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Temperature, Humidity and Air Pollution Relationships during a Period of Rainy and Dry Seasons in Lagos, West Africa

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Abstract: Air pollution is a concern in the West Africa region where it is known that meteorological parameters such as ambient temperature and humidity can affect the particulate matter loading through atmospheric convection and dry deposition. In this study, we extend the investigation of these relationships to particulate matter less than 1 µm in diameter (PM_1), nitrogen dioxide (NO_2), nitrogen monoxide (NO) and ozone (O_3), for a complete period of rainy and dry seasons in Lagos. Regression analysis of the results indicate that there is a negligible to weak correlation ($r < 0.39$) between the temperature, humidity and air pollutants during the year, except for NO_2 and O_3 which respond moderately to humidity during the dry season, an observation previously unreported. The mean monthly values for all the air pollutants are lower during the rainy season compared to the dry season, indicating a potential higher contribution of the transport of pollutants from the north-eastern desert regions and the reduction of the wet removal of particles during the dry season. The World Health Organization air quality guidelines are mostly exceeded for fine particles with diameters less than 2.5 µm ($PM_{2.5}$), supporting previous studies, as well as for the NO_2 concentration levels. As $PM_{2.5}$ contributes to at least 70% of the particulate matter pollution throughout the year, policy guidelines could be enacted for people with chronic respiratory issues during the January/February months of intense high air pollution, high temperature but low humidity values.

Keywords: air pollution; rainy wet dry seasons; west Africa; temperature humidity; ozone; nitrogen monoxide dioxide; particulate matter; air mass trajectory; meteorological parameters; air quality correlation

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1. Introduction

Air pollution has been shown to be detrimental to human health, including on occupational health in West Africa [1]. Air pollutants can be classed as primary (e.g., nitrogen oxides (NOx); particulate matter (PM)), or as secondary if they are as consequences of chemical reactions in the lower atmosphere (e.g., ozone (O_3)) [2]. The atmosphere is a medium in which air pollutants are dispersed away from their sources [3] and as meteorological parameters such as temperature, and humidity vary daily, it is important to consider their relationship with air pollutants.

Several studies have presented the influence of meteorological parameters on air pollution. For instance, some studies have observed that temperature and sunshine duration had the strongest influence on the local surface O_3 concentration while the impacts of relative humidity and precipitation were weak and the impact of wind speed varied greatly between the cities in the Shanxi Province in China [4]. In the study, if local surface O_3 concentration in a city in the Shanxi Province was significantly correlated with meteorological parameters that impacted photochemical reactions (e.g., temperature and sunshine duration), then the O_3 pollution was regarded to be mainly brought about by local photochemical build up; otherwise, regional wind direction and speed were the main attributes [4]. All the monitoring stations used for the study were located in urban areas, therefore the meteorological interactions between urban, and rural areas that affect the photochemical processes that determine the O_3 production were not included in the results.

Studies on the association of PM concentration levels and the meteorological parameters are common as PM is considered impactful [5–7]. The results from the evaluation of the temperature and humidity effects on PM concentrations in Auckland, New Zealand showed that the temperature values had a negative correlation with the PM_{10} concentration values over a diurnal period and that the relative humidity generally presented a positive correlation with PM_{10}, but this correlation ceased beyond the 75% relative humidity value [5]. The researchers posited that this is because with increasing humidity levels, moisture particles increasingly grow in size until they reach a threshold where dry deposition happens, therefore reducing the PM_{10} concentrations in the atmosphere. The natural deposition of PM is affected by relative humidity and atmospheric PM concentration increases as the moisture particles adhere to PM [5]; this study was carried out over an eight-week period. The influences of temperature, relative humidity, wind speed, and wind direction on PM_{10} concentrations were evaluated in a study in urban and rural environments in İzmir, Türkiye [6]. The levels of relative humidity were found to be the most influencing factors on the PM_{10} concentration levels in both the urban and rural environments, however the recorded temperature values were not found to have any statistically significant effect on the PM_{10} concentration levels. The researchers indicated that incorporating further meteorological parameters such as atmospheric pressure and precipitation would improve the regression models presented in the study [6].

Air pollution studies in West Africa have been carried out in the past, but fewer studies exist on the correlations between meteorological parameters and air pollution. In [8], the correlation between temperature, humidity and PM (PM_1, $PM_{2.5}$, PM_{10}) was studied using data from five monitoring centres in five states (Osun, Kebbi, FCT, Delta, Lagos) in Nigeria, West Africa. One of the five stations was located further north of the country where there are short rainy seasons (four months), compared to one in the centre of the country (7 months of the rainy season) and the three of the stations in the south west of the country (8 months). The results indicated strong correlations between all the PM sizes (PM_1, $PM_{2.5}$, PM_{10}) and relative humidity in Delta. However, for the other states, the correlations were weak. The studies presented weak correlations between the PM sizes (PM_1, $PM_{2.5}$, PM_{10}) and the ambient temperature values for all five sites in the states [8]. The studies, however, were carried out over different periods at the five sites, ranging from 2 (Kebbi) to 7 months (Abuja).

The influences of the wind direction and speed, rainfall, ambient temperature and relative humidity on the $PM_{2.5}$, and PM_{10} concentration values were presented in a study at an urban site in Port Harcourt, West Africa [9]. It was reported that the wind speed, rainfall and ambient temperature all significantly affected the $PM_{2.5}$, and PM_{10} concentration values but with weak correlations. The observed relative humidity values showed a weak but significant correlation with PM_{10} concentration values and a weak but insignificant correlation with $PM_{2.5}$ concentration values. The study was carried out over a period of 8 months. A similar study at Akure, West Africa [10] found weak correlations between the values of wind speed, humidity, temperature and the PM_{10} and $PM_{2.5}$ concentration values. An earlier study at Ile-Ife, West Africa [11] had similar results but only 162 samples of PM ($PM_{2.5}$, and PM_{10}) were collected over 10 months of the study.

The results from the studies of the relationships between meteorological parameters and air pollution can aid the development of air quality management plans [9], especially in West Africa where there is a dearth of local air quality monitoring stations [8]. The present study contributes to these by evaluating the relationships between temperature and humidity for not just PM_{10} and $PM_{2.5}$ concentrations but also the NO, NO_2, O_3, and PM_1 concentrations which are air pollutants that have been uncommonly studied in the region. Secondly, the study uses hourly data covering the complete dry and rainy seasons over a period of 12 months; typically, previous studies in this region have not presented such complete continuous data. Lastly, the location (Akoka/Lagos, the largest city in West Africa [1]) and use of calibrated sensors allow for a robust assessment of the results. The next section presents the materials and methods used for the study. A detailed assessment of the results, including the measures of central tendency and the temporal evolution of the air pollution then follows. The comparison of the results to previous studies is presented next and the conclusions section also presents suggestions for future work in this area.

2. Materials and Methods

2.1. Study Location

The data for this study were gathered in Lagos, a metropolitan city in the south-western part of Nigeria in West Africa. Lagos was chosen as a research site because it represents typical population exposure as the largest and most populous city in West Africa. This study made use of a 1 year (2020–2021) rainy and dry seasons data series of NO, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10} levels, as well as meteorological data (temperature in °C, humidity in %). The air quality monitoring and weather stations at the University of Lagos (6.52 N, 3.40 E) was used to collect the data (Figure 1).

Figure 1. Lagos, highlighted, south-western part of Nigeria showing a monitoring site at the University of Lagos [1]. Map adapted from Google Maps (accessed on 12 March 23).

2.2. Air Quality Data

Air quality data (NO, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10}) required for this study were obtained from two sensors in monitoring stations situated at the University of Lagos, Akoka, in Lagos. Akoka Lagos is an urban background station located on the western edge of the campus, with the Lagos Lagoon situated about 2.4 km east of, and the Atlantic Ocean, about 13 km south of the station. There are roads, trees and buildings within 10 m of the location. The altitude is about 4 m above sea level. Hourly mean values of the air quality data (NO, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10}) were collected for 7885 h from July 2020 to August 2021 (excluding ~720 h between October and November 2020 for maintenance and re-calibration) using Zephyr® air quality sensors [12] with some of the specifications presented in Table 1.

Table 1. Air quality sensor (Zephyr® [12]) specifications for the air pollutants (NO, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10}) used for the study.

	Air Pollutant Type					
	NO	**NO_2**	**PM_1**	**$PM_{2.5}$**	**PM_{10}**	**O_3**
Measurement Range	0–20,000 μg/m^3					
Estimated Accuracy	±5 μg/m^3					±8 μg/m^3

2.3. Temperature and Humidity Data

Hourly ambient temperature and ambient humidity data (for 7885 h, corresponding to the NO, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10} data) from July 2020 to August 2021 were also collected from the University of Lagos, Akoka, monitoring stations housing the air quality sensors as stated above. This system had the advantage of collecting the air quality and metrological data from the same location.

2.4. Climate and Season Definitions

The definitions of the climate and seasons in Lagos were made using the Köppen-Geiger climate classification system [13]. The procedure is as presented in Figure 2 using data from Table 2. The precipitation and ambient temperature data (Table 2) for the classification were taken from available historical (2005–2015) annual weather averages [14]. Using the classification from [13], summer (winter) is taken as the six-month period that is hotter (colder) between April to September and October to March and both the historical [14] and collected data in this study suggest that the April to September period is the Winter season whilst the October to March period is the Summer season. These are called the rainy/wet (April to September; historical average precipitation 134.2 mm [14]) and the dry (October to March; historical average precipitation 84.9 mm [14]) seasons, respectively. Thus, using these classifications and procedures (see Figure 2) the climate at the University of Lagos, Akoka stations used for this study can be classified as Tropical Savannah [Aw].

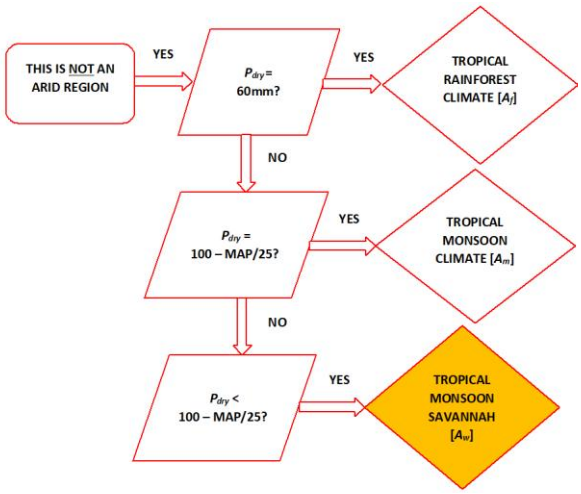


Figure 2. The Köppen-Geiger climate classification procedure. Adapted from Beck et al. [13]. Definitions of variables: MAP = mean annual precipitation (mm/year); P_{dry} = precipitation in the driest month (mm/month); A_f = tropical rainforest climate; A_m = tropical monsoon climate; A_w = tropical monsoon savannah. Summer (winter) is the six-month period that is warmer (colder) between April-September and October-March. Using this procedure and the data from Table 2, the climate at Akoka Lagos can be classified as tropical monsoon savannah with rainy (April to September) and dry (October to March) seasons.

Table 2. Mean precipitation and ambient temperature values obtained from the annual weather averages based on weather reports collected during 2005–2015 from a weather station at Ikeja/Lagos [14], 13 km north from Akoka/Lagos where the data for the present studies were collected. The shaded sections indicate the dry season months.

Month	Annual Weather Averages From 2005 to 2015 [14]	
	Mean Ambient Temperature	Mean Precipitation
	[°C]	[mm]
January	28	49.4
February	29	51.7
March	29.5	85.4
April	29	85.3
May	28	132
June	27	186.8
July	26	138.9
August	26	98.7
September	26.5	163.2
October	27	157.3
November	28	122
December	28	43.6
Wet Season:		
April to September	27.1	134.2
Dry Season:		
October to March	28.3	84.9

2.5. Data Analysis

A simple linear regression model was used to determine the relationship between the hourly average ambient temperature and humidity values and the air pollution levels in Lagos, so as to draw attention to any possible correlation between the ambient temperature and humidity and the air pollutants during the rainy and wet seasons. The statistical analyses were performed using the Data Analysis Tool application in Microsoft Excel software [15]. The definitions of the correlation coefficient thresholds were adapted from [16] and presented in Table 3 below.

Table 3. Definitions of the correlation coefficient (r) thresholds used for the study, adapted from [16].

Observed Correlation Coefficient, r	Interpretation
0.00 to 0.10	Negligible correlation
0.10 to 0.39	Weak correlation
0.40 to 0.69	Moderate correlation
0.70 to 0.89	Strong correlation
0.90 to 1.00	Very strong correlation

A null hypothesis is constructed for the analysis as follows:

H_0. *"There is no statistical significance between the independent meteorological variable and the air pollutant."*
where "*independent meteorological variable*" = (ambient temperature, ambient humidity) and "*air pollutant*" = (NO, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10}).

$$\mathbf{H_0: r = 0} \quad (1)$$

where r is the correlation coefficient.

To test the null hypothesis, a significance level of 5% is selected, in a two-tailed test. This choice of an alpha (α) value (significance level) of 0.05 is common and for the study presented here is based on arguments presented in [17,18] as being a reasonable cut-off for statistical significance. The null hypothesis is accepted if the p-value is greater than 0.05. The level of statistical significance attached to the relationships is described as presented in Table 4 below.

Table 4. Interpretation of the statistical significance of the relationships between the independent meteorological parameters and the air pollutants based on the calculated p-value.

Critical Values	Interpretation	
$p > 0.05$	Not statistically significant	Accept null hypothesis
$p \leq 0.05$ $p \leq 0.01$	Statistically significant Highly statistically significant	Reject null hypothesis

3. Results

3.1. Measures of Central Tendency of Air Pollutants, Temperature and Humidity

The results presented in this study cover the period between July 2020 and June 2021, encompassing a complete period of rainy and dry seasons. The data presented were collected over 4256 h over the rainy season and 3629 h during the dry season, for a total of 7885 h of data collection (Tables 5 and 6).

Table 5. Temperature, humidity and concentration values of air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) during the dry season (October 2020 to March 2021).

	NO_2	*O_3*	*NO*	*PM_1*	*$PM_{2.5}$*	*PM_{10}*	*Ambient Temp*	*Ambient Humidity*
	μg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3	°C	%
Mean	51.4	56.8	19.5	13.4	18.2	25.2	29.5	76.6
Mode	30.0	79.0	3.2	10.7	15.7	19.3	26.0	87.0
Minimum	0.0	0.0	0.3	1.9	2.0	5.6	22.0	35.0
Maximum	6963.9	279.0	452.3	138.6	398.7	286.7	42.0	97.0
Hours [1]	4256	4256	4256	4256	4256	4256	4256	4256

[1] Number of complete hours of data collection.

Table 6. Temperature, humidity and concentration values of air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) during the dry season (October 2020 to March 2021).

	NO_2	*O_3*	*NO*	*PM_1*	*$PM_{2.5}$*	*PM_{10}*	*Ambient Temp*	*Ambient Humidity*
	μg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3	°C	%
Mean	30.5	62.9	24.4	22.3	25.1	35.8	31.7	69.9
Mode	30.0	78.0	3.0	20.5	23.8	31.2	30.0	78.0
Minimum	0.0	0.0	0.0	3.7	3.9	7.5	22.0	15.0
Maximum	62.3	259.6	304.7	139.3	195.0	225.1	42.0	90.0
Hours [1]	3629	3629	3629	3629	3629	3629	3629	3629

[1] Number of complete hours of data collection.

3.1.1. Measured Air Pollutant Concentrations Levels and the WHO AQG

The measured mean values of the concentration of all the air pollutants (excluding O_3), for both the rainy and dry seasons (Tables 5 and 6), exceeded the World Health Organization (WHO) recommended Air Quality Guidelines (AQG) [19] levels, for both the annual and 24 h averaging times. For example, during the dry season, the AQG 24 h averaging time concentration level was exceeded 87.1% of the total number of hours for the study for $PM_{2.5}$, 18.3% for PM_{10}, and 89.0% for NO_2. In contrast this was exceeded for just 1% of the period for O_3 (Table 7). However, this is not unusual in the West Africa region, out of more than 20 air pollution monitoring sites reported in the region [8–11,20], only one, the monitoring site at Osun [8], recorded mean PM_{10} concentration levels (20.4 μg/m^3 measured over 4 months) that were below the WHO AQG annual level of 45 μg/m^3 indicating the seriousness of the levels of concentration of air pollutants in this region.

Table 7. Percentage of hours during the study in dry season in which the recommended WHO AQG levels [19] were exceeded for air pollutants (NO_2, O_3, $PM_{2.5}$, PM_{10}).

Pollutant	Averaging Time [Hours]	Recommended WHO AQG Level [μg/m^3]	Hours WHO AQG Level Was Exceeded during The Study Period [%]
$PM_{2.5}$	24	15	**87.1**
PM_{10}	24	45	**18.3**
O_3	8	100	**1.0**
NO_2	24	25	**89.0**

3.1.2. Descriptive Statistics of Temperature and Humidity

From Tables 5 and 6, in both the rainy and dry seasons, the ambient temperature values ranged from 22.0 to 42.0 °C, though the mean and mode ambient temperature values were higher for the dry season (31.7 °C; 30.0 °C) compared to the rainy season (29.5 °C; 26.0 °C). These are similar to the mean ambient temperature values trends recorded over the 2005 to 2015 period by [14] in Ikeja/Lagos (see Table 2), where dry seasons were also hotter than the rainy seasons. A mean value of 33.4 °C, and a range of 26.7 to 42.8 °C (converted from the Fahrenheit scale data) were observed by [8] over a December to April (dry season) period from a site in Ikeja/Lagos which is ~15 km from the monitoring site presented in this study. In Akure, which is about 300 km south-west of Akoka Lagos, ambient temperature ranges of 22 to 27 °C (rainy season) and 33 to 35 °C (dry season) have been recorded [10]. The recorded ambient humidity values for the dry season (range 15.0 to 90.0%; mean 69.9%; mode 78.0%) were lower compared to those of the rainy season (range 35.0 to 97.0%; mean 76.6%; mode 87.0%). The dry season is characterized by prevailing north-easterly winds [21], including a period of "harmattan" from December to March bringing dry and dusty conditions across West Africa, therefore, there is a wider temperature range during the day (lower at night, higher during the day time) and lower humidity [22]. This is unlike winter seasons in which lower humidity values are accompanied by lower temperature values [22]. Others have recorded a mean relative humidity during a late December to April dry season period (corresponding incidentally to the harmattan phase of the season) in Lagos of 55.4% [8]. Thus, in this region, dry seasons present lower ambient humidity levels compared with the rainy seasons (see also [10]).

3.1.3. Descriptive Statistics of PM_1/Coarse Particle Ratios

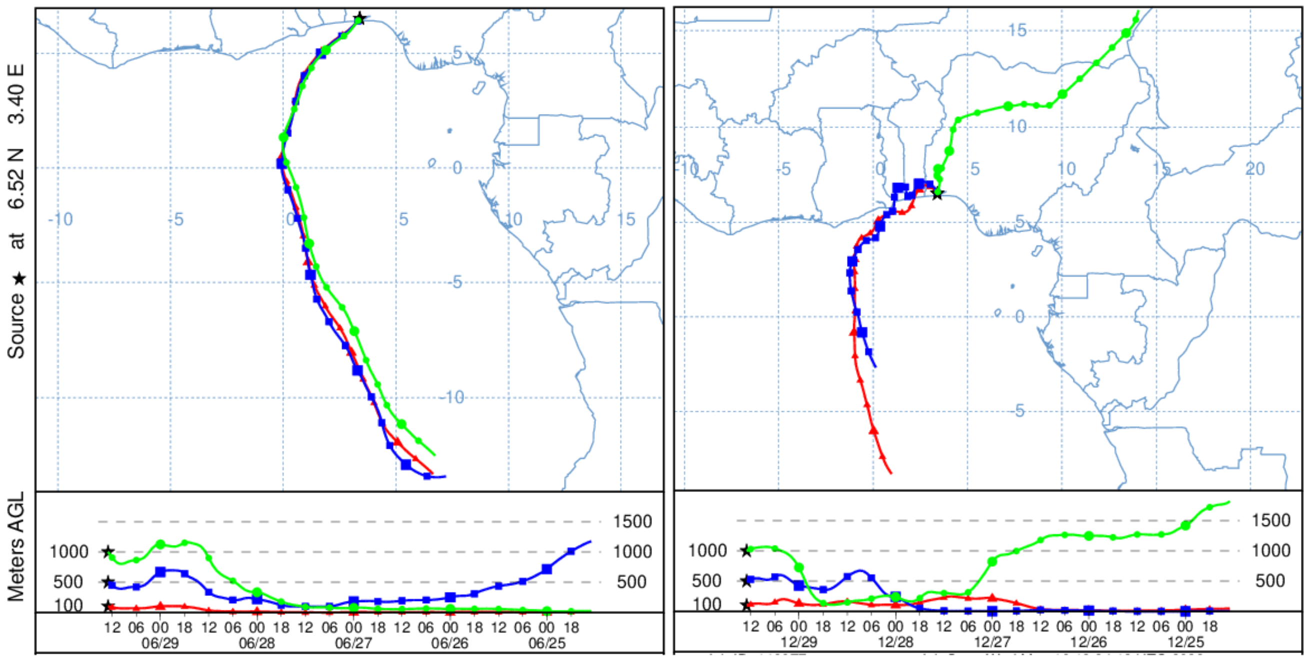
PM_1 sized particles are more likely than $PM_{2.5}$ or coarse (PM_{10}) sized particles to pass through the nose and throat and enter the lungs and thus are of at least equal concern, hence they should be studied in this region. The observed mean PM_1/coarse particle concentration ratios (PM_1/PM_{10}) for the rainy (0.53) and dry (0.62) seasons indicate that combustion and similar activities that produce very small particles contribute high proportions of the particulate concentrations in this area, more so during the dry season. A ratio of 0.63 was reported by [8], however this was during the dry season and for a duration of 2.5 months; these types of studies are rare in this region.

3.1.4. Descriptive Statistics of PM, and Fine/Coarse Particle Ratios

The mean fine/coarse particle concentration ratios ($PM_{2.5}/PM_{10}$) for both the rainy (0.72) and dry (0.70) seasons compare to another Lagos study (0.85 for 2.5 months during the dry season [8]), 0.87 over a week during the winter in New Zealand [5] and Akure [10] (ranging from 0.63 to 0.83 during the wet season and 0.65 to 0.73 during the dry season). However, in Port-Harcourt, this ratio ranges from 0.261 to 0.349 over 8 months [9].

Coarse particles are usually formed by mechanical activities, e.g., grinding or wind blowing, whereas fine particles are mostly formed in the atmosphere by chemical reactions and organic compounds. Thus, a high ($PM_{2.5}/PM_{10}$) ratio indicates significant contributions to the PM concentration from fine particles such as those from combustion sources, whereas a low ($PM_{2.5}/PM_{10}$) ratio indicates a higher contribution to the PM concentration from coarse particles such as those from re-suspended soil or road dust [23].

All the mean PM concentration values recorded during the dry season were at least ~1.3 times higher than those recorded during the rainy season (Tables 5 and 6). The absence of intensive wet removal due to the rains [23] and long-range transport of pollutants from north-eastern desert regions [22] during this period may contribute to higher PM levels during the dry season. To test the later assumption, the directions and distances of the sources of the air parcel over the air pollutants measurement site in this study were computed using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) backward trajectory model [24,25], and the simulation results (Figure 3) indicate a contribution of north-eastern desert winds to the air mass over the site during the dry season. This seasonal variation of higher $PM_{2.5}$ values during the dry season compared to lower ones during the rainy season was also observed at Ile Ife [11], about 210 km north-east of the Akoka Lagos site.



(**a**) (**b**)

Figure 3. Simulated backward trajectories of the air mass, using the HYSPLIT [24,25] model, from the air pollutants measurements site in Lagos (Source). The air mass motions were simulated over three Above Ground Level (AGL) heights (red lines – 100 m, blue lines – 500 m, green lines - 1000 m) over 5 days. (**a**) Backward trajectories at 1300 UTC 29 June 2021 for the rainy season example. (**b**) Backward trajectories at 1300 UTC 29 December 2020 for the dry season example. These simulation results indicate a contribution of north-eastern desert winds to the air mass during the dry season (**b**) not seen during the rainy season (**a**). (**a**) Rainy season. (**b**) Dry season.

3.1.5. Descriptive Statistics of NO_2, O_3, and NO

The recorded mode values of the NO_2, O_3, and NO concentrations for the rainy season (30.0 μg/m^3, 79.0 μg/m^3, and 3.2 μg/m^3, respectively) are similar to those of the dry season (30.0 μg/m^3, 78.0 μg/m^3 and 3.0 μg/m^3, respectively), however the mean NO_2

concentration value recorded during the rainy season (51.4 μg/m^3) is higher than that recorded during the dry season (30.5 μg/m^3), see also Figures 4–6. This could be due to a period of 19 h in July 2020 in which the mean concentration values per hour of ~7000 (and for NO, ~450) μg/m^3 were recorded and intense vehicular and other human activities occurred in preparation for an annual event close to the site, which might have contributed to these values. These values were within the measurement range of the sensors used for the study (Zephyr® [12] and Table 1: NO/NO_2: range 0 to 20,000 μg/m^3, estimated accuracy ±5 μg/m^3) and these were co-located and calibrated (Root Mean Square Error (RMSE) 3.677 μg/m^3) with reference units before the start of the data collection. The recorded mean O_3 and NO concentration values were ~11% higher during the dry season compared to the rainy season (Tables 5 and 6).

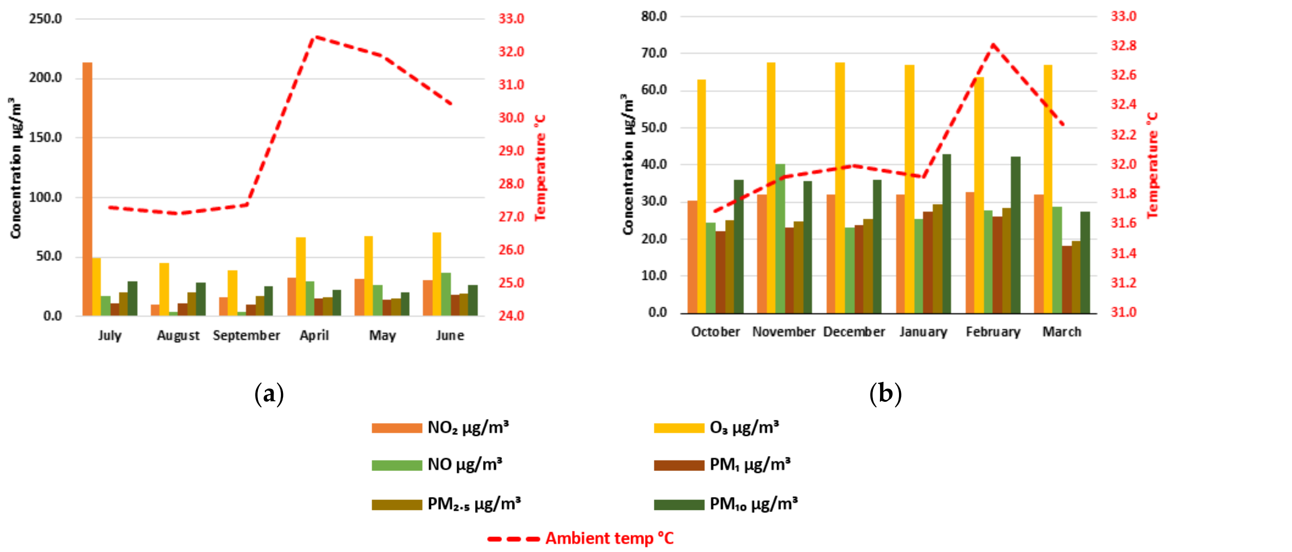


Figure 4. Mean temperature, and concentration values of air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) during the rainy (July to September 2020, April to June 2021) and dry (October 2020 to March 2021) seasons. (**a**) Rainy season. (**b**) Dry season.

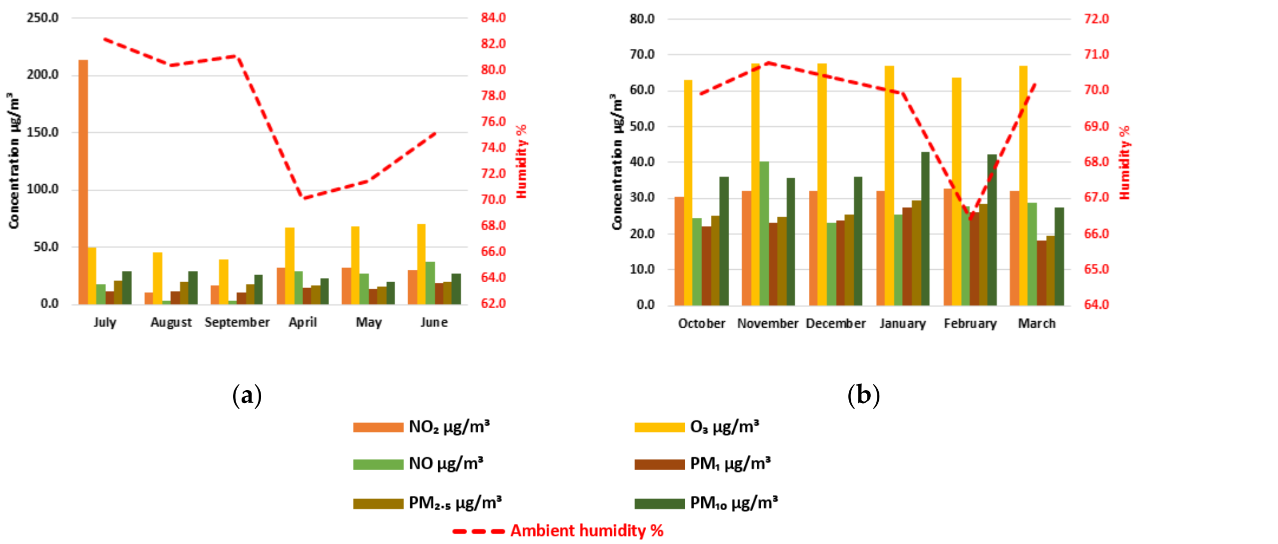


Figure 5. Mean humidity, and concentration values of air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) during the rainy (July to September 2020, April to June 2021) and dry (October 2020 to March 2021) seasons. (**a**) Rainy season. (**b**) Dry season.

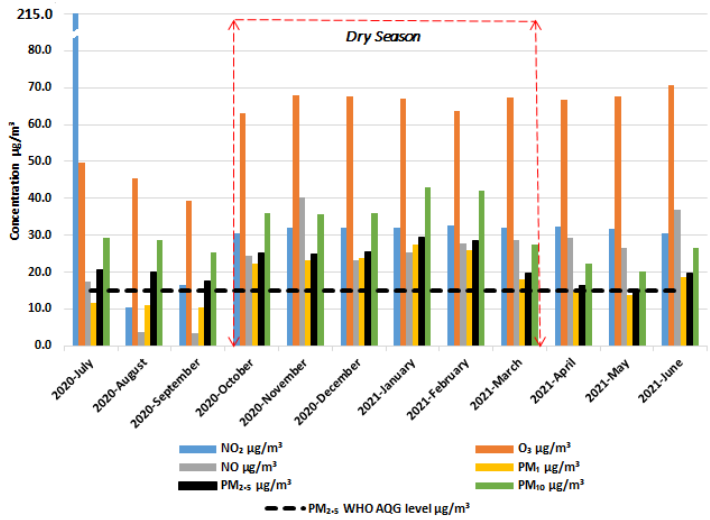


Figure 6. Concentration values of air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) during the rainy (July to September 2020, April to June 2021) and dry (October 2020 to March 2021) seasons, with the recommended 24 h average $PM_{2.5}$ WHO Air Quality Guidelines concentration level.

3.2. Temporal Variation of Air Pollutants, Temperature and Humidity

The temporal variation trends observed in Figures 4 and 5 corroborate the observations presented in the "Measurements of central tendency" section. The mean monthly temperature versus air pollutant concentration values for both seasons are shown in Figure 4. For 3 (July to September) of the 6 months during the rainy season, the recorded mean monthly values fell below 30.0 °C, with the highest mean monthly value of 32.5 °C in April during the season, whereas during the dry season all the six months recorded mean temperature values above 30.0 °C with the hottest month being February (32.8 °C). Similarly for 3 (July to September) months of the 6 months of the rainy season, the recorded humidity levels were all above 80%, whereas during the dry season, the recorded values where all ~70%.

Generally, the monthly mean concentration values of the air pollutants are higher during the dry season compared to the rainy season (Figure 6) and as discussed in Sections 3.1.3, 3.1.4, 4 and 5, these could have implications for human respiratory health. The monthly mean air pollutants concentration values remain relatively constant throughout the dry season except for spikes for the NO concentration in November (40.2 $\mu g/m^3$), and for PM_{10} in January and February (42.8 $\mu g/m^3$ and 42.1 $\mu g/m^3$, respectively). For the rainy season the monthly mean air pollutants concentration values also remained relatively constant, although the monthly mean concentration of NO_2 for July was 213.5 $\mu g/m^3$ and the monthly mean concentration NO values fell in August and September (3.6 $\mu g/m^3$ and 3.5 $\mu g/m^3$, respectively). From Figure 6, it can be seen that the WHO AQG concentration level for $PM_{2.5}$ was exceeded most of the time during the study year (see Section 3.1.1).

3.3. Temperature, Humidity and Air Pollution Relationships during the Rainy and Dry Seasons

From the details presented in Table 8, over the period covered in this study, the mean concentration value of NO_2 was statistically significantly less ($p < 0.0001$) during the dry season than during the rainy season. Conversely, the mean concentration value of O_3 was statistically significantly more ($p < 0.0001$) during the dry season than during the rainy season. There were no statistically significant differences in the mean concentration values, between the dry and rainy seasons, for NO ($p = 0.3598$), PM_1 ($p = 0.3528$), $PM_{2.5}$ ($p = 0.3543$), and PM_{10} ($p = 0.1730$).

Table 8. The hourly mean temperature, humidity and concentration values of air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) during the rainy (July to September 2020, April to June 2021) and dry (October 2020 to March 2021) seasons. For this table, 3629 complete hours of data collection for both seasons were used. $\alpha = 0.05$.

	Dry Season		*Wet Season*		
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**	***p*-Value**
NO_2 [µg/m^3]	30.5	7.1	55.0	481.2	<0.0001
O_3 [µg/m^3]	62.9	22.1	54.4	25.2	<0.0001
NO [µg/m^3]	24.4	18.6	16.7	34.1	0.3598
PM_1 [µg/m^3]	22.3	11.6	12.7	7.2	0.3528
$PM_{2.5}$ [µg/m^3]	25.1	13.3	18.0	11.9	0.3543
PM_{10} [µg/m^3]	35.8	16.7	25.1	12.0	0.1730
Ambient temp [°C]	31.7	3.8	29.3	3.8	<0.0001
Ambient humidity [%]	69.9	13.6	76.9	11.9	<0.0001

The mean ambient temperature values were statistically more significant ($p < 0.0001$) during the dry season than during the rainy season. However, the ambient humidity values were statistically less significant ($p < 0.0001$) during the dry season compared to the rainy season (Table 8).

3.4. Correlation Analysis of Temperature, Humidity and Air Pollutants during the Rainy and Dry Seasons

Using linear regression analysis as described in the "Data Analysis" section, the relationships between the values of the concentrations of the air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}), and the measured ambient temperature and humidity values during the rainy and wet seasons are presented in Tables 9 and 10, respectively. The results indicate that for the rainy season, most of the recorded values of the mean hourly concentration for the air pollutants are weakly correlated with the recorded hourly ambient temperature values and that these values are mostly statistically highly significant (Table 9). This observation is similarly observed during the dry season except for PM_{10} where negligible correlation with the ambient temperature values were observed (Table 10).

Table 9. Correlation matrix of mean temperature, humidity, and air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) values during the rainy (July to September 2020, April to June 2021) season ($n = 4256$).

	NO_2	**O_3**	**NO**	**PM_1**	**$PM_{2.5}$**	**PM_{10}**	**Ambient Temp**	**Ambient Humidity**
NO_2	1							
O_3	−0.15	1						
NO	0.86	0.12	1					
PM_1	0.03	0.22	0.26	1				
$PM_{2.5}$	0.08	−0.09	0.09	0.80	1			
PM_{10}	0.10	−0.13	0.10	0.82	0.95	1		
Ambient temp	*−0.04*	**0.21**	**0.10**	**−0.13**	**−0.24**	**−0.37**	1	
Ambient humidity	**0.06**	**−0.16**	[−0.02]	**0.22**	**0.26**	**0.37**	−0.94	1

The numbers in bold represent statistically highly significant associations, those in italics significant associations, and those in brackets no associations.

Table 10. Correlation matrix of mean temperature, humidity, and air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) values during the dry (October 2020 to March 2021) season (n = 3629).

	NO_2	**O_3**	**NO**	**PM_1**	**$PM_{2.5}$**	**PM_{10}**	**Ambient Temp**	**Ambient Humidity**
NO_2	1							
O_3	−0.21	1						
NO	0.11	0.31	1					
PM_1	0.17	0.14	0.34	1				
$PM_{2.5}$	0.20	−0.10	0.18	0.91	1			
PM_{10}	0.21	−0.09	0.23	0.93	0.96	1		
Ambient temp	**0.61**	**−0.24**	**−0.12**	**−0.11**	**−0.05**	[0.00]	1	
Ambient humidity	**−0.48**	**0.49**	**0.17**	*0.04*	**−0.10**	**−0.17**	−0.86	1

The numbers in bold represent statistically highly significant associations, those in italics significant associations, and those in brackets no associations.

The results for the measured ambient humidity values from Tables 9 and 10 during the rainy and dry seasons indicate that the mean hourly concentration for the air pollutants are, at most, moderately correlated with the recorded hourly ambient humidity values and that these values are mostly statistically highly significant.

3.4.1. Nitrogen Dioxide (NO_2)

A negligible negative correlation exists between the mean concentration values of NO_2 and the mean ambient temperature during the rainy season (Table 9) and this relationship is statistically significant (R^2 = 0.0012; p = 0.021. (Table 11)). However, during the dry season (Table 10), there is a moderate positive correlation between the two parameters and the relationship is statistically highly significant (R^2 = 0.3706; p = 0. (Table 11)). Thus, the variability of the NO_2 concentration levels can be "explained" more by the ambient temperature values during the dry season than during the rainy season, for the periods the data were collected for this study. From Tables 9–11, the correlation between the mean hourly concentration of NO_2 and the mean hourly ambient humidity levels is stronger during the dry season than during the rainy season and these are statistically highly significant (rainy season: R^2 = 0.0034, p = 0.0001; dry season: R^2 = 0.2339, p = <0.0001).

Table 11. Calculated critical values for the mean temperature, humidity, and concentration values of air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) during the rainy (July to September 2020, April to June 2021) and dry (October 2020 to March 2021) seasons. The null hypothesis is accepted for the relationships with p-values in bold figures.

	***p*-Values**					
	NO_2	*O_3*	*NO*	*PM_1*	*$PM_{2.5}$*	*PM_{10}*
Wet season						
Ambient temp	0.0210	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Ambient humidity	0.0001	<0.0001	**0.2980**	<0.0001	<0.0001	<0.0001
Dry season						
Ambient temp	0.0000	<0.0001	<0.0001	<0.0001	0.0018	**0.9915**
Ambient humidity	<0.0001	<0.0001	<0.0001	0.0282	<0.0001	<0.0001

3.4.2. Ozone (O_3)

Reviewing Tables 9–11, it is ascertained that a weak positive correlation exists between the mean concentration values of O_3 and the mean ambient temperature during the rainy season and this relationship is statistically highly significant (R^2 = 0.0432; p = <0.0001). The relationships during the dry season are similar (R^2 = 0.0561; p = <0.0001). There is a moderate correlation (R^2 = 0.2365) between the mean concentration of O_3 and the mean humidity values across the dry season compared to weak correlation (R^2 = 0.0241) for this relationship over the wet season. The relationship between both variables is statistically significant over both seasons (p = <0.0001).

3.4.3. Nitrogen Oxide (NO)

There is a weak correlation between the mean concentration values of NO (Tables 9–11) and the mean ambient temperature during the rainy and dry seasons and these relationships are statistically highly significant (rainy season: R^2 = 0.0101, p = <0.0001; dry season: R^2 = 0.0145, p = <0.0001). From Table 11, during the rainy season there is no statistical significance due to the weak correlation between the mean concentration of NO and the mean humidity levels (R^2 = 0.0003, p = 0.298). Over the duration of the dry season, the weak relationship (R^2 = 0.0305) between both variables does have a statistically high significance (p = <0.0001).

3.4.4. Particulate Matter (PM_1, $PM_{2.5}$, PM_{10})

Again, Tables 9–11 reveal that the correlation between the mean concentration values of PM_1 and the mean ambient temperature during the rainy and dry seasons is weak and these relationships are statistically highly significant (rainy season: R^2 = 0.0164, p = <0.0001; dry season: R^2 = 0.0124, p = <0.0001).

The correlations between the mean concentration values of $PM_{2.5}$ and PM_{10} and the mean ambient temperature during the rainy seasons are weak and statistically highly significant ($PM_{2.5}$: R^2 = 0.0584, p = <0.0001; PM_{10}: R^2 = 0.1364, p = <0.0001). During the rainy season the relationship between the PM_{10} concentration levels can be "explained" more by the ambient temperature values than that of the correlation between the $PM_{2.5}$ concentration values and the ambient temperature, for the periods these were observed for this study.

During the dry season there is a negligible correlation between the mean $PM_{2.5}$ concentration levels and the recorded ambient temperature and this is statistically highly significant (R^2 = 0.0027; p = 0.0018). This relationship is similar for the mean PM_{10} concentration levels ($R^2 = 3.1 \times 10^{-8}$; p = 0.9915), though it is not statistically significant.

There is a stronger relationship between the PM_1 mean concentration values and the mean ambient humidity values during the rainy season (R^2 = 0.0489) compared to that during the dry season (R^2 = 0.0013). This trend is also observed for the cases of $PM_{2.5}$ and PM_{10} for both seasons and the correlations are highly significant (Tables 9–11).

4. Discussion

The results of the analyses of the relationships between the values of the concentrations of the air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}), and the measured ambient temperature and humidity values during the rainy and wet seasons are compared to published work in this area in this section. Most of the work in literature has examined mainly $PM_{2.5}$, and PM_{10} concentration values, thus there is limited data on correlations between ambient temperature and humidity values and NO_2, O_3, NO, and PM_1 concentration values.

The results indicate that for the rainy season, the recorded values of the mean concentration for the air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) are at best weakly correlated with both the recorded mean ambient temperature and humidity values and all of these values are at most statistically highly significant except for the correlation between NO and ambient humidity which is not statistically significant (Table 12). The study at Akure [10] is the closest comparison with the present work but only $PM_{2.5}$, and PM_{10} concentration values were measured and these were determined to have a weak correlation with both the ambient temperature and humidity values and were all statistically insignificant. Thus, for the rainy season, the air pollutant concentration values in the present work and in published literature correlate weakly with both the ambient temperature and humidity.

Table 12. Correlation and statistical significance of the mean temperature, humidity, and concentration values of air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) during the rainy (July to September 2020, April to June 2021) and dry (October 2020 to March 2021) seasons, compared with results from published studies. The shaded sections indicate lack of data from the study for the pollutants.

		NO_2		*O_3*		*NO*		*PM_1*		*$PM_{2.5}$*		*PM_{10}*		
	Location	*Correlation*	*Statistical significance*	*Correlation*	*Statistical significance*	*Correlation*	*Statistical significance*	*Correlation*	*Statistical significance*	*Correlation*	*Statistical significance*	*Correlation*	*Statistical significance*	*Duration of study*
Rainy season														
Ambient temp	**Lagos [Present study]**	**negligible**	**significant**	**weak**	**highly significant**	**weak**	**highly significant**	**weak**	**highly significant**	**weak**	**highly significant**	**weak**	**highly significant**	**6 months each (complete season)**
	Akure [10]									**negligible**	**not significant**	**negligible**	**not significant**	**not specified**
Ambient humidity	**Lagos [Present study]**	**negligible**	**highly significant**	**weak**	**highly significant**	**negligible**	**not significant**	**weak**	**highly significant**	**weak**	**highly significant**	**weak**	**highly significant**	**6 months each (complete season)**
	Akure [10]									**weak**	**not significant**	**weak**	**not significant**	**not specified**
Dry season														
Ambient temp	**Lagos [Present study]**	**moderate**	**highly significant**	**weak**	**highly significant**	**weak**	**highly significant**	**weak**	**highly significant**	**weak**	**highly significant**	**weak**	**not significant**	**6 months each (complete season)**
	Lagos [8]							**weak**		**weak**		**weak**		**2.5 months**
	Akure [10]									**weak**	**not significant**	**weak**	**not significant**	**not specified**
Ambient humidity	**Lagos [Present study]**	**moderate**	**highly significant**	**moderate**	**highly significant**	**weak**	**highly significant**	**negligible**	**significant**	**weak**	**highly significant**	**weak**	**highly significant**	**6 months each (complete season)**
	Lagos [8]							**weak**		**weak**		**weak**		**2.5 months**
	Akure [10]									**weak**	**not significant**	**weak**	**not significant**	**not specified**

Table 12. *Cont.*

		NO_2		O_3		NO		PM_1		$PM_{2.5}$		PM_{10}		
	Location	*Correlation*	*Statistical significance*	*Correlation*	*Statistical significance*	*Correlation*	*Statistical significance*	*Correlation*	*Statistical significance*	*Correlation*	*Statistical significance*	*Correlation*	*Statistical significance*	*Duration of study*
Seasons not split														
Ambient temp	**Port Harcourt [9]**									**weak**	**highly significant**	**weak**	**highly significant**	**7 months (4 months rainy, 3 months wet)**
	Ile-Ife [11]									**weak**	**not significant**			**10 months (5 months each of rainy and dry season)**
Ambient humidity	**Port Harcourt [9]**									**negliglible**	**not significant**	**negliglible**	**significant**	**7 months (4 months rainy, 3 months wet)**
	Ile-Ife [11]									**weak**	**not significant**			**10 months (5 months each of rainy and dry season)**

The results for the dry season are less consistent (Table 12). For the air pollutants (O_3, NO, PM_1, $PM_{2.5}$, PM_{10}), the concentrations values are at most weakly correlated with the ambient temperature and humidity values and these are statistically highly significant at best, except for the correlation between O_3 and ambient humidity (moderate) and the statistical significance of the relationship between PM_{10} and ambient temperature (insignificant). However, the concentration of NO_2 responds moderately to changes in the ambient temperature and humidity and these are highly significant. A previous study in Lagos found weak correlations between the PM (PM_1, $PM_{2.5}$, PM_{10}) concentrations and the ambient temperature and humidity values [8]. The observed PM ($PM_{2.5}$, PM_{10}) concentrations at Akure are also weakly correlated with the ambient temperature and humidity values and these are not statistically significant [10]. The relationship between the PM and humidity can depend on the rate of particulate absorption in the atmosphere, washout due to rainfall, and dry deposition of the particles due to high humidity [5,10,23]. The ambient temperature level can advance the photochemical reaction between particles and gases and atmospheric dispersion proceeds more effectively under hot air masses [10]. In summary for the dry season, the air pollutant concentrations present a weak correlation with the ambient temperature and humidity for the work presented here and for those published in literature, except for the observed NO_2 concentration which correlate moderately with temperature and humidity.

Other studies exist in the literature which did not clearly delineate the rainy and dry seasons whilst evaluating the correlation effects of the meteorological parameters on the air pollutant concentrations. The studies at IIe-Ife showed that the concentration of $PM_{2.5}$ is weakly correlated to both the ambient temperature and humidity values and these are not statistically significant [11]. For PM ($PM_{2.5}$, PM_{10}) concentrations in Port Harcourt [9], the relationship with ambient temperature and humidity is weak and statistically highly significant, however this is negligible and insignificant for ambient humidity and negligible and significant for PM_{10}. Therefore, other studies from West Africa have shown that PM has a weak relationship with ambient temperature and humidity values (Table 12).

5. Conclusions

This work scrutinized the relationship between the ambient humidity, ambient temperature and air pollution during the rainy and dry seasons in Lagos, West Africa. The climate in Lagos was defined as Tropical Savannah, with the rainy (winter) season lasting from April to September and the dry (summer) season lasting from October to March.

The results from the study indicate that the monthly mean concentration values of all the pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) are higher during the dry season than those during the rainy season. The lack of wet removal due to less rainfall and the dispersion of pollutants in the air parcels from the north-eastern desert regions during the dry season might account for some of these higher pollutant concentration levels.

5.1. Summary

In summary, during the year, the concentration of the air pollutants (NO_2, O_3, NO, PM_1, $PM_{2.5}$, PM_{10}) tend to increase or decrease in response to the ambient temperature or humidity levels rather weakly, though during the dry season this response could be moderate for NO_2, and O_3. A high proportion (~70%) of the particulate matter pollutants concentrations is due to fine particles with diameters generally 2.5 μm or smaller. Thus, the $PM_{2.5}$ and NO_2 concentration levels exceeded those of the WHO air quality guidelines nearly 90% of the time during the test period.

The effects of NO_2, O_3, NO, and PM_1 concentrations in this region have rarely been examined and this study adds to the knowledge.

5.2. Limitations of Study

A total of 7885 h of data over 12 months were used for this study, however a study over a longer period, possibly a decade, and including other meteorological parameters such as wind speed and rainfall patterns, might be needed to examine these relationships more extensively over several seasons. This is because sudden sustained high busts in emissions levels, unaccompanied by meteorological changes (as occurred in July 2020 for NO_2 emissions during the study) can skew the data. The results would also inform air pollution dispersion models better.

5.3. Practical Implications

To use the results from these types of studies for policy development, care should be taken to avoid inferring causation from correlation; the details of the data must be examined. For example, as a consequence of the moderate (rather than negligible or weak) correlations indicated during the dry season, examinations of data from the months of January and February indicated consistently high ambient temperature values, low ambient humidity values and high concentration values of all air pollutants, and these could have implications for intervention measures for people with chronic respiratory conditions and or those prone to high temperature/dry environments.

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