This pattern is mainly ascribed to the lower atmosphere and stagnant wind conditions, which aggravate pollutants and increase particle matter concentrations. Furthermore, it was observed that O₃ concentration was higher in the daytime than in the nighttime during all seasons. This occurred due to the increase in solar radiations during daytime which attributes to a significant effect of UVB radiations, temperature, and relative humidity on ozone concentrations. Warminski and

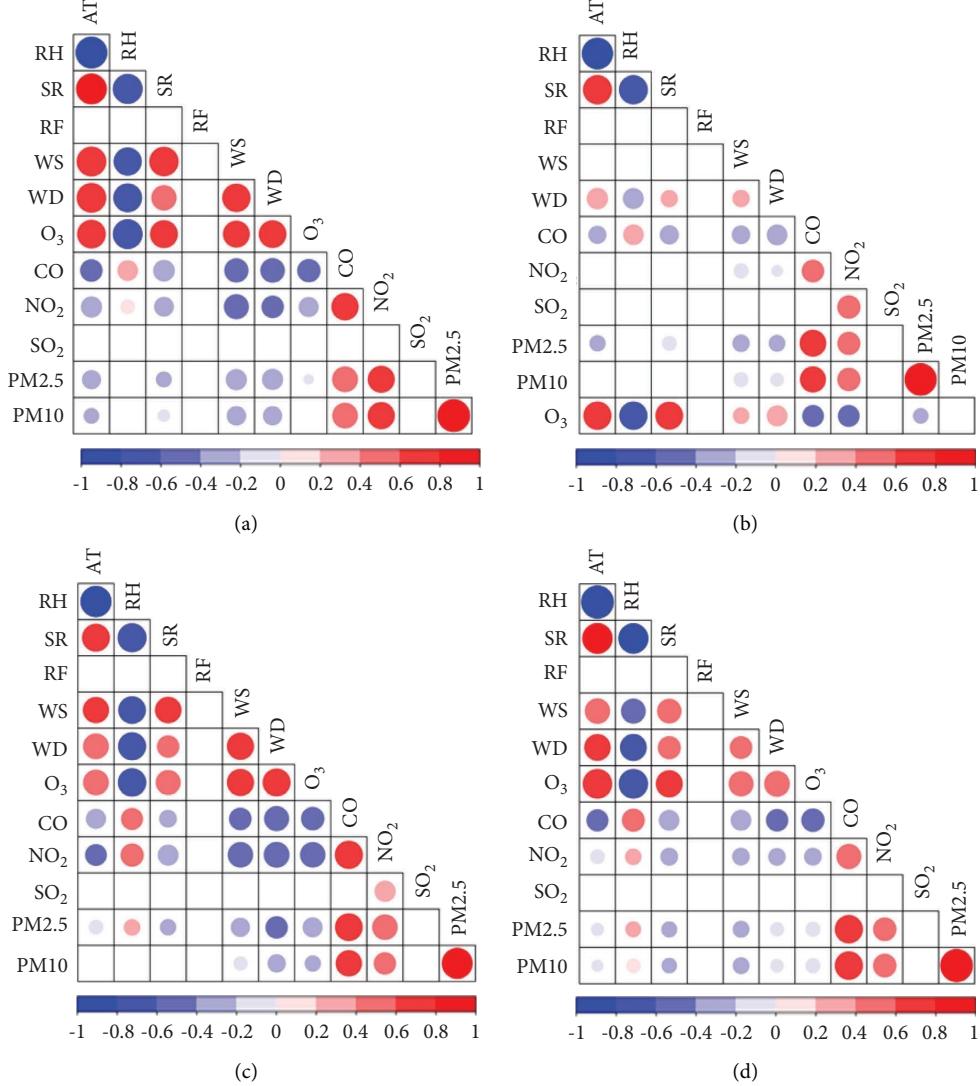


FIGURE 5: Corrplot for the daily air pollutant concentration (CO, NO₂, SO₂, O₃, PM2.5, and PM10) and meteorological variables for (a) first intermonsoon (b) northeast monsoon, (c) southwest monsoon, and (d) second intermonsoon seasons for Battaramulla.

Bes [45] and Sousa et al. [46] also observed higher O₃ concentrations during the daytime than at nighttime. The daytime SO₂ concentration in Battaramulla was slightly higher than that at nighttime during the FIM, NEM, and SIM seasons.

In Kandy, the maximum daytime concentration of O₃ (21.1 ppb), NO₂ (16.4 ppb), PM2.5(21.9 $\mu\text{g}/\text{m}^3$), and PM10 (41.2 $\mu\text{g}/\text{m}^3$) were recorded for the FIM season, while CO (763.6 ppb) as well as SO₂ (1.8 ppb) recorded maximum concentration during the SWM season. The nighttime concentration of air pollutants except CO and particulate matter follows the same pattern as shown in Table 1. In addition, it was observed that daytime CO, SO₂, O₃, NO₂, PM2.5, and PM10 concentrations were much higher than the nighttime concentration during all seasons. For instance, the daytime CO concentration (763.6 ppb) was comparatively higher than its nighttime concentration (543.9 ppb).

In addition, daytime CO concentration in Kandy was much higher than in Battaramulla for NEM, SIM, and SWM

seasons, while a contrast pattern was observed for the nighttime CO concentration in Battaramulla. The nighttime PM2.5 concentration for all the seasons was higher than those for Kandy. In the NEM season, PM2.5 in Battaramulla (29.5 $\mu\text{g}/\text{m}^3$) was higher than PM2.5 in Kandy (16.6 $\mu\text{g}/\text{m}^3$), while the contrast pattern was observed in the SWM season. It was also noticed that Kandy and Battaramulla attributed quite similar PM2.5 concentrations during the FIM and SIM seasons. The nighttime NO₂ concentration for all the seasons depicts a dominant variation between the two stations, where Battaramulla recorded a higher NO₂ concentration than that of Kandy. NO₂ concentration in both stations recorded a marginal difference for FIM and SIM seasons during the daytime, but a large difference in NO₂ concentration was found for two monsoon periods. The table revealed that the pollutant concentrations in both the cities exhibit obvious seasonal and cyclical fluctuation patterns. Air pollution in Battaramulla was more severe in NEM and FIM and slightly better in the SWM and SIM seasons.

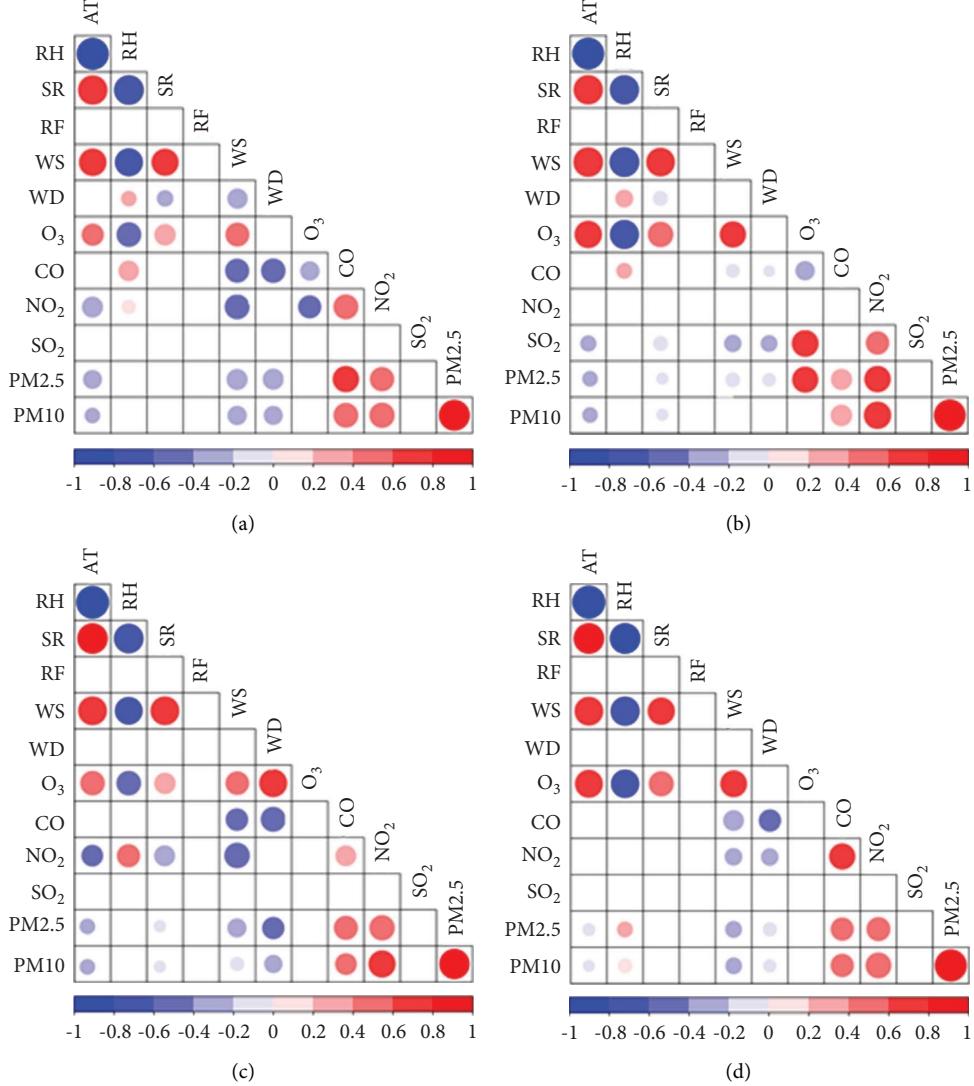


FIGURE 6: Corrplot for the daily air pollutant concentration (CO, NO₂, SO₂, O₃, PM2.5, and PM10) and meteorological variables for (a) first intermonsoon, (b) northeast monsoon, (c) southwest monsoon, and (d) second intermonsoon seasons for Kandy.

On the other hand, air pollutants in Kandy are higher in the SWM and FIM seasons than in the other two seasons. These findings highlight that the concentration of air pollutants and particulate matter fluctuates dramatically in different seasons.

Understanding and quantifying air pollutant dispersion over complex topography is much more challenging than over flat areas, as dispersion processes are affected by atmospheric interactions with the orography at different spatial scales [47]. For instance, we found that the daytime air pollutant concentration in Kandy, with complex terrain, is higher than that in Battaramulla even though fewer industries are located near Kandy AQMS. In mountainous terrain, depending on the alignment of the upper-level wind with the valley axis [48], the valley bottom may be sheltered from downward intrusions of the wind from above. In addition, the penetration of the upper-level wind down to the lowest levels of valleys and basins may be further prevented by underlying preexisting and persistent stable layers.

Under these conditions, the flow inside valleys is decoupled from the airflow situation above the crest level, which favors pollutant accumulation at the lowest levels. At the meso-scale, land-sea and mountain-valley breezes may support the variation of pollutant concentration, and orographic features enhance the recirculation of pollutants.

3.4. Relationship between Meteorological Parameters and Air Pollutant Concentration. Meteorological parameters play a significant role in deciding the ambient air quality of an urban environment [1, 12, 18, 27, 43]. On the other hand, Liu et al. [2] and Singh et al. [49] found that air pollution and meteorological elements have prominent seasonal and regional characteristics. Therefore, the relationship between seasonal variations of the concentrations of air pollutants in two cities with temperature, rainfall, solar radiation, relative humidity, wind speed, and direction was determined by using Pearson correlation analysis with a 5% significant

level. Figures 5 and 6 show the correlation between pollutant concentration and meteorological variables in Battaramulla and Kandy, respectively. The insignificant correlation at 95% is marked out from the corplot. AT, RH, SR, RF, WS, and WD represent air temperature, relative humidity, solar radiation, rainfall, wind direction, and speed, respectively.

Hunova et al. [50] revealed that meteorology is extremely important for O_3 formation. For further evidence, it was also found that O_3 concentration in both cities negatively correlates with relative humidity. At the same time, a positive relationship is observed for O_3 concentration with air temperature and solar radiation in all seasons (refer to Figures 5 and 6), which reflects the importance of photochemistry in ozone formation. In addition, wind speed and wind direction affect ozone formation. Similarly, other researchers [51–53] observed significantly strong positive correlations for O_3 with temperature and solar radiation and a strong negative correlation with relative humidity during different seasons.

According to Rozante et al. [54], precipitation, wind speed, temperature, and relative humidity contribute to the modulation of the CO seasonal cycle. Similarly, it was also found that CO concentration in Battaramulla has a positive relationship with relative humidity and negative relationships with air temperature, solar radiation, wind speed, and wind direction during all seasons (Figures 5(a)–5(d)). However, CO concentration in Kandy depicted a strong correlation with wind speed and wind direction compared to the rest of the meteorological variables (Figures 6(a)–6(d)). Furthermore, we noticed that high correlation coefficients were achieved between CO and NO_2 in both cities during all the seasons, which was expected because CO influences the oxidation of NO to NO_2 . This finding was also reported by Kovac-Andric et al. [53].

In Battaramulla, The PM2.5 concentration for all seasons was negatively related to air temperature, solar radiation, wind speed, and wind direction. In accordance with the present results, previous studies have demonstrated that the influence of temperature, humidity, and wind on PM2.5 concentrations was much larger than that of other meteorological factors, while temperature depicts the strongest and most stable influence on national PM2.5 concentration [55]. Furthermore, it was found a negative relationship between PM2.5 and relative humidity in SWM and SIM seasons. Similar to PM2.5, PM10 in all the monsoon seasons was also negatively correlated with wind speed and directions, while a negative relationship with temperature and solar radiation for all the seasons except the SWM season was observed (Figures 5(a)–5(d)). In Kandy, PM2.5 and PM10 depict a statistically significant positive correlation with air temperature, wind speed, and direction for FIM, SWM, and SIM seasons (Figures 6(a), 6(c), and 6(d)).

The NO_2 concentration in Battaramulla had a positive relationship with relative humidity and negatively with air temperature, wind speed, and wind directions during NEM, SWM, and SIM except in the FIM season (Figure 5(b)). It was also observed the same for Kandy except for wind direction in SWM and NEM seasons (Figures 6(a)–6(c)). This

study supports evidence from previous studies by Miyama et al. [56]. At high air temperatures, the reaction proceeds toward producing NO_2 ($2HONO \leftrightarrow NO + NO_2 + H_2O$) while high humidity promotes reverse reaction and an abundance of HONO production [57]. As shown in Figures 5 and 6, it was detected a weak correlation between SO_2 concentration with the meteorological variables in the four seasons. This finding is consistent with a previous study in Coimbatore, Southern India. A weak influence of temperature, wind speed, and relative humidity was found on SO_2 concentration [27].

Interestingly, none of the pollutants are statistically correlated with rainfall during four monsoon seasons. This might be confusing as rainfall can play a vital role in washing out atmospheric dust. However, these results align with recent studies indicating that precipitation played a weak role in affecting local PM2.5 concentrations in Beijing [58]. Nevertheless, this finding is contrary to previous studies [59], which suggested statistically significant negative correlations between pollutant concentrations and rainfall intensity for PM10, SO_2 , NO_2 , and CO due to precipitation scavenging.

Hagenbjork et al. [60] revealed that the generation of O_3 is dependent on the NO_2 concentration in the presence of solar radiation ($NO_2 + h\nu + O_2 \rightarrow NO + O_3$). It is well established that NO_2 has a negative correlation with O_3 , and the relationship may have seasonal variation [56]. The current study also observed a negative relationship between these two pollutants in Battaramulla for all seasons. However, the relationship is getting weak in Kandy, as shown in Figure 6.

It was found that wind speed and wind direction strongly correlate with air pollutant concentration. Therefore, polar plots were used to investigate the dependence of pollutants on wind speed and wind direction. The relationships of different air pollutants with wind speed and wind direction are illustrated in Figures 7 and 8 with the help of a bivariate polar plot. There were multiple sources of PM10 and PM2.5 in Battaramulla during the SWM season of 2013 (Figures 7(a) and 7(b)). Figure 7 suggests that locally sourced particulate matter was present, as potentially indicated by the elevated concentrations at low wind speeds, but the lowest concentrations were experienced with westerly winds when wind speeds were high ($\approx 5 \text{ ms}^{-1}$). These results reflect previous findings that high concentrations of PM10 were mostly associated with low wind speed conditions and when weak winds prevail along the northwest and southeast [42].

As shown in Figure 7(c), CO showed elevated concentrations only when wind speeds were low due to a lack of pollutant dispersion. The lowest CO concentration was observed with westerly winds when wind speeds were high ($\approx 5 \text{ ms}^{-1}$). NO_2 concentrations of $10 \mu\text{g}/\text{m}^3$ and above occur in the east and southeast directions. The wind speed in the directions of these concentrations was around $0\text{--}3 \text{ ms}^{-1}$ (Figure 7(d)). In the SWM season, 6–7 ppb concentration of SO_2 was determined to come from the southwest ($5\text{--}7 \text{ m s}^{-1}$). In addition, dominant SO_2 concentrations ($>6 \text{ ppb}$) originate from the west ($0\text{--}3 \text{ ms}^{-1}$). High concentrations of O_3 (12 and above) originate from the

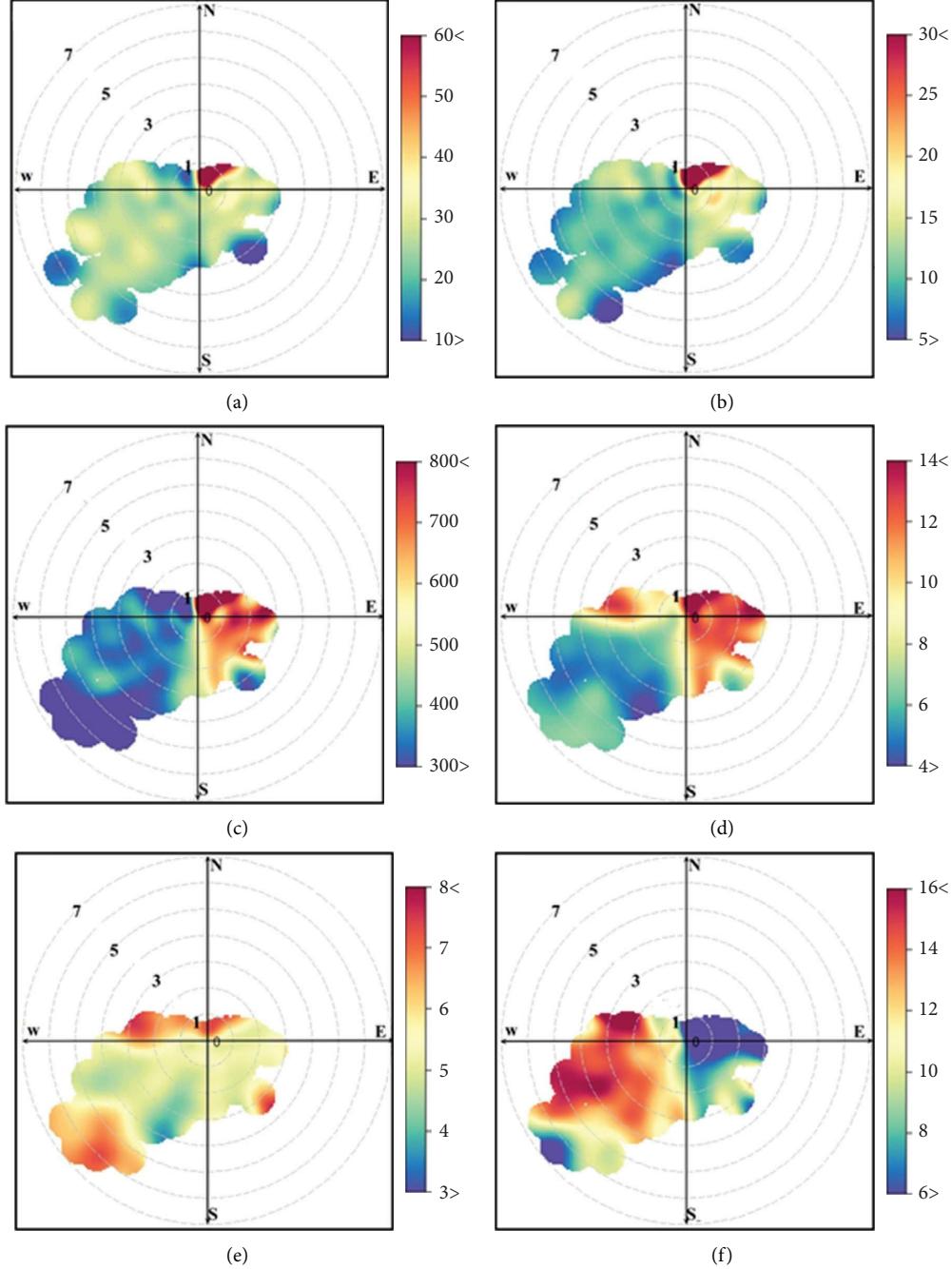


FIGURE 7: Polar plots of mean concentrations of (a) PM10, (b) PM2.5, (c) CO, (d) NO₂, (e) SO₂, and (f) O₃ for the southwest monsoon season (June to September) at Battaramulla.

southwest and west ($2\sim 5 \text{ ms}^{-1}$), while the lowest concentration was observed with easterly winds when wind speeds were low ($0\sim 3 \text{ ms}^{-1}$) (Figure 7(f)).

The PM10 concentration of $50\sim 55 \mu\text{g/m}^3$ measured at the Kandy station occurs in the direction of the southwest ($2\sim 3 \text{ m s}^{-1}$). Meanwhile, PM10 concentrations of $40\sim 50 \mu\text{g/m}^3$ measured at the station consist of various points such as southeast ($1\sim 3 \text{ ms}^{-1}$) and south ($2\sim 3 \text{ ms}^{-1}$). Furthermore, we found that $>35 \mu\text{g/m}^3$ PM10 value comes from the northwest to the northeast ($0\sim 1.5 \text{ ms}^{-1}$) (Figure 8(a)). PM2.5 in Kandy station arises especially from the west to south

($0\sim 2.5 \text{ ms}^{-1}$). In addition, the PM2.5 concentration is comparatively higher in the east, as shown in Figure 8(b), while the lowest comes from the northeast.

According to Figure 8(c), it can be seen that the densest CO concentrations measured at the Kandy station are 900 ppb and above, which were determined to be in the east ($1\sim 2 \text{ m s}^{-1}$) with a point close to the AQMS_{Kan}. In addition, 700–800 ppb CO concentration comes from near the station and from the west to the south. When the dispersion graphics presented in Figure 8(d) is examined, it can be seen that NO₂ concentration of 15–20 ppb measured at the

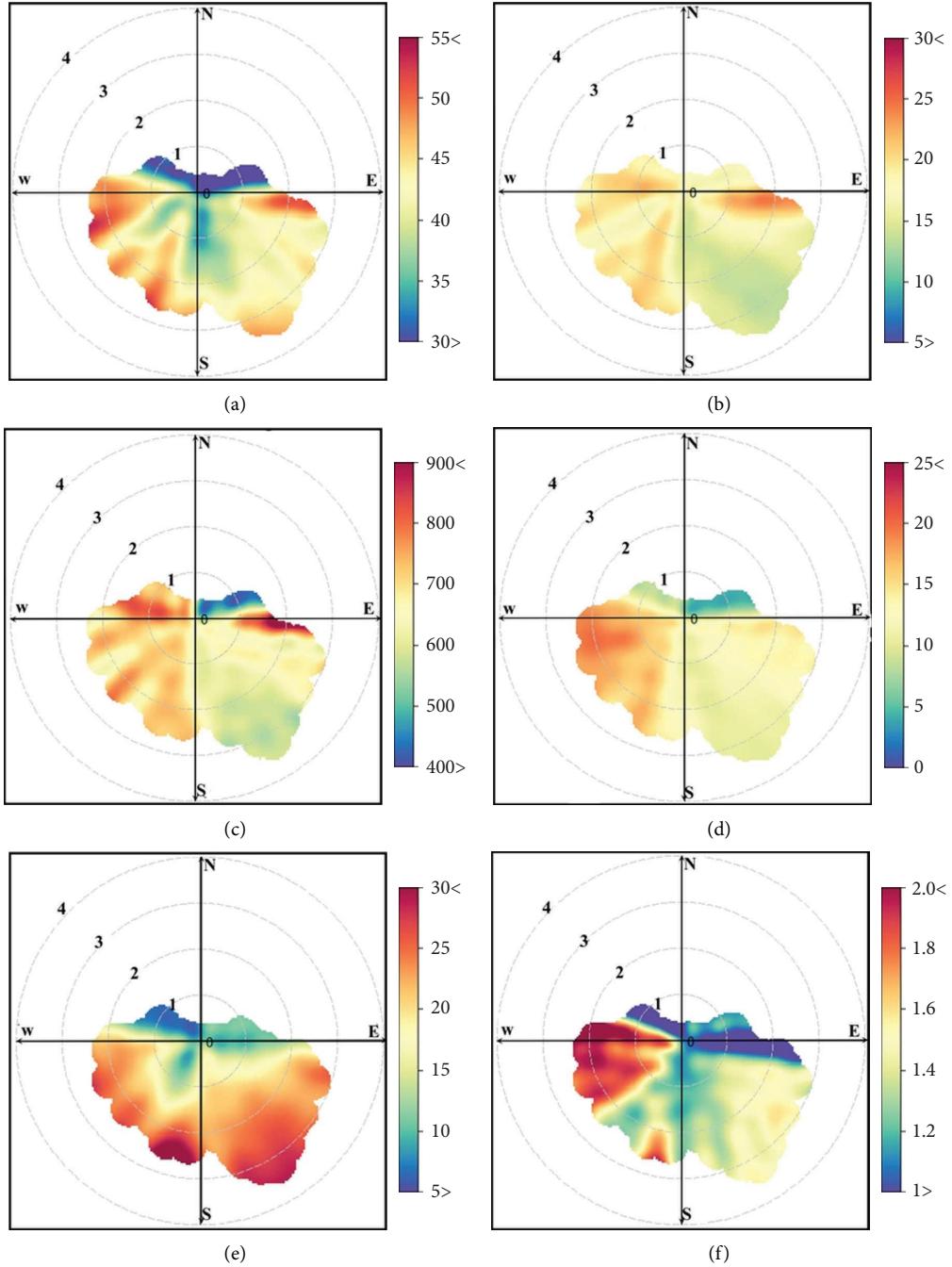


FIGURE 8: Polar plots of mean concentrations of (a) PM10, (b) PM2.5, (c) CO, (d) NO₂, (e) SO₂, and (f) O₃ for the northeast monsoon season (December to February) in Kandy.

Kandy station occurs in the direction of the southwest ($1\text{--}3 \text{ ms}^{-1}$); meanwhile, less than 5 ppb NO₂ value measured at the station mainly occurred in the northeast to the east ($0\text{--}1.5 \text{ ms}^{-1}$). During the NEM season, the maximum SO₂ concentration range measured in Kandy was determined to be >30 ppb which occurred in the southwest. Furthermore, the SO₂ concentration is comparatively higher in the southeast, while the lowest is coming from the north. The maximum O₃ concentration range measured in Kandy was determined to be >2 ppb ($1\text{--}2 \text{ ms}^{-1}$), whereas the minimum

concentration was determined as 1 ppb, and it was determined that the pollutants came from two directions as northwest and east.

3.5. Discussion of the Results. This study investigates the seasonal variation of air pollutant concentrations and the impacts of the meteorological variables on pollutants in two major cities in Sri Lanka during the 2019–2021 period. Interestingly, the observed morning and evening peaks of

pollutant concentrations coincided very well with the morning and evening rush hour traffic. It suggests that increasing severity and duration of traffic congestion in these two periods increase air pollutant load and degrade air quality, particularly near large roadways. Similar to our findings, two peaks of pollutants corresponding to the morning and evening rush traffic hours were observed in Chennai, India [44], and Kathmandu Valley, Nepal [61]. This finding was also reported for Sao Paulo, where the maximum CO concentration was recorded in the morning (between 8 and 9 h) and early evening (between 19 and 20 h) [54]. On the other hand, low turbulence of the planetary boundary layer in the morning and evening periods affects the pollutants dispersing efficiently [62], contributing to observed high pollution concentrations in the morning and evening.

It was observed higher O₃ concentrations in the daytime compared to the nighttime and an inverse relationship between NO₂ and O₃ concentrations. This relationship is ascribed to the occurrence of a series of photochemical reactions induced by sunlight. During the daytime, NO₂ is formed from the reaction of NO and O₃. Then, NO₂ is transformed back to NO as a result of photolysis and regenerates O₃ [63–66]. Our findings well agree with the David and Nair [67] study, which found that a decrease in NO_x coincides with a rise in ozone concentration during the daytime. A similar observation was recorded in a semiarid urban site in western India [51].

Our results revealed strong seasonal variation of pollutant concentrations in both the cities. In Colombo, the lowest pollutant concentrations were recorded in the SWM season. During this season, low-level jets from the Arabian sea direction toward the air quality monitoring station cross fewer pollutant sources, and it helps to disperse the pollutant. In contrast, during the NEM season, the wind crosses pollutant sources (power plants and industrial states), bringing more pollutants to the monitoring station. Results from the recent research for all megacities in India showcased the seasonal behaviour of pollutant gas concentration. They have higher concentrations in winter whereas lower in summer seasons [49]. Biswas et al. [68] also found that strong seasonal variation of pollutants in Kolkata and Siliguri, India, and suggested that changing the meteorological conditions is responsible for observed seasonal variation.

In tropical countries, investigating the effect of monsoon winds circulation on atmospheric pollutants is significant [1] because wind speed and direction significantly determine the particle concentration and distributions as they relocate from the major source [37, 69–71]. These facts highlighted that wind speed and direction is the key meteorological component for observed seasonal variation of pollutant concentrations in two cities. Similar to our findings, a seasonal variation of air pollutants is caused by seasonal variations of meteorological factors such as atmospheric wind speed, relative humidity, and temperature [27]. In addition to these large-scale circulations, mesoscale circulation (Sea breeze) can affect the distribution of pollutants in coastal urban environments [72, 73]. Therefore, we have to

investigate the influence of sea breeze on pollutant concentrations in coastal cities.

The previous studies found that the temperature negatively affects the air pollutant concentration [2, 74], while some studies detected an increasing pollutant concentration with the increase in temperature [17, 75]. Pateraki et al. [76] and Chaloulakou et al. [77] found that higher wind speeds reduce air pollutant concentrations which can be ascribed to the dilution of pollutants with flowing air mass and displacement of pollutants over longer distances [78].

Back trajectory analysis is widely used to investigate pollutant transport from the sources with air mass movement [79]. Therefore, it was strongly suggested that computing isentropic air mass back trajectories to understand the influence of remotely located pollutant sources on air pollutant concentrations in measuring sites. It has also observed significant seasonal variations in air pollutant concentration in the two cities. Therefore, it is highly recommended to conduct the trajectory analysis for the southwest, northeast monsoon, and intermonsoon seasons.

As discussed in the study of Akinwumiju et al. [80], the results of this study can be used for future urban planning in Colombo and Kandy cities. Thus, sustainable urban development may be expected with the expansions of these cities.

4. Conclusions

This study examined the diurnal and seasonal variations of ambient air quality status at two different locations in Sri Lanka during 2019–2021. These findings suggest that changes in meteorological parameters and emission of pollutants from their sources of pollutant concentrations in the two cities contribute to the observed diurnal, seasonal, and annual cycles of the pollutant concentration. The results show that the annual average concentration of PM_{2.5} and PM₁₀ in the two cities was less than the air quality guideline values of 25 μgm^{-3} and 50 μgm^{-3} , respectively, prescribed by the National Environmental (Ambient Air Quality) Regulations, 1994, made by Minister of Environment and Natural Resources (<http://www.ceal.lk/web/en/acts-regulations>). We realized that long-term continuous measurements of air pollutants and meteorological factors in the main cities in Sri Lanka are vital for identifying the variation of air pollutants at the regional level. As a solution, we recommended using advanced modeling approaches to characterize pollution transport and distribution for managing local air quality. In addition, source apportionment and trajectory analysis have to be conducted to identify probable sources and source region attribution. Meanwhile, comprehensive studies are essential to understand an adverse impact on human health using an appropriate risk analysis in future studies.

Data Availability

The data used in this research work are not publicly available. However, request to access the datasets should be directed to sranasinghedsanay2@huskers.unl.edu for only research purposes.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

SS and GL designed the research, analysed the data, and generated the figures. SS, GL, BP, and SJ wrote the original manuscript and UR edited the manuscript. LDJ and AJ measured air pollutant emissions. All authors reviewed the manuscript.

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