Arabian Journal of Geosciences (2018) 11: 62
https://doi.org/10.1007/s12517-018-3403-z

ORIGINAL PAPER

Temporal analysis of air pollution and its relationship with meteorological parameters in Bahrain, 2006–2012

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Received: 23 August 2017 / Accepted: 11 January 2018 / Published online: 31 January 2018

Abstract

The objective of this paper is to analyze temporal and seasonal trends of air pollution in Bahrain between 2006 and 2012 by utilizing datasets from five air quality monitoring stations. The non-parametric and robust Theil-Sen approach is employed to study quantitatively temporal variations of particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3). The calculated annual concentrations for PM_{10} and $PM_{2.5}$ in Bahrain were substantially higher than recommended World Health Organization (WHO) guideline standards. Results showed increasing trends for PM_{10}, $PM_{2.5}$, and SO_2 whereas O_3 and its precursor NO_2 showed decreasing behavior. The general increase in air pollution trends is in agreement with prediction of air pollution models for Middle East region due to economic growth, industrialization, and urbanization. The significances of long-term trends were examined. Additional to actual (unadjusted) trends, meteorological adjusted (deseasonalized) trends and seasonal trends were quantified. The box-plot analysis visually illustrated monthly variations of key air pollutants. It showed that only PM_{10} and $PM_{2.5}$ exhibited seasonal pattern, and their concentrations increased during summer and decreased during winter. The effects of ambient air temperature, relative humidity, wind speed, and rainfall on particulate matter (PM) concentrations were further investigated. The Spearman correlation coefficient results demonstrated significant negative correlation between relative humidity and PM concentrations (− 0.595 for PM_{10} and − 0.526 for $PM_{2.5}$) while significant positive correlation was observed between temperature and PM concentrations (0.420 for PM_{10} and 0.482 for $PM_{2.5}$).

Keywords Air quality monitoring · Arabian Peninsula · Long-term trend analysis · Particulate matter · Seasonal variations · Theil-Sen approach

Introduction

Air pollution has received growing worldwide attention from both the public and governmental policy makers due to its serious impacts on mortality, morbidity, biodiversity, ecosystem, and welfare costs (OECD 2016). The severity, extent of exposure, and source apportionment of air pollution in the Middle East and North Africa (MENA) region differ in comparison to other parts of the world because of its geographical characteristics and pace of human development progress. This region is arid and semi-arid resulting in being a major natural source of desert dust (Goudie 2009). The wealth of natural energy resources resulted in economic development based upon rapid urbanization, industrialization, population growth, and environmental degradation.

The World Bank reported premature death of 127,000 in 2013 in the MENA region due to air pollution (World Bank 2016). The World Health Organization (WHO) considers it as an environmental mortality risk factor due to lung cancer and cardiopulmonary and respiratory diseases (WHO 2009). Therefore, the analysis of long-term trends of air pollutants determines whether its levels have increased, decreased, or stayed unchanged for a certain

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period. Additionally, monitoring is essential to determine compliance of air quality with ambient air quality standards, to understand long-term temporal and seasonal trends, to evaluate the effectiveness of air quality management, and to ensure implementation of air quality control regulations (Boubel et al. 1994). However, the long-term air quality studies are limited in the countries of the MENA region.

The scatter plot analyses of air pollutants in the City of Jahra in Kuwait between the years 2000–2007 showed decreasing annual trend for SO_2 concentrations and increasing trend for NO_2 concentrations (Al-Anzi et al. 2016). Their multivariate statistical analyses showed seasonal variations for O_3, PM_{10}, NO, SO_2, and CO. A climate modeling study supported by satellite measurements suggested that the Arabian Gulf region is ozone hotspot with increasing trends of O_3 and NO_x emissions between 1996 and 2006 (Lelieveld et al. 2009). The authors recommended reporting available ground-based air pollution measurements in the region. The observed ground level $PM_{2.5}$ concentration in Makkah was higher than satellite-derived data by a factor of 2.5 between 2001 and 2007 (Munir et al. 2016). The backward trajectories analysis from 13 stations across the Kingdom of Saudi Arabia (KSA) in 2005–2012 showed that dust storms are most common during Feb–June with peak in Mar (Notaro et al. 2013). The analysis of aerosol related parameters over eight cities in the MENA region between 1999 and 2015 showed that seasonality and geographic location are major contributors to type of aerosols (Farahat et al. 2016). A recent review of source apportionment and health impacts of PM suggested that there is limited number of air pollution monitoring studies in the MENA region (Tsiouri et al. 2015).

Bahrain, like most other countries in the MENA region, is affected by dust storms originating from Iraq, Kuwait, and KSA (Smirnov et al. 2002). The inhabitants of the densely populated islands of Bahrain are further exposed to numerous anthropogenic sources of air pollution. The most recent air quality study is a non-parametric Kruskal-Wallis test that was utilized to analyze 6 months air quality data between Jan 2007 and June 2007. It concluded that air pollutants are mainly originating from industrial sources, power generation plants, and developmental activities (Khamdan et al. 2009).

There are diverse approaches to quantify temporal trends of air pollution. The most common methodology is linear regression modeling with correlated errors to estimate trends based upon mean or maximum pollutant concentrations (Hess et al. 2001). Rigorous statistical modeling and neural modeling approaches were also evaluated to predict air pollution (Schlink et al. 2003). The utilization of robust Theil-Sen statistical approach for the assessment of temporal trends in the field of air pollution is insightful because it takes into account nonlinearities, and it is applicable to both normally and non-normally distributed data (Munir et al. 2013).

The distribution of anthropogenic air pollutants is a complex chemical and physical phenomena influenced by meteorological parameters such as wind speed, turbulence level, air temperature, and precipitation. Correlation analysis demonstrated that PM_{10} levels were influenced by meteorological parameters (Karar and Gupta 2006). The work of Wise and Comrie (2005) also manifested that the meteorological variability accounts for 20 to 50% of PM_{10} variability in the southwestern USA. The study of Bhaskar and Mehta (2010) highlighted strong negative correlation between PM concentrations and rainfall.

The purpose of this study is to investigate the temporal and seasonal trends of PM_{10}, $PM_{2.5}$, NO_2, SO_2, and O_3 between 2006 and 2012 by employing robust and non-parametric Theil-Sen approach. We hypothesize that the air pollutants concentrations should increase during the scrutinized period due to industrialization, population growth, climate change, and higher frequencies of dust storms. We aim to analyze the effects of meteorological conditions (ambient air temperature, relative humidity,

Table 1 Annual statistics of meteorological parameters in Bahrain

Year	Temperature (°C)			Relative humidity (%)			Wind speed (m/s)			Rainfall (mm)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
2006	15.9	35.3	27.1	47	71	60	2.9	5.7	4.3	0	120	18
2007	15.2	35.2	27.1	51	76	61	2.9	5.2	4.2	0	28	4
2008	15.3	35.4	26.9	41	68	58	3.5	6.0	4.5	0	15	1
2009	15.9	35.5	27.4	36	69	55	3.6	5.7	4.7	0	57	6
2010	19.2	35.8	28.2	44	64	55	3.4	5.0	4.4	0	10	2
2011	17.6	35.5	27.1	38	70	53	3.9	6.1	4.9	0	57	8
2012	17.4	36.0	27.5	35	63	51	3.3	6.1	4.5	0	15	3

Table 2 Locations of air quality monitoring sites in Bahrain between 2006 and 2012

Governorate	2006	2007	2008	2009	2010	2011	2012
Capital	Manama	Manama	Manama (Jan-Aug) Nabih Saleh (Sept-Dec)	Nabih Saleh	Nabih Saleh	Nabih Saleh	Nabih Saleh (Jan-July) Tubli (Aug-Dec)
Central	Maameer	Maameer (Jan-May) Sitra (June-Dec)	Sitra (Jan- Aug) Salmabad (Sept - Dec)	Salmabad (Jan - May) Maameer (June-Dec)	Maameer	Maameer	Maameer
Muharraq	Hidd (July-Dec)	Hidd (Jan-April) Samaheej (May-Dec)	Samaheej (Jan-July) Arad (Aug-Dec)	Arad (Jan-Sept) Busateen (Nov-Dec)	Busateen	Busateen (Jan) Hidd (Feb-Dec)	Hidd
Northern	Hamala (July-Dec)	Hamala (Jan-Oct)	Hamala (Jan-Oct) Hamad Town (Nov-Dec)	Hamad Town	Hamad Town	Hamad Town	Hamad Town (Jan-July) Bahrain Fort (Aug-Dec)
Southern	Riffa (July-Dec)	Riffa	Riffa (Jan-May) Jaww (June-Dec)	Jaww (Jan-Feb) Al Areen (Mar-May) Ras Hayan (June-Dec)	Ras Hayan	Ras Hayan	Ras Hayan

wind speed, and rainfall) on air pollutant concentrations that show significant seasonal variations in order to elucidate the role of climatic conditions in a long-term temporal study of air pollution in Bahrain.

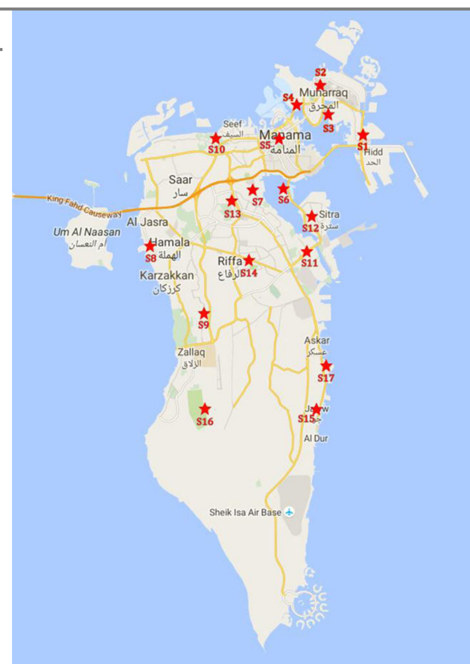
Materials and methods

Details of study area

The Kingdom of Bahrain is an archipelago of 33 natural islands and shoals with total area of 759 km^2. It is connected to KSA via 25 km King Fahad Causeway. The average population density is 1614 residents per square kilometer (Bahrain Census 2010). The country's sustainable development vision is encountering environmental challenges including deterioration of ambient air quality. The possible sources of air pollution are heavy traffic with increased number of vehicles, absence of public transportation, expansion of heavy industries including petroleum and aluminum sectors, completed/ongoing reclamation and infrastructure projects, and consumption of high amount of fossil fuel. Furthermore, Bahrain is located in an arid region thus exposed to frequent sandstorms. Wind trajectories show that Bahrain is struck by sandstorm

Table 3 Geographical coordinates of 17 air quality monitoring sites utilized in this study

Monitoring Site	Station ID	Latitude	Longitude
Hidd	S1	N 26 14.109	E 50 39.569
Samaheej	S2	N 26 16.574	E 50 37.141
Arad	S3	N 26 15.120	E 50 37.607
Busateen	S4	N 26 15.617	E 50 35.810
Manama	S5	N 26 13.876	E 50 34.815
Nabeeh Saleh	S6	N 26 11.359	E 50 35.057
Tubli	S7	N 26 11.295	E 50 33.334
Hamala	S8	N 26 08.441	E 50 27.547
Hamad Town	S9	N 26 05.031	E 50 30.588
Bahrain Fort	S10	N 26 13.899	E 50 31.240
Maameer	S11	N 26 08.162	E 50 36.376
Sitra	S12	N 26 09.952	E 50 36.655
Salmabad	S13	N 26 10.735	E 50 32.144
Riffa	S14	N 26 07.729	E 50 33.107
Jaww	S15	N 26 00.180	E 50 36.931
Al-Areen	S16	N 26 00.201	E 50 30.638
Ras Hayan	S17	N 26 02.395	E 50 37.494



originated in the deserts of Iraq, Syria, Jordan, Kuwait, Oman, KSA, and the Sahara (Draxler et al. 2001; Givehchi et al. 2013; Cao et al. 2015).

Meteorological conditions

Bahrain is characterized with arid climate resulting in extreme hot summer and mild winter. The summer temperatures may reach more than 40 °C, and the humidity is relatively high due to maritime airflow produced by water bodies surrounding the country. The average annual rainfall is 76 mm and usually confined to the winter and spring months (Elagib and Abdu 1997). The prevailing wind is the *Shamal*, which is moist and blows from the north-west, more frequently in the summer months (Smirnov et al. 2002; Goudie and Middleton 2006).

The meteorological dataset was received from the Meteorological Directorate, and instruments for the measurement of meteorological data were located at Bahrain International Airport in Muharraq. Table 1 summarizes the annual statistics of meteorological parameters (ambient temperature, relative humidity, wind speed, and rainfall) based on recorded monthly average values.

Air quality monitoring network and instrumentations

The Supreme Council for Environment (SCE), the official Environmental Authority, designated five mobile air quality monitoring stations in which each station is located at one of the governorates (Capital, Central, Muharraq, Northern, and Southern) in Bahrain in 2006. These stations continuously monitored selected air pollutants between 2006 and 2012. However, operation of these stations has been ceased since December 2012 due to maintenance issues and has not been yet activated.

These custom-built and identical monitoring stations were equipped with advanced instrumentation including monitoring analyzers as previously described (Khamdan et al. 2009). The calibration of analyzers is based upon manufacturers' instruction/operation manuals with identified time lapse between successive calibrations in order to maintain accuracy. They measure 12 air pollutants: ground level ozone (O_3), particulate matters with a diameter size of less than 10 μm (PM_{10}), particulate matters with a diameter size of less than 2.5 μm ($PM_{2.5}$), total non-methane hydrocarbons (TNMHC), ammonia (NH_3), nitrogen dioxide (NO_2), hydrogen sulfide (H_2S), sulfur dioxide (SO_2), carbon monoxide (CO), benzene (C_6H_6), toluene (C_6H_5-CH_3), and xylene (C_8H_{10}).

The five mobile air quality monitoring stations have not been kept at fixed locations, and they occasionally moved to alternative locations as a part of strategic planning. Total 17 monitoring sites have been utilized during the scrutinized period (July 2006–December 2012). Table 2 summarizes the locations of air quality monitoring sites in Bahrain between 2006 and 2012. Table 3 presents the geographical coordinates of 17 sites utilized together with their exact location on map of Bahrain.

Data analysis

The frequency distributions for SO_2, NO_2, O_3, PM_{10}, and $PM_{2.5}$ concentrations are presented as histograms in Fig. 1. It is evident that the data distribution are not normal and have long right tails (right-skewed). Therefore, in this paper, we have applied non-parametric statistical approach, including Spearman's rank correlation and Theil-Sen test that is applicable to non-normally distributed data.

The robust and non-parametric Theil-Sen approach was employed to determine temporal trends for various air pollutants between 2006 and 2012. The Theil-Sen approach is applicable to non-normal distribution of air quality data, and it is resistant to outliers in the right tail of the distribution because it is based on the median of the dataset. Openair package was utilized to apply Theil-Sen function (Carslaw and Ropkins 2012). Trends are also adjusted for meteorological effects applying the seasonal trend decomposition loess (stl) test, which deseasonalizes the trend. According to Carslaw and Ropkins (2012), the year is divided to four seasons: spring (MAM—Mar, Apr, May), summer (JJA—June, July, Aug), autumn (SON—Sept, Oct, Nov), and winter (DJF—Dec, Jan, Feb). The Arabian Gulf region has approximately similar seasonal decomposition based upon long-term climatology study (Smirnov et al. 2002).

The coefficient of variation (CV) is a standardized measure of dispersion of a probability distribution. It is often expressed as a percentage and is defined as the ratio of the standard deviation to the mean. It shows the extent of variability in relation to the mean of the population. We utilized CV to analyze the variations of key air pollutant concentrations. The CV for key air pollutants was computed using Minitab (version 17.1).

The Spearman's rank correlation coefficient (r) is a measure of the relationship strength between two variables. The p value is utilized to determine whether the correlation between selected variables is important with a significance level of ($p < 0.01$) indicating strong relationship. The Spearman's rank correlation analysis was utilized to investigate relationships between PM_{10}, $PM_{2.5}$, and meteorological parameters such as ambient air temperature, relative humidity, wind speed, and rainfall.

Results and discussion

The World Health Organization (WHO) published air quality guidelines for selected pollutants that affect

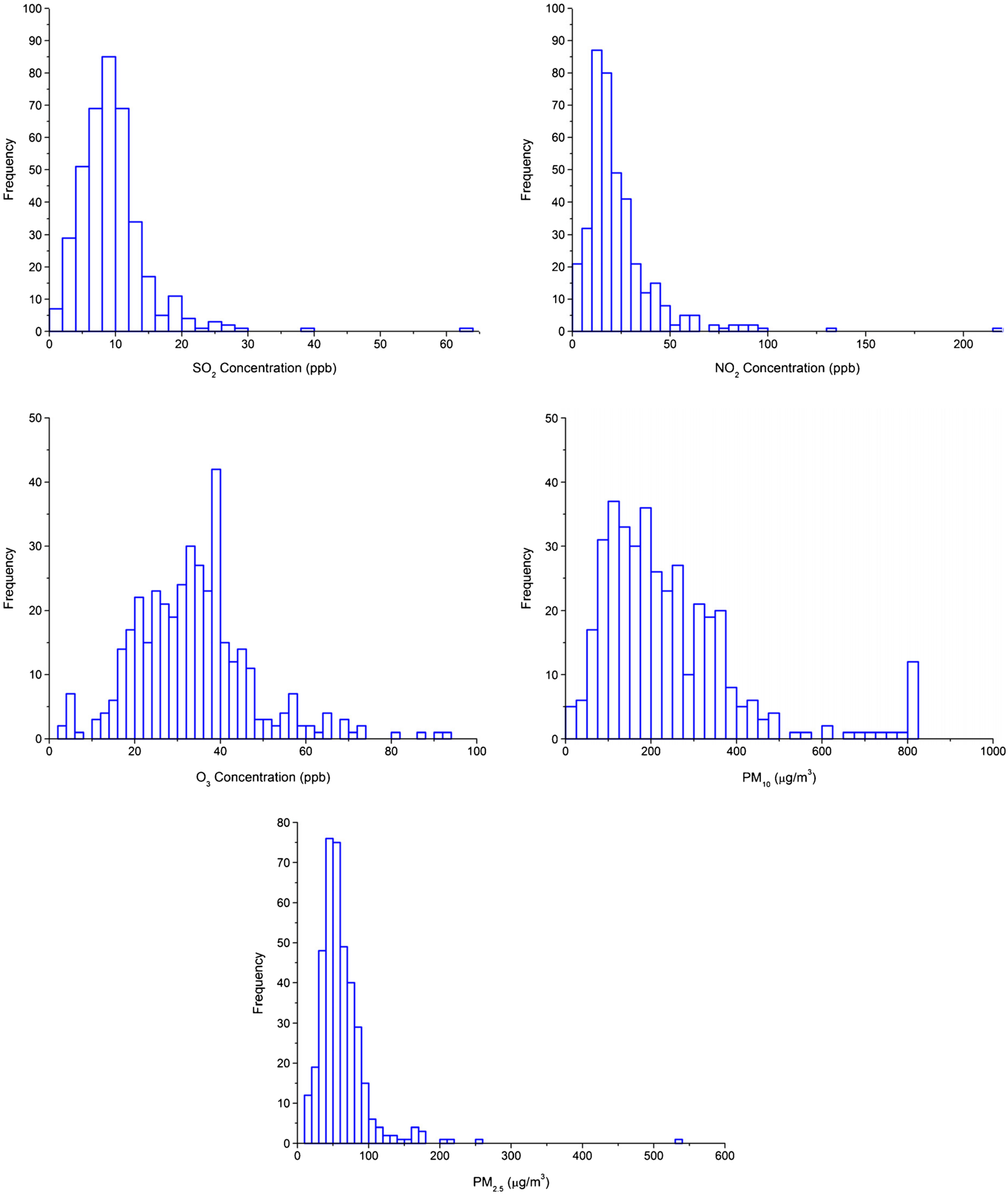


Fig. 1 Histograms of SO_2, NO_2, O_3, PM_{10}, and $PM_{2.5}$ concentrations

health: particulate matter (PM), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3) (WHO 2005). The annual mean concentrations of these pollutants were calculated using monthly averages of air quality monitoring dataset and presented in Table 4. The following sub-sections analyze temporal trends of pollutants, investigate their annual cycles, and examine role of metrological parameters on PM concentrations.

Table 4 Annual mean concentrations of key air pollutants from 2006 to 2012

Year	PM_{10} (μg/m^3)	$PM_{2.5}$ (μg/m^3)	NO_2 (ppb)	SO_2 (ppb)	O_3 (ppb)
2006	101.8	46.0	22.8	5.4	45.1
2007	236.8	52.8	21.9	7.5	41.0
2008	336.6	70.2	22.8	8.4	33.6
2009	266.6	74.6	24.5	9.0	29.8
2010	222.3	69.7	32.4	9.4	26.7
2011	220.4	60.5	20.4	11.7	34.2
2012	258.8	54.3	19.3	12.9	31.7

Analysis of temporal trends of key air pollutants

Trend of sulfur dioxide (SO_2)

The satellite-based, global emission inventory for SO_2 demonstrated that third of missing large sources for SO_2 in the world are clustered in the Arabian Gulf (McLinden et al. 2016). Their work suggested that the regional bottom–up emission inventories were outdated to assess impacts. The total anthropogenic emission for SO_2 in Bahrain was 26 Gg in year 2000, and its sector distribution was as follows: energy industries (26%), manufacturing and construction industries (26%), transport sector (7.5%), and metal production (40.5%) (BSNC 2012).

The temporal trend of SO_2 is presented in Fig. 2 using monthly mean concentrations. Figure 2a shows the observed trend with actual data, whereas Fig. 2b shows the deseasonalized trend, which is the trend after removing the seasonal effect by using seasonal trend decomposition loess (stl) methods. Seasonal trends of SO_2 are estimated in Fig. 2c. Both observed trend (1.03 ppb/year) and deseasonalized (also known as adjusted trend) (1.00 ppb/year) are positive and highly significant ($p < 0.001 = ***$), which implies that SO_2 level has significantly increased during the study period. Trend analysis (Fig. 2c) shows that SO_2 concentration has significantly increased in all seasons; however, the level of significance is lower in spring ($p < 0.1 = +$).

There are environmental efforts to curb the burden of SO_2 emissions. The Bahrain Petroleum Company (BAPCO) refinery started up low-sulfur diesel complex with sulfur content of diesel fuel lowered to 500 ppm from an average of 5000 ppm in 2007. However, the manufacturing and energy industries sectors increased with commissioning of a new aluminum potline in 2005 and the country boosted the total energy production by opening two natural gas power plants: 950 MW in Al Hidd in 2006 and 1240 MW in Al Durr in 2012.

The concentration of SO_2 continued to increase despite the abatement measure to lower its emissions from diesel engine trucks. It is evident that this action had been offset with higher emissions from other sectors like energy and metal productions. This exhibited long-term trend is consistent with prediction of Greenhouse gas—Air pollution Interactions and Synergies (GAINS) model for Middle East region between 2000 and 2010 due to industrialization, economic development, and shipping (Klimont et al. 2013).

Trend of nitrogen dioxide (NO_2)

The investigation of temporal trend of NO_2 is important in urban-industrialized developing regions because it is an indicator for combustion-generated air pollution (WHO 2005; Melkonyan and Kuttler 2012). The mobile stations in Hidd (S1), Maameer (S11), Sitra (S12), and Riffa (S14) were located near heavy industries including refining, petrochemical, aluminum, and steel production.

The calculated mass inventory of NO_x in Bahrain in year 2000 was 18 Gg from energy industries, 18 Gg from manufacturing and construction activities, and 14 Gg from transport (BSNC 2012). These data are outdated and have not been revised to include effects of abatement environmental measures like the replacement of high NO_x emission burners in Riffa power station between 2006 and 2009. The utilization of stringent vehicle emission technologies and improved fuel quality are considered as abatement measures to counteract consistent vehicle growth (Roy et al. 2009). The rapid motorization that is associated with adopted emission standards and controls for new vehicles is leading to reduction of emission rates of air pollutants over time (Kobza and Geremek 2017). We therefore believe the utilization of modern car models in Bahrain due to higher income levels might assist in reducing the NO_x emissions from traffic. This needs further investigation for confirmation.

The temporal trend (ppb/year) for NO_2 concentrations was − 0.46 (unadjusted) and − 0.43 (adjusted) during the examined period as shown in Fig. 3. Overall, NO_2 concentration is lowering despite a significant spike in early 2010. This is possibly attributed to flaring of associated natural gas with the implementation of improved oil recovery (IOR) in Bahrain field to increase crude oil production in 2010. In 1992, Madany et al. (1993) reported that the overall average NO_2 concentration in 55 sites at 21 locations throughout Bahrain was 17 ppb. If we considered their concentration as a baseline, then this study demonstrates increased average concentrations of NO_2 as shown in Table 4.

Seasonal trends of NO_2 were − 1.8, + 0.61, + 0.26, − 1.47 in spring, summer, autumn and winter respectively. NO_2 negative trend was significant only in spring ($p < 0.5$). The summer and autumn have positive trends, and this is possibly attributed to emissions from energy generation stations due to excess utilization of air conditions in hot and humid climate (Hamdi et al. 2014).

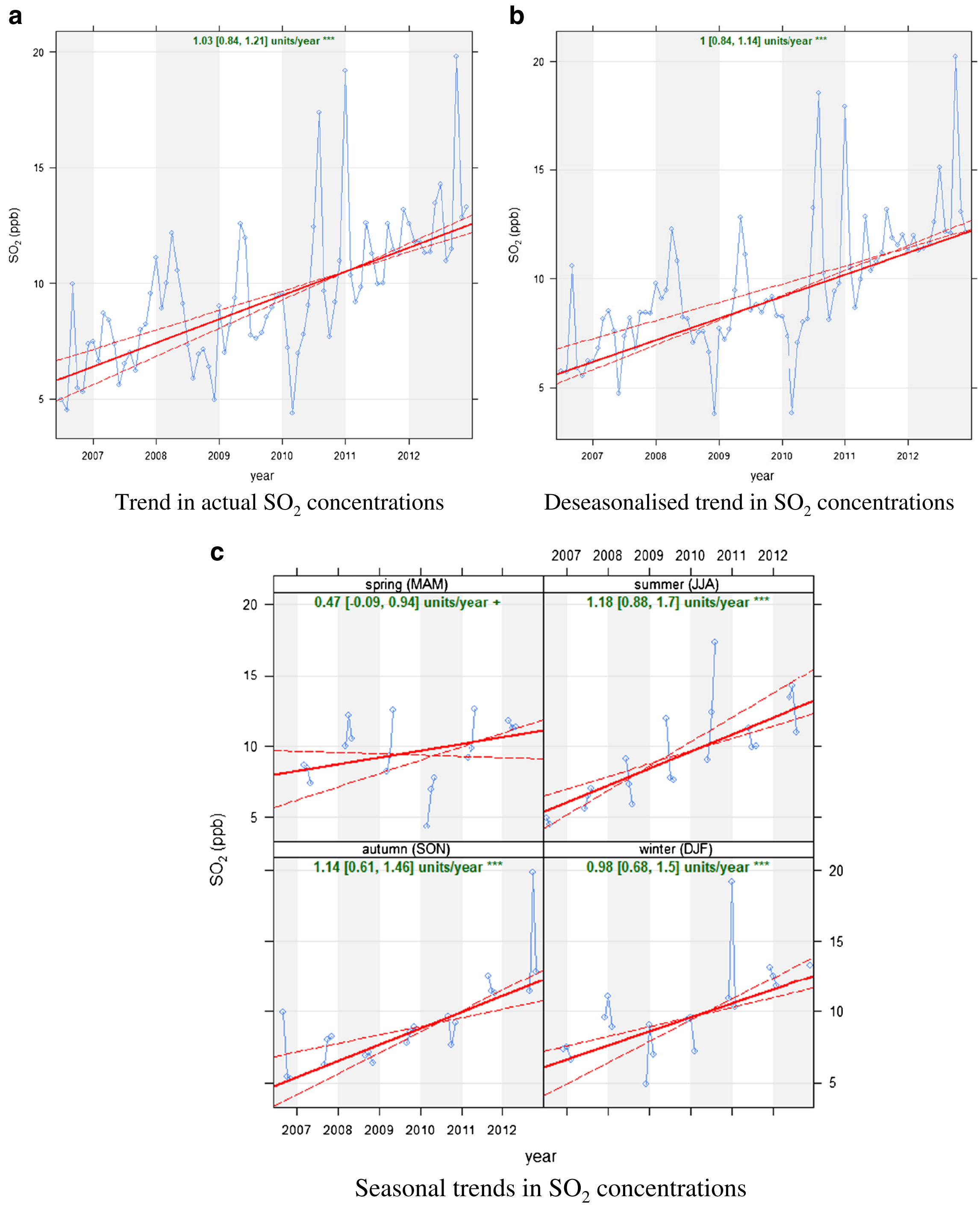


Fig. 2 SO_2 temporal trend (ppb/year) during 2006 to 2012 calculated from monthly mean concentrations. The blue line shows the actual monthly concentrations, the red solid line shows the calculated trend, and the red dashed lines show the confidence interval (CI = 95%). The number in green color at the top is the overall trend along with 95% CI. The three asterisks, two asterisks, one asterisk, and plus sign (+) show the significance of the trends to the 0.001, 0.01, 0.05, and 0.1 levels, respectively. **a** Trend in actual SO_2 concentrations. **b** Deseasonalized trend in SO_2 concentrations. **c** Seasonal trends in SO_2 concentrations

Trend of ozone (O_3)

O_3 is a secondary air pollutant, which is formed in the stratosphere from the photochemical reaction of its precursors, such as NO_2 and non-methane hydrocarbons in the presence of solar radiation (Atkinson 2000). Temporal trend of O_3 is depicted in Fig. 4, where O_3 experienced negative trend during the study period. As shown in Fig. 4a, O_3 concentrations has decreased by − 1.9 ppb/year (highly significant, $p < 0.001$). The meteorological adjusted trend (Fig. 4b) was found to be − 1.7 ppb/year

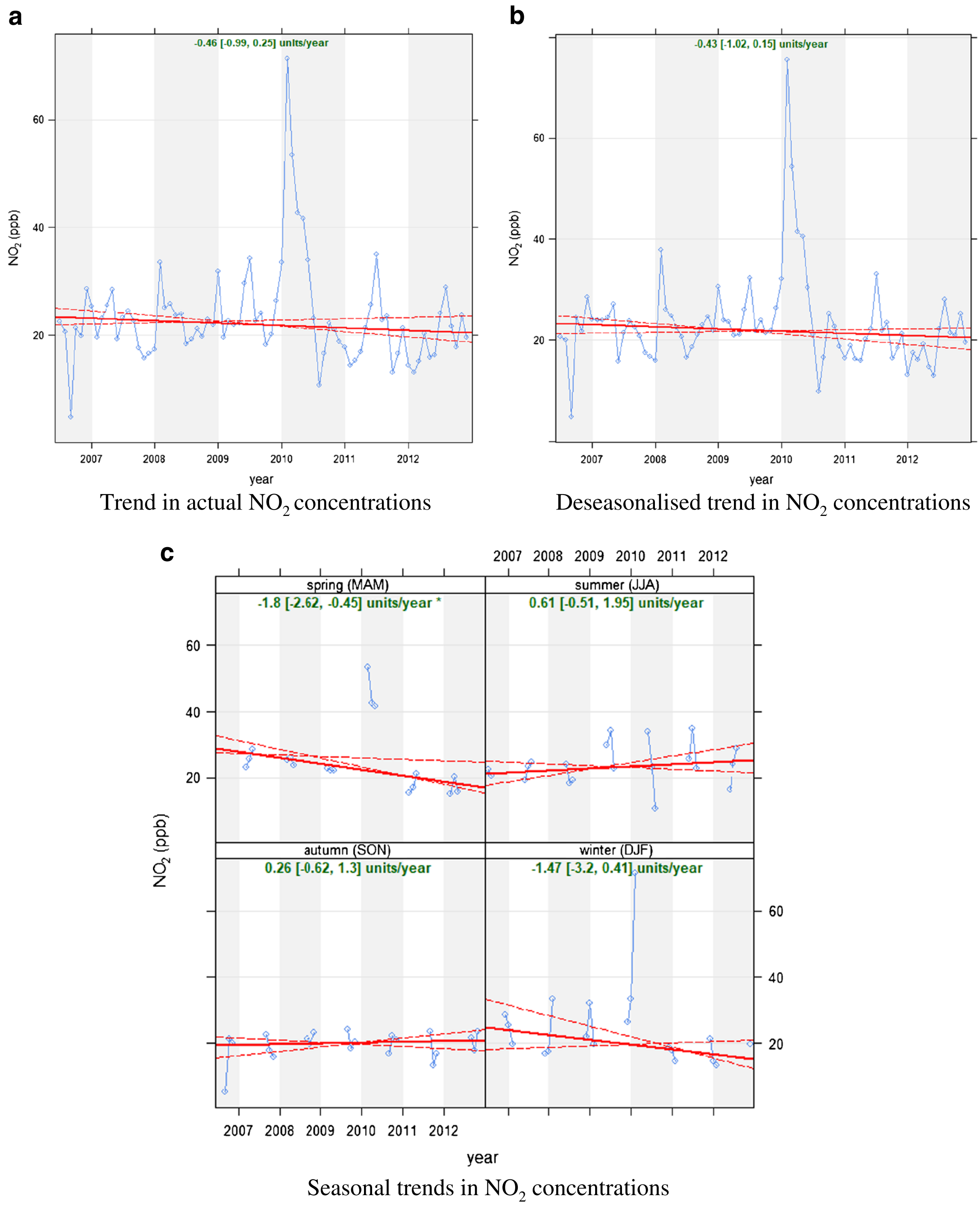


Fig. 3 NO_2 temporal trend (ppb/year) during 2006 to 2012 calculated from monthly mean concentrations. The blue line shows the actual monthly concentrations, the red solid line shows the calculated trend, and the red dashed lines show the confidence interval (CI = 95%). The number in green color at the top is the overall trend along with 95% CI. The three asterisks, two asterisks, one asterisk, and plus sign show the significance of the trends to the 0.001, 0.01, 0.05, and 0.1 levels, respectively. **a** Trend in actual NO_2 concentrations. **b** Deseasonalized trend in NO_2 concentrations. **c** Seasonal trends in NO_2 concentrations

(negative and highly significant, $p < 0.001$). The O_3 concentration in the atmosphere is dependent not only on its precursors but also on meteorological parameters. However, the magnitude of the meteorological adjusted trend shows that the negative trend is probably mainly due to reduction in the levels of precursors and is not caused by changes in climatic factors. The reduction in NO_2 emissions and hence its limited availability for photochemical reaction attributed to negative O_3 trend.

O_3 displayed negative seasonal temporal trends as shown in Fig. 4c. The strongest negative trend was observed in spring

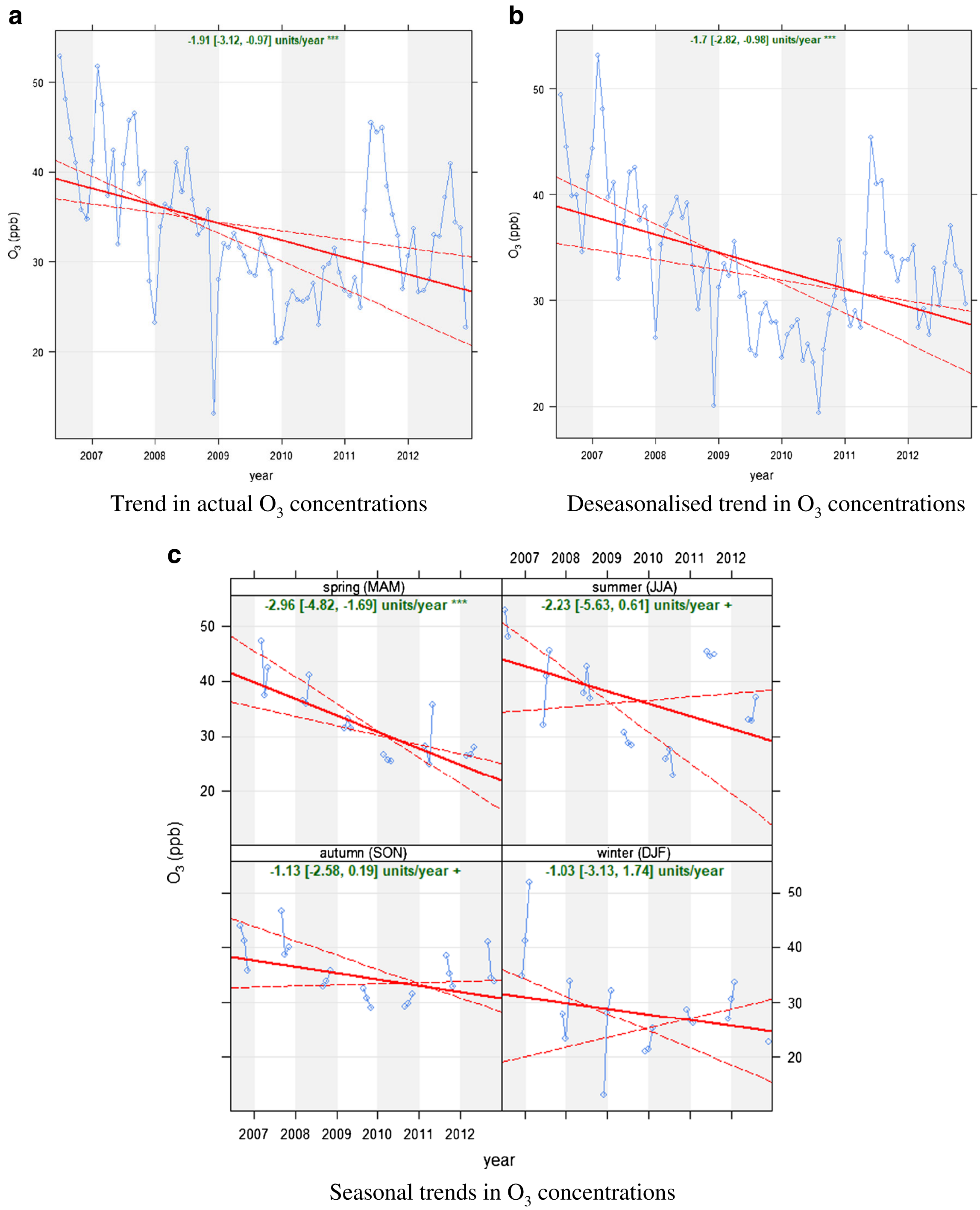


Fig. 4 O_3 temporal trend (ppb/year) during 2006 to 2012 calculated from monthly mean concentrations. The blue line shows the actual monthly concentrations, the red solid line shows the calculated trend, and the red dashed lines show the confidence interval (CI = 95%). The number in green color at the top is the overall trend along with 95% CI. The three asterisks, two asterisks, one asterisk, and plus sign show the significance of the trends to the 0.001, 0.01, 0.05, and 0.1 levels, respectively. **a** Trend in actual O_3 concentrations. **b** Deseasonalized trend in O_3 concentrations. **c** Seasonal trends in O_3 concentrations

(MAM) which was − 2.96 ppb/year (highly significant, $p < 0.001$) and the weakest in winter (DJF) which was − 1.03 ppb/year (non-significant), whereas O_3 trends in summer (− 2.23 ppb/year) and autumn (− 1.13 ppb/year) were significant only at $p < 0.1$. The seasonal concentration of O_3 in spring and summer is highest because the photochemical reaction for ozone production is catalyzed by sunlight (Alghamdi et al. 2014). The O_3 trend was negative and highly significant in the spring season in parallel with NO_2 concentrations indicating strong mutual link.

Trends of particulate matter (PM_{10} and $PM_{2.5}$)

Figure 5a shows the trend in actual PM_{10} concentrations, Fig. 5b shows deseasonalized trend, and Fig. 5c shows seasonal trends in PM_{10} concentrations. Temporal trend ($\mu g/m^3$/year) in PM_{10} concentrations from 2006 to 2012 was 6.05, whereas the adjusted trend was 7.13. The increase in measured PM_{10} levels confirms that

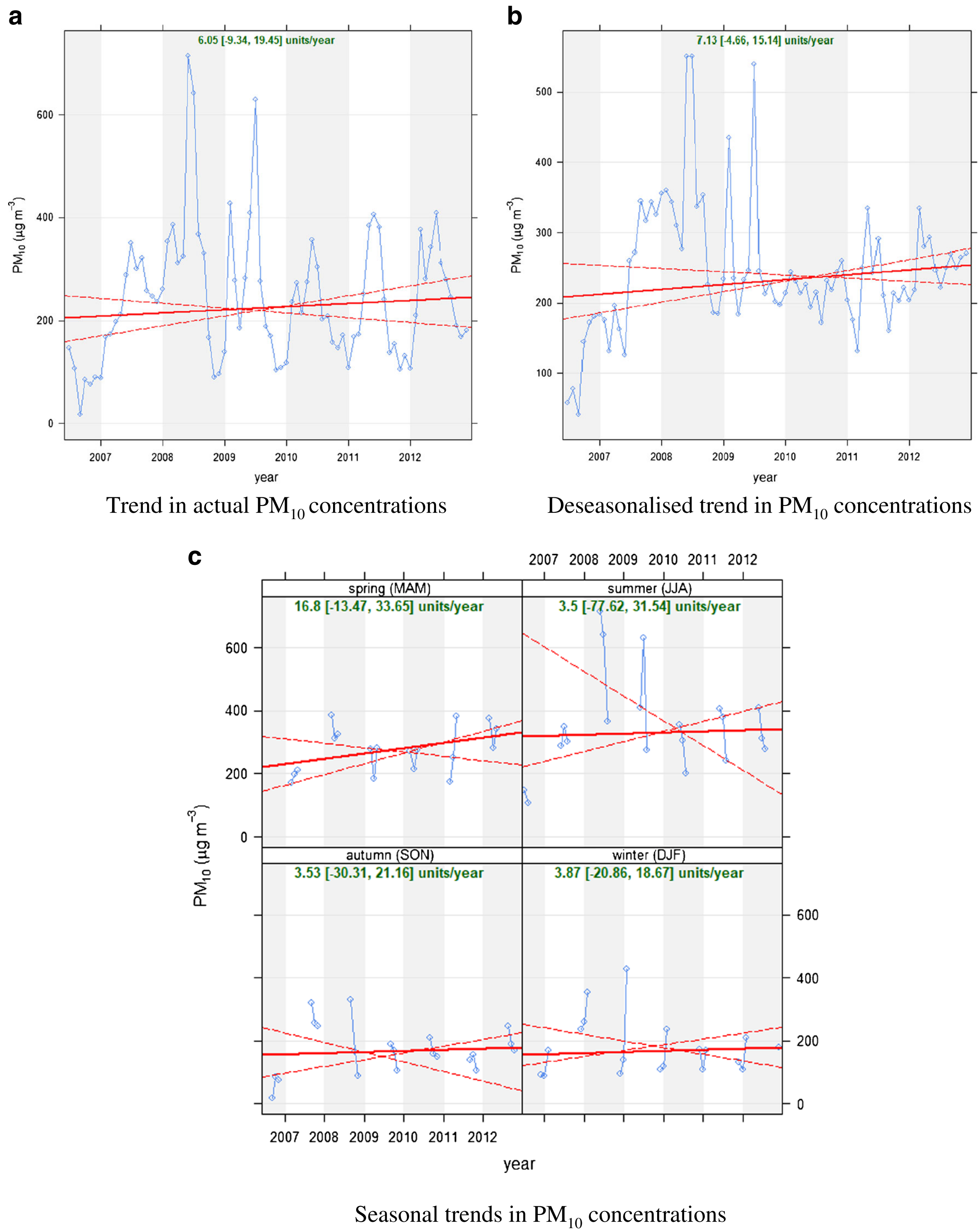


Fig. 5 PM_{10} temporal trend ($\mu g/m^3$/year) during 2006 to 2012 calculated from monthly mean concentrations. The blue line shows the actual monthly concentrations, the red solid line shows the calculated trend, and the red dashed lines show the confidence interval (CI = 95%). The number in green color at the top is the overall trend along with 95% CI. The three asterisks, two asterisks, one asterisk, and plus sign show the significance of the trends to the 0.001, 0.01, 0.05, and 0.1 levels, respectively. **a** Trend in actual PM_{10} concentrations. **b** Deseasonalized trend in PM_{10} concentrations. **c** Seasonal trends in PM_{10} concentrations

the regional dust events in the MENA region are becoming more frequent and intense in the last decade (Karimi et al. 2012).

Both observed and adjusted trends were positive but non-significant. PM_{10} trends (μg/m^3/year) in various seasons of the year were 16.8 in spring, 3.5 in summer, 3.53 in autumn, and 3.87 in winter. Trends were also non-significant in all four seasons. The results are consistent with seasonality work of (Notaro et al. 2013) that showed that dust storms are most common in spring in KSA.

Unadjusted or observed temporal trend (μg/m^3/year) in $PM_{2.5}$ concentrations was 0.56 during the study period, whereas the adjusted trend was 0.77. Temporal trends in spring, summer, autumn, and winter were 0.54, 1.04, 0.39, and 0.68, respectively (diagrams not shown for brevity). Both adjusted and un-adjusted trends were positive but non-significant. The $PM_{2.5}$ trends in all seasons were non-significant indicating that meteorological factors are not playing a substantial role to $PM_{2.5}$ concentrations in ambient air and the $PM_{2.5}$ emissions from traffic and industrial activities are approximately similar throughout the year.

Annual cycles of key air pollutants

For the investigated period 2006–2012, the descriptive statistics of average monthly air pollutant concentrations and coefficient of variations (CV) are presented in Table 5. The pollutants NO_2, PM_{10}, and SO_2 exhibited significant temporal variability with CV values of 82.52, 68.40, and 58.42%, respectively. The CV values were relatively lower for $PM_{2.5}$ and O_3 with 49.71 and 42.42%. The high fluctuations could be attributed to increase in air pollution events such as more frequent dust storm episodes and because the data are inclusive of seasonal variations.

A comparison of annual average concentrations of key air pollutants in Bahrain with WHO shows that PM_{10} and $PM_{2.5}$ are the critical air pollutants. The annual mean concentration of PM_{10} over the study period was 240.97 μg/m^3, and that is ten times more than average annual level recommended by WHO ($PM_{10} = 20$ μg/m^3). The average concentration of $PM_{2.5}$ over the study period was 55.08 μg/m^3, and that is five times more than average annual level recommended by WHO ($PM_{2.5} = 10$ μg/m^3). The $PM_{2.5}$ might have various toxic metals and acids as most of them are originating from industrial sources (Curtis et al. 2006).

The box-plot analysis was implemented to assess visually the monthly/seasonal variations of air quality data. The upper and lower whisker lines show the highest and lowest data values. The bottom and top horizontal lines of the box refer respectively to first (25%) and third (75%) quartiles. The middle horizontal line refers to median value that is less effected by extreme values and skewed data. The square symbol (□) refers to mean value, the cross symbol (X) refers to 1st and 99th percentiles, and the en dash (–) symbol that coincides with center of cross symbol (X) refers to minimum and maximum values. Figure 6 presents box-plots of monthly concentrations of key air pollutants.

The monthly median lines of box-plots show that PM_{10} and $PM_{2.5}$ exhibit seasonal variations with concentrations peaking in the summer (highest in June). PM concentrations were higher during summer months and lower in the winter months, which were caused by dust bearing hot winds of Middle East like Shamal and Simoom during summer period (Goudie and Middleton 2006). This seasonal behavior is in agreement with dust erosion in the Middle East as it is active throughout the year but low in winter months (Shao 2008). However, the median lines for NO_2, SO_2, and O_3 are almost consistent and do not show seasonal variations.

The role of meteorological parameters on PM concentrations

The Spearman correlation coefficients (*r*) and calculated *p*-values associated with correlation between PM (PM_{10} and $PM_{2.5}$) concentrations and the meteorological parameters are computed and presented in Table 6.

The highest association between PM and meteorological parameters is for relative humidity. The corresponding coefficient values were −0.595 and −0.526 for PM_{10} and $PM_{2.5}$, respectively ($p < 0.01$). Both PM_{10} and $PM_{2.5}$ showed significant positive correlation with temperature indicating that

Table 5 Descriptive statistics of monthly average pollutant concentrations

Pollutant	Min	Q1	Median	Mean	Q3	Max	SD	CV (%)
PM_{10} (μg/m^3)	16.19	126.74	199.67	240.97	310.59	821.45	163.14	67.70
$PM_{2.5}$ (μg/m^3)	10.98	42.32	55.08	60.83	73.39	252.68	30.24	49.71
NO_2 (ppb)	0.78	11.98	18.97	23.50	28.10	215.69	19.39	82.52
SO_2 (ppb)	0.79	6.26	8.97	9.47	11.32	63.87	5.52	58.25
O_3 (ppb)	3.70	24.53	33.06	33.77	39.99	118.56	14.33	42.42

Q1 25th percentile, *Q3* 75th percentile, *SD* standard deviation

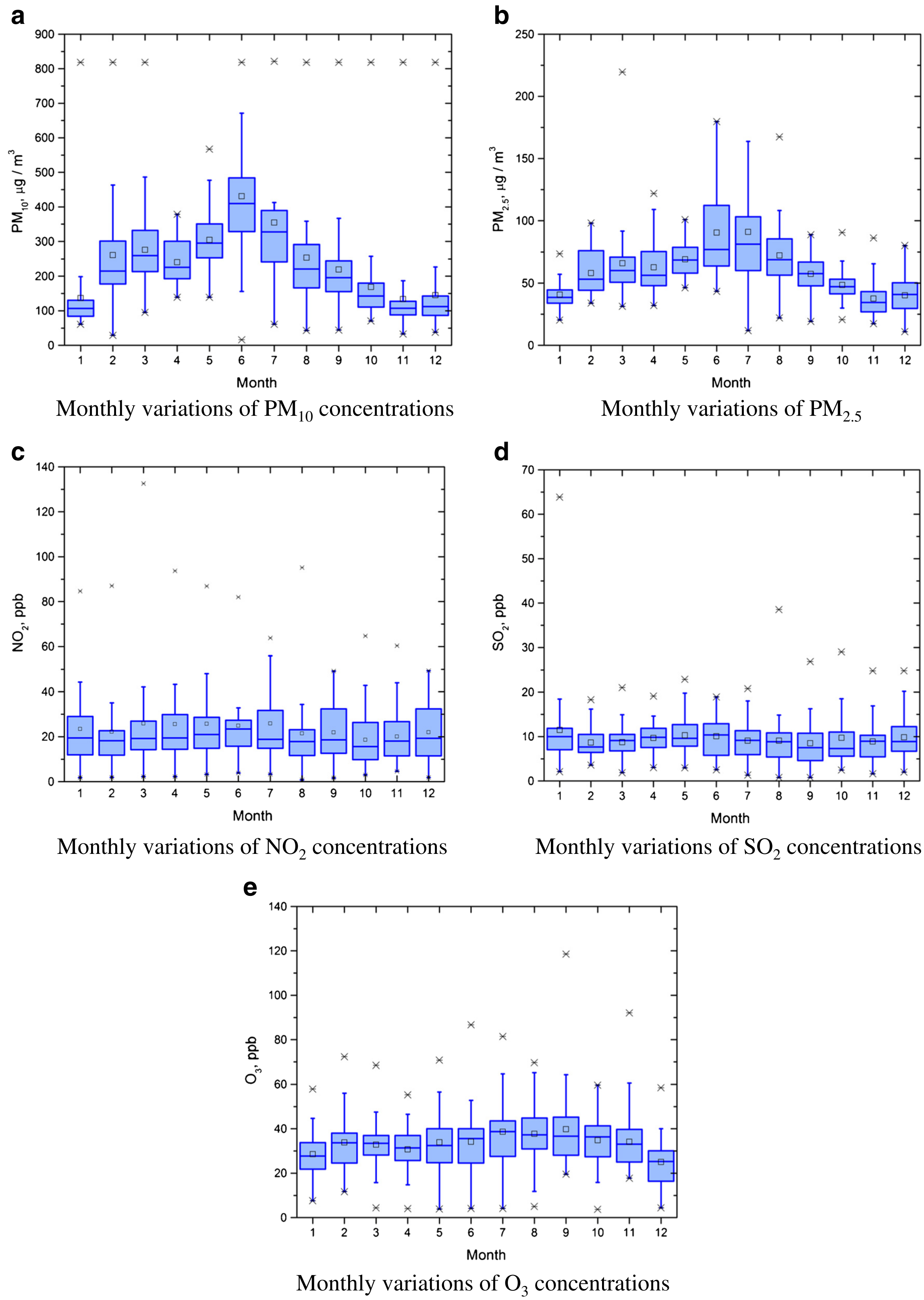


Fig. 6 Box-plots of key air pollutants' concentrations. **a** Monthly variations of PM_{10} concentrations. **b** Monthly variations of $PM_{2.5}$. **c** Monthly variations of NO_2 concentrations. **d** Monthly variations of SO_2 concentrations. **e** Monthly variations of O_3 concentrations

higher PM concentrations were observed at higher ambient temperatures. The Spearman correlation coefficient values for temperature were calculated as 0.420 and 0.482 for PM_{10} and $PM_{2.5}$ pollutants, respectively ($p < 0.01$).

Table 6 Spearman's rank correlation coefficients and *p* values between PM_{10}, $PM_{2.5}$, and meteorological parameters

	Temperature	Relative humidity	Wind speed	Rainfall	$PM_{2.5}$
PM_{10}					
r	0.420	− 0.595	0.121	− 0.235	0.707
p value	0.000	0.000	0.017	0.000	0.000
$PM_{2.5}$					
r	0.482	− 0.526	0.044	− 0.262	0.707
p value	0.000	0.000	0.389	0.000	0.000

PM_{10} and $PM_{2.5}$ showed negative association with rainfall indicating lower concentrations of PM in the atmosphere during rainfall. The Spearman correlation coefficient values for rainfall were calculated as − 0.235 and − 0.262 for PM_{10} and $PM_{2.5}$ pollutants, respectively. Wet scavenging is considered a significant removal mechanism of aerosol particles in the atmosphere. However, Bahrain has light showers with low rainfall intensity; thus, washout of aerosols by precipitation is confined to few days annually in winter and spring (Elagib and Abdu 1997). At constant rainfall intensity, Laakso et al. (2003) showed that wet scavenging is more efficient for coarse and fine particle sizes.

The Spearman correlation analysis exhibited strong link between PM_{10} and $PM_{2.5}$ with a value of 0.707. The sources of PM_{10} pollution are from road dust, sand storms, and construction activities whereas $PM_{2.5}$ pollution is generated from fuel burning, industrial combustion processes, and vehicular emissions. The high value of Spearman coefficient shows that greatest fraction of $PM_{2.5}$ pollution is originating from similar sources of PM_{10} in Bahrain and industrial sources of $PM_{2.5}$ emissions are not dominating over PM_{10} pollution.

Figure 7 presents the monthly variations of PM_{10} concentrations with meteorological parameters (temperature, relative humidity, wind speed, and rainfall). Similarly, the monthly variations of $PM_{2.5}$ concentrations with meteorological parameters are shown in Fig. 8.

Conclusion

Non-parametric and robust statistical tools were utilized to evaluate extent of air pollution in Bahrain from 2006 to

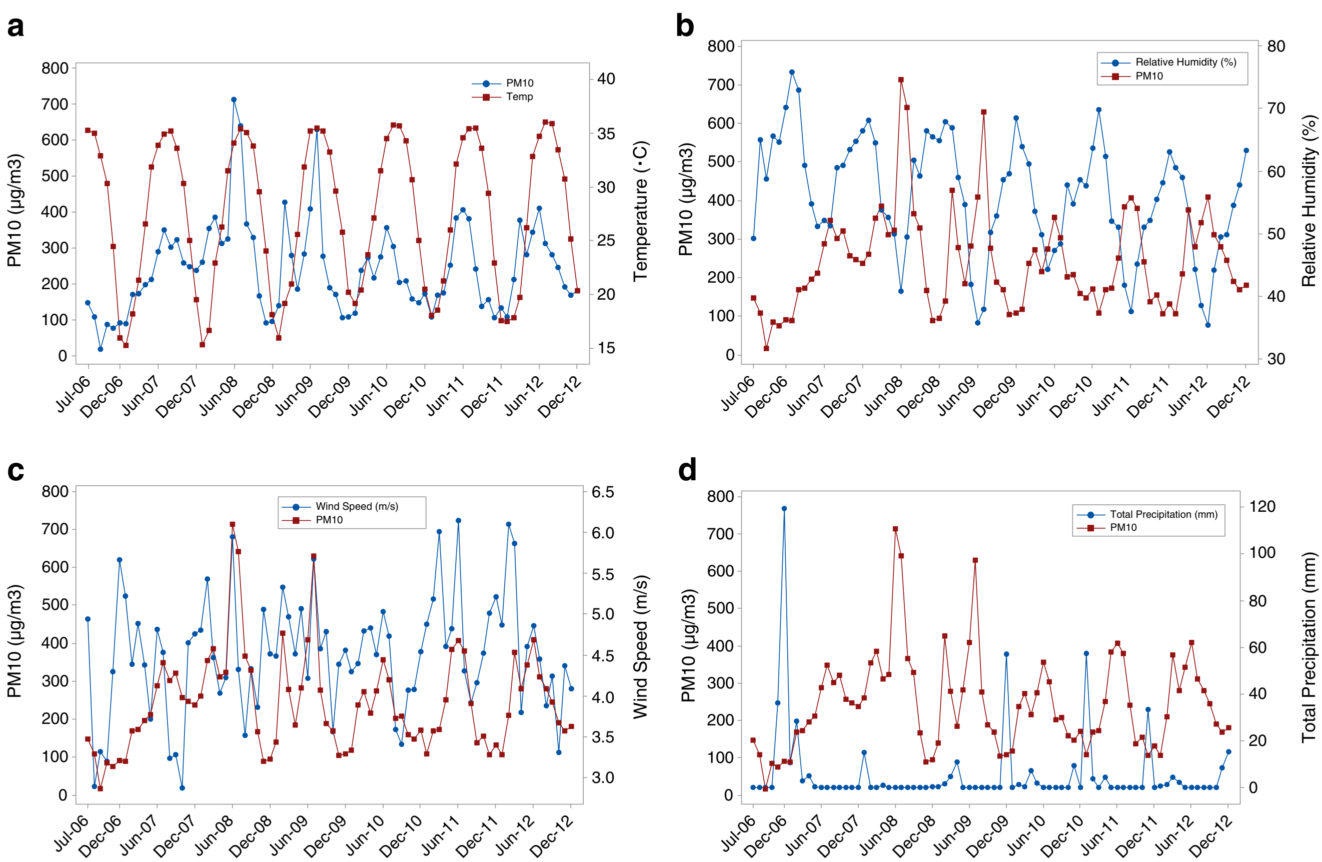


Fig. 7 Monthly variations of PM_{10} with meteorological parameters. **a** Temperature. **b** Relative humidity. **c** Wind speed. **d** Rainfall

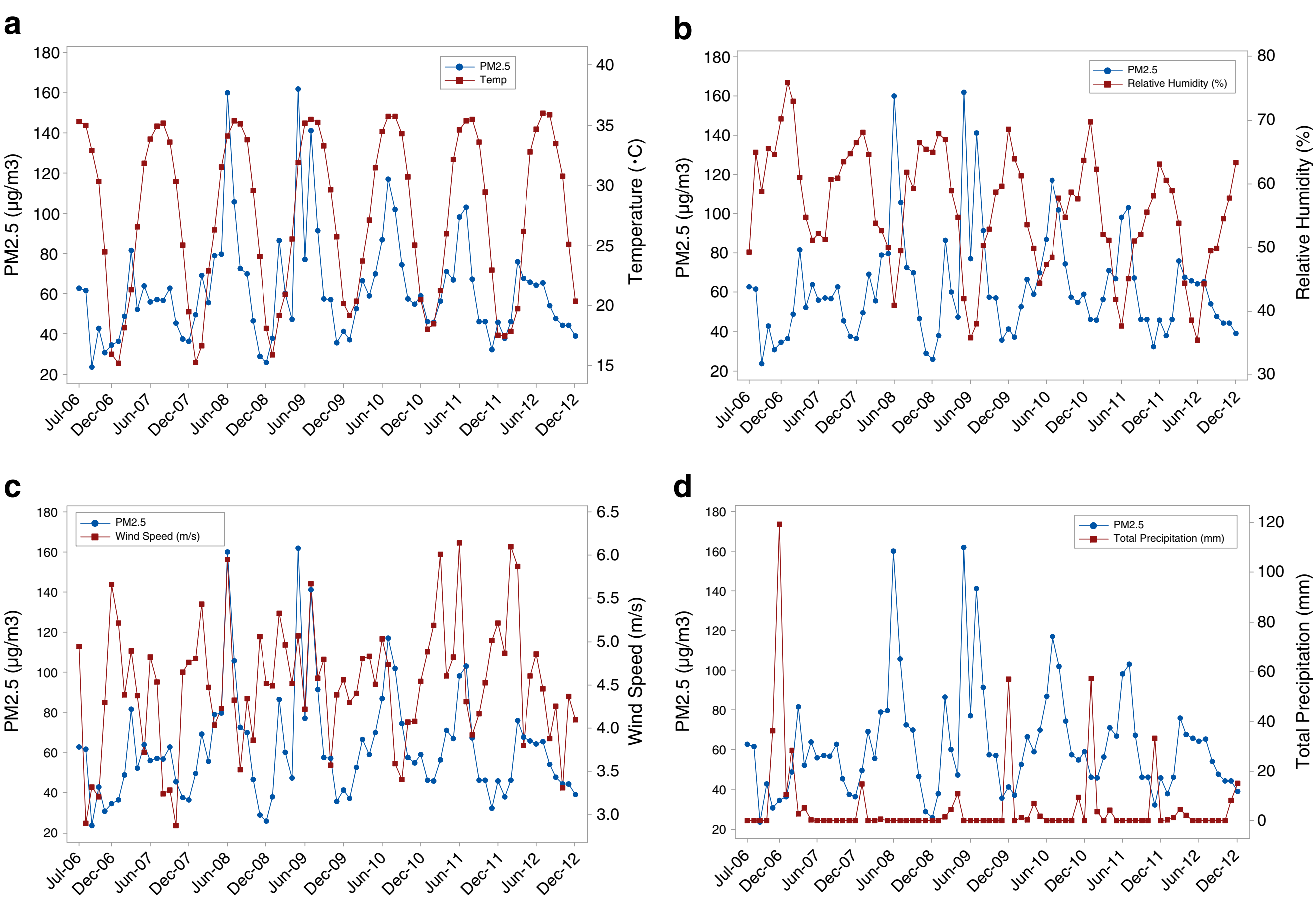


Fig. 8 Monthly variations of $PM_{2.5}$ with meteorological parameters. **a** Temperature. **b** Relative humidity. **c** Wind speed. **d** Rainfall

2012. This long-term analysis comprehensively quantifies pollution levels of SO_2, NO_2, O_3, PM_{10}, and $PM_{2.5}$ datasets from mobile monitoring stations. Results showed increasing concentrations for PM_{10} (6.05 µg/m^3/year), $PM_{2.5}$ (0.56 µg/m^3/year), and SO_2 (1.03 ppb/year) which most probably infers the impacts of industrialization, urbanization, and frequent regional dust storms.

Results showed decreasing behavior for O_3 (−1.91 ppb/year) and NO_2 (−0.64 ppb/year). However, reductions in O_3 levels were more prominent (highly significant at p value < 0.001) than NO_2 (non-significant). Although O_3 exhibited negative trend, the number of monthly exceedances for O_3 was highest among other air pollutants. This behavior confirms that Arabian Gulf is a hotspot for ground level of O_3 with high health risk association. The trends of SO_2 and O_3 were significant ($p < 0.001$).

This is the first paper dealing with long-term trends of key air pollutants in Bahrain. The study recommends improvements to control anthropogenic emission sources particularly in sectors of construction, industry, and transportation. There is a requirement to update the Bahraini emission standards to counterbalance higher pollutants concentrations and to introduce new mitigation policies to lower emissions that are posing serious health risks.

Acknowledgements Any opinion, findings, conclusions, or recommendations expressed herein are those of the authors. They are grateful to the Supreme Council for Environment (SCE) for kindly providing ambient air monitoring data. They are grateful to Climate and Observation Section in the Meteorological Directorate of Bahrain for kindly providing meteorological data.

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