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Impact of Meteorological Factors on Seasonal and Diurnal Variation of $PM_{2.5}$ at a Site in Mbarara, Uganda

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Abstract: Because $PM_{2.5}$ concentrations are not regularly monitored in Mbarara, Uganda, this study was implemented to test whether correlations exist between weather parameters and $PM_{2.5}$ concentration, which could then be used to estimate $PM_{2.5}$ concentrations. $PM_{2.5}$ was monitored for 24 h periods once every week for eight months, while weather parameters were monitored every day. The mean dry and wet season $PM_{2.5}$ concentrations were 70.1 and 39.4 $\mu g/m^3$, respectively. Diurnal trends for $PM_{2.5}$ levels show bimodal peaks in the morning and evening. The univariate regression analysis between $PM_{2.5}$ and meteorological factors for the 24 h averages yields a significant correlation with air pressure when all data are considered, and when the data are separated by season, there is a significant correlation between $PM_{2.5}$ concentration and wind speed in the dry season. A strong correlation is seen between diurnal variations in $PM_{2.5}$ concentration and most weather parameters, but our analysis suggests that in modeling $PM_{2.5}$ concentrations, the importance of these meteorological factors is mainly due to their correlation with underlying causes including diurnal changes in the atmospheric boundary layer height and changes in sources both hourly and seasonally. While additional measurements are needed to confirm the results, this study contributes to the knowledge of short-term and seasonal variation in $PM_{2.5}$ concentration in Mbarara and forms a basis for modeling short-term variation in $PM_{2.5}$ concentration and determining the effect of seasonal and diurnal sources on $PM_{2.5}$ concentration.

Keywords: ambient air pollution; $PM_{2.5}$; meteorological factors; seasonal variations; diurnal variations; short term exposure

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1. Introduction

Each year, 4.2 million premature deaths worldwide occur due to ambient air pollution [1]. An important air pollutant is particulate matter (PM), which is a mixture of solid and liquid particles suspended in the air. While PM ranges in aerodynamic diameter from nanometers to hundreds of micrometers, $PM_{2.5}$ (particles with aerodynamic diameter of 2.5 microns or less) is of major importance to human health. $PM_{2.5}$ can reside in the atmosphere for long periods [2]. Additionally, when inhaled, $PM_{2.5}$ can penetrate deep into the lungs, causing health problems [3–5]. Some of the symptoms that result from short-term exposure to escalated levels of $PM_{2.5}$ include cough, sneezing, difficulty in breathing, asthma, stroke, and coronary heart disease [6,7]. These symptoms are most prevalent among vulnerable populations such as children, the elderly, and individuals with pre-existing respiratory conditions [1,6]. Due to the dangers associated with exposure to $PM_{2.5}$, the World Health Organization (WHO) recently reduced its air quality guidelines for $PM_{2.5}$ levels averaged over 24 h from 25 $\mu g/m^3$ to 15 $\mu g/m^3$ and the air quality guidelines for $PM_{2.5}$ levels averaged over one year from 10 $\mu g/m^3$ to 5 $\mu g/m^3$ [1].

In Uganda, several studies have reported elevated levels of $PM_{2.5}$ ranging from 3 to 10 times the previous WHO air quality guidelines [8–13]. These studies report significant spatial and temporal variations in $PM_{2.5}$ concentrations. Seasonal differences and diurnal variations have been attributed to differences in $PM_{2.5}$ source intensities and variations in atmospheric and meteorological conditions that influence the dispersion and dilution of particles. The leading sources of $PM_{2.5}$ in Mbarara include traffic-related sources, biomass and secondary aerosols, industry and metallurgy, fuel combustion, fine soil, and salt aerosol [13].

A few studies in the region have investigated the impact of meteorological factors such as precipitation, temperature, relative humidity, and wind speed on $PM_{2.5}$ levels. In Uganda, a study conducted in Mbarara, Kyebando, and Rubindi indicated an inverse relationship between atmospheric boundary layer height (ABLH) and PM concentrations [14]. Additionally, in Kampala, an inverse relationship was observed between seasonal $PM_{2.5}$ concentrations and precipitation [10], a positive correlation was observed with relative humidity, and a negative correlation was observed with temperature [15]. In Kenya, research found that $PM_{2.5}$ concentrations are positively correlated with temperature and wind speed, but negatively correlated with relative humidity [16].

None of these studies reported the impact of meteorological factors on the diurnal scale. Yet, short-term changes in the meteorological conditions may have a significant impact on $PM_{2.5}$ exposure levels [9,17] and significantly increase health risks associated with $PM_{2.5}$ exposure [6,7]. For instance, high temperatures enhance the rate of chemical reactions in the atmosphere and may lead to the increased formation of secondary pollutants while at the same time causing an increase in the atmospheric boundary layer height, allowing for a greater volume for dilution [14,18]. Therefore, an increase in temperature may either lead to an increase or decrease in PM levels. High relative humidity enhances the hygroscopic growth of PM in the atmosphere, thereby accelerating gravitational settling, which may result in reduced $PM_{2.5}$ levels [18,19]. Low wind speeds may lead to air stagnation, trapping pollutants close to the ground and increasing exposure levels. Changes in atmospheric pressure influence the dispersion of $PM_{2.5}$ and may result in accumulation in certain areas and dilution in others [19].

Therefore, this study aimed to evaluate the correlation of meteorological factors with both the daily average and the diurnal variation of $PM_{2.5}$ concentration. This study contributes to the knowledge of short-term variation of $PM_{2.5}$ concentration. It seeks to identify which meteorological factors to consider when modeling regional short-term $PM_{2.5}$ variation and when designing educational materials to encourage behavioral change to reduce exposure among vulnerable populations.

2. Materials and Methods

2.1. Study SITE and Data Collection

This study was conducted in Mbarara, Uganda, at a site described previously [13]. As shown in Figure 1, the site is a grassy area on a university campus within a small city. $PM_{2.5}$ concentrations were collected for 24 h once every week for a period of eight months using a photometric instrument (SidePak [20] with an impactor of 2.5 µm cut-off) with a time resolution of 1 min. The instrument was packaged in a waterproof plastic box with inlets connected using a short tube to a point outside the box sheltered from rain. The box was hung at about 1.5 m above the ground to ensure that it sampled air from the area where people breathe. Weather data (temperature, humidity, wind speed, wind direction, and air pressure) were collected using an Onset Hobo U30 weather station [21] recording data every 10 min.

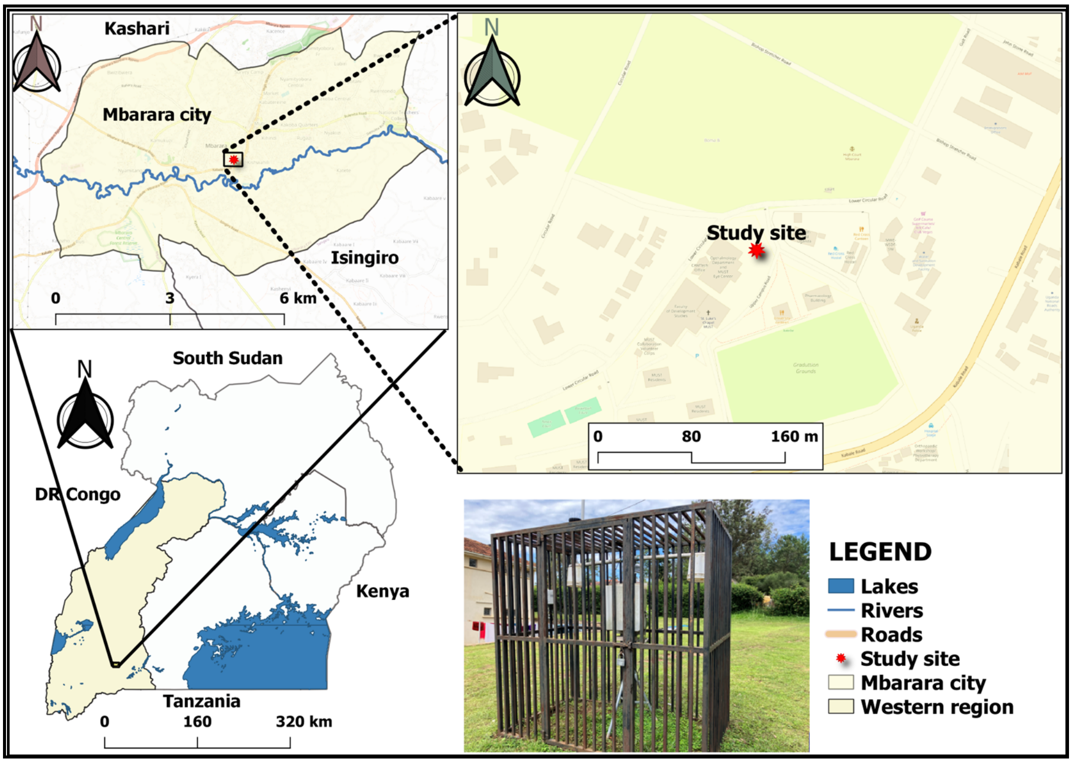

Figure 1. A map showing the study site in Mbarara city. Source QGIS Ver 3.18.0.

2.2. Data Preparation and Analysis

While the data collection extended over a period of 8 months, the SidePak particulate monitor malfunctioned frequently, so many data collection periods did not result in any measurements. Only 16 data measurement periods were completed before it became completely dysfunctional, ending the data collection. Of these measurement periods, one was for 18 h and one for 21 h; the others were for a full 24 h. For each measurement period, hourly data points were generated by averaging the 60 corresponding minutes, and a daily data point was generated by averaging all the recorded one-minute values. Hourly and daily data points were also generated for the meteorological data. The data points were grouped into wet and dry seasons based on the calendar seasons: June–August and December–February are the dry seasons, while March–May and September–November are the wet seasons.

Wind direction was analyzed to check for a correlation with $PM_{2.5}$ levels. The vector components of the wind were calculated along the north–south axis and the east–west axis. Wind from the north or east was defined as positive, while wind from the south or west was defined as negative, consistent with the normal practice of setting north to be 0°. The hourly and daily wind data are calculated as a vector average of measurements made each minute. For vector quantities, the magnitude of an average is not the same as the average of the magnitudes, and therefore, correlations were calculated separately between $PM_{2.5}$ levels and the north–south component, the east–west component, and the average speed.

In order to characterize diurnal variation of $PM_{2.5}$ levels and meteorological factors, the hourly data points at corresponding times in different measurement periods were averaged, both across the whole data set and separately for the wet and dry seasons. Additionally, the data were grouped to find day/night averages, with the daytime from 7:00 to 18:00 and the night from 19:00 to 6:00. Note that in Uganda, the Local Time is nearly one hour offset from Solar Time. Local Time is used in the data presented here.

To test whether differences (seasonal and day/night) were statistically significant, the non-parametric Mann–Whitney U-test was used.

To find the correlations between daily $PM_{2.5}$ and individual meteorological factors, linear regressions were performed. The coefficient of determination, slope, and p-value were obtained to determine the extent to which the meteorological factors are correlated with daily average $PM_{2.5}$ concentrations. Similar linear regressions were performed to determine correlations between hourly averages of $PM_{2.5}$ and meteorological factors, both over the data set as a whole and separately for dry and wet seasons.

3. Results

3.1. Seasonal and Diurnal $PM_{2.5}$ Concentration and Meteorological Factors

3.1.1. Data Summary

A summary of descriptive statistics for $PM_{2.5}$ concentrations and meteorological factors is presented in Table 1.

Table 1. Daily average values of $PM_{2.5}$ and meteorological factors for the entire sampling period. N is the number of samples, SEM is the standard error of the mean, Q_1 is 25th percentile, Q_3 is 75th percentile, Min is minimum, and Max is maximum value.

Variable	**N**	**Min**	**Q_1**	**Mean ± SEM**	**Median**	**Q_3**	**Max**
$PM_{2.5}$ (μg/m^3)	16	9.4	35.5	49 ± 5.7	40.4	70.5	94.0
Temperature (°C)	153	18.72	20.66	21.56 ± 0.10	21.63	22.59	24.04
Relative humidity (%)	153	50.66	60.19	71.61 ±0.89	74.35	81.03	89.68
Wind speed (m/s)	151	0.02	0.16	0.29 ± 0.01	0.25	0.40	0.80
Wind N/S (m/s)	151	−0.59	−0.13	−0.06 ± 0.01	−0.03	0.04	0.24
Wind E/W (m/s)	151	−0.17	0.03	0.17 ± 0.01	0.14	0.28	0.60
Air pressure (in Hg)	153	25.24	25.30	25.32 ± 0.00	25.32	25.34	25.41

The mean 24 h $PM_{2.5}$ concentration is approximately 3.3 times the WHO daily guideline of 15 μg/m^3 and nearly ten times the guideline for the annual average concentration. There are large variations in the values of $PM_{2.5}$ concentrations and moderate variations in the meteorological factors. The meteorology of the site is characterized by moderate atmospheric conditions such as moderate temperature, high relative humidity, low wind speed, and stable atmospheric air pressure, as seen in Table 1 and Figure 2.

3.1.2. Seasonal Differences

The box plots in Figure 2 display the seasonal differences in the $PM_{2.5}$ concentrations and meteorological factors.

The sample means of $PM_{2.5}$ concentrations for the dry and wet seasons (70.1 μg/m^3 and 39.4 μg/m^3) were 14 and 8 times the WHO annual guidelines. Higher $PM_{2.5}$ concentration, temperature, wind speed, and air pressure were observed during the dry season, while relative humidity levels were higher during the wet season. A Mann–Whitney U test was performed, and the seasonal differences for all parameters were statistically significant, with *p*-values less than 0.05.

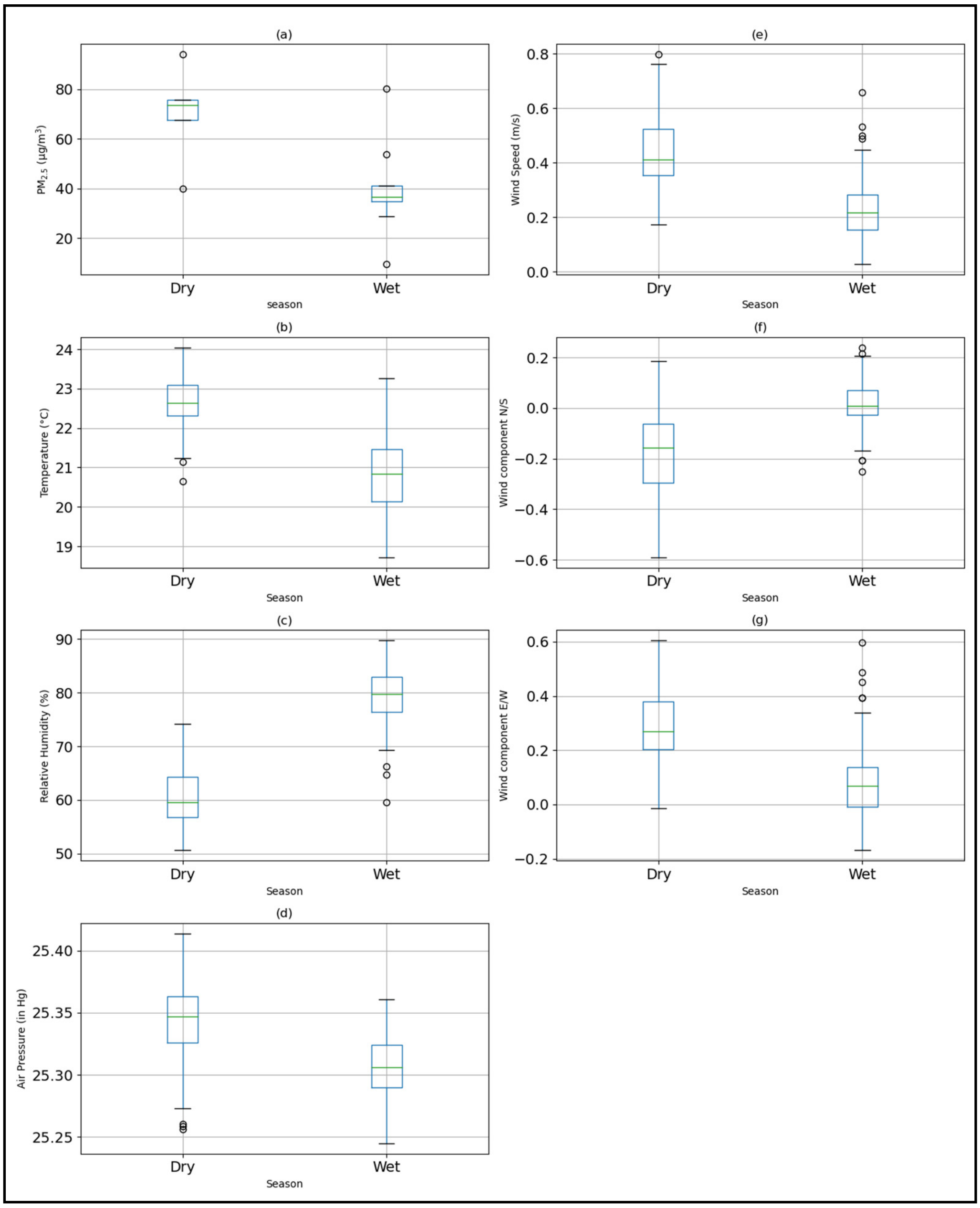

Figure 2. Seasonal differences of (**a**) $PM_{2.5}$ concentration, (**b**) temperature, (**c**) relative humidity, (**d**) air pressure, (**e**) wind speed, (**f**) wind component N/S, and (**g**) wind component E/W. The box plots display the median (green line), middle 50% (blue rectangle), upper and lower extremes (black bars), and individual outliers (black circles), which are points that fall below the lower limit or above the upper limit. The lower limit is the 25th quartile minus 1.5 times the interquartile range, and the upper limit is the 75th quartile plus 1.5 times the interquartile range.

3.1.3. Diurnal Variations

The average diurnal variations of the measured quantities were calculated by averaging values collected on different days during the same hour. Before averaging, the days were grouped by season: either wet or dry. These seasonal mean diurnal variations in $PM_{2.5}$ mass concentration, temperature, air pressure, wind speed, wind direction components, and air pressure are presented in Figure 3.

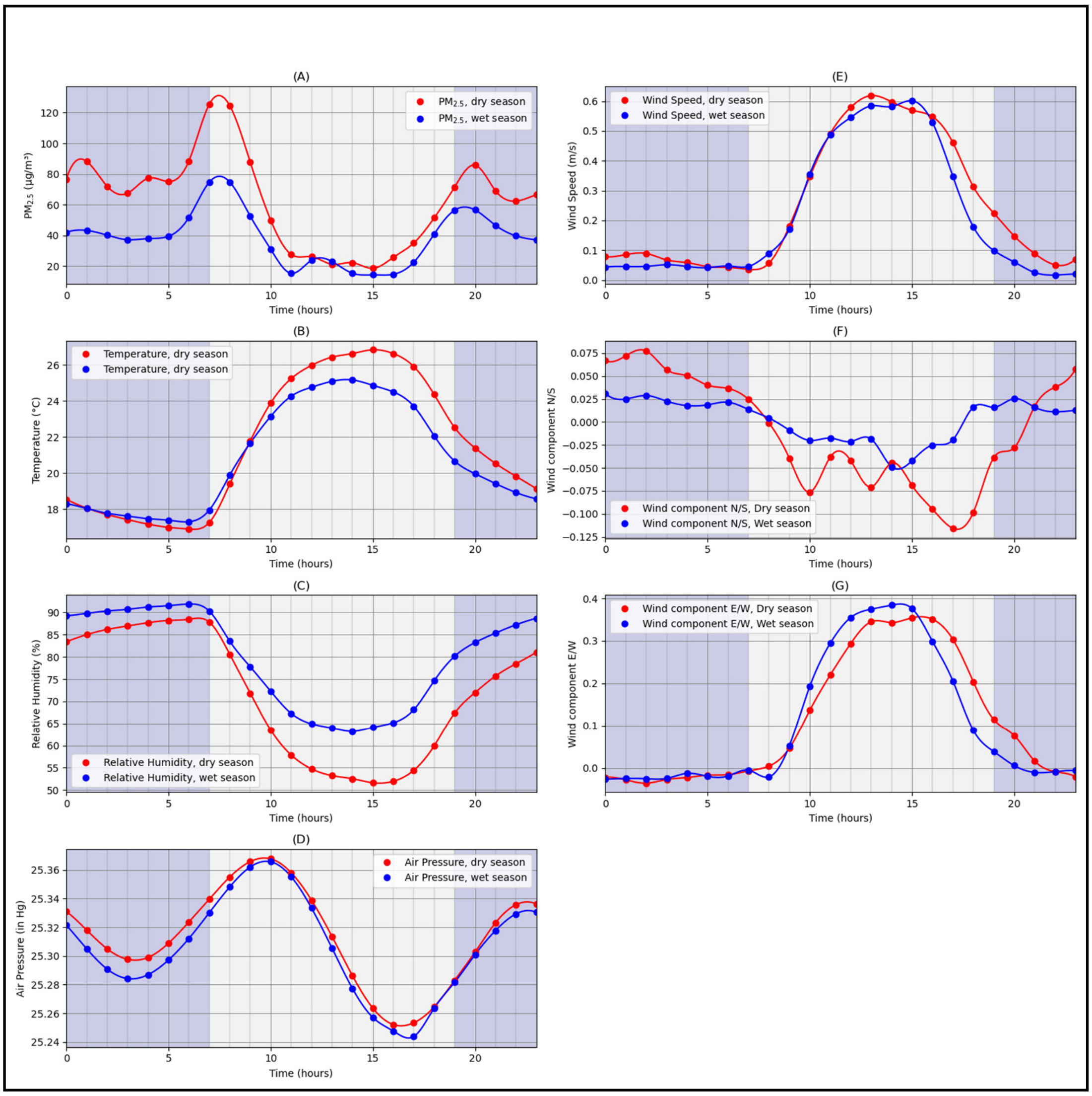

Figure 3. Diurnal variation of (**A**) $PM_{2.5}$ concentration, (**B**) temperature, (**C**) relative humidity, (**D**) air pressure, (**E**) wind speed, (**F**) wind component N/S, (**G**) wind component E/W. The time shown is local time. Dark blue background represents nighttime hours, and gray background represents daytime hours.

The $PM_{2.5}$ concentration shows bimodal peaks from 7:00 to 8:00 and 19:00 to 20:00. The morning peak is higher than the evening peak for both the dry and wet seasons. The temperature increased steadily after sunrise and peaked between 14:00 to 15:00, then decreased to a minimum in the early morning. The relative humidity peaked before sunrise (6:00), decreased to its minimum between 14:00 to 15:00, and then rose again through the evening and night. The air pressure varied with a daily rise and fall, with the maximum values at 10:00. The wind speed gradually increased after sunrise, reaching a maximum in the afternoon hours, and gradually decreased after sunset. The wind was normally from the west and slightly north in the afternoons. Overnight, the wind speed was much lower, with an average direction from the southeast.

The $PM_{2.5}$ concentration and relative humidity were high during nighttime for both the dry and wet seasons while temperature, wind speed, and air pressure were high during daytime. From the Mann–Whitney U test, p-values < 0.05 were obtained between the daytime and nighttime values of temperature, relative humidity, and wind speed, while the difference in air pressure was not statistically significant ($p = 0.67$).

3.2. Effect of Meteorological Factors on $PM_{2.5}$ Concentration

3.2.1. Effect of Meteorological Factors on Daily Averages of $PM_{2.5}$ Concentration

The extent to which each meteorological factor influences variation in daily average $PM_{2.5}$ concentration is presented in Table 2. We see that only air pressure has a statistically significant effect with a *p*-value less than 0.05.

Table 2. Daily averages. Linear regression results for each of the meteorological factors (considered individually as the independent variable) with $PM_{2.5}$; S is the slope; R^2 is the co-efficient of determination; *p*-value is the probability value.

Meteorological Factor	S	R^2	*p*-Value
Temperature	53.7	0.08	0.41
Relative humidity	−92.4	0.26	0.11
Wind speed	69.7	0.19	0.18
Air pressure	462	0.42	0.03
Wind component N/S	−74.0	0.32	0.09
Wind component E/W	88.9	0.26	0.13

3.2.2. Seasonal Effect of Meteorological Factors on Daily Average $PM_{2.5}$ Concentration

When the data are separated by season, the relationships change, as seen in Table 3. While some of the R^2 values are high, indicating a strong correlation, most of the *p*-values exceed 0.05 due to the small number of data points in each season. Wind speed in the dry season has a high R^2 value and a *p*-value indicating significance.

Table 3. Daily averages separated by season. Linear regression for each of the meteorological factors (considered individually) with $PM_{2.5}$; S is the slope; R^2 is the coefficient of determination; *p*-value is the probability value.

	Dry Season			Wet Season		
Meteorological Factor	**S**	R^2	***p*-Value**	**S**	R^2	***p*-Value**
Temperature	−20.7	0.36	0.40	−5.23	0.04	0.71
Relative humidity	−694	0.79	0.11	427	0.47	0.14
Wind speed	626	0.93	0.03	−88.2	0.16	0.43
Air pressure	432	0.16	0.61	373	0.24	0.33
Wind component N/S	−415	0.67	0.39	−25.0	0.01	0.88
Wind component E/W	286	0.24	0.67	20.7	0.01	0.86

3.2.3. Effect of Meteorological Factors on Diurnal Variation of $PM_{2.5}$ Concentration

The extent to which each meteorological factor correlates with the diurnal variation in the hourly average $PM_{2.5}$ concentrations is presented in Table 4.

Temperature, relative humidity, and wind speed had high values of R^2, while air pressure had the lowest R^2 value. The E/W component of wind speed had a higher R^2 value than the N/S component. Temperature and wind speed had a negative impact on hourly $PM_{2.5}$ concentration, while relative humidity and air pressure had a positive impact. The impact of all the parameters on $PM_{2.5}$ concentration was statistically significant except for barometric pressure.

Table 4. Diurnal variation. Linear regression for each of the meteorological factors (considered individually) with $PM_{2.5}$; S is the slope; R^2 is the co-efficient of determination.

Meteorological Factor	S	R^2	*p*-Value
Temperature	−4.40	0.57	0.00
Relative humidity	118	0.58	0.00
Wind speed	−61.3	0.58	0.00
Air pressure	236	0.15	0.06
Wind component N/S	104	0.21	0.03
Wind component E/W	−104	0.60	0.00

3.2.4. Seasonal Impact of Meteorological Factors on the Diurnal Variation of $PM_{2.5}$ Concentration

When the data were split into wet and dry seasons, as seen in Table 5, only the relationship between the north/south wind component and hourly $PM_{2.5}$ differed between the dry and wet seasons, in that the slope was negative in the wet season and positive in the dry season. All weather data except air pressure (both seasons) and north/south wind component (wet season) were strongly correlated with hourly $PM_{2.5}$ during both the dry and wet seasons, and the correlation was statistically significant.

Table 5. Diurnal variation separated by season. Linear regression for each of the meteorological factors (considered separately) with $PM_{2.5}$; S is the slope; R^2 is the co-efficient of determination; *p*-value is the probability value.

Meteorological Factors	Dry Season			Wet Season		
	S	R^2	*p*-Value	S	R^2	*p*-Value
Temperature	−5.10	0.65	0.00	−4.23	0.50	0.00
Relative humidity	134	0.62	0.00	119	0.55	0.00
Wind speed	−57.7	0.55	0.00	−58.5	0.50	0.00
Air pressure	358	0.15	0.06	182	0.15	0.06
Wind component N/S	83.7	0.41	0.00	−34.4	0.02	0.49
Wind component E/W	−98.1	0.61	0.00	−82.4	0.42	0.00

4. Discussion

4.1. Seasonal and Diurnal Variation of $PM_{2.5}$ Concentration

4.1.1. Ambient $PM_{2.5}$ Concentration

The $PM_{2.5}$ levels were high, indicating unhealthy air conditions at the site. The mean concentration of 49.0 μg/m^3 reported in this study is higher compared to the mean concentration of 26.7 μg/m^3 reported in another study in Mbarara that was conducted in 2018–2019 [13]. This discrepancy suggests worsening air conditions in the area. However, there was road construction near the site during this study period, and we do not have the ability to distinguish between the local effect of road construction and a more general effect.

4.1.2. Seasonal Variation of $PM_{2.5}$ Concentration

Statistically significant seasonal differences in the $PM_{2.5}$ concentration, with a higher concentration during the dry season compared to the wet season, are attributed to the contribution of seasonal sources and changes in weather conditions. At this site, factors that could have contributed to an increase in $PM_{2.5}$ concentration during the dry season include the re-suspension of dust due to traffic and road construction, waste burning, and less rainfall. The observation of higher $PM_{2.5}$ concentration in the dry season is consistent with other studies in the region [10,13].

4.1.3. Diurnal Variation of $PM_{2.5}$ Concentration

The diurnal $PM_{2.5}$ concentration shows bimodal peaks in the morning and evening hours during the wet and dry seasons. This is attributed to changes in the intensity of diurnal $PM_{2.5}$ sources and variations in atmospheric conditions. Human-caused $PM_{2.5}$ emissions increase during the daytime, but the atmospheric boundary layer also increases in height during the daytime, which dilutes the $PM_{2.5}$ concentration during the middle of the day. This dilution has a greater effect than the increase in emission rates, resulting in lower $PM_{2.5}$ concentrations during these midday hours. However, the stable atmosphere during the morning and evening hours, along with temperature inversions where a layer of warm air traps cooler air beneath, tends to lower the atmospheric boundary layer and inhibit the dispersion of particles, thereby increasing their concentration during these hours. Similar observations of bimodal peaks in the morning and evening hours were reported by other studies in the region [9,10].

This study observed peaks occurring between 7:00 to 8:00 and 19:00 to 20:00 Local Time. Local Time at our site is 57 min ahead of Local Solar Time (LST), defined as UTC + (longitude/15°). In LST, the observed peaks occur between 6:00 to 7:00 and 18:00 to 19:00. These differ from worldwide averages, which show later peaks from 7:00 to 10:00 and 21:00–23:00 LST, although they are close to the diurnal cycle observed in East Asia [22]. In much of the world, traffic-related emissions such as vehicle emissions and dust re-suspension tend to increase in the morning and evening rush hours hence increasing $PM_{2.5}$ concentrations [23,24], but in Mbarara, where there is comparatively little vehicle traffic, other sources may cause the earlier morning peaks, particularly cooking over wood-burning fires.

4.2. Effect of Meteorological Factors on the Seasonal and Diurnal Variation of $PM_{2.5}$ Concentration

The initial analysis of correlations between average daily $PM_{2.5}$ and meteorological factors presented in Table 2, before separating the data by season, found that the only regression showing significance was with air pressure, which correlated positively with $PM_{2.5}$ concentration. However, as shown in Figure 2, all these variables show significant differences between the wet and the dry seasons. For that reason, we turn to Table 3 to see the correlations between $PM_{2.5}$ and the meteorological factors within the wet and dry seasons. Once the effect of the season is removed, then wind speed during the dry season is the only variable with a significant correlation. Wind speed is positively correlated with $PM_{2.5}$ in this season, which tells us that local sources of $PM_{2.5}$ are dispersed by the wind at a lower rate than wind creates new airborne $PM_{2.5}$ through the re-suspension of particles. The results of this study can be compared with studies in similar regions [15,25]. Measurements in Kampala, Uganda showed that the daily $PM_{2.5}$ average concentrations were positively correlated with humidity up to a threshold of 80% relative humidity and then decreased at higher humidities [15]. That study did not separate the rainy and dry seasons, making it difficult to compare to our results. Measurements in Lagos, Nigeria, reported a negative correlation between PM and temperature and a positive correlation with relative humidity in the rainy season, while the correlations were negative for both temperature and relative humidity in the dry season, which is similar to what is reported in this study [25].

Since the daily average $PM_{2.5}$ concentrations showed different correlations with meteorological factors depending on whether the data were separated into seasons, we also checked whether separating the data into seasons affected correlations between diurnal

$PM_{2.5}$ levels and meteorological factors. However, we found much less change in this case. The reason why the diurnal correlations are not much affected by the seasons is probably because the underlying causes of the variation are not much affected. These factors are the atmospheric boundary layer height and the local $PM_{2.5}$ sources. The atmospheric boundary layer tends to rise in the morning and lower in the evening, so $PM_{2.5}$ levels are lowest at midday when they are diluted by a larger volume of the atmosphere. They peak in the morning and evening when the lowering atmospheric boundary layer interacts with increasing local sources due to cooking and possibly traffic. Therefore, meteorological factors including temperature and wind speed that tend to increase during the daytime due to increasing solar radiation are negatively correlated with diurnal $PM_{2.5}$ concentration, while relative humidity, which decreases with increasing temperature, is positively correlated with diurnal $PM_{2.5}$ concentration. Barometric pressure, which peaks in the morning and dips in the afternoon, exhibits a weak or no correlation with $PM_{2.5}$. Similar results with a positive correlation between hourly PM and relative humidity, a negative correlation with temperature and wind speed were observed in the Ugandan cities of Kampala and Jinja [9].

One motivation for this study was the possibility that, even if real-time measurements of $PM_{2.5}$ were not available, individuals might be able to estimate when $PM_{2.5}$ levels were high by using correlations with weather data and then reduce their exposure during those times. The strong correlation between wind speed and daily average $PM_{2.5}$ levels during the dry season offers one possibility, especially since wind speed is one of the easiest weather parameters to estimate without sophisticated equipment. The diurnal variation also shows strong correlations with many weather parameters, but we found that this correlation may not be as useful. The underlying cause of the correlations between the hourly $PM_{2.5}$ concentrations and the weather data is simply that the weather data correlates with the time of day, as does the $PM_{2.5}$ concentration. Once the time of day is accounted for, including the weather data does not improve the prediction of the $PM_{2.5}$ concentration.

5. Conclusions

The ambient air in Mbarara, Uganda, is severely polluted with $PM_{2.5}$ concentrations that are much higher than the WHO-recommended limits. Significant seasonal and diurnal variations were observed. Temperature, relative humidity, wind speed, and wind direction were the factors that significantly correlated with the diurnal variation of $PM_{2.5}$ concentration, while air pressure contributed at low levels. The findings of this study contribute to the knowledge of short-term variations of $PM_{2.5}$ and also form a basis for determining the effect of seasonal and diurnal sources on $PM_{2.5}$ concentration. We also recommend consideration of public awareness campaigns that will help reduce exposure during peak pollution times as well as measures to reduce particulates from biomass burning and road dust. We suggest that studies could test the effectiveness of such public awareness campaigns. Additionally, we recommend a study to investigate the impact of road construction on PM levels, and because the number of data collection periods was limited, we recommend further longitudinal study.

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