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Temporal and spatial variations of the quality of ambient air in the Kingdom of Bahrain during 2007

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Abstract The main objective of the present investigation is to study the temporal and spatial variations of the quality of ambient air in the Kingdom of Bahrain. The non-parametric Kruskal–Wallis (KW) test showed significant spatial variations and interactions of spatial-temporal among five mobile monitoring stations for 11 air pollutants. The Mann Whitney (MW) test demonstrated the seasonality of spring over winter for the PM_{10}, $PM_{2.5}$, NO_2, CO and p-xylene, the seasonality of winter over spring for O_3, and no significant seasonal variation for NH_3, benzene, SO_2, toluene and H_2S. It is concluded that emissions from automobile exhaust, industrial and developmental projects are responsible for the spatial air pollution, and that air temperature is the controlling factor for the seasonal variations.

Keywords Bahrain · Ambient air quality · Spatial · Seasonal variation · Industries · Automobiles

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Introduction

The air quality monitoring programme reporting was limited to the annual reports since 1986. In 2006, however, it was decided to issue summarised monthly Air Quality Monitoring Programme (AQMP) reports and disseminated to the Cabinet of Ministers and to the media. All previous reports issued by the Environmental Affairs dealt with exceedances and central tendency statistics; i.e. means, maxima and minima in accordance with the reporting format and national environmental standards. Madany and Danish (1988) reported air pollutants; H_2S. NO_x, NO_2, NO, SO_2, O_3, CO, CH_4, and NMHC, from various locations in Bahrain and found that most pollutants are at lower levels compared with standards accepted by different countries, with the exception of CH_4 and NMHC. They attributed their findings to the location of the station in the proximity of the power and desalination plants and petroleum storage tanks as well as a petrochemical industry. Danish and Madany (1992) surveyed the atmospheric NO_2 throughout Bahrain. The results revealed marked spatial variations in NO_2 concentrations and reasoned for the automobile exhaust emissions.

The purpose of this study

The purpose of this paper is firstly, to study the temporal and spatial variations of the ambient air quality for the period from January until June 2007 reported from five mobile stations, secondly, to expand the scientific knowledge of the status of air quality, and thirdly, to outline policies concerning the mitigation of the sources of air pollution in the Kingdom of Bahrain.

Materials and methods

A brief description of the monitoring sites

Five sites were chosen by a public hearing from representatives from the parliament, legislative court, municipality and its councils, governorates and media. The sites (Fig. 1) distributed in the five governorates, and detailed in Table 1.

Mobile stations and instrumentations

Five newly purchased mobile stations are deployed in the five districts over the Kingdom of Bahrain. Eleven air pollutants measured by sensors (PM_{10} and $PM_{2.5}$, ET BAM1020, Met One Ins., Beta-attenuation;NO_2 and NH_3; ET M201E, API, chemiluminescent; CO, ET M300E,API, Gas Filter Correlation; SO_2, ET M100E, UV Fluorescent; H_2S, ET M101,API, UV Fluorescent; O_3, ET M400E,API, UV Absorption; benzene, toluene and *p*-xylene, VOC-GC 955 series 600 Model 601, Syntec Spectras, Gas Chromatograph). Data are averaged at every 15-min intervals and then submitted through sensor-data logger-modem GSM to the central computing laboratory in the Environmental Monitoring Section. High Quality Assurance was followed in maintaining the stations and instrumentations including calibrations in accordance with the manufacturer's operating manuals and under the warranty period by the supplier. The captured data were filtered to exclude anomalies and transformed to daily averages and prepared for statistical treatment.

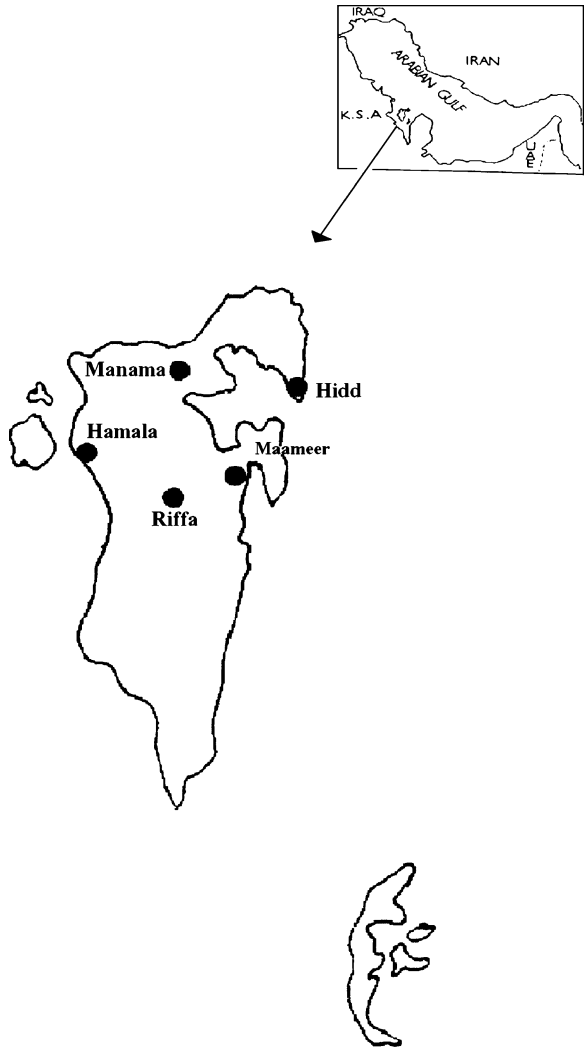

Fig. 1 Distribution of air monitoring stations in Bahrain. See Table 1 for sites description

Statistical treatment of data

It was intended to use two-way analysis of variance (TWANOVA) to test three hypotheses to each pollutant in interest. Firstly, to test temporal variation, secondly, to test spatial variation, and thirdly, to test whether there is interaction between sites and months. Since one of the assumptions of this parametric TWANOVA is the homogeneity of variance that was violated (Levene test), even when data were log_{10} or square root transformed. Therefore, it was decided to use the non-parametric Kruskal–Wallis(KW) test for

Table 1 General description of location of the air monitoring stations and main sources of pollution

Station	General description
HAMALA	Situated in the northern governorate, south of King Fahad causeway, at the water storage tanks. The area is coastal, cultivated. The chicken farms and vehicles are potential sources of pollution
HIDD	Located in the Muharraq governorate, in the Directorate of Meteorology at the Bahrain airport. The site is near a coast surrounded by heavy traffic avenue, Hidd industrial zone, Hidd power and desalination plant all of which are thought to contribute to the pollution levels
MAAMEER	Positioned in the central governorate, in the Maameer club yard, a residential area surrounded by both industrial zone and the refinery that are sources of pollution
MANAMA	Placed in the capital governorate, in the Manama girls' secondary school. This is a residential area with a high traffic that is the major source of pollution
RIFFA	Sited in the southern governorate, at the water storage tanks. This is a residential area surrounded by Riffa gas power station and heavy traffic both of which are potential source of pollution

k-independent samples, analogous to the one-way ANOVA. This had, in fact, reduced the comparisons intended through combining both the site and season as one dataset. However, Mr. Majeed Isa (personal communication, Meteorology Office) of the opinion that, in Bahrain, the seasonality is better classified as follows; winter season extends from December until February, transitional period includes both March and April, summer season extends from May until September, and one more transitional period that includes both October and November). It is difficult to have a clear description of Bahrain seasons since the transitional periods or at least 1 month in either period may favours summer or winter. In order to ease the presentation of the data, it was decided on the basis of temperature fluctuations as measured in the monitoring stations, that there are two periods after recoding the months to arbitrary seasons, (January until March was given winter, and April until June was given spring of the year 2007).

To determine if a statistical difference exists among site-season groups that represent the tempo-spatial variation, a KW (SPSS-Statistical Package) test was performed on all 10 datasets. The null hypothesis of this test states that the mean ranks of site-season groups are equal. In this test all cases from the site season groups are combined and ranked. The average ranks are assigned in the case of ties. For each group, the ranks are summed, and the KW *chi-square* (χ^2) statistic is computed from these sums. The small observed significance level suggests that the site-season groups are significantly different, and at least one comparison between the higher mean rank group is significantly different from the lower

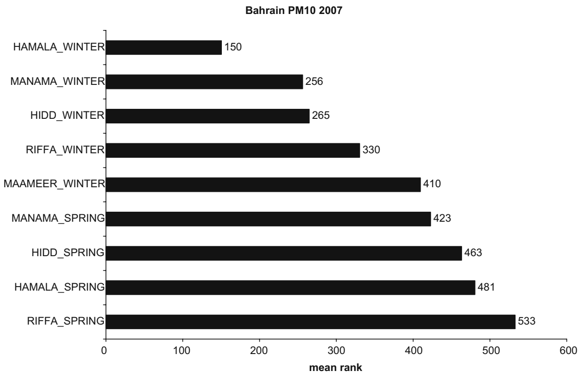

Fig. 2 KW mean rank analysis for PM_{10} monitored at five stations in winter and spring 2007

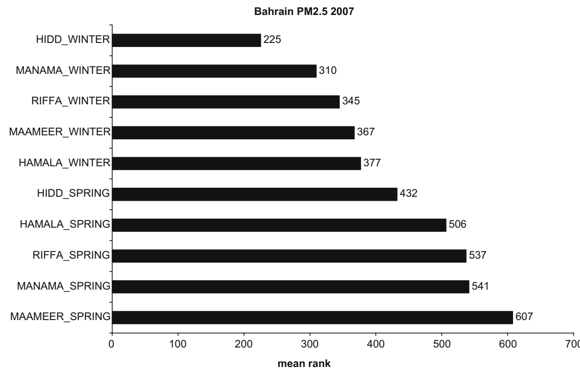

Fig. 3 KW mean rank analysis for $PM_{2.5}$ monitored at five stations in winter and spring 2007

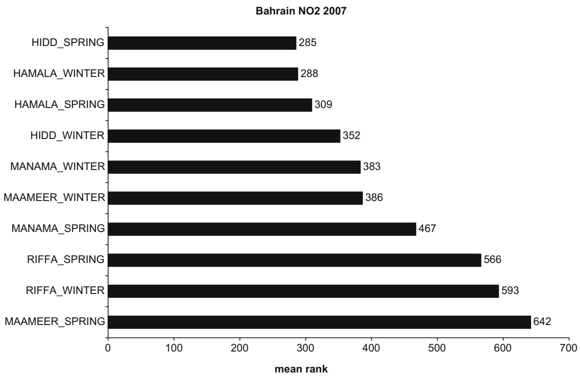

Fig. 4 KW mean rank analysis for NO_2 monitored at five stations in winter and spring 2007

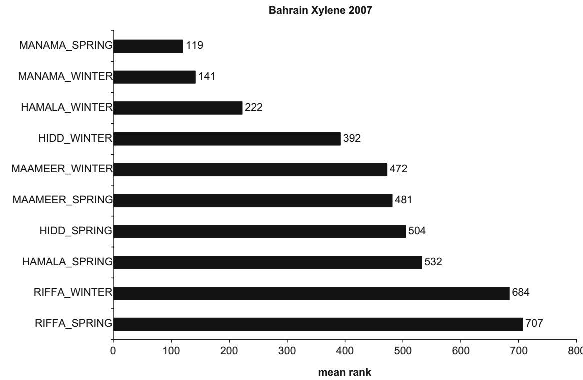

Fig. 6 KW mean rank analysis for xylene monitored at five stations in winter and spring 2007

mean rank group. The mean rank results for all air pollutants are presented in Figs. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12. The seasonality i.e. (winter and spring) was tested using the Mann Whitney (MW) test that is equivalent to the two samples Student's *t* test. The MW tests the hypothesis that the two independent samples come from population having the same distribution. Furthermore, percentages of data capture are given in Table 2 that shows the percentage ranged from 64.3% for H_2S and 96.4 for BTX (benzene, toluene and xylene). Accordingly, all data capture is more than 60% criterion and should be statistically manipulated as suggested by the US Army Corps of Engineers (2003). Table 3 gives the summary statistics for each air parameter and includes the mean, standard deviation, and number of observations(n). Pearson's chi-square (χ^2) *cross tabulation* statistic was used to test correlations between the reported exceeded values of both PM_{10} (Bahrain daily standard is 340 μg m^{-3}) and $PM_{2.5}$ (Bahrain daily guidelines value is 50 μg m^{-3}), and haze and non haze days, season and station (Table 4). This statistic is used to test the hypothesis of no association of columns and rows in tabular data. A chi-square probability of 0.05 or less is commonly interpreted as justification for rejecting the null hypothesis that the row variable is unrelated.

Results and discussion

Table 3 gives summary statistics of air pollutants measured for site season and the overall pooled totals. It can be seen from these totals and despite the clear intrinsic variation among

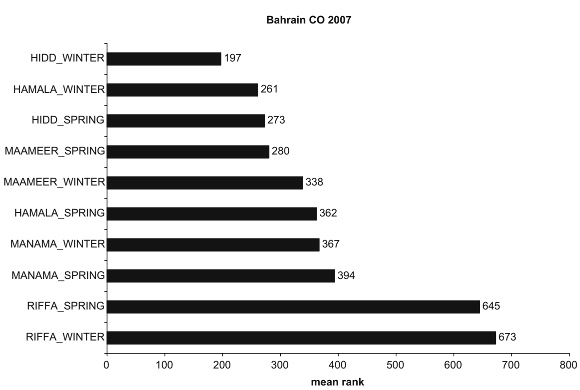

Fig. 5 KW mean rank analysis for CO monitored at five stations in winter and spring 2007

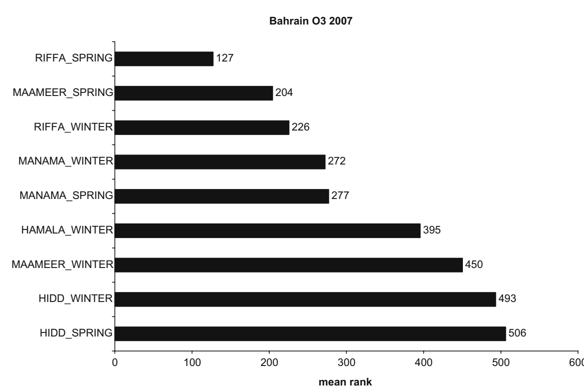

Fig. 7 KW mean rank analysis for O_3 monitored at five stations in winter and spring 2007

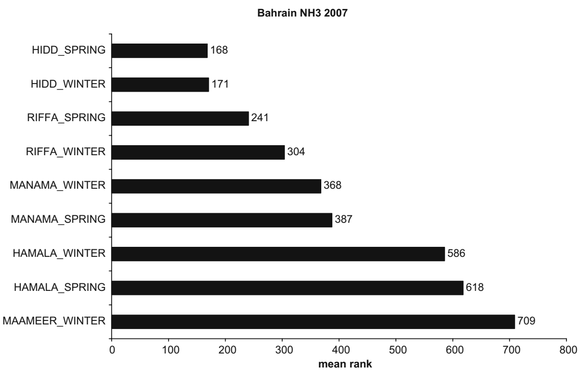

Fig. 8 KW mean rank analysis for NH_3 monitored at five stations in winter and spring 2007

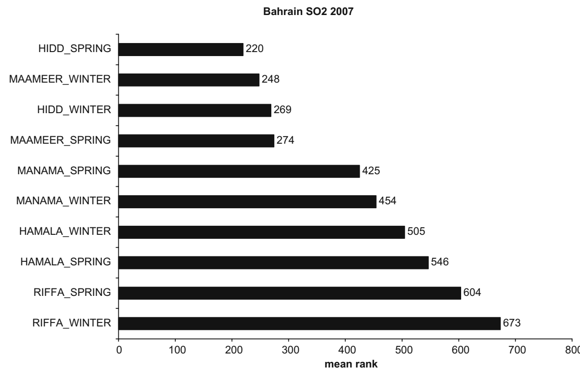

Fig. 10 KW mean rank analysis for SO_2 monitored at five stations in winter and spring 2007

air pollutant alone, that higher variability exists among sites and air pollutants. The most variable is toluene measured in ppb with a mean of 0.9 ± 1 standard deviation(SD) ppb, followed by NH_3 15.3 ± 16.7 ppb, PM_{10} 181.6 ± 168.7 μg/m^3, Xylene 0.7 ± 0.6 ppb, benzene 0.4 ± 0.3 ppb, $PM_{2.5}$ 51.3 ± 38 μg/m^3, SO_2 7.5 ± 5.4 ppb, H_2S 8.7 ± 4.9 ppb, O_3 42.5 ± 22.4 ppb, CO 0.5 ± 0.4 ppm and NO_2 23.8 ± 10.6 ppb. All variables showed heteroscedasticity and this further confirmed by the Levene test on the homogeneity of variance. Therefore ANOVA tests were discontinued and the non-parametric Kruskal–Wallis (KW) test for k-independent samples, analogous to the one-way ANOVA is applied in order to elucidate temporal and spatial variations.

Figure 2 demonstrates the KW mean rank for PM_{10} that shows a clear spatial-temporal variation among site-season groups ($\chi^2 = 202$, $df = 8$, $p < 0.000$). Both Riffa and Hamala in spring exhibited mean ranks of 533 and 481, respectively, compared with lowest mean rank of 150, for Hamala in winter. The MW test further indicates significant difference between spring and winter ($U = 35{,}537.5$, $Z = -11.7$, $p < 0.000$).

In addition, (Fig. 3) shows the KW mean rank for PM $_{2.5}$ that exhibited significant spatial variation($\chi^2 = 184.7$, $df = 9$, $p < 0.000$). Both Maameer and Manama in spring showed higher mean ranks, 607 and 541, respectively. This can be attributed to the impact of flaring in industrial activities of Oil Refinery, and to both sand washing plants and brick factories in the Maameer, and to the congested traffic in Manama. The MW test resulted significant seasonal variation between spring and winter (U= 46,523.5, $Z = -11.9$, $p < 0.000$). In this study the exceedances in both PM_{10} and $PM_{2.5}$ in haze and non haze days were crossed tabulated by season and station to investigate the correlation of haze episodes with the reported

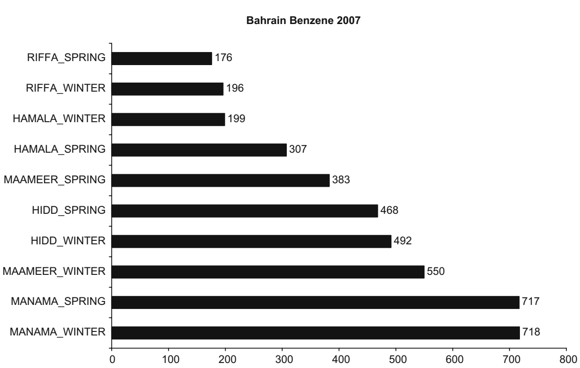

Fig. 9 KW mean rank analysis for benzene monitored at five stations in winter and spring 2007

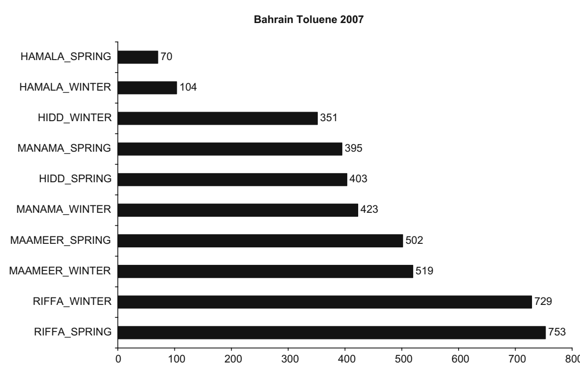

Fig. 11 KW mean rank analysis for toluene monitored at five stations in winter and spring 2007

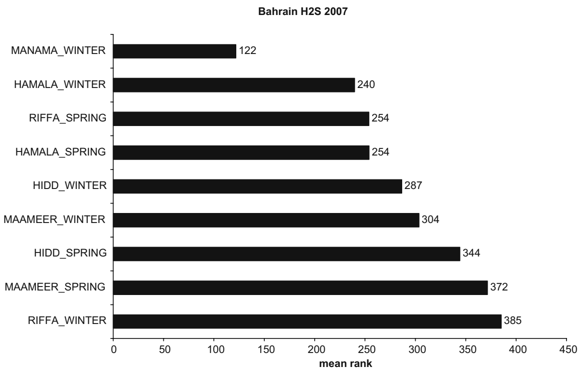

Fig. 12 KW mean rank analysis for H_2S monitored at five stations in winter and spring 2007

exceedances (Table 4). Cross tabulation test of both PM_{10} and $PM_{2.5}$ exhibited significant association with season (Pearson $\chi^2 = 11.9$, $df = 7$, $p < 0.103$; $\chi^2 = 18$, $df = 13$, $p < 0.158$, respectively), with day ($\chi^2 = 13$, $df = 7$, $p < 0.072$; $\chi^2 = 20$, $df = 13$, $p < 0.095$, respectively) and with station ($\chi^2 = 25.9$, $df = 28$, $p < 0.580$; $\chi^2 = 50$, $df = 52$, $p < 0.553$, respectively).Therefore, the results suggest that there are significant correlations between both PM_{10} and $PM_{2.5}$ exceeded values and the haze episodes. Both Riffa and Hamala are exposed and close to the Bahrain desert and to the Arabia mainland. Higher temperature, less precipitation, and wind turbulence in spring promote sand storms especially from the desert in southern Iraq which impacts Kuwait, eastern province of Saudi Arabia and Bahrain. Dust and sand storms are among the important weather phenomena in the Arabian Gulf region. This area is particularly susceptible to these storms on accounts of its low topographic relief, scanty vegetation cover, light textured topsoil and recurring strong and turbulent winds. The dominant wind is called *shamal* (Arabic = north) that is north and north-westerly. This *shamal* wind can reach speed of 153 km h^{-1}, causing dust storms and haze. Dust storms may deposit about 1,003 t km^{-2} of sediment in July (ROPME 2004).

Yang (2002) studied the spatial and seasonal variation of PM_{10} mass concentrations in Taiwan and found that in northern sites, the highest concentration occurs in March–May, which is attributed to the occurrence of dust storms in arid regions of central Asia and the transport of dust by north-easterly monsoon. The dust storms in arid regions of central Asia has been attributed to the increase of PM_{10} concentration over Taiwan (Liu et al. 2006; Cheng et al. 2007), Saliba et al. (2006) attributed the higher values of PM_{10} and O_3 over the city of Beirut, Lebanon as a result of several local and long-range transport phenomena, and Griffin et al. (2007) studied ground-based dust measured at several sites in Erdemli, Turkey and found that the region is routinely impacted by dust generated regionally and from North Africa, and that the highest African dust deposition occurred in the month of April. Furthermore, Sánchez et al. (2007) attributed the seasonal and spatial variation among stations in Spain to the impact of Saharan dust outbreak.

Figure 4 presents the KW mean rank for NO_2 that shows a clear spatial variation among sites ($\chi^2 = 210.40$, $df = 9$, $p < 0.000$). Two sites clustered together, the Riffa and Hamala. Maameer showed higher mean rank 642 compared with Hidd 285. The impact of NO_2 on Maameer may be from Oil Refinery, and that on Riffa may be attributed to the power station and aluminium smelter. The NO_2 forms brownish cloud over the power station and becomes a major environmental issue. Lahmeyer International (1999) found that the power station, the oil refinery and aluminium smelter are the major contributors to the NO_x emissions in Bahrain, all of which exceeded national, regional and international emission standards. Danish and Madany (1992) examined the concentrations of NO_2 throughout Bahrain and by including sites representing residential, heavy

Table 2 Percentages of data capture of studied air pollutants

Variable	Valid N	% Data captured
PM_{10} ($\mu g/m^3$)	751	85.1
$PM_{2.5}$ ($\mu g/m^3$)	842	95.4
NO_2 (ppb)	844	95.6
CO (ppm)	756	85.6
Xylene (ppb)	851	96.4
O_3 (ppm)	658	74.5
NH_3 (ppb)	731	82.8
Benzene (ppb)	851	96.4
SO_2 (ppb)	849	96.1
Toluene (ppb)	851	96.4
H_2S (ppb)	568	64.3

Table 3 Summary statistics of studied air pollutants

Site_season	Statistics	PM_{10} (μg/m^3)	$PM_{2.5}$ (μg/m^3)	NO_2 (ppb)	CO (ppm)	Xylene (ppb)	O_3 (ppm)	NH_3 (ppb)	Benzene (ppb)	SO_2 (ppb)	Toluene (ppb)	H_2 S(ppb)
HIDD_WINTER	Mean	129.1	36.3	20.6	0.2	0.5	56.8	7.5	0.4	4.9	0.5	8.5
	Standard deviation	138.9	39.5	7.7	0.2	0.2	10.7	13.5	0.1	2.7	0.3	3.6
	N	90.0	90.0	90.0	88.0	90.0	68.0	89.0	90.0	88.0	90.0	71.0
HIDD_SPRING	Mean	219.4	53.2	18.1	0.3	0.7	61.4	6.0	0.3	4.5	0.6	10.8
	Standard deviation	182.2	38.3	8.4	0.2	0.2	17.6	4.1	0.1	4.7	0.2	6.1
	N	82.0	82.0	91.0	71.0	91.0	87.0	91.0	91.0	91.0	91.0	81.0
MANAMA_WINTER	Mean	128.6	42.0	21.9	0.4	0.2	34.3	9.5	0.7	8.4	0.6	4.0
	Standard deviation	132.3	34.9	8.7	0.2	0.1	12.0	2.7	0.2	5.8	0.2	3.0
	N	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	49.0
MANAMA_SPRING	Mean	196.4	62.3	25.1	0.5	0.2	35.4	9.8	0.7	7.2	0.6	
	Standard deviation	170.7	41.9	8.1	0.3	0.1	14.6	2.3	0.3	4.0	0.3	
	N	91.0	91.0	91.0	77.0	91.0	91.0	91.0	91.0	91.0	91.0	
HAMALA_WINTER	Mean	83.4	45.9	18.3	0.3	0.3	50.8	24.3	0.1	8.1	0.1	7.1
	Standard deviation	99.8	27.2	6.6	0.3	0.3	24.5	9.0	0.1	3.9	0.1	1.7
	N	56.0	74.0	74.0	74.0	74.0	46.0	74.0	74.0	74.0	74.0	37.0
HAMALA_SPRING	Mean	233.7	55.6	19.0	0.4	0.7		31.4	0.2	8.6	0.1	7.4
	Standard deviation	191.1	32.3	6.6	0.1	0.2		16.0	0.1	4.0	0.0	0.9
	N	86.0	91.0	91.0	59.0	91.0		91.0	91.0	91.0	91.0	91.0
RIFFA_WINTER	Mean	164.8	45.3	31.3	1.2	1.4	30.0	8.6	0.2	12.4	2.3	12.5
	Standard deviation	161.3	38.7	10.1	0.4	0.7	10.8	3.8	0.3	7.0	1.1	6.0
	N	85.0	85.0	83.0	62.0	85.0	71.0	83.0	85.0	85.0	85.0	59.0
RIFFA_SPRING	Mean	258.3	59.0	29.5	1.0	1.5	22.3	8.0	0.1	10.9	2.4	8.3
	Standard deviation	180.6	33.1	9.3	0.3	0.7	7.6	6.1	0.3	7.0	0.9	4.9
	N	91.0	91.0	91.0	91.0	91.0	91.0	91.0	91.0	91.0	91.0	91.0
MAAMEER_WINTER	Mean	187.7	47.5	22.7	0.4	0.6	61.1	67.9	0.4	4.6	0.9	9.4
	Standard deviation	159.1	40.2	14.1	0.2	0.3	30.5	18.1	0.1	2.0	0.5	6.1
	N	80.0	83.0	78.0	80.0	83.0	83.0	31.0	83.0	83.0	83.0	51.0
MAAMEER_SPRING	Mean		69.8	34.2	0.3	0.6	27.9		0.3	5.0	0.8	10.6
	Standard deviation		41.4	11.1	0.2	0.2	12.4		0.1	2.6	0.3	3.5
	N		65.0	65.0	64.0	65.0	31.0		65.0	65.0	65.0	38.0
Total	Mean	181.6	51.3	23.8	0.5	0.7	42.5	15.3	0.4	7.5	0.9	8.7
	Standard deviation	168.7	38.0	10.6	0.4	0.6	22.4	16.7	0.3	5.4	1.0	4.9
	N	751.0	842.0	844.0	756.0	851.0	658.0	731.0	851.0	849.0	851.0	568.0

Blank spaces indicate not detected data

Table 4 Cross tabulation of exceedances in PM_{10} and $PM_{2.5}$ in haze (H) and non-haze days (NH) classified by season and station

Season	Day	HIDD		MANAMA		HAMALA		RIFFA		MAAMEER	
		PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.6}$
Winter	H	5	5	4	5	2	3	5	5	5	5
	NH	1	6	0	7	0	17	5	9	4	11
Spring	H	10	14	10	16	13	13	13	16	NA	16
	NH	0	11	0	31	1	23	3	37	NA	32
Total Exceedances		16	36	14	59	16	56	26	67	9	64

NA Not available data

and low traffic roads, industrial, airport and commercial areas. Their results revealed marked spatial variations in NO_2 concentrations. The weekly mean NO_2 values varied from 76 $\mu g\ m^{-3}$ in the north-eastern part of Bahrain to 13 $\mu g\ m^{-3}$ in the south-east of Muharraq. Generally, NO_2 values decreased from the north to the south, where traffic volume and density also decreased. In addition, the results indicated that high traffic areas had higher NO_2 levels compared with airport and industrial areas. The highest NO_2 concentrations were measured in roads characterised by being narrow and confined, with many traffic lights and roundabouts, indicating the influence of road geometry on NO_2 levels. The MW test further demonstrates significant difference between spring and winter ($U = 80{,}450.5$, $Z = -2.4$, $p < 0.016$).

Figure 5 illustrates the KW mean rank for CO that shows a clear spatial variation among sites ($\chi^2 = 363.3$, $df = 9$, $p < 0.000$). Three sites clustered together, the Riffa, Manama, and Maameer. Riffa showed higher mean rank 673 compared with Hidd 197. The impact of CO on Riffa may be attributed to the power station and vehicle exhaust emissions, whereas in Manama is due to vehicle exhaust emissions. The MW test further demonstrates significant difference between spring and winter ($U = 60, 657$, $Z = -3.6$, $p < 0.000$).

The seasonal variations found for both NO_2 and CO and not for SO_2, perhaps, may be attributed to the sour gas burning in power station for the production of more electricity demand used in air-conditioning in spring than winter.

Figure 6 gives the KW mean rank for *p*-Xylene and shows a clear spatial variation among sites ($\chi^2 = 560.8$, $df = 9$, $p < 0.000$). Three sites clustered together, the Riffa, Maameer, and Manama. Riffa showed higher mean rank 707 compared with Manama 119.The MW test further demonstrates significant difference between spring and winter ($U = 72, 440$, $Z = -5.0$, $p < 0.000$). Similar patterns have been reported by Costabile et al. (2006) in Suzhou, China. Since the benzene (will be discussed later) did not follow the pattern found for both *p*-Xylene and toluene then it is evident that the sources come from industrial emissions rather than the contribution from traffic. The general conclusion that can be drawn from the seasonal variations is that the air parameters; PM_{10}, $PM_{2.5}$, NO_2, CO and *p*-Xylene are affected by the air temperature rise in spring (from minimum = 10.8°C in winter to maximum = 38.9°C in spring). This has been confirmed by Spearman's correlation coefficient tests (Table 5) that showed significant associations of PM_{10} (Spearman's rho = 0.500, $p < 0.01$,), $PM_{2.5}$ ($rs = 0.432$, $p < 0.01$), NO_2 ($rs = 0.068$, $p < 0.05$), CO ($rs = 0.118$, $p < 0.01$), and *p*-xylene ($rs = 0.169$, $p < 0.01$) with air temperature.

Apart from the PM_{10} and $PM_{2.5}$ as shown in Table 4, only NO_2, O_3 and SO_2 showed exceedances above the standards and guidelines values (Table 6). Since the standard and guideline values are based on the mean values thus it is not unexpected that variation among these air pollutants as discussed earlier could be attributed to these exceedances. This however has been taken into the account of the Environmental Management (the Directorate of Environmental Assessment and Planning) through its decision to initiate a comprehensive GIS data base project to register all industrial and developmental projects

Table 5 Spearman's correlation coefficient and its significance for five variables correlated with air temperature

Variable	Statistics	PM_{10} (μg m^{-3})	$PM_{2.5}$ (μg m^{-3})	NO_2 (ppb)	CO (ppm)	Xylene (ppb)
Temperature (°C)	Correlation Coefficient	0.500[a]	0.432[a]	0.068[b]	0.118[a]	0.169[a]
	Significant (two-tailed)	0.000	0.000	0.047	0.001	0.000
	N	750	841	843	755	850

[a]Correlation is significant at the 0.01 level (two-tailed)
[b]Correlation is significant at the 0.05 level (two-tailed)

as well as to revise air quality standards and guidelines by a refereed international expert (UNDP consultant).

Figure 7 exhibits the KW mean rank for Ozone that shows a clear spatial variation among sites ($\chi^2 = 317.3$, $df = 8$, $p < 0.000$). Two sites clustered together, the Hidd and Manama. Hidd showed higher mean rank 506 compared with Riffa 127.The MW test further demonstrates significant difference of winter over spring ($U =$ 42,029, $Z = -4.8$, $p < 0.000$). Lahmeyer International (1999) claimed that the power station in Hidd is one of major contributors of NO_x. Since the lowest concentration of NO_2 is reported in Hidd which is the main precursor of the O_3, and then it is expected to produce the O_3, therefore the higher concentration in O_3 in Hidd may be reasoned to the contribution of the aircraft emissions that is influenced by sea breeze regime since the Hidd station is not far away from the coast compared with other inland monitoring stations and this perhaps exaggerated in foggy days in winter. Airport impacts have been reported for Atlanta's Hartsfield–Jackson airport (Unal et al. 2005), and London's Heathrow airport (Carslaw et al. 2006). Sea breeze regime, recirculation of polluted air mass, impacts have been reported in several coastal cities, in India (Nair et al. 2002), Taiwan (Cheng 2002), Korea (Oh et al. 2006), France (Ghiaus 2005), Portugal Evtyugina et al. (2006). So and Wang (2003) found seasonal pattern of O_3 in Hong Kong where low O_3 level was found in summer and elevated levels occurred in autumn and spring.

Figure 8 gives the KW mean rank for NH_3 that shows a clear spatial variation among sites ($\chi^2 = 487.9$, $df = 8$, $p < 0.000$). Almost all sites clustered together. The Maameer site in winter showed higher mean rank 709 compared with 168 for the Hidd site in spring. The MW test demonstrates no significant difference between winter and spring (U = 62,303, $Z = -1.6$, $p < 0.116$). Gilliland et al. (2006) claimed that significant uncertainty exists in the seasonal distribution of NH_3 emissions since the predominant sources are animal husbandry and fertilizer application. Löflund et al. (2002) found no seasonality but vehicle traffic and livestock breeding as causative factors for elevated NH_3 in Vienna. Skybova (2001) reasoned the higher concentration of NH_3 in the Czech Republic to the breeding of cattle, pigs, and poultry. Hao et al. (2006) reasoned the releases of NH_3 to the livestock manure in feedlots in Alberta, Canada. Lee (2006) attributed elevated NH_3 in air in Hong Kong to the sewage treatment plant and vehicle emission. In this study, sewage treatment plants in both Tubli and Nuwaidrat, and the sheep farms in Sitra, and municipal waste container in the vicinity of the monitoring station can be reasoned for the higher concentration of NH_3 reported in Maameer and to the poultry farm and diary farm in Demstan to account for this spatial variation found in Hamala.

Figure 9 demonstrates the KW mean rank for benzene that shows a clear spatial variation among sites ($\chi^2 = 539.2$, $df = 9$, $p < 0.000$). Almost all sites clustered together except Maameer. Manama showed higher mean rank 718 compared with Riff 176.The MW test demonstrates no significant difference between winter and spring (U = 84,457, $Z = -1.7$, $p < 0.091$). Benzene is a member of Volatile Organic Compounds (VOCs), found in emissions from burning coal, oil and gasoline, and in evaporation at gasoline service stations and vehicle exhausts. These and other sources all contribute to the baseline level of benzene found in outdoor air. Benzene is also released from tobacco smoke. Could it be reasoned

Table 6 Number of exceedances of the 11 air pollutants monitored in winter and spring 2007 in five monitoring stations

	Winter					Spring				
	HAMALA	HIDD	MAAMEER	MANAMA	RIFFA	HAMALA	HIDD	MAAMEER	MANAMA	RIFFA
NO_2 1 h = 106 ppb (S)	0	0	3	0	2	1	0	1	0	0
CO 1 h = 26 ppm (S)	0	0	0	0	0	0	0	0	0	0
Xylene 1 h = 168 ppb (G)	0	0	0	0	0	0	0	0	0	0
O_3 1 h = 100 ppm (G)	131	13	383	0	2	NA	73	0	33	0
NH_3 1 h = 800 ppb (G)	0	0	0	0	0	0	0	0	0	0
Benzene 24 h = 4 ppb (G)	0	0	0	0	0	0	0	0	0	0
SO_2 1h = 134 ppb (S)	0	0	0	2	5	2	0	0	1	7
Toluene 24 h = 623 ppb (G)	0	0	0	0	0	0	0	0	0	0
H_2S 1 h = 30 ppb (G)	1	1	24	0	18	0	1	3	0	6

S and G in brackets represent standard and guideline level. Particulate matters are presented in Table 4.

NA nonavailable data

for the *Shisha* (water pipe) Hubble-bubble smoking café in Manama? Lee et al. (2002) claimed that the traffic in Hong Kong is responsible for the higher values of benzene and found that it increases in winter than summer. Han and Naeher (2006) in their review concluded that the benzene in the air in the developing world mainly comes from traffic. This has also been found by Hellen et al. (2005) in Helsinki, Finland. Therefore, the spatial variation found for benzene in this study may represent the impact of traffic on these localities.

Figure 10 illustrates the KW mean rank for SO_2 that shows a clear spatial variation among sites ($\chi^2 = 334.2$, $df = 9$, $p < 0.000$). Almost all sites clustered together except Maameer. Riffa showed higher mean rank 673 compared with Hidd 220.The MW test demonstrates no significant difference between winter and spring ($U = 88,896$, $Z = -0.3$, $p < 0.738$). The Riffa data for NO_2 and CO are indeed in concomitant with SO_2 and this may suggest the impact of the gas-fired power station on Riffa site. However, in Kuwait, Al-Rashidi et al. (2005) were unsuccessful to model SO_2 in six stations and concluded that the existing locations of the Kuwait-EPA monitoring stations are not suitable for measuring the actual impact of SO_2. Therefore, there is a need for relocation of these sites to register the highest levels of SO_2 emitted from the current power stations in the State of Kuwait.

Figure 11 gives the KW mean rank for toluene that shows a clear spatial variation among sites ($\chi^2 = 636.3$, $df = 9$, $p < 0.000$). Three sites clustered together, the Riffa, Maameer and Hamala. Riffa showed higher mean rank 753 compared with Hamala 70. The MW test demonstrates no significant difference between winter and spring ($U = 87,929.5$, $Z = -.7$, $p < 0.470$). The increases of toluene in Riffa site with concomitant increase of *p*-Xylene followed by the lowest levels of benzene can not be attributed to the car exhaust and suggest industrial sources.

Figure 12 features the KW mean rank for H_2S that shows a clear spatial variation among sites ($\chi^2 = 101.5$, $df = 8$, $p < 0.000$). Riffa showed higher mean rank 385 compared with Manama 122. The MW test demonstrates no significant difference between winter and spring ($U = 37,605$,

$Z = -1.3$, $p < 0.187$). The higher values in Riffa may be attributed to the natural gas exploration in the area or else fugitive gas leakage from main pipeline.

General conclusions

This study provides fundamental information regarding the temporal and spatial variations of air pollutants and also gives the status of the ambient air quality in the Kingdom of Bahrain.

One of the major findings of this study is that both PM_{10} and $PM_{2.5}$ are originated from dust storms from the typical nature of the local desert and trans-boundary airborne effects from southern Iraq desert that not only impacts Bahrain but also Kuwait and eastern province of Saudi Arabia and perhaps extends further to the Arabian Gulf. It is therefore suggested to study this natural phenomenon via satellite imagery by the concerned regional organisation such as the Regional Organization for the Protection of the Marine Environment (ROPME).

The proper use of statistical manipulation of data enabled us to detect the higher levels of pollution being in Riffa and these findings have been shown to further support the argument that the impact is from industrial and developmental sources, and the gas-fired power station is the major contributor to these elevations. Maameer exhibited the second order of magnitude. This indicates clearly the contributions of the industrial area itself that is characterised by the sand-based factories, heavy truck traffic and to the oil refinery, power station and aluminium smelter all of which have been found to contribute to NO_2 pollution level as modelled by real emission calculations by Lahmeyer International (1999), and this indeed strengthens the efforts and measures already taken by the General Directorate for the Protection of Environment and Wildlife to impose compliance policies on these three major sources of air pollutants. Other managerial steps have been taken to imitate GIS data base for industrial and development projects and revision of air quality standards and guidelines.

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