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Research article

Temporal and spatial analysis of traffic – Related pollutant under the influence of the seasonality and meteorological variables over an urban city in Peru

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ABSTRACT

A four yearlong air monitoring data (since 2015 to 2018) was collected to assess the impact of meteorological parameters such as temperature, relative humidity, wind speed and wind direction on the spatial and temporal variability of CO (carbon monoxide), NO_2 (nitrogen oxide), O_3 (ozone), SO_2 (sulfur dioxide), PM_{10} and $PM_{2.5}$ (particulate matter with diameter aerodynamic less than 2.5 μm and 10 μm respectively) in Lima Metropolitan Area (LMA). Data from eight air quality monitoring stations, currently under the supervision of the National Meteorological and Hydrological Service (SENAMHI), was used to capture traffic – related pollutants concentrations under various local traffic conditions. Effects on meteorological events on seasonal traffic-related pollutants concentration variability were identified. Using average data from the eight stations, it was found that the monthly mean traffic-related pollutants since 2015 to 2018 were higher in spring and winter and lower in autumn and summer. Low-wind speed was associated with events that contribute to elevated seasonal $PM_{2.5}$ levels. Correlation coefficients between $PM_{2.5}$ concentrations and meteorological variables fluctuated significaly across different seasons. High $PM_{2.5}$ concentrations were associated with low relative humidity and high wind conditions in spring. Results suggest that there exist a seasonal variation of $PM_{2.5}$ concentration, and set the need of future work on the understanding of the air pollution effects on human health.

1. Introduction

About 7 million deaths reported every year worldwide result from air pollution (WHO (World Health Organization), 2019). The 2018 Lancet commission on pollution point out that it correspond to about 16% of all deaths worldwide, where 4.2 million are due to ambient air $PM_{2.5}$ (Landrigan et al., 2018). On the other hand, there exists a clear evidence health effects of air pollution such as chronic obstructive pulmonary disease (COPD), lung cancer, cardiovascular disease, according to several studies (Backes et al., 2013; Costa et al., 2017; Gurjar et al., 2010; Ierodiakonou et al., 2016; Kim et al., 2017; Nyhan et al., 2013; Pope et al., 2009; Landrigan et al., 2018), especially, if we consider the latest research associated with prolonged and short-term contamination: "Given that even short-term exposures can elicit biochemical alterations associated with such diseases, occupational exposures in workplaces of generally low air pollution are also of concern. Measures to decrease emissions leading to poor air quality are the obvious first choice to pursue in the effort to protect human health" (Costa et al., 2017). Peru has a population of 31,2 million in 2017, besides, it was found that about 2,300 premature deaths annually result from particulates matter (PMs) pollutant at outdoor level, and about 3,000 by using biomass burning stoves at indoor level. On the other hand, Lima has become one of the most critical city associated to air pollution and vehicle traffic in South America regional level, with a population of 8,785 million, and 1,752 million motor vehicles in 2018 (the old units are working across Lima), where the projection of total vehicle growth is 7 % per year, in the last ten year (Posada, 2018), then, vehicle emission are the main sources due to the continuous growth of vehicle units and their old age (more than 14 years old mainly) according to (Romero et al., 2019), which results in about 80% contribution to the total pollutant emission in LMA (San Miguel, 2006). Particulate matter is also affecting the ground or water by changing the nutrient balance in coastal waters and large rivers basins affecting the diversity of ecosystems. These effects on the environment indirectly affect people, who use these resources as raw material. Currently, there is some evidence to identify differences in the effects of particles with different chemical compositions or various sources such as

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combustion sources (diesel engine, gasoline engine, and others), versus non-combustion sources (Cassee et al., 2013; Park et al., 2018).

There have been several case studies about the effects of meteorological parameters in air quality regarding fine particulate matter with diameter of 1, 2.5 and 10 μm. The three main purposes of studies behind these two variables are the following: (1) removing the effect of meteorological variability in analyses of long - term trends of air quality, (2) construction of empirical models of air quality forecasts, (3) gain insight into the processes affecting pollutant concentration (Jacob and Winner, 2009). The meteorological parameters was identified to influence the concentration of PMs are surface air temperature, surface air relative humidity, daily total precipitation, total column cloud cover, surface wind speed and direction of wind speed (Tai et al., 2010). Correlations between PMs concentrations and meteorological data are not consistent across different studies mainly because of the varied composition of the PMs (sulphate, nitrate, organic carbon, elemental carbon, soil, and sea salt) and therefore are location-dependent (Jacob and Winner, 2009). According to Sheehan and Bowman (2001), sulphate concentrations are expected to increase with temperature due to faster SO_2 oxidation, additionally, it also stablished a proportional relationship between temperature and rate of oxidation of BVOC (Biogenic volatile organic compounds), which therefore increases the production of semi-volatile components (this can be formed by oxidation of BVOC), under the condition that oxidant levels are the same or increased. On the other hand, there exist a significant negative correlation between clouds and sulphates, although clouds fulfil a significant role in generation of sulphates, through wet deposition, and higher relative humidity promotes the formation of ammonium nitrate (Sheehan and Bowman, 2001).

According to Kumar (2018), at high temperatures, nitrogen molecules in air react with oxygen to form NO gases, which is characteristic of the combustion chamber of engines. Similarly, NO_2 is mainly produce from the reaction of NO and peroxy radicals, and rapidly converted back to NO at high temperature environments, where. Most of the NO gas emitted from the tailpipe is oxidized to NO_2 in the atmosphere; therefore, exposure to NO_x is often represented by NO_2 concentrations.

NO_2 is known to have a negative health effects, that can trigger cell damage and inflammatory processes in the respiratory system (Particulate and Oxide, 2016; Persinger et al., 2002; Valavanidis et al., 2013). These gases are the main effect of air pollution as well as particulate matter.

To the authors' knowledge, it is needed a better understanding of traffic - related pollutants in LMA. Then, objective of this study is to analyze historical traffic-related pollutants at different locations, meteorological parameters and its relationship with ground transportation in the LMA. The resulting analysis is developed for future potential application in air quality efforts and environmental health studies.

This paper is structured as follows: Section 2 is developed with the study area, monitoring, instrumentation, and data analysis. In Section 3, some descriptive statistics are developed along with evaluation of the seasonal traffic - related pollutants and diurnal variation, and correlations analyses are carried out. In this case, it includes a discussion with data analysis, limitations and the knowledge contribution for future works. Finally, the section 4 includes the main conclusions.

2. Methodology

2.1. Study area

The study was conducted on the Lima Metropolitan Area, Peru's capital city with and 2,700 km^2, one of the most important socioeconomic development center and largest metropolitan areas. This is based at 150 m above sea level near the cool water of the Pacific Ocean, resulting in a lower temperature than that expected to tropical deserts. As a result, Lima's climate is consider as a desert with a subtropical temperatures ranges (no less than 12 °C and no more than 29 °C) in overage. The two most representative season are summer (from December to March), and winter (from June to September), with May and November as transition months with a significantly warm-to-cool weather variation. Relative humidity is constantly high, mainly in mornings; on the other hands, rainfall is very low because the atmospheric stability. In Figure 1, the difference between summer (Figure 1a) and winter (Figure 1b) is clear in this zone, latitude and longitude of Lima, Peru are -12.046374, -77.042793 respectively., with strong influence with Pacific Ocean for wind velocity and direction, as well as, particulate matter. On the other hands, LMA's one of the main air quality problem is associated with ground transportation (Dawidowski et al., 2014; MINAM (Perús Ministry of Environment), 2010; Romero et al., 2019). In addition, the districts of "Ate, Independencia, La Victoria, Santa Anita and Rımac", in that order, are those that reported the most complaints regarding particulate matter (dust) (INEI (National Institute of Statistics and Informatics), 2016). In those particular cases, districts such as Villa Maria del Triunfo, Ate, and Santa Anita present a high pollutants generation, where Villa Maria del Triunfo is considered an industrial zone, and the adjust district "Villa El Salvador" contains one of the largest industrial parks. On the other hand, Ate and Santa Anita are high-frequency areas of inter-provincial buses, which mostly come from cities where the sulfur content in diesel fuel can reach 1,500 ppm, so the concentrations of this Parameters are higher in these districts than others in the city of LMA (MINAM (Perús Ministry of Environment), 2015).

According to Romero et al. (2019), and Velásquez et al. (2019), there exist limited studies associated with the temporal and spatial vehicle emissions disaggregation in LMA. Therefore, results from this study will improve these basic models by considering the seasonal traffic - related pollutants variations.

2.2. Monitoring

Cities in rapidly growing economies, such as the Lima in Peru are particularly affected by the poor air quality conditions due to the abundant vehicle and industrial sources. Traffic-related pollutants data was collected in the LMA from January 1st, 2015 through December 31st, 2018. The Figure 1c shows the reference grade air quality monitoring stations that currently exist in Lima under the SENAMHI administration, and which were used for the current study. These monitoring stations measure pollution concentration levels in a number of time intervals during the day, and a daily average is calculated each day for each site and for each pollutant such as CO, NO_2, O_3, SO_2, PM_{10} and $PM_{2.5}$. Nine of these stations are distributed in different districts over LMA: Puente Piedra (AQSPiedra), San Juan de Lurigancho (AQSLuri), Carabayllo (AQSCarab), San Martín de Porres, Ate (AQSAte), Santa Anita (AQSAnita), Campo de Marte (AQSMarte), San Borja (AQSBorja) and Villa María del Triunfo (AQSVilla), but one of them is not currently in operation due to of maintenance and calibration (see Table 1). Meteorological data for the study period was obtain from the Campo de Marte station, a fixed monitoring systems that measured parameters such as temperature, relative humidity, wind speed, and wind direction. These parameters were choosen as they are known to impact traffic - related pollutants, secondary aerosol production and particle dispersion process (Kozawa et al., 2012).

2.3. Instrumentation

PM_{10} and $PM_{2.5}$ concentration from AQSMarte station are measured by GRIMM EDM 180 technology, which is the leading Automated Measurement System (AMS) for PMs measurements. This system offers outstanding features such as simultaneous PMs measurements in 31 particle size channels, 0.1 μg/m^3 resolutions. This sensor can measure values in a range of 0.25–32 μm in regards to particle size and have selectable storage intervals between 6 s and 60 min, by working in a temperature range of -20 to 50 °C and 160 W of power consumption with a maximum current of 1.4 A approximately. On the other hand, for the other seven monitors (AQSPiedra, AQSLuri, AQSCarab, AQSAte,

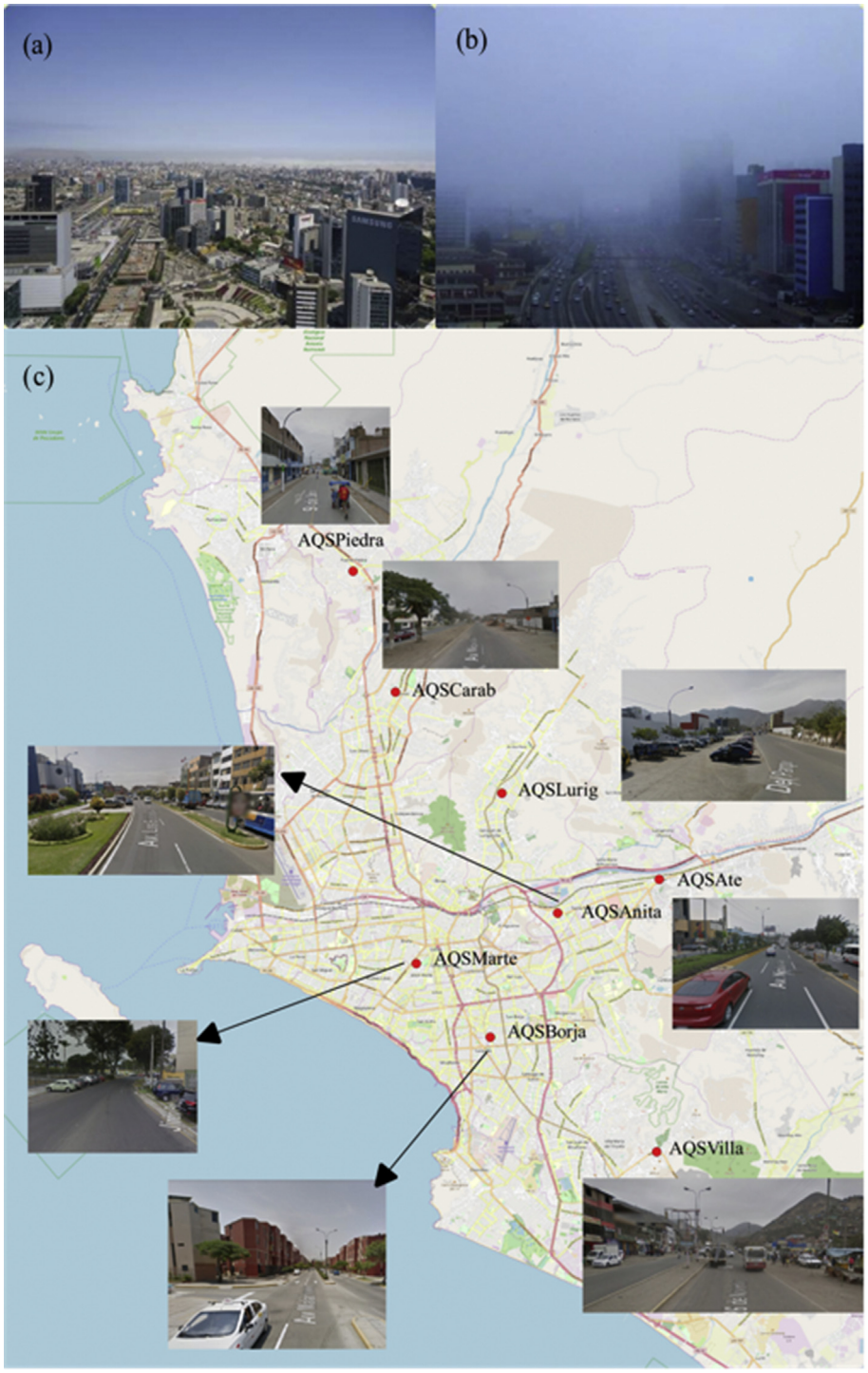

Figure 1. Climate characteristics of Lima and air quality locations over the study area: (a) photo from the air on a sunny summer day; (b) photo from the air on a winter day; (c) map of the LMA study domain and the total quality monitoring sites locations under SENMAHI administration and used for the study.

AQSAnita, AQSBorja, and AQSVilla), an equipment (5014i Beta) designed by Thermo Fisher Scientific Company is used to measure PM_{10} and $PM_{2.5}$ concentrations. It utilizes a beta measurement method, which is a widely used air monitoring technique that employs the absorption of beta radiation by solid particles extracted from air flow. The equipment, with a dimension of $58.4 \times 42.5 \times 21.9$ cm, was designed to calculate the average measurements every one second and its measurement resolution is of 0.1 $\mu g/m^3$. It has a range of 0–10 $\mu g/m^3$ with the following precision for specific conditions: $\pm 2.0 \mu g/m^3 < 80 \mu g/m^3$, $\pm 4 - 50 \mu g/ m^3 > 800 \mu g/m^3$ (specifically for 24-hour average), and an operating temperature from -30° to 50 °C.

On the other hands, SO_2, NO_2, O_3, and CO concentrations (in $\mu g/m^3$) were measured by using Teledyne technology based on the Models T100, T200, T300, and T400 respectively. All these Models present an operating temperature range of 5–40° (with US EPA Approval), and a time response less than 120, 80, 80, and 30 s all to 95% severally. In all the cases, pollutants concentrations are average in one hour time scale for the study purposes in $\mu g/m^3$ unit.

Table 1. Nature of air quality monitoring stations in Lima Metropolitan Area.

Site number	Site name	Location (latitude, longitude)	Area
1	AQSMarte	-12.0695416, -77.0465975	Urban
2	AQSAnita	-12.043451, -76.9735609	Urban
3	AQSAte	-12.0259968, -76.9211046	Urban
4	AQSBorja	-12.1076048, -77.0083742	Urban
5	AQSCarab	-11.9292496, -77.0573599	Urban
6	AQSLurig	-11.9814876, -77.0023552	Urban
7	AQSPiedra	-11.8667559, -77.0792547	Urban
8	AQSVilla	-12.1668606, -76.9224195	Urban

2.4. Data analysis

Data from each instrument was manually checked in order to avoid negative and zero values because of errors. A few numbers of negative values were identified in the eight stations because of the registration of values under the equipment minimum resolution (as case example AQSMarte, with 0.1 μm) and were eliminated before being processed in an hourly time scale and compiled a single excel file for each of the eight station.

Variability of the seasonal and diurnal PMs concentration was analyzed and explored graphically. Additionally, a study of the relationship between temperature, relative humidity, wind speed, and wind direction with the PMs concentration variability by site and season was carried out by applying using Pearson correlations coefficients.

3. Results and discussion

3.1. Temporal and spatial analysis of traffic-related pollutants in Lima

Santa Anita Station (Figure 2.a) shows the average hourly, daily and monthly mean variation in $PM_{2.5}$, O_3, SO_2, PM_{10}, $PM_{2.5}$ mass concentration of LMA since 2015 to 2018. As Shown in the Figure 2a, on average, the $PM_{2.5}$ mass concentration variation present similar change over the time at daily and hourly scales for the two different stations (AQSAnita, and AQSAte) and for the others documented in the Figures 3, 4, and 5. Hourly mean $PM_{2.5}$ concentration for all the stations were usually below 50 $\mu g/m^3$. Two main average hourly pollutants mass concentration peaks were observed for the eight stations. The first and second peak, with PM_{10} exceeding 90 $\mu g/m^3$ between the 8:00–10:00 h and 18:00–20:00 h respectively, were both seems to be caused by the traffic emission at these times rush hours coincide. In the LMA, most citizen start to work between the 8:00 to 9:00 h in the morning, and finished to work between 18:00 to 19:00 h in the evening from Monday to Friday or Saturday, which result in this particular aspect and correlation between peak traffic or vehicle congestion and the peaks traffic-related pollutants (CO, NO_x, N_2O, SO_2, NO, NO_2) mass concentration over main roads of LMA during a year. According to Romero et al. (2019), transport sector is one of the main sources of particulate matter and other pollutants (CO, NO_x, N_2O, SO_2, NO, NO_2), and one of the main causes of the poor air quality, which need more efforts to measure and estimate the emission over LMA in order to promote national initiatives and environmental policies. Daily main (Figure 2 a, and b) for two stations, and the other detailed in Figures 3, 4, and 5, shows a constant variation from Monday to Saturday (working days), with a significant decrease on Sunday (no working day).

Monthly average $PM_{2.5}$ concentration in Lima during 2015–2018 range between 15 and 20 $\mu g/m^3$, 20 and 40 $\mu g/m^3$, and 35–50 $\mu g/m^3$ for AQSMarte, AQSAnita, and AQSAte respectively, where both showed a typical V-shape pattern with peak and trough $PM_{2.5}$ on July and September for most of the AQSs (Fig. 2a-b, and Figures 3, 4, and 5). In Lima, and base on the data available from all monitors (see Table 2), the maximun $PM_{2.5}$ seasonal average mass concentrations were observed in Summer (January–March, 389.4 $\mu g/m^3$), Spring (October–December, 178.8 $\mu g/m^3$), followed by Autumn (April–June, 177.9 $\mu g/m^3$), and Winter (July–September, 154.7 $\mu g/m^3$). Table 2 summarized the seasonal and annual $PM_{2.5}$ mean concentration at different urban areas in Lima. In particular, AQSAnita and AQSAte stations showed highest mass concentration over the year and seasonal because additional industrial sources in these areas.

Santa Anita station (AQSAnita) is located approximately 10 km East of Centre of Lima. The data from this station shown in Figure 2a primarily shows NO_2; $PM_{2.5}$ and PM_{10}have a strong correlation between their values. This can be seen clearly in Fig. 2a and b, also for AQSAte station, which represent how pollutant concentration varies between hours along those stations. These behaviors that can be seen in both graphs suggest that the particles might be coming from the same source. To do a deeper analysis about the suggested main source between nitrates, nitrogen oxide and PMs, we studied the Fig. 2a and b. They suggest that during traffic peak hours, which are two defined periods in Lima 7:00–10:00 h and 18:00–23:00 h, pollutants concentration increase drastically. Gasoline and diesel engines have primary emissions of hydrocarbons, nitrates and particulate matter, therefore, a conclusion can be made that these are primary source of pollutant in Santa Anita station. Figure 2 also supports this hypothesis due to a decrease in these pollutant concentrations during Saturday and Sunday. These two days usually have less tense traffic and this can be seen as lower pollutant concentrations. Particulate matter has the highest measurement concentration between all pollutants and this can be explained due to its varied composition, which mainly includes sulphate, nitrate, organic carbon, elemental carbon, soil, and sea salt. Due to its composition, which includes nitrates, it can be explained that there is a higher concentration of nitrates in the particulate matter composition and therefore when one of these pollutants concentrations increases, the other should also increase. Figure 2 suggests this hypothesis but monthly averages variation does not. Monthly average variation shows that average monthly concentration of PM_{10} does not follow either $PM_{2.5}$ or NO_2 pattern. This is as the highest peak of particulate matter concentration can be seen in April and which also coincidentally happens with the lowest slumber (peak) of NO_2. Once again, due to varied composition of PM_{10}, a deeper study has to be done on particulate matter in Lima or even by districts to understand how this composition varies between months and to understand which component of PM_{10} decreases drastically during fall season. NO_2 shows a positive correlation with $PM_{2.5}$ and PM_{10} at the weekday, hour, and weekend scale (Figures 2, 3, 4, and 5). An observation of this behavior is that this component follows the pattern of particulate matter throughout the first peak (7:00–10:00 h). In contrast, throughout the second peak (18:00–23:00 h), nitrogen dioxide concentration does not increase that much during the second peak further study needed. SO_2shows a weak positive correlation with PM and NO_2 at the weekday and hour scale (see Figures 2, 3, 4, and 5). In hourly-day average variations, there are two distinguished peaks that happen during the previously mentioned high-traffic hours. The monthly and weekday average concentration variation in Figure 2 suggests that this component is not produced by the same source at it does not follow any pattern of the other known pollutants. O_3 has a much defined course of concentration levels throughout the day, which mainly increase during the highest peak of solar radiation 10:00–16:00 h (with the peak at just after noon). Ozone is formed by the interaction of sunlight, particularly ultraviolet light, with hydrocarbons and nitrogen oxides and as explained before, gasoline and diesel engines release these components and in Figure 2, concentration of nitrate can be seen. Therefore, as required "elements" can be found, production of ozone happens during the strongest solar radiation hours. The monthly average variation can be used to identify the season in which highest concentration of pollutants can be found. One clear observation that can be found from this is that the highest peak of concentration of PM_{10} and $PM_{2.5}$ do not occur in the same season. The peak of PM_{10} occurs just between summer and fall, and the peak of $PM_{2.5}$ concentration occurs in fall and winter (a stable trend). In contrast, lowest concentration of $PM_{2.5}$ happens in summer and PM_{10}

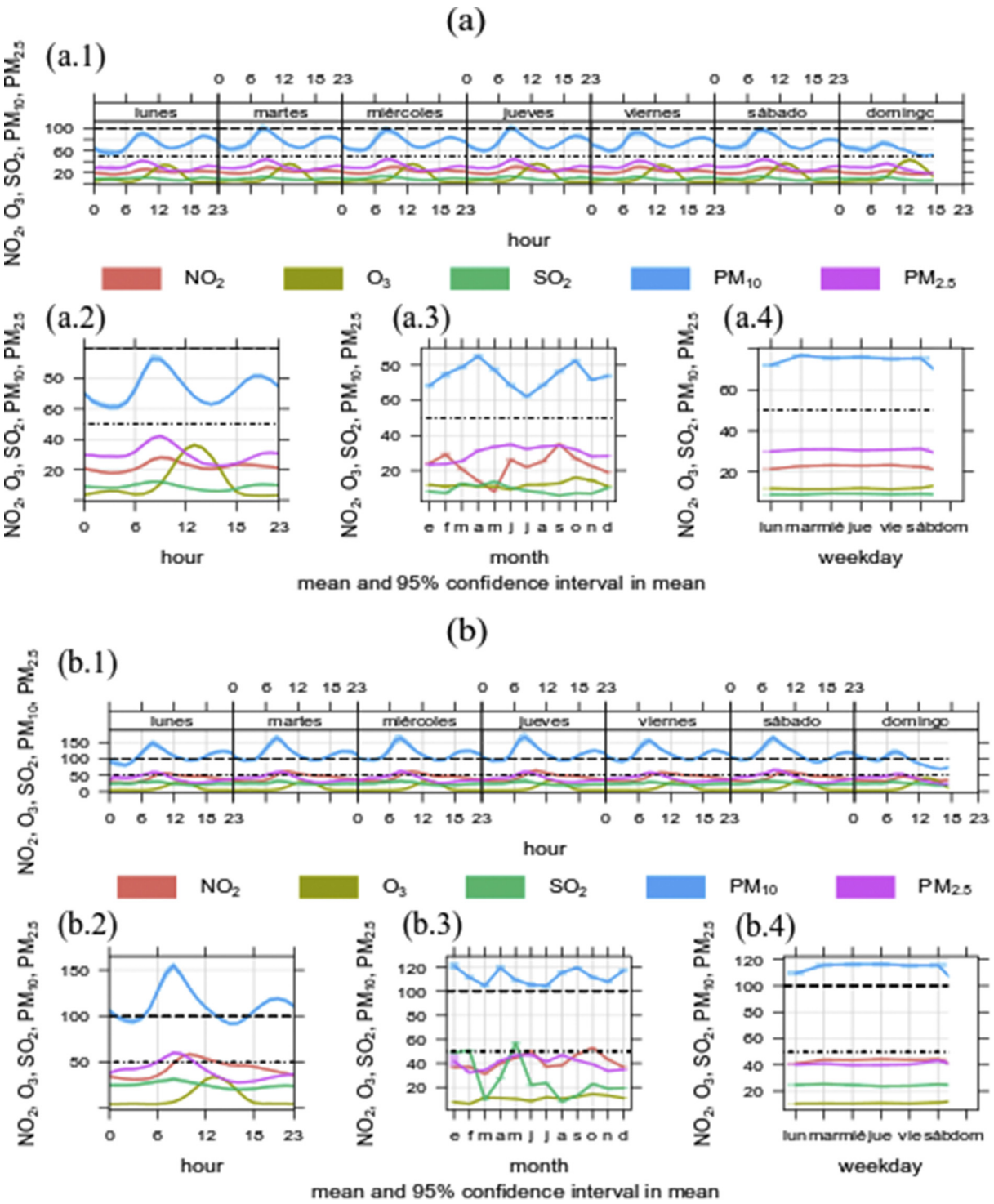

Figure 2. Summary of the average mass concentration variation of NO_2, O_3, SO_2, PM_{10} and $PM_{2.5}$ (in $\mu g/m^3$) at different time scales during the study period, 2015. (a) Site 2 – AQSAnita, and (b) Site 3 – AQSAte composed with the average concentration panels at different scales: (a.1, b.1) diurnal variation for all day, (a.2, b.2) hourly, (a.3, b.3) monthly, and (a.4, b.4) weekdays and weekends scales.

happens between fall and winter (months with the highest wind speed). The only noticeable correlation between pollutants is nitrogen dioxide and ozone, this happens due to nitrogen dioxide providing the oxygen molecule needed for the formation of ozone.

In Figure 5.b (AQSVilla station), it can be seen the daily PM_{10} maximum concentrations only on Saturday, and the maximum hourly concentration with almost all in the period of 8:00 to 10:00 h and 18:00 to 20:00 h. To the case of $PM_{2.5}$, it can see the highest hourly concentration in the period of 8:00 to 11:00 h. However, no daily concentration peak was detected through the weekdays (Figure 5 – b.1). In the case of traffic-related gases, it can be worked with gases such as NO_2, O_3 and SO_2. In the first case (NO_2), it can be seen the maximum concentration in the period of the fortnight of March to fortnight of April, more specific, in the period of 8:00 to 9:00 h (Figure 5-b.2). In the second case (O_3), it can be seen the maximum concentration in the period of August to September (Figure 5-b.3), more specific, in the

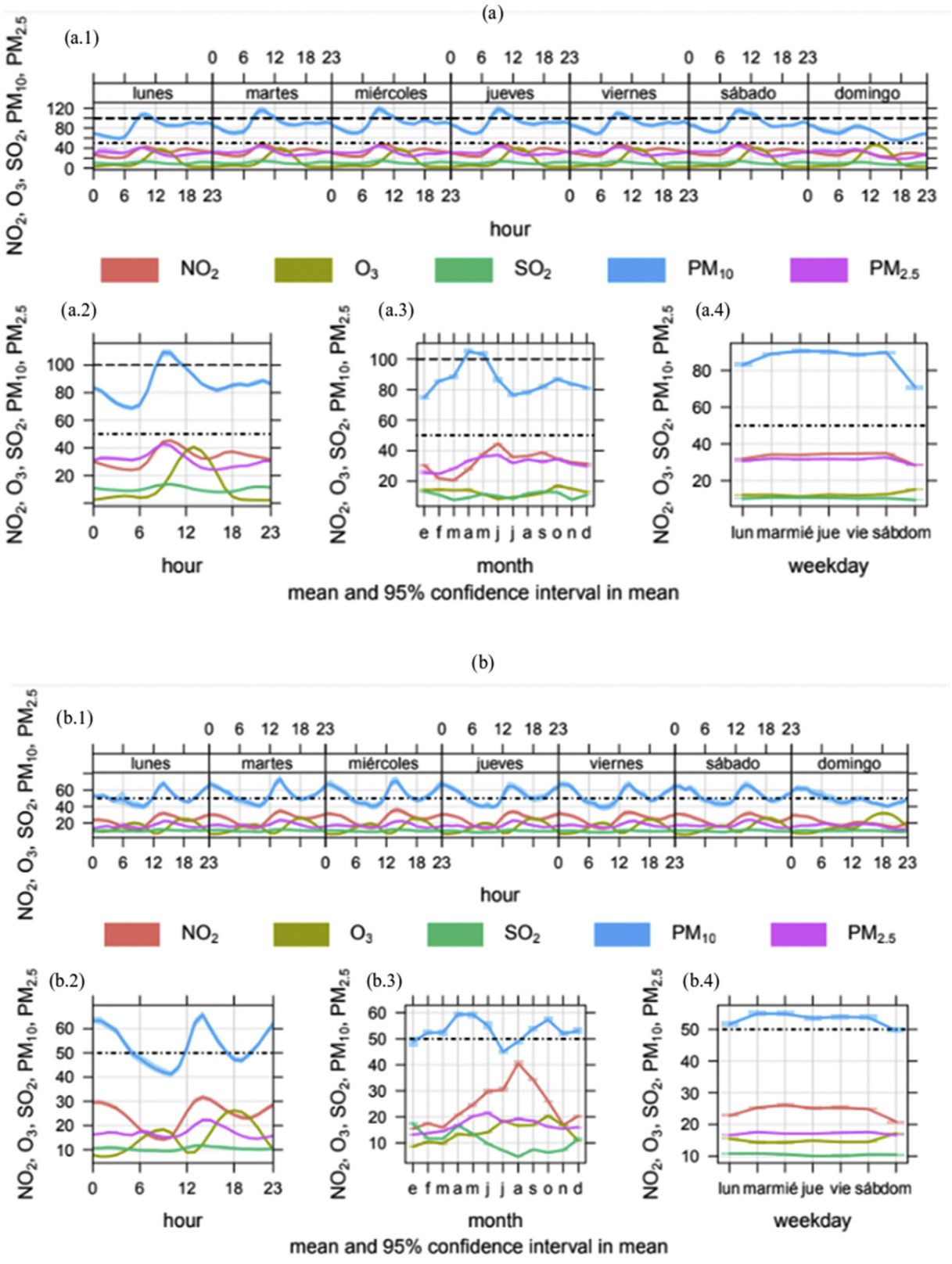

Figure 3. Summary of the average mass concentration variation of NO_2, O_3, SO_2, PM_{10} and $PM_{2.5}$ (in $\mu g/m^3$) at different time scales during the study period, 2015. (a) Site 3 – AQSLuri, and (b) Site 4 – AQSBorja composed with the average concentration panels at different scales: (a.1, b.1) diurnal variation for all day, (a.2, b.2) hourly, (a.3, b.3) monthly, and (a.4, b.4) weekdays and weekends scales.

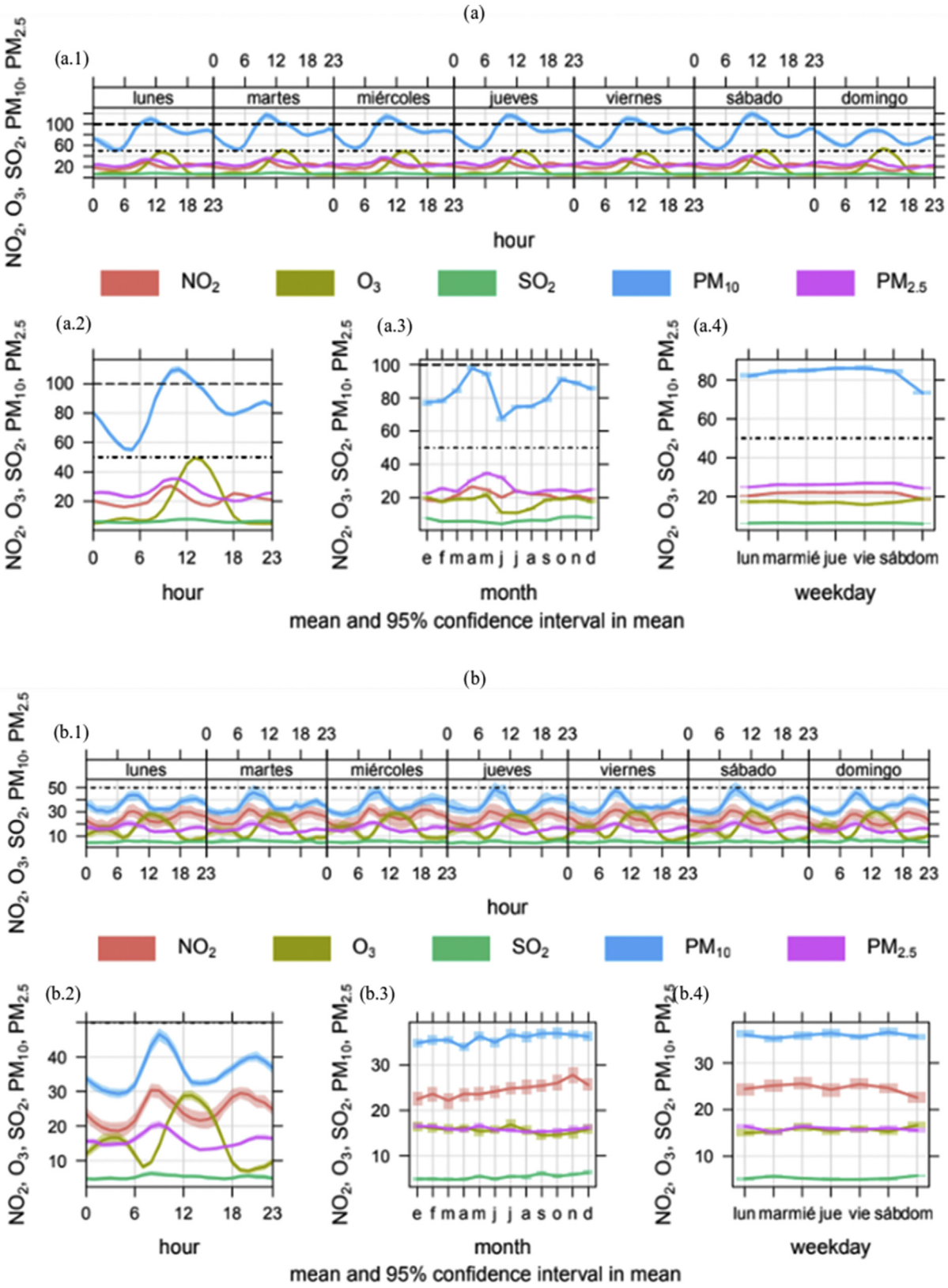

Figure 4. Summary of the average mass concentration variation of NO_2, O_3, SO_2, PM_{10} and $PM_{2.5}$ (in $\mu g/m^3$) at different time scales during the study period, 2015. (a) Site 5 – AQSCarab, and (b) Site 6 – AQSMarte composed with the average concentration panels at different scales: (a.1, b.1) diurnal variation for all day, (a.2, b.2) hourly, (a.3, b.3) monthly, and (a.4, b.4) weekdays and weekends scales.

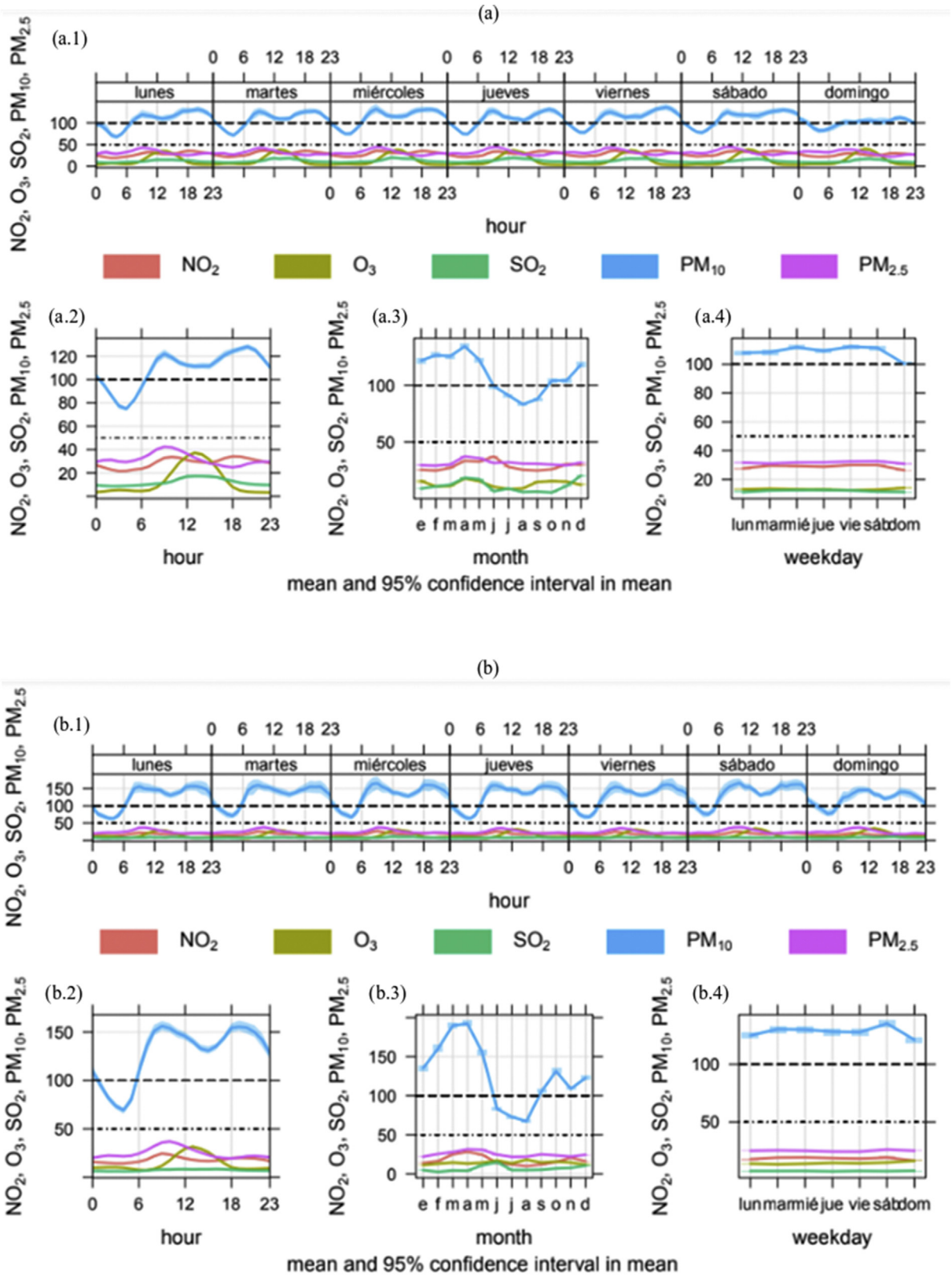

Figure 5. Summary of the average mass concentration variation of NO_2, O_3, SO_2, PM_{10} and $PM_{2.5}$ (in $\mu g/m^3$) at different time scales during the study period, 2015. (a) Site 7 – AQSPiedra, and (b) Site 8 – AQSVilla composed with the average concentration panels at different scales: (a.1, b.1) diurnal variation for all day, (a.2, b.2) hourly, (a.3, b.3) monthly, and (a.4, b.4) weekdays and weekends scales.

Table 2. Statistical results for $PM_{2.5}$ concentration and meteorological parameters for the study period, since 2015 to 2018.

Stations		Annual (2015–2018)			Winter (JJA)				Spring (SON)				Summer (DJF)				Autumn (MAM)			
Parameters		N	Mean	Var	Mean	Var	Min	Max	Mean	Var	Min	Max	Mean	Var	Min	Max	Mean	Var	Min	Max
Temperature (°C)		33426	19.8	11.4	17.4	5.5	13.9	26.2	17.9	5.1	14	26.2	22.6	6.1	16.7	30.8	21.9	7.7	15	30.6
Relative Humidity (%)		33416	82.1	79.1	84.7	59.0	60.0	98.0	86.3	64.1	56	98	79.3	82.4	42	96	80.9	94.1	45	98
Wind speed (m/s)		33419	2.1	1.6	2.0	1.3	0	7.1	2.6	1.6	0	8.5	2.2	1.75	0	8.5	1.9	1.5	0	12.8
$PM_{2.5}$	AQSMarte	27493	16.0	84.4	15.6	66.4	3.1	71.22	15.5	69.2	3.0	96.4	16.2	88.8	3.0	94.1	16.0	83.2	3.0	77.4
	AQSAnita	28344	30.2	278.6	33.43	276.93	3.75	159.1	31.23	286.80	3.06	535.2	25.24	252.2	3.08	391.8	29.90	270.8	3.2	207.0
	AQSAte	23869	40.2	609.9	45.06	688.10	3.22	210.0	38.4	175.5	3.2	157.9	34.4	801.2	3.04	786.9	40.9	584.4	3.1	276.8
	AQSBorja	28270	17.1	99.1	19.6	133.1	3.0	92.8	16.6	79.9	3.1	103.8	14.4	72.6	3.0	223.8	17.7	95.63	3.0	91.4
	AQSCarab	19421	25.9	227.8	25.3	238.6	3.1	153.1	108.3	128.2	3.1	108.3	24.0	240.5	3.1	250.6	29.7	295.6	3.1	189.2
	AQSLuri	28344	31.2	338.2	34.4	312.4	3.0	284.1	32.6	260.3	3.0	132.9	26.8	471.8	3.0	720.7	32.1	254.3	3.0	259.1
	AQSPiedra	28637	31.7	220.0	31.6	179.9	3.1	120.0	30.2	162.0	4.2	131.8	30.1	293.5	3.0	455.6	34.7	240.2	3.0	143.8
	AQSVilla	24023	24.9	215.5	22.5	222.7	3.04	147.0	23.4	214.4	3.2	164.2	23.7	191.9	3.0	191.9	29.7	201.6	3.4	178.9

period of 12:00 to 13:00 h (Figure 5-b.2). Finally, in the third case (SO_2), it can be seen the maximum concentration in the period of the fortnight of May to the fortnight of June but unlike the previous cases, the same concentration is maintained during the day, so there is no peak time since there is a small difference but where a greater difference is seen is when data is taken on a monthly scale. In Figure 5.a (AQSPiedra), it can be seen the maximum PM_{10} daily average concentration in the period of Wednesday to Saturday, mainly in the period from 19:00 to 20:00 h (Figure 5-a.2 and a.4). To the case of $PM_{2.5}$, it can be seen the maximum monthly mean concentration in the month of March and April (Figure 5-a.3), in the period of 8:00 to 11:00 h (Figure 5-a.2). A similar analysis can be made based on the rest of the stations (Figures 3, 4, and 5), but, it is clear that there exist a similar behavior of the traffic-related pollutant concentrations.

See Tables 1 and 2 for more references about the area characteristics based on their location, and the maximum annual and seasonal mass concentration during the study period, 2015–2018.

3.2. Spatial variability of $PM_{2.5}$ mass concentrations

Monthly $PM_{2.5}$ concentrations variation at eight stations in LMA from January to December 2015–2018 is shows in Figures 2, 3, 4, and 5. High $PM_{2.5}$ concentration from all stations was identified during winter period, while in the summer period presented the lower $PM_{2.5}$ concentration. In particular, based on the hourly PM_{10} concentration data available, the highest PM_{10} mass concentration of 157.8 $\mu g/m^3$ was identified in September at Ate District (AQSAte), followed by 126.5 $\mu g/m^3$ at Santa Anita District (ASQAnita) in February. Both located in an urban area surrounded by industrial sources. The lowest $PM_{2.5}$ concentrations were observed at Jesus Maria District (AQSMarte) in September, which was located in an urban forest area (Campo de Marte Park) with a little presence of traffic and anthropogenic activities.

The eight station were identified as a urban areas, as summarized in Table 1; the seasonal average $PM_{2.5}$ mass concentration from 2015 to 2018 in each of these areas are listed in Table 2. The $PM_{2.5}$ mass concentration observed in the urban areas, Surco and Jesús María districts

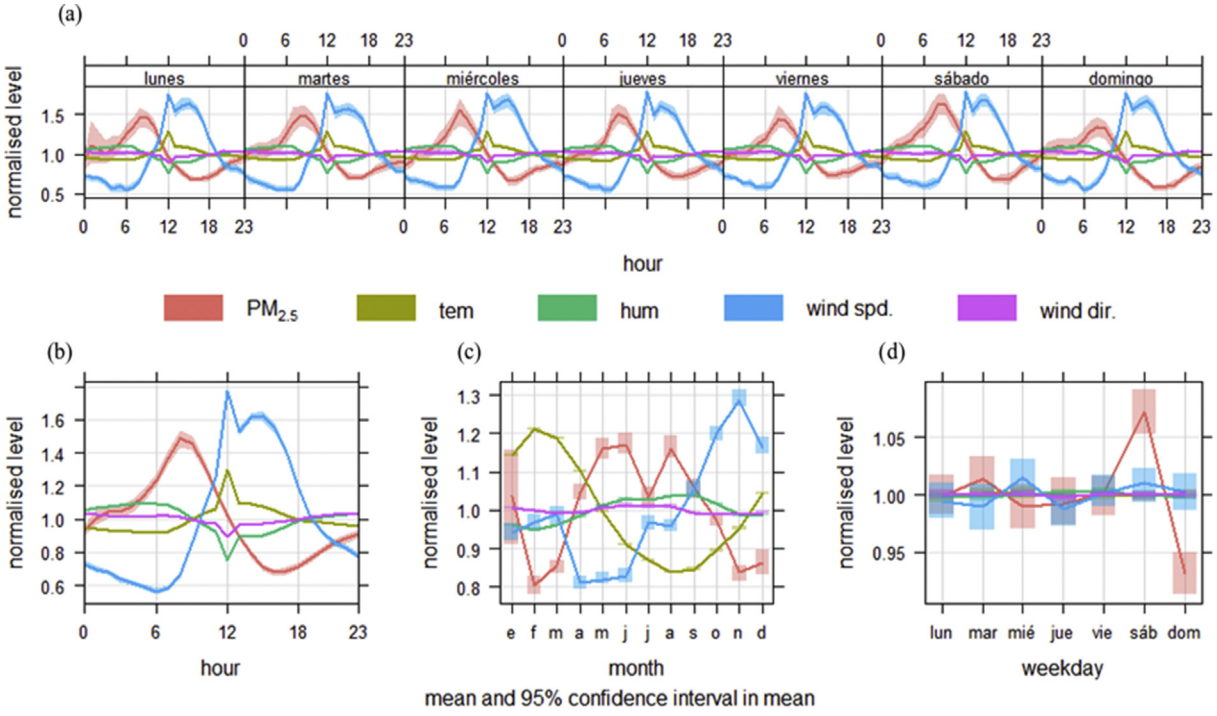

Figure 6. Time series particulate matter concentration ($PM_{2.5}$), temperature (tem), humidity (hum), and wind speed (ws) variation at site 1 (AQSAnita), in Santa Anita District, during the study period 2015 to 2018 at (a) diurnal variation for all days, (b) hourly, (c) monthly, and (d) weekday and weekends scales. Meteorological data were obtained from the AQSMarte. In this plot, the parameters measurements are normalized.

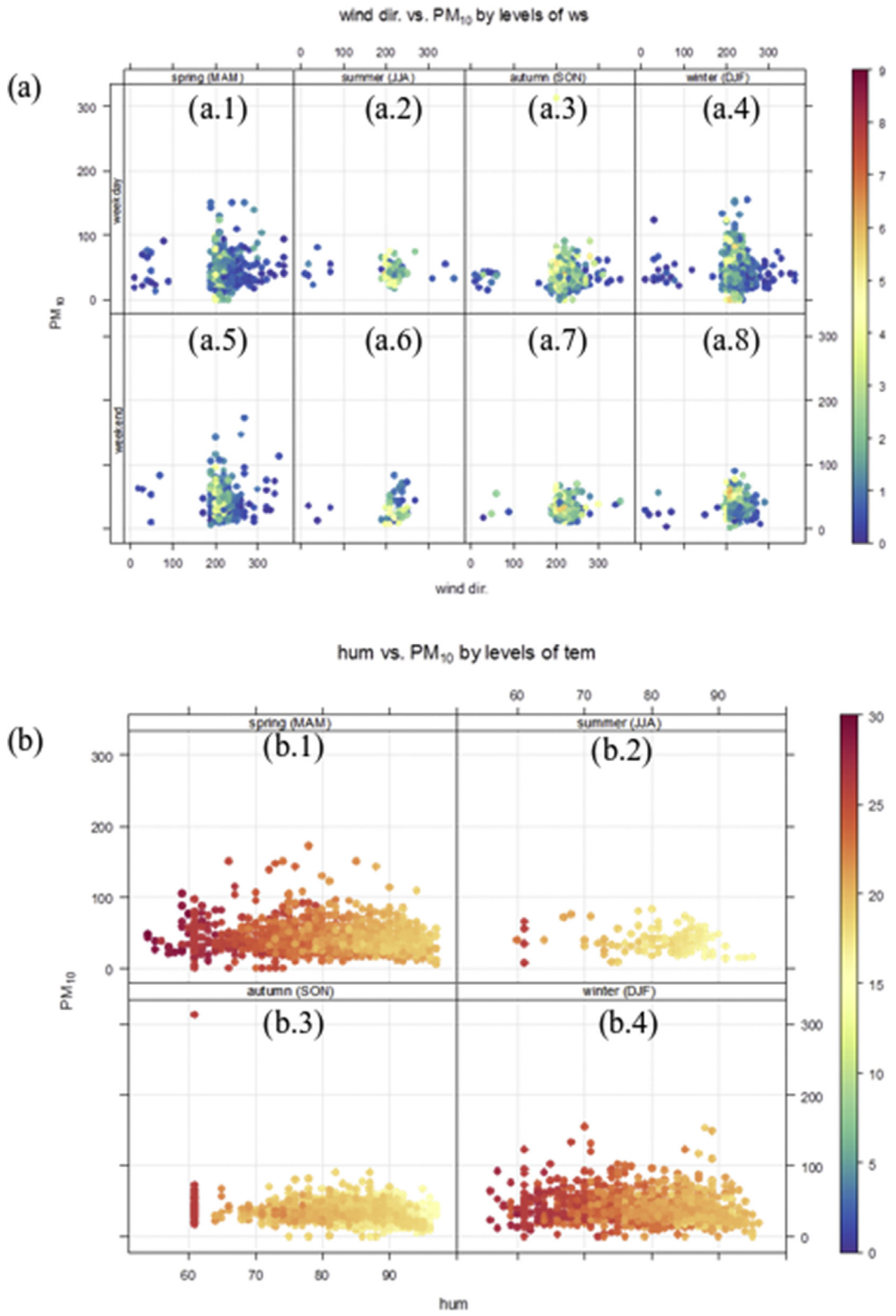

Figure 7. (a) Wind direction versus particulate matter (PM_{10}) mass concentration (in $\mu g/m^3$) by different values of wind speed (m/s), distributed seasonally at the weekdays (a.1, a.2, a.3, a.4) and weekend days (a.5, a.6, a.7, a.8). (b) Outdoor humidity versus particulate matter (PM_{10}) mass concentration (in $\mu g/m^3$) by different values of atmospheric temperature (°C) at different seasons: (b.1) spring, (b.2) summer, (b.3) autumn, and (b.4) winter. Both during 2015–2018 at site 1 (AQSMarte).

were lower compared with the rest locations for all seasons without exception. It could be because such as urban areas present industrial sources, additionally to vehicle emission, but, in the particular urban area (site 1), it is surrounding by a big forest area. Ate and Santa Anita districts are identified as urban development areas, which result in area with a high presence of land construction projects, plastic and textile industries which has increased during last years, and which result in dust emissions. Ate district present a diverse use of the terrain (agriculture, arqueological, mining, and urban areas which include industrial sources, and others).

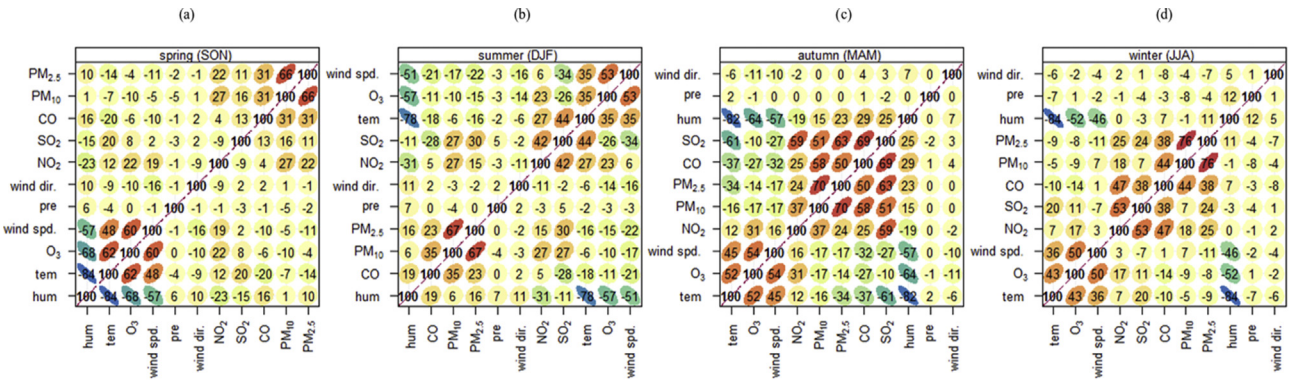

Figure 8. Correlation coefficients (in %) between traffic-related pollutants mass concentrations with temperature, relative humidity, wind speed, and wind direction at site 1 (AQSAnita) during the study period, 2015 to 2018 for (a) spring, (b) summer, (c) autumn, and (d) winter. R values range from 0 to 1 or from 0 to 100%.

3.3. Diurnal variations of over different urban areas

Figure 2 shows the diurnal variation of $PM_{2.5}$ mass concentration observed at AQSAnita, and AQSAte stations (Figures 3, 4, and 5). At all the stations, the PM_{10} mass concentration presents two peaks, as mention previously. The first peak is presented in the period between 8:00–10:00 h, corresponding to the morning peak traffic hour, after which it is observed a significant concentration reduction until 16:00–18:00 h, see Fig. 2a, and b for more details.

The diurnal variation patterns of PM_{10} mass concentration were similar at all the stations, as shown in Fig. 2a, and b.

3.4. Temporal variations of meteorological parameters

Figure 6 shows the $PM_{2.5}$ mean concentration at hourly, daily, and monthly scales, relative humidity, temperature, and wind speed during the study period (2015–2018), at site 2. Wind speed was identified to be high in spring (2.6 ± 0.57 m/s), followed by winter (2.0 ± 0.76 m/s), summer (2.2 ± 0.17 m/s), and finally autumn (1.9 ± 0.40 m/s) (Figure 6). Dispersion of pollutants in the atmosphere, as well as the emission and transport of dust particles, is controlled by the wind speed in spring. The monthly mean temperature variation presents the highest value in February (23.8 °C) and the lower in August (17.9 °C). The hourly mean temperature variation presents the maximum value between 12:00 to 14:00 h. The daily mean temperature variation shows distinct seasonal variation during the year, ranging from 15.4 °C (October) to 30 °C (March). The daily mean relative humidity varied from 80 to 90 %, and it is approximately constant during the year, however, the lower average relative humidity is identified in summer, with values from 78 to 80%, and the highest during the spring, autumn, and winter with values between to 80–85%. As is show in the Figure 2, some data are missing due to instrument problems for the measurement of PM_{10} and meteorological data (AQSMarte), however, hourly, daily and monthly variation can be analyzed.

3.5. Correlation analysis between $PM_{2.5}$ concentration and some meteorological parameters

Figure 7a shows a strong relationship between PM_{10} mass concentration and an approximately constant change in wind direction. In this last, the wind direction stays around 220° (SW), with the maximum wind speed values. Figure 7b shows the relationship between temperature, relative humidity and PM_{10} concentration. Based on that, there exist an indirect co-dependency between the temperature and relative humidity.

The correlation coefficient between wind speed and mass concentration of $PM_{2.5}$, as is the case at the site 1 (AQSAnita) across different seasons in 2015–2018 are in the Figure 8. It shows that $PM_{2.5}$ mass concentration present negative correlation with wind speed across all the spring, summer, an autumn, and winter. This shows that there exists a strong horizontal dispersion played in reducing $PM_{2.5}$ mass concentration, particle for those associated with vehicle sources (fine particles). It is important to take into account that the maximum wind speed values where identified in spring (mean value of 8.5 m/s), followed by summer, winter and autumn. More frequent dust events and high $PM_{2.5}$ mass concentration have a positive correlation to strong winds (Li and Zhang, 2012)According to our results, we inferred that strong winds help to release and transport dust particles (with significant diameter $PM_{2.5}$ or bigger) from ground surface in the spring (Figure 8).

There exist a weak negative correlation between temperature and $PM_{2.5}$ mass concentration in all the seasons. The positive correlation in summer and winter, it could be because the secondary particles transformation by photochemical process under higher air temperature conditions. A particular observation is that the higher positive correlation is present in winter because the particular temperature variation in Lima compared with other study areas.

As is shows in Figure 8, $PM_{2.5}$ concentration presents a weak positive correlation with the average relative humidity during the study period in all the seasons, with the highest negative value in winter ($R = 0.11$) and lowest in autumn ($R = 0.23$). Partitioning of semi-volatile species into aerosol phase is improved at high relative humidity according to Hu et al. (2008).

In general, the relationship between $PM_{2.5}$ and meteorological parameters shows a seasonal variation during the study period 2015–2018. In order to a better analysis it is required to take into account the combine effects of boundary layer high, radiation, air temperature, wind speed, and relative humidity.

4. Conclusions

In the present study, a temporal and spatial analysis of traffic-related pollutants in LMA during 2015–2018 by using eight different air quality monitoring station and a reference meteorological station simultaneously was carried out. A valuation of a correlation between $PM_{2.5}$ with some meteorological parameters such as temperature, relative humidity, wind direction, and wind speed was carried out at a seasonal level that can be used for future works associated to pollution analysis and temporal-spatial analysis.

In summary, the main contributions:

- The $PM_{2.5}$ concentration levels were identified to be high in some urban areas such as Santa Anita, and Ate districts. The monthly average $PM_{2.5}$ concentration was calculated and summary on Figure 2, 3, 4, and 5. At the seasonal level, it was observed that $PM_{2.5}$ concentration was largest in summer (389.4 $\mu g/m^3$) and spring (178.8 $\mu g/m^3$), and lower in autumn (177.9 $\mu g/m^3$) and winter (145.7 $\mu g/m^3$). The diurnal variation in $PM_{2.5}$ concentration was

identified two peaks over the year. The first peak at 8:00 to 10:00 LT, and the second at 12:00 to 14:00 LT at the eight sites, and which is associated with the rush hours during the working days (mostly from Monday to Saturday).

- Correlations show that there exists an average negative correlation between $PM_{2.5}$ and wind speed at different season due to the strong horizontal dispersion.
- $PM_{2.5}$ had a weak negative correlation with temperature in spring (R = -0.14) and autumn (R = -0.34), summer (R = - 0.16) but higher negative correlation in winter (R = - 0.9) during for the complete period from 2015 to 2018. On the other hands, it was found that relative humidity present a positive correlation at all the seasons; such as in winter (R = 0.11), followed by summer (R = 0.16), autumn (R = 0.23), and spring (R = 0.10); verified by Figure 7.

Authors consider that it is important to carry out a further correlation analysis because the improvement of the evaluation of particulate matter concentration over timer before and after an environment policies. Protecting and improving air quality standards required knowledge of different types and concentration levels of pollutants. Therefore, the best measurement and monitoring capabilities will lead to, the best policies and investments for reducing emission from various sources, therefore, identified the main factor that affect the PM_{10} mass concentration variation, as in this case meteorological parameters, is fundamental for implementing air quality modeling studies.

Advance statistical analysis, by taken into account private and public monitoring stations over the last 4 years would be carried out as a future research.

Declarations

Author contribution statement

Yovitza Romero: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Ian Meldrum, Cesar Diaz: Analyzed and interpreted the data; Wrote the paper.

Ricardo Arias, Julien Noel: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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