Environ Monit Assess (2019) 191: 143
https://doi.org/10.1007/s10661-019-7259-9

Long-term trends in ambient fine particulate matter from 1980 to 2016 in United Arab Emirates

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Received: 20 September 2018 / Accepted: 22 January 2019 / Published online: 8 February 2019

Abstract This paper presents the most comprehensive datasets of ambient fine particulate matter ($PM_{2.5}$) for the UAE from 1980 to 2016. The long-term distributions of $PM_{2.5}$ showed the annual average $PM_{2.5}$ concentrations constantly exceeded the EPA and WHO guidelines. They varied from 77 to 49 μg/m^3 with an overall average of 61.25 μg/m^3. While the inter-annual variability in $PM_{2.5}$ concentrations showed relatively a cyclic pattern, with successive ups and downs, it broadly exhibited an increasing trend, particularly, over the last 14 years. $PM_{2.5}$ concentrations displayed a strong seasonal pattern, with greatest values observed during warm summer season, a period of high demand of electricity and dust events. The lowest values found in autumn are attributable to reduced demand of energy. Decreased atmospheric temperatures and high relative humidity coinciding with this period are likely to reduce the secondary formation of $PM_{2.5}$. The spatial changes in $PM_{2.5}$ concentrations exhibited gradual downward trends to the north and northeast directions. Airborne $PM_{2.5}$ is prevalent in the southern and western regions, where the majority of oil and gas fields are located. $PM_{2.5}/PM_{10}$ ratio indicated that ambient aerosols are principally associated with anthropogenic sources. Peaks in $PM_{2.5}$/CO ratio were frequently observed during June, July, and August, although few were concurrent with March. This indicates that secondary formation plays an important role in $PM_{2.5}$ levels measured in these months, especially as the photochemical activities become relatively strong in these periods. The lowest $PM_{2.5}$/CO ratios were found during September, October, and November (autumn) suggesting a considerable contribution of primary combustion emissions, especially vehicular emissions, to $PM_{2.5}$ concentration. $PM_{2.5}$ concentrations are positively correlated with sulfate levels. In addition to sea and dust aerosols, sulfate concentration in the coastal region is also related to fossil fuel burning from power plants, oil and gas fields, and oil industries. The population-weighted average of $PM_{2.5}$ in UAE was 63.9 μg/m^3, which is more than three times greater than the global population-weighted mean of 20 μg/m^3.

Keywords $PM_{2.5}$ · Aerosol · Emissions · UAE

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Introduction

Air quality issues in United Arab Emirates (UAE) are of growing public and environmental concerns. Over the last decades, the UAE has observed a rapid economic development, expansion in transportation sector, and a significant increase in industrial activities transforming the country into regional and global centers for commerce and industry. These changes have placed substantial burden on air quality and posed potential threat to public health. Despite significant improvements in public health, air pollution still presents a potentially environmental threat and is considered a priority health issue by the country's national strategic plan (Al Jaberi et al. 2010; Reid et al. 2004).

Among others, elevated levels of ambient air particulate matter (PM) remain in the forefront of the UAE efforts to provide mitigation measures and ensure compliance with national ambient air quality standards. The adverse health impacts associated with exposure to PM aerosols are well documented (Goldberg et al. 2001; Analitis et al. 2006; Ostro et al. 2006;Zanobetti and Schwartz 2009; Silbajoris et al. 2011; Agay-Shay et al. 2013; Li et al. 2013; Burnett et al. 2014; Zhang et al. 2014) including reduction in life expectancy (Keuken et al. 2011; Pascal et al. 2014).

Li et al. (2010) estimated that during 2017, about 545 excess deaths in the UAE have been attributed to ambient air PM accounting for about 7% of the total deaths occurred in that year. In addition, they concluded that anthropogenic ambient air pollution, especially PM, has considerably contributed to premature deaths in the UAE.

PM can also affect ecosystems, reduce visibility, decreased photosynthesis, alter the soil physicochemical properties, and affect meteorological processes (Grantz et al. 2003; Lin et al. 2012; Von Schneidemesser et al. 2015). PM can be of natural or anthropogenic origins. Natural sources include crustal dust, biological materials, and sea spray, whereas anthropogenic PM is directly emitted into the atmosphere or formed as secondary pollutants (including sulfate, nitrate, ammonium, and organic matter) when primary air pollutants undergo chemical transformations to form fine particles (EPA 2003).

Reducing particulate matter levels in the UAE and improving ambient air quality are difficult tasks because there are many sources both inside and outside the country's borders. In addition to sea salt aerosols, the heavy traffic volumes, combustion process, construction sites, power plants, and the ever-present desert sand (within or surrounding the country) all work simultaneously to elevate ambient PM levels.

The prevailing arid to hyper-arid climatic conditions in the UAE with high temperatures and relative humidity (> 90%) are important contributors to PM concentrations. The formation of secondary aerosols (by gas to particle conversion) is a temperature-driven process. Variations in the relative humidity can influence the hygroscopic aerosol particle, where absorption of water increases the particle size and affects its lifetime in the atmosphere (Nilsson 1994).

Airborne PM of greatest health concern is $PM_{2.5}$ (with aerodynamic diameter smaller than 2.5 μm), where epidemiological studies have found association between exposure to $PM_{2.5}$ and increased rates of mortality and morbidity (Samet et al. 2000; Pope III et al. 1995).

This paper presents the most comprehensive datasets of ambient fine particulate matter ($PM_{2.5}$) for the UAE from 1980 to 2016. These datasets are used to investigate the spatiotemporal distribution and the potential sources of $PM_{2.5}$. This assessment is likely to enhance our understanding of the general behavior of $PM_{2.5}$ in the UAE air and unveil the long-term trends. Also, it can inform whether effective measures should be implemented to mitigate health and environmental outcomes, and ensures compliance with ambient air quality guidelines.

Methodology

Description of study area

The UAE is an arid country, with more than 80% of the country's total area is classified as a desert. It lies between 22° 29′ and 26° 4′ north latitude and between 51° 5′ and 56° 23′ east longitude. The Tropic of Cancer passes through the southern part of UAE causing substantially higher temperatures throughout the year, particularly from June through August (Table 1). The annual average temperature in the UAE is 35 °C, where it decreases to 18 °C in December through February (winter). It receives occasional wintertime rainfall from December to February, though it may extend from November through March, during which temperatures rarely drop below 6 °C. The annual average precipitation is about 120 mm (Farahat et al. 2015) with higher rainfall and lower temperatures occurring in the northeastern part compared to the southern and western regions (Farahat 2016). The wintertime monsoon accounts for

Table 1 Meteorological data of the UAE (2017) (National Centre of Meteorology 2017)

Month	Temperature (°C)					Humidity (%)			Rainfall (mm)	Wind (km/h)			Solar radiation (wh/m^2)
	Max	Mean max	Mean	Mean min	Min	Mean max	Mean	Mean min		Mean	Max	Mean max	
January	31.3	22.6	20.1	17.7	12.9	80	66	51	9.2	13.8	54	23.5	4204.4
February	36.2	24.1	21	18.5	13.2	81	66	48	4.4	15.1	59.4	26.1	4979.4
March	40.2	27.1	23.6	20.8	13.4	80	63	42	9.4	15	73.4	27.2	5835.7
April	43	31.3	27.4	24.5	17.5	77	59	36	7	13.5	68.8	25.9	6501.7
May	45.7	35.6	31.4	28.4	23.8	75	57	34	0	12.9	49.7	24.2	6965.5
June	46.7	36.6	33.1	30.3	25.3	78	62	41	0	13.7	47.9	24.9	6787.1
July	47.9	38.9	35	32.3	28.5	78	61	39	0	13.8	47.2	25.3	6428.8
August	48	40.3	35.5	32.8	29.1	78	59	33	0	13.9	43.2	26.1	6337.7
September	45	37.2	33.6	30.9	27.4	79	63	41	0	13.2	47.5	24.6	5937.4
October	41.6	33.7	30.8	27.9	24	79	63	45	0	12.8	62.3	22.6	5347.5
November	37.4	29.6	26.9	24.3	19	75	61	45	2.4	13.4	64.8	23.3	4426.3
December	31.6	24.5	22.4	20	12.6	79	66	53	15.1	13.7	51.1	23.5	4098.4

the majority of rainfall precipitation in the lower elevations of the UAE (UAE Science Plan 2004). Summer season, extending from June through August, is very hot and humid with temperatures rising to about 48 °C and humidity of greater than 90%. Winds are predominantly from the north and northwest directions, though the southerly winds are also common (Fig. 5).

Data acquisition

The number of existing air quality monitoring sites in the UAE is relatively small and often located to monitor known pollution sources or capture background air quality levels. We used satellite-derived $PM_{2.5}$ estimates as they offer sources for long-term $PM_{2.5}$ concentrations and can allow for temporal and spatial distribution analyses compared to limited ground-based $PM_{2.5}$ observations. These datasets, obtained from MERRA-2 (the second Modern-Era Retrospective analysis for Research and Applications), provide daily and monthly mean $PM_{2.5}$ concentrations for the period 1980 to 2016 (https://disc.gsfc.nasa.gov/daac-bin/FTPSubset2.pl?LOOKUPID_List=M2TMNXAER). Summary of data sources utilized is tabulated in Table 2.

MERRA-2 is a NASA atmospheric reanalysis that begins in 1980 (GMAO 2015). An overview of the MERRA-2 modeling system is found in Gelaro et al. (2017) and Randles et al. (2017). MERRA-2 uses the Goddard Earth Observing System version 5 (GEOS-5) atmospheric model and data assimilation system (DAS) (Rienecker et al. 2008; Molod et al. 2015). The dataset offers two-dimensional diagnostics of surface fluxes, single-level meteorology, vertical integrals, and land states, generated at 1 hourly, 3 hourly, daily, and monthly intervals. This paper utilizes the Dust Column Mass Density - $PM_{2.5}$ (M2TMNXAER) from the single-level diagnostic tavgM_2d_rad_Nx data product averaged over a monthly interval (GMAO 2015).

Table 2 presents a summary of the key parameters of the data sources analyzed in this study. More detailed information from each of the data sources are presented in the following paragraphs.

The MERRA-2 data product and system

The MERRA-2 reanalysis is produced by the NASA Global Modeling and Assimilation Office (GMAO) using the GEOS-5.12.4 system (Bosilovich et al. 2015, 2016; http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2). It replaces and extends the original MERRA reanalysis (Rienecker et al. 2011) and includes updates to the AGCM (Molod et al. 2012, 2015) and to the

Table 2 Summary of data sources utilized in this study

Data source	Data type	Spatial resolution	Period
MERRA-2	Reanalysis	0.5 × 0.625	1980–2016

global statistical interpolation (GSI) atmospheric analysis scheme of Wu et al. (2002). In addition to the atmospheric in situ and remote sensing observations assimilated in MERRA, the MERRA-2 system also ingests observations from newer microwave sounders and hyperspectral infrared radiance instruments, as well as other new data types. One notable change is the assimilation of aerosol observations, including black and organic carbon, sulfate, and dust. The MERRA-2 meteorological observing system includes numerous additions that are detailed in McCarty et al. (2016). Bosilovich et al. (2016) presents the validation of the MERRA-2 meteorological, radiation, ozone, and cryospheric fields.

Data obtained from MERRA-2 did not require special software. The spatial distribution maps and figures were created using the software Arc GIS 9.

Results and discussion

Temporal variations

The long-term distributions of annual average concentrations of $PM_{2.5}$ in UAE from 1980 to 2016 are presented in Fig. 1 and Table 3. The annual average $PM_{2.5}$ concentrations constantly exceeded the EPA and WHO guidelines for ambient air quality of 35 μg/m^3 (EPA 2015) and 10 μg/m^3 (WHO 2005), respectively. The mean long-term concentration of ambient $PM_{2.5}$ during the survey period was 61.25 μg/m^3 with annual average maximum and minimum values of about 77 μg/m^3 (occurring in 2008, 2009, and 2012) and 49 μg/m^3 (recorded in 1989), respectively.

The annual average concentrations of $PM_{2.5}$ broadly showed an overall increasing trend, particularly, over the last 14 years (Fig. 1). High economic growth rates, low energy costs (subsidized by the federal government), and a growing population number have placed the UAE among the countries with highest rates of energy consumption (Farahat 2016). The expansion in power generation industry to meet the growing demands contributes substantially to ambient $PM_{2.5}$ levels. In the UAE, power plants rely primarily on natural gas, but heavy oil and diesel are occasionally used (EAD 2008). Particle emissions from natural gas-fired generating units, driven by combustion turbines, showed elevated emissions at rates of orders of magnitude higher than background particle concentrations (Brewer et al. 2016).

MERRA data is point data, where every point contains the information on the climate variables at this location. Fig. 2 shows the distribution of the 20 selected MERRA points over UAE.

In addition to the expansion in transportation sector, infrastructure development and increasing industrial activities, the climate change is likely to contribute to increased levels of ambient $PM_{2.5}$, due to decreased rainfall precipitation and enhanced secondary photoformation of $PM_{2.5}$ (Racherla and Adams 2006).

The inter-annual variability in $PM_{2.5}$ concentrations showed relatively a cyclic pattern, with successive ups and downs (Fig. 1 and Table 3). This is clearly demonstrated when the ambient $PM_{2.5}$ levels were averaged and plotted in 5-year intervals (Fig. 3). The results showed apparent fluctuations with a repetitive increase–decrease pattern in the levels of $PM_{2.5}$ and a tendency for higher $PM_{2.5}$ concentrations over the course of study period, where the concentrations showed slightly continuous but unequal increases both in the lower and the higher values.

$PM_{2.5}$ levels showed a remarkable monthly variability, with the greatest value found in July (89.6 μg/m^3) (Fig. 4). This is coinciding with periods of the driest conditions (Table 1), high demand of electricity, and

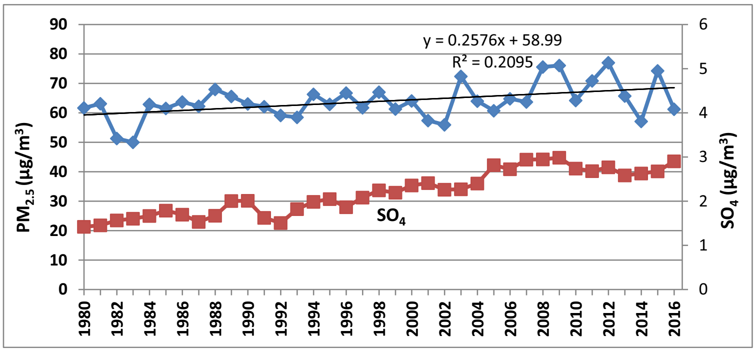


Fig. 1 Temporal variations in ambient $PM_{2.5}$ and sulfate concentrations in the UAE from 1981 to 2016

Table 3 Annual ambient $PM_{2.5}$ levels ($\mu g/m^3$) in UAE from 1980 to 2016

Year	Data location																				Min	Max	Mean	STD
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	16	16	17	18	19	20				
1980	85.4	76.5	74.8	77.5	74.8	66	65.1	68.2	66.7	73.8	62	55.7	55.3	58.6	53.8	47.8	48.4	45.9	39.8	37.3	37.3	85.4	61.6	13.5
1981	84.6	77.6	77.6	82	72.9	66.8	67.9	72.9	68.4	68	59.3	56.3	58.9	63.5	55.2	52	50.3	47.7	41.4	38.7	38.7	84.6	63	13.1
1982	73.6	66.3	65.5	69.3	61	54.6	54.9	58.9	59.3	56.8	47.6	43.7	44.3	48.2	46.2	37.7	40.2	36.8	32	29.6	29.6	73.6	51.3	12.6
1983	70.5	64.8	64.6	68.6	58.6	53	53.7	58	60.3	55.3	45.4	41.7	42.7	46.8	46	35.4	39.6	35.8	31.3	28.4	28.4	70.5	50	12.6
1984	84.8	76.5	76.1	79.8	74.4	66.6	66.4	70.2	69.7	74.7	61.9	56.5	56.8	60	56.3	49.2	50.5	46.9	42	38.9	38.9	84.8	62.8	13.1
1985	82.6	76.6	77.6	83.6	68.5	62.4	65.1	72.6	73.8	65.8	53.6	49.9	53.3	60.8	57.4	48.8	50.3	47.3	41.4	38.6	38.6	83.6	61.5	13.5
1986	83.5	76.8	77.2	81.7	74.7	67.4	67.9	72.8	73.8	72.8	63.1	58	58.8	63.5	58.4	52.9	50.7	46.5	38.1	35.2	35.2	83.5	63.3	13.8
1987	82	75.3	76.7	82.7	70.1	63.9	66.1	73	74.8	66.8	56.4	53.1	56.2	63.1	59.8	51	52.2	47.3	39.1	36.1	36.1	82.7	62	13.4
1988	93.6	85.2	84.4	89.6	78.8	71.3	72.3	78.8	80.4	74.9	62.2	57.4	60	66.9	63.5	54	55.5	50.6	41.5	37.9	37.9	93.6	67.7	15.6
1989	89.4	82.8	83.1	88.9	74.8	68.7	70.3	77.4	77.2	71.1	58.7	54.2	56.5	63.7	61.5	49.6	54	49.1	41.8	38.3	38.3	89.4	65.4	15.2
1990	82.3	76.8	78.1	84.6	68.7	63.7	66.1	73.3	79.3	66.8	54.8	51.3	54.3	61.2	63.3	48.6	55	50.3	42.7	39.2	39.2	84.6	62.9	13.3
1991	85.4	76.1	74.8	78.6	74.3	65.5	65.3	69.8	71.3	75.3	61.4	54.9	55.4	60.3	57.1	48.4	50.6	46.9	37.5	33.7	33.7	85.4	61.9	14
1992	86.1	76	73.7	76.4	73.6	64.7	63.9	67.5	64.9	71	58.6	52.9	53.3	57.4	50.8	44.9	44.4	40.8	32.7	29	29	86.1	59	15.5
1993	82.1	74.3	73.8	78.5	69.8	62.6	63.2	68.7	67.4	66.3	54.9	50.1	52.1	57.9	52.3	45.2	45.5	41.4	33.6	30.4	30.4	82.1	58.3	14.6
1994	93.7	84.9	83	86	80.2	71.8	71.4	75.4	72.9	76.3	63.7	58.1	59.3	64.1	58.2	51.6	52	48.2	39	35.7	35.7	93.7	66.1	16
1995	86.1	79	79.1	83.4	73.4	67	68.5	74.1	70.3	68.8	58.9	55.4	57.4	63.2	56.3	50.5	49.8	45.8	37.1	33.7	33.7	86.1	62.6	14.7
1996	89.3	82.4	81.5	85.1	78.2	72.1	73.8	78.7	75.1	68.6	62.7	61	65.1	71.4	60.1	59.2	52.6	48.2	36	33.4	33.4	89.3	66.2	15.4
1997	86.1	77.8	76.7	80.9	73.8	65.7	65.4	70	72.4	71.9	59.2	53.3	53.4	58	58.1	45.6	50.8	45.6	36.7	33.2	33.2	86.1	61.5	14.8
1998	89.7	83	83.4	88.9	77.8	71.7	73.3	79.7	78	70	62.2	59	61.7	68.9	62.2	55.8	54.1	48.7	37.6	34.7	34.7	89.7	66.6	15.7
1999	82.4	75.3	76.1	82	69.8	64.2	67	74.3	71	64.9	55.2	52.8	57.1	65.4	55.5	52.7	48.8	45.1	34.5	31.7	31.7	82.4	60.9	14.4
2000	88.8	81.4	81.6	86.8	75.5	68.5	69.5	75.7	73.5	71	59.8	55.4	57.3	63.1	57.4	49.5	50	45.3	36.6	34.1	34.1	88.8	63.8	15.9
2001	79.1	73	73.5	79.3	65.5	59.6	61.4	67.9	70.5	62	50.1	46.2	48.4	54.9	55.3	41.6	47.2	42.5	36.1	33.3	33.3	79.3	57.3	14
2002	76.3	69.3	69.5	75.2	63.5	57.4	58.8	65.3	69.5	60.2	49.5	45.8	48.1	54.8	54.7	42.8	47.5	43.3	35	32	32	76.3	55.8	12.8
2003	93.9	86.6	86.6	92.1	82.9	76.1	77	83.5	83.2	78	67.7	64.4	66.7	73.9	67.6	61.2	60.6	57.3	45.3	42.9	42.9	93.9	72	14.3
2004	87.9	79.1	77.4	82	74.7	67.1	66.9	72.2	75	72	59.1	54.8	55.8	61.5	60	49.3	53.4	50.3	41.7	40.1	40.1	87.9	64	13.5
2005	83.4	75.3	73.7	77.7	71	63.9	63.6	68.2	70	68.3	56.5	52	52.9	57.5	57.2	46.8	51	47.4	39.9	37.7	37.7	83.4	60.7	12.8
2006	88.8	80.9	78.5	81.8	76.6	69.5	68.6	72.7	73.7	71.6	60.9	56.9	58.1	62.6	59.4	50.7	53.3	49.9	41.8	39.3	39.3	88.8	64.7	13.7
2007	86.3	78.5	76.5	79.9	74.7	67.8	67.3	71.9	70.4	72.2	59.9	55.9	57.2	62.6	57.9	51.7	52.7	50	41.1	39.7	39.7	86.3	63.6	12.9
2008	98	89.7	87.9	91.4	86.5	78.7	78.2	83	83.7	87.4	73	67.5	68.1	73.5	70.9	63.4	65.2	62.3	52.8	50.4	50.4	98	75.5	13.1
2009	99.4	91.5	89.6	92.7	88.7	81	80.2	84.3	83	87.2	74.8	69.3	69.7	74.3	70.2	62.6	64.2	61	50.1	47.4	47.4	99.4	75.8	14.2

Table 3 (continued)

Year	Data location																				Min	Max	Mean	STD
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	16	16	17	18	19	20				
2010	85	77.9	76.9	82.1	73.1	66.9	67.3	73.4	75.9	69.7	58.6	55.3	57.3	64.1	61.4	53.2	54.6	51.4	41	39.4	39.4	85	64	12.9
2011	97.7	88.6	86.8	90	84.6	76	75.9	80.7	77.3	84.5	68.6	62.3	63.6	69.6	62.5	56.4	56.1	53.3	42.3	40.1	40.1	97.7	70.7	16.1
2012	103	95	93	96.1	89.7	82.2	82	86.2	84.1	85.6	73.3	68.7	70	75.3	70.3	62.7	64	61.1	50.4	47.9	47.9	103	76.9	15.2
2013	92.3	84.6	82.3	84.6	78.8	71.3	71	75	73	75.8	60.9	55.6	57.3	63.1	58.9	49.6	52.7	49.6	40.1	37.4	37.4	92.3	65.6	15.5
2014	76.6	70.5	69.9	74.9	65	59.3	60	65.7	69.2	62.4	51.2	47.5	49.6	55.7	55.8	44.7	49.2	45.3	35.8	33.4	33.4	76.6	56.9	12.4
2015	99.9	90.4	88	92.3	87.8	79	78.6	83.5	81.1	87	72.4	67.2	68.6	74.2	66.4	62.7	59.9	57.6	45.6	43.5	43.5	99.9	74.1	15.3
2016	86.3	78.9	78.6	82.9	70.9	64.1	65.5	71.7	70.9	67.9	54.1	49.7	52.1	58.9	56.1	46.8	49.2	46.1	38.3	36.2	36.2	86.3	61.3	14.7
Min	70.5	64.8	64.6	68.6	58.6	53	53.7	58	59.3	55.3	45.4	41.7	42.7	46.8	46	35.4	39.6	35.8	31.3	28.4				
Max	103	95	93	96.1	89.7	82.2	82	86.2	84.1	87.4	74.8	69.3	70	75.3	70.9	63.4	65.2	62.3	52.8	50.4				
Mean	86.9	79.3	78.6	83	74.5	67.5	68.1	73.4	73.3	71.4	59.8	55.4	57.1	62.8	58.8	50.7	52.1	48.3	39.7	37				
STD	7.3	6.7	6.3	6.3	7.3	6.7	6.4	6.5	5.9	7.9	6.9	6.6	6.5	6.8	5.7	6.7	5.7	5.9	4.9	5.1				

dust events. The concentrations are declining steadily from July through to a minimum in November (37.9 μg/m^3), before rising again in March. A slight decrease in $PM_{2.5}$ is then observed through to May before increasing considerably to approach the maximum concentrations in July. A similar pattern is likely to be recorded every year and is linked to greater emissions of both primary (related to fossil fuel burning) and secondary PM precursors.

The lowest values found in November are corresponding to the end period of autumn season with decreased atmospheric temperatures (Table 1). Lower temperatures and high relative humidity are likely to reduce the secondary formation of $PM_{2.5}$ in November. Also, the decline in $PM_{2.5}$ concentrations during November is probably attributable to reduced demand of energy, which marks the end of extremely hot episodes.

Seasonal fluctuations in $PM_{2.5}$ are evident (Table 4). Peak in $PM_{2.5}$ was observed in the hot dry summer (June–August) with an average concentration of 81.2 μg/m^3. The summertime values ranged between 40.3 and 142.2 μg/m^3. However, the lowest average $PM_{2.5}$ was found in autumn (September–November) with a mean concentration of about 44.3 μg/m^3 (varying from 129.6 to 36.9 μg/m^3).

Dust storms are an important source of $PM_{2.5}$ (Shen et al. 2011). van Donkelaar et al. (2010) argued that dust and sea salt components of $PM_{2.5}$ account for about half the population-weighted mean $PM_{2.5}$ concentrations in the Middle East, including the UAE. While summer season experiences frequent dust storms, the frequency of occurrence of dust events is higher in springtime (Basha et al. 2015). Another contributing factor to summertime $PM_{2.5}$ peaks is emissions from electricity-generating power plants. Energy consumption in the UAE increases considerably during summer. Residential buildings account for about 90% of the total annual electricity consumption in the UAE, mostly in Dubai and Abu Dhabi (Dubey and Krarti 2017). Air conditioning, among others, is responsible for a large proportion of the country's energy consumption, representing 79% of the total annual domestic electricity consumption in Abu Dhabi (Dubey and Krarti 2017). Similar consumption rates were observed for Dubai, where the increase in energy demand is likely to rise the primary emissions of ambient $PM_{2.5}$ through fossil fuel burning for power generation (Hamdan et al. 2016).

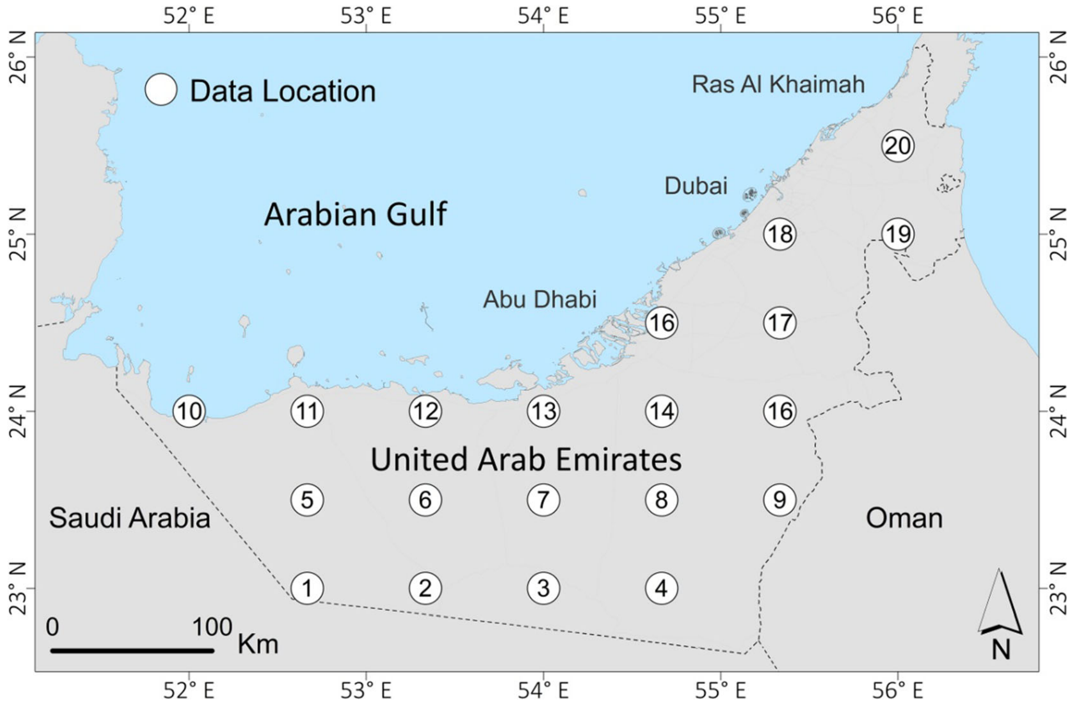
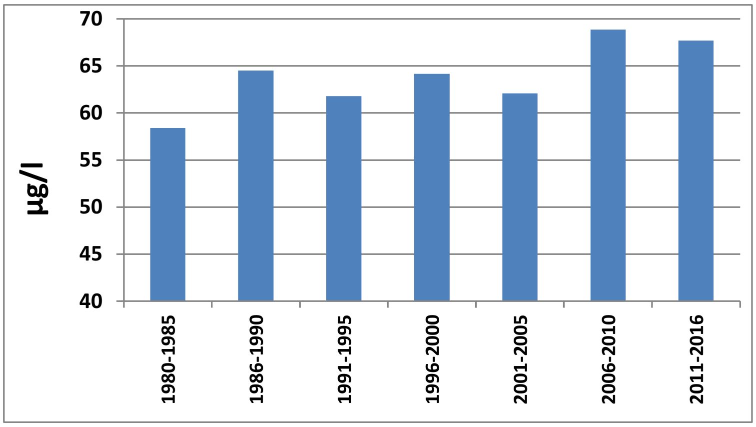


Fig. 2 Distribution map of the 20 selected MERRA points over UAE

In addition to increased anthropogenic emissions from fossil fuel burning (for air conditioning, power generation, industries, vehicles, etc.), the summer $PM_{2.5}$ maximum may also be related to weather conditions (Table 1). It has been reported that PM concentration is influenced by various factors such as land use, population density, and meteorology condition (Xu et al. 2016). The dry and hot summer season with higher atmospheric UV radiation (Table 1) may enhance the formation of secondary $PM_{2.5}$, through the photochemical reaction of precursors (VOCs and NO_x), during which fine particulate matters are formed, among others (Hamdan et al. 2016).

Airborne $PM_{2.5}$ concentrations decreased in the winter season (December–February), compared to summertime values, ranging between 20.8 and 119.6 μg/m^3 with an average value of 55.0 μg/m^3. Intermittent and low rainfall is received in wintertime with an amount totaling of about 120 mm. The occurrence of precipitation and mixing of relatively clean air mass may result in a deposition, dispersion, and dilution of $PM_{2.5}$ in winter (Table 1). The decreased temperatures during winter season are likely to reduce the secondary formation of $PM_{2.5}$. The industrial and domestic demand of energy for cooling is at low levels during winter, where the

Fig. 3 Ambient $PM_{2.5}$ concentrations plotted as 5-year intervals



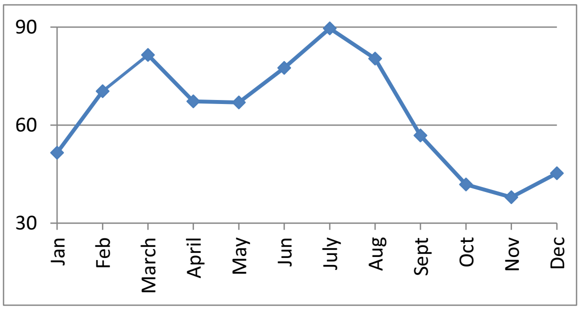


Fig. 4 Monthly average of ambient $PM_{2.5}$ in UAE from 1980 to 2016

overall energy consumption decreases considerably with subsequent reduction in $PM_{2.5}$.

In spring time, however, elevated levels of $PM_{2.5}$ have been observed with values varying from 36.9 to 129.6 μg/m^3 and a mean concentration of 70.9 μg/m^3. Dust storm events peak during the premonsoon season (March–May) when dust aerosols are transported by southwesterly winds (Middleton 1986; Basha et al. 2015). Dust storms are originated from the Arabian Gulf and Rub' al Khali "Empty Quarter" (which is the largest sand desert in the world, comprising most of the southern part of the Arabian Peninsula). In general, the UAE, and the majority of the Middle East region, is affected by dust storm events for almost 30% of the time during various season (Al-Taani et al. 2015; Furman 2003). They can also originate from the southeastern Iraq, where dusts are transported by the northerly and northwesterly winds (Fig. 5) towards the UAE (Ministry of Presidential Affairs 2011).

These dust clouds effect the vertical distribution of temperature and create thermal inversion, with a cooling effect at the surface and warming in the atmosphere (Basha et al. 2015). During the storm, dust particles absorb the incident solar radiation resulting in increased atmospheric temperatures at higher altitudes, where the temperature of dust cloud changes with variations in dust particle size (Vinkovic 2006). The temperature inversion is likely to trap $PM_{2.5}$ near the surface and increases the $PM_{2.5}$ concentrations (Liu et al. 2016).

Shen et al. (2011) observed higher mean concentration of 528.0 μg/m^3 for $PM_{2.5}$ during dust storms in a semi-arid area of Tongyu, China, whereas during non-dust storm periods, the value decreased to 111.7 μg/m^3. Many others have reported similar observations (Chung et al. 2003; Cao et al. 2005; Shen et al. 2007).

The Arabian Peninsula hosts the largest oil reserve in the world and is a home to leading oil and petrochemical industries (Batayneh et al. 2014, 2015; Al-Taani et al. 2013), especially on the western coast of the Arabian Gulf. For example, the eastern Saudi Arabia hosts SABIC (one of the largest petrochemical industries in the world) and ARAMCO (a leading crude oil exporter with largest oil refineries). These industries are located in the north and northwest directions of the UAE and are likely to contribute substantially to ambient $PM_{2.5}$ through primary emissions or secondary precursors, where airborne emissions are transported by the northerly winds towards the UAE.

In addition to local oil, petrochemical and other various industries in the UAE, the Iranian onshore oil ports with various petrochemical industries (situated on the other side, facing the eastern coast of UAE), are also potential sources of ambient $PM_{2.5}$ as well.

Table 4 Statistical summary of seasonal variations in $PM_{2.5}$ (μg/m^3) in UAE for data representing the period from 1980 to 2016

	Mean	Max	Min	STD
	μg/m^3			
Winter	55.7	102.1	23.9	18.45
Spring	71.9	113.3	44.0	16.25
Summer	82.5	118.9	42.4	18.66
Autumn	45.5	81.2	22.1	13.50

Spatial variations

Figure 6 shows the spatial changes of annual average of $PM_{2.5}$ concentrations across the UAE since 1980–2016. Airborne $PM_{2.5}$ is prevalent in the southern and western UAE, where the majority of oil and gas fields are located. While the annual mean $PM_{2.5}$ levels exceeded the EPA and WHO air quality standards in all emirates, the spatial distribution exhibited gradual downward trends to the north and northeast directions, reaching the minimum values in Ras Al-Khaimah. The lower levels of airborne $PM_{2.5}$ observed in the far northeastern regions are related to multiple factors. Meteorological conditions of higher rainfall and lower temperatures in the northeastern part (compared to the southern and western regions; Farahat 2016), may result in deposition of $PM_{2.5}$ and reduce the secondary formation processes.

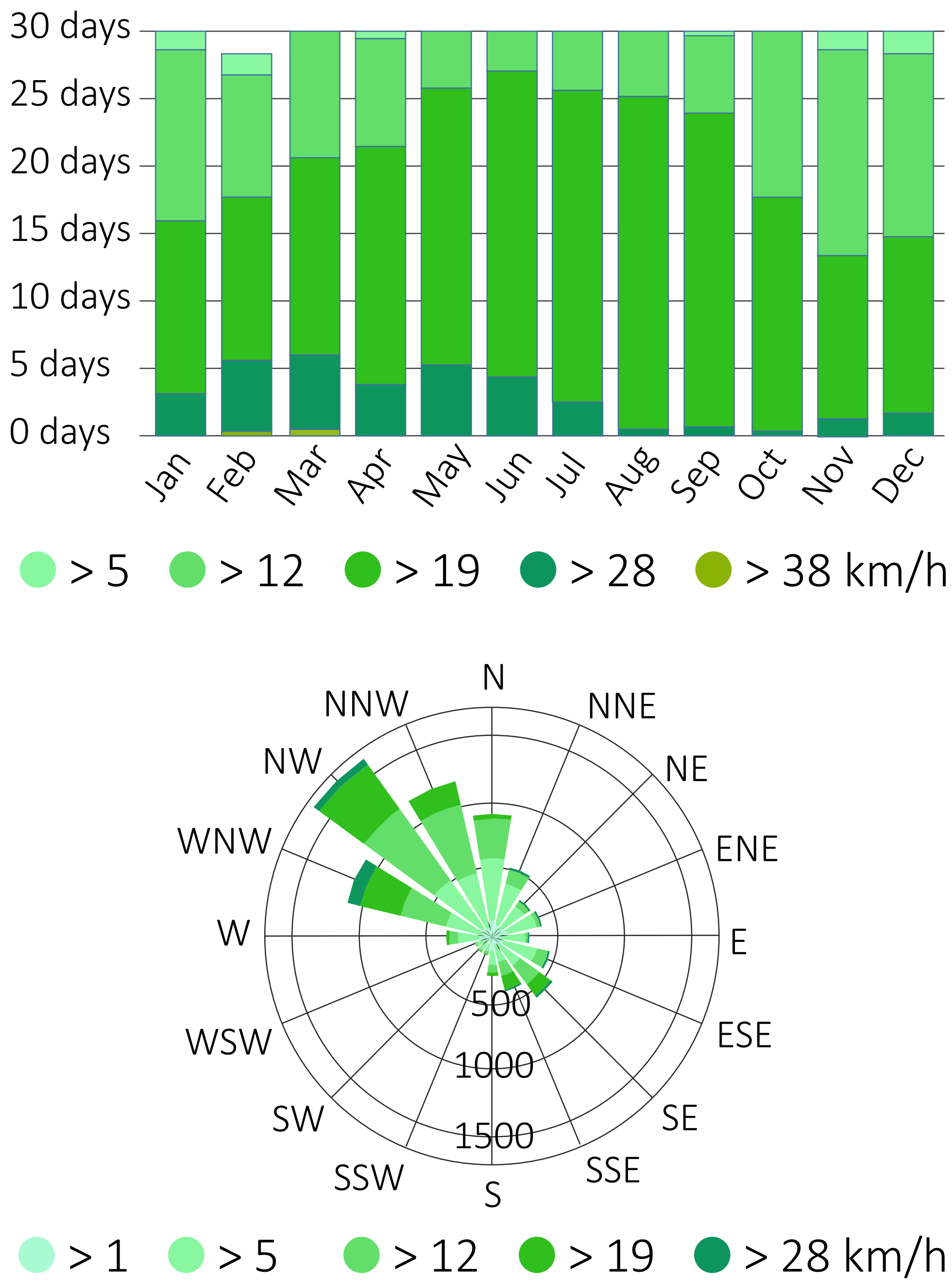


Fig. 5 Wind speeds by class and direction. (Source: https://www.meteoblue.com/en/weather/forecast/modelclimate/abu-dhabi_united-arab-emirates_292968)

Abu Dhabi is a highly populated emirate which occupies the western and southern UAE and accounts for about 85% of the country's total area. It hosts most of oil and gas fields as well as other large industries. The population number deceases in the northeastern part, except in Dubai. Dubai is the second largest emirates in terms of population number, and a home to a variety of heavy and medium-sized industries. Higher population number in Abu Dhabi and Dubai is associated with high $PM_{2.5}$ emissions (from motor

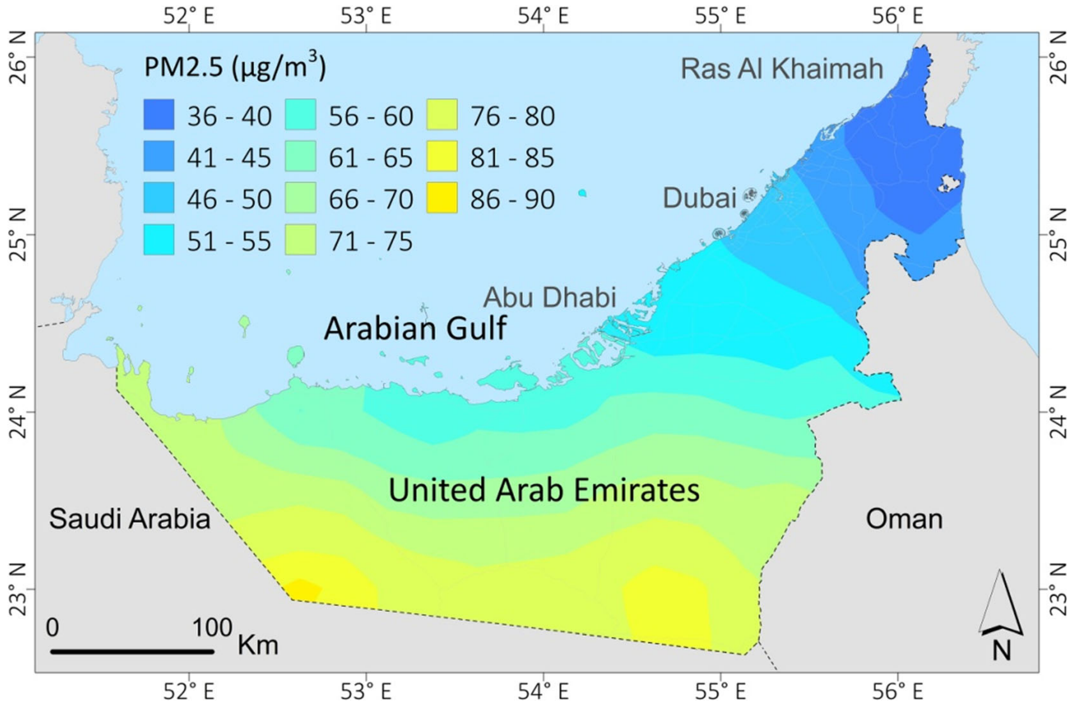


Fig. 6 Spatial distribution of annual mean concentration of $PM_{2.5}$ (μg/m^3) in UAE from 1980 to 2016

vehicles and various industrial activities) (Xu et al. 2016). However, air masses traversing from north (northerly winds) (Fig. 5) tend to disperse airborne PM and may result in relatively high $PM_{2.5}$ concentrations over the western and southern UAE.

The coastal regions demonstrated similar spatial patterns, with higher levels observed in the northwestern coast decreasing towards the northeastern coast, though $PM_{2.5}$ averages in the northwestern coast tend to show lower values than that in the inland regions. Of significant importance is the emission from power plants. Most power plants are located on the UAE coastal area, but the dispersion effect (due to northerly winds; Fig. 5) pushes PM further south and southwest, where elevated concentrations were observed.

The plots of 5-year average levels of $PM_{2.5}$ (1980–1985, 1986–1990, 1991–1995, 1996–2000, 2001–2005, 2006–2010, and 2011–2016) (Fig. 7) demonstrated similar spatial patterns across much of the UAE, though the intensity and magnitude of ambient $PM_{2.5}$ emissions have been consistently rising over the survey period (Fig. 9).

Comparison of the plots indicates where and by how much concentrations have increased across the UAE from 1980 to 2016. The lowest $PM_{2.5}$ concentrations were observed in Ras Al-Khaimah and the northeastern UAE. This is probably related both to lower anthropogenic emissions and favorable meteorological conditions for atmospheric dispersion and dilution.

As explained earlier, the enhanced $PM_{2.5}$ pollution in the UAE is not only due to the primary emissions from local sources (such as industrial and traffic emissions) but may also be related to the regional transported contributions (Saudi Arabia, Qatar, Kuwait, and Iran). In addition, the climatic conditions of high UV radiations lead to favorable atmospheric conditions for aerosols formation.

Seasonal and monthly variations

The monthly average $PM_{2.5}$ concentrations for November (minimum average) and July (maximum average) were spatially plotted to examine trend variability (Fig. 8). Spatial pattern showed slight variations in $PM_{2.5}$ with generally steady downward trends in the north and northeastern directions. In July, $PM_{2.5}$ peaks were observed in the southeastern regions, whereas in November, the greatest concentrations were recorded in the southwestern part.

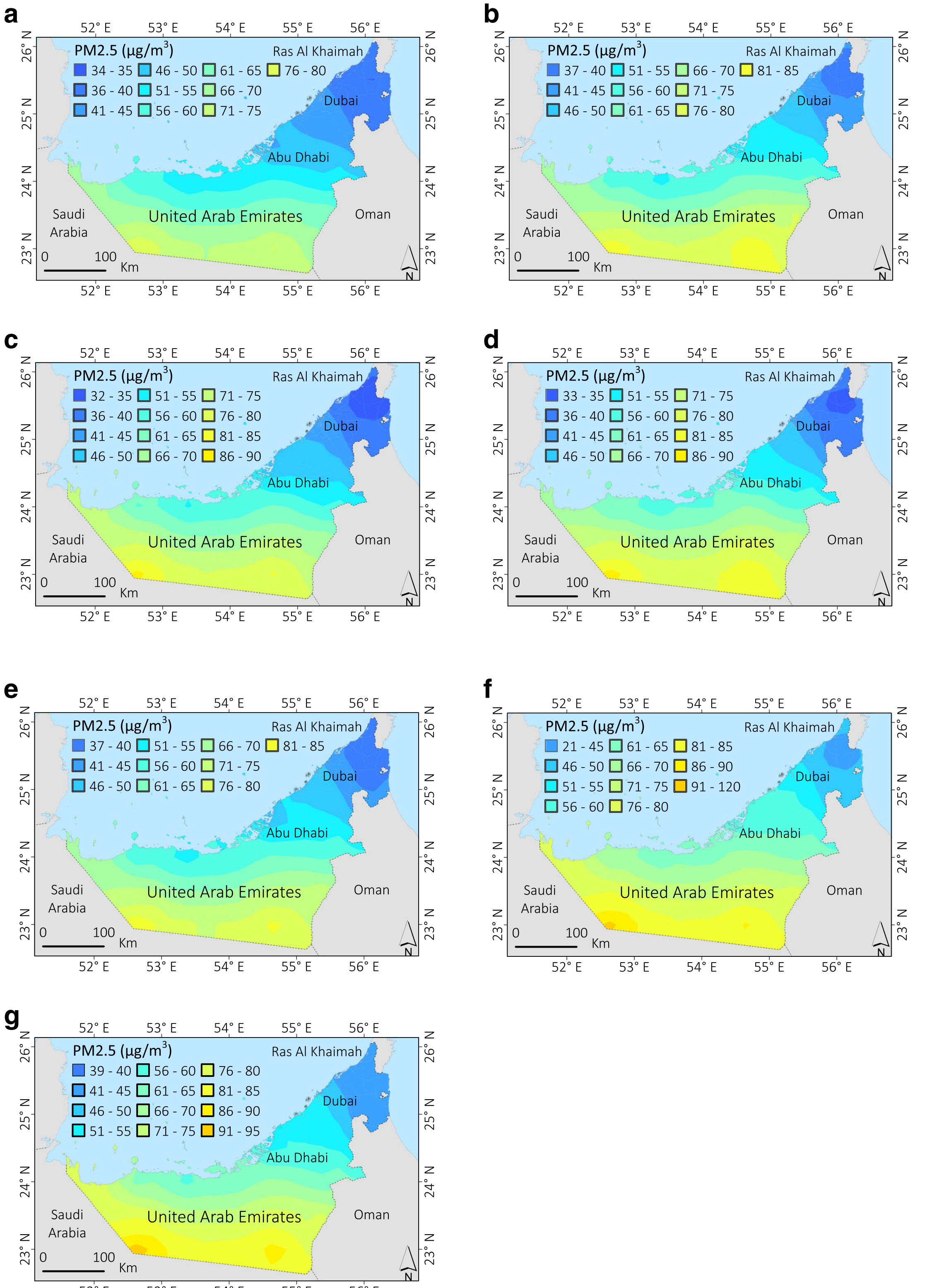


Fig. 7 The annual mean levels of $PM_{2.5}$ (μg/m^3) clustered in 5-year intervals, where **a** 1980–1985, **b** 1986–1990, **c** 1991–1995, **d** 1996–2000, **e** 2001–2005, **f** 2006–2010, **g** 2011–2016

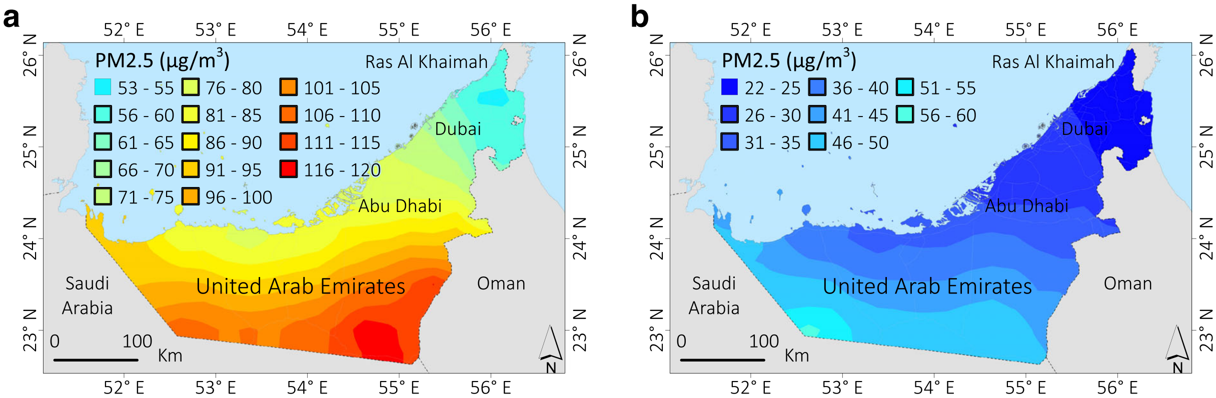


Fig. 8 Monthly average concentrations of $PM_{2.5}$ ($\mu g/m^3$) in **a** July (maximum monthly average) and **b** November (minimum monthly average) for the period from 1980 to 2016

The gradual increase from south (southwest) to north suggests dispersion of $PM_{2.5}$ due to wind direction (Fig. 5). Airborne $PM_{2.5}$ is probably transported in July by the southward winds to reach its maximum value in the far southeastern region, whereas in November, the wind direction is slightly diverted to the west, where elevated levels of $PM_{2.5}$ are accumulated in the far south-southwestern border of the UAE. It is noteworthy to mention that there are a number of oil and gas fields at the Saudi border adjacent to the UAE (western, southwestern, and southern areas) which are potentially contributing sources to $PM_{2.5}$ levels in this region.

More homogenous and better ambient air quality was observed in November compared to that in July. The prevailing meteorological conditions in November (Table 1) will likely to improve the atmospheric air quality with less fine particulates. Power plants are operating at high capacities in summer (including July) to cope with increased demand of energy, especially for cooling. These power plants will probably contribute to $PM_{2.5}$ emissions.

Potential sources of $PM_{2.5}$

The monthly average concentrations of ambient PM_{10} (for daily dataset from 18 September 2014 to 15 October 2017) demonstrated higher levels during dust season, particularly in July (Fig. 9). They varied from 74.4 to 216.7 $\mu g/m^3$ with a long-term monthly average value of 128.2 $\mu g/m^3$.

The UAE is located in an extremely arid region with negligible rainfall (Table 1). It is surrounded by desert regions, except for the north and northwest. Its location amid desert regions makes it subject to intense and frequent dust storms, where a large fraction of the aerosols delivered to UAE is principally derived from adjacent arid lands. Also, the UAE receives long-range atmospheric dust from distant deserts (e.g., Iraq, Iran, Pakistan (Ministry of Presidential Affairs 2011)). Dust storm episodes in the UAE extend from March to July. The source of windblown dust is dependent on the wind direction, where the UAE is subject to two winds directions, the northerly winds, and the extremely hot southerly-southeasterly winds (Fig. 5 and Table 1). The northerly winds (blown over the Arabian Gulf with mild and humid air) transport relatively lower quantities of fine particles.

Basha et al. (2015) identified the prevailing sources of air masses flowing towards the UAE as Saudi Arabia, Iran, and the Arabian Gulf (40% in winter by the southwesterly winds and 71% in summer by the prevailing northerly winds), in addition to Africa (in winter) and Pakistan, Iraq, and Afghanistan (in the summer).

Fine and coarse particles come from diverse sources. The $PM_{2.5}/PM_{10}$ ratio can provide crucial information about the particle origin, formation process, and effects on human health (Speranza et al. 2014; Blanco-Becerra et al. 2015). Higher ratios of $PM_{2.5}/PM_{10}$ are attributed to anthropogenic sources, whereas smaller ratios indicate considerable contribution of coarse particles, which may be related to natural sources, e.g., dust storm (Sugimoto et al. 2016; Xu et al. 2017). $PM_{2.5}/PM_{10}$ ratio for the period 18 September 2014–15 October 2017 varied from 0.52 to 0.80 with a mean value of 0.72. These ratios indicate that ambient aerosols are probably

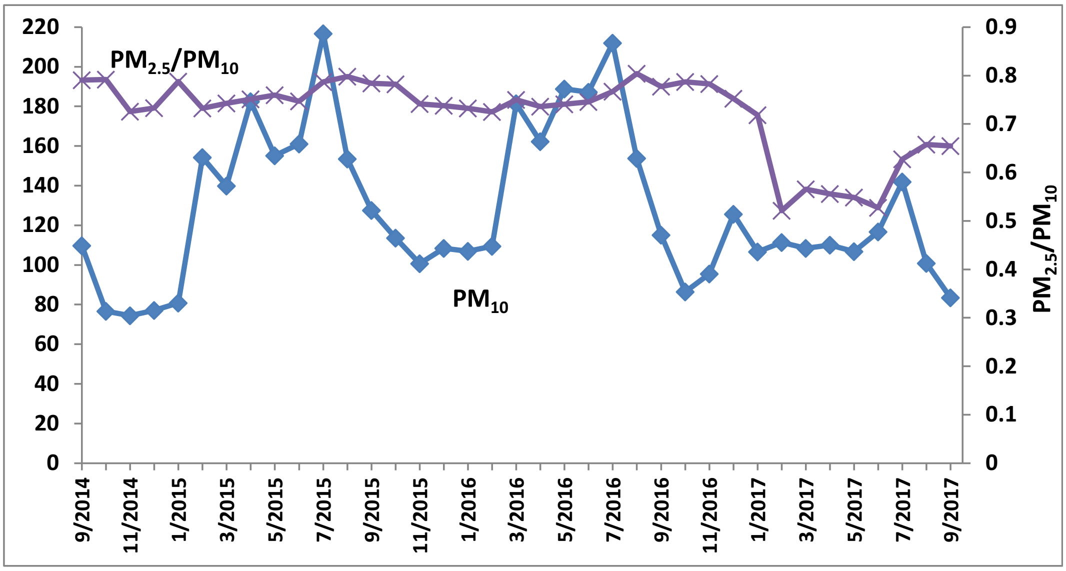


Fig. 9 Annual variations in ambient PM_{10} concentrations and $PM_{2.5}/PM_{10}$ ratio in the UAE from 18 September 2014 to 15 October 2017

associated with anthropogenic sources. The $PM_{2.5}/PM_{10}$ ratio remains relatively unchanged from September 2014 to December 2016, before it declined over the last year. This suggests that the relative contribution of $PM_{2.5}$ from anthropogenic emissions has slightly deceased in 2017.

The monthly $PM_{2.5}$/CO ratios were plotted to assess the relative significance of secondary formation to ambient $PM_{2.5}$ throughout the period 1980–2016 (Fig. 10). Peaks in $PM_{2.5}$/CO ratio were frequently observed during June, July, and August, though few were found in March. This suggests that secondary formation plays an important role in $PM_{2.5}$ concentrations in these months, especially as the photochemical activities become relatively strong. Prolonged sunlight radiation (with abundant UV light; Table 1) associated with increasing O_3 concentrations will likely to enhance photochemical formation of secondary aerosol particles, and rise $PM_{2.5}$ levels (Zang and Cao 2015). Secondary organic aerosol formation is also possible, where high VOCs emissions in the UAE (Al-Taani et al. 2018) along with high temperature (Table 1) result in increasing ambient $PM_{2.5}$. The plausible explanation for higher ratios in March is that the secondary $PM_{2.5}$ may have been transported with air masses flowing towards the UAE.

The lowest $PM_{2.5}$/CO ratios were found during September, October, and November (autumn) suggesting a considerable contribution of primary combustion emissions, especially vehicular emissions, to $PM_{2.5}$ concentrations.

The average concentrations of sulfate varied annually, but their variations showed generally an increasing pattern throughout the period 1980–2016 (Fig. 1). Figure 11 shows that airborne sulfate declined slightly in the northeastern and southeastern UAE.

Sea salts are potentially important sources to ambient $PM_{2.5}$ levels. It has been estimated that dust and sea salt components of $PM_{2.5}$ account for about half the population-weighted mean of $PM_{2.5}$ concentrations calculated for the Middle East, including the UAE (van Donkelaar et al. 2010). In addition to sea spray, ambient sulfate concentration is influenced by direct emissions of sulfur dioxide from excessive use of fossil fuel and its conversion to ammonium sulfate in the fine and ultra fine PM (Hamdan et al. 2015; Hamdan et al. 2016). Engelbrecht et al. (2009) have measured high concentrations of sulfate, partly as secondary ammonium sulfate and also as gypsum, in $PM_{2.5}$ in UAE. Sulfate as secondary ammonium sulfate has been attributed to sulfur dioxide emissions from petrochemical and other industries in the Middle East region (Engelbrecht et al. 2009).

A large number of power plants, oil and gas fields, and oil industries is located in the coastal region of the UAE and may contribute to sulfate levels through photochemical transformation of sulfur. The heavily polluted air mass is often transported from Northern Arabian Gulf as oil refineries, petrochemical industries, power plants, and

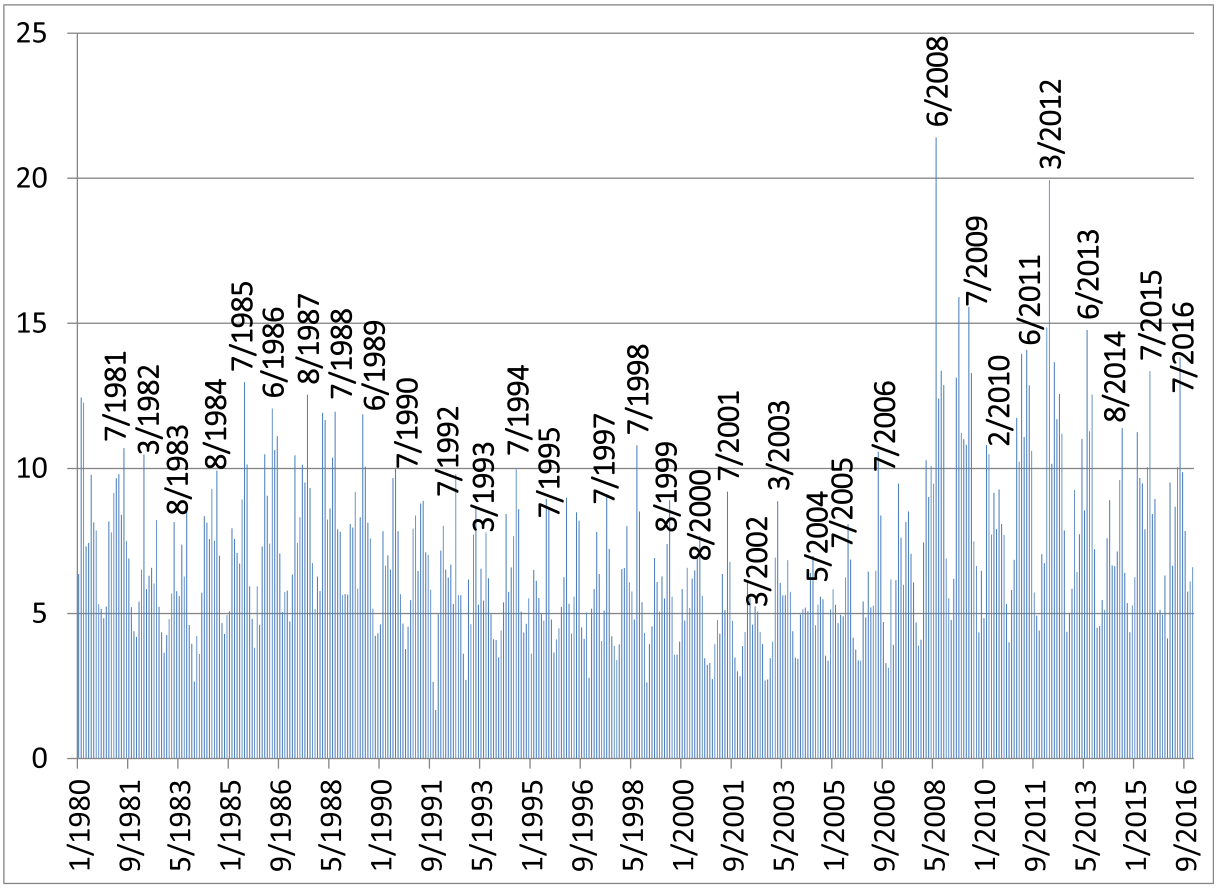


Fig. 10 The monthly $PM_{2.5}/CO$ ratio from 1980 to 2016

desalination plants (fueled with natural gas and heavy oil) are located on the Arabian Gulf coast. These are likely to affect the regional air quality, especially sulfur.

Ambient air $PM_{2.5}$ concentrations are positively correlated with sulfate levels ($r = 0.51$), suggesting that sulfate aerosols constitute an important portion of $PM_{2.5}$. This is consistent with results of van Donkelaar et al. (2010), Hamdan et al. (2016), and Engelbrecht et al. (2009). Hamdan et al. (2015) found that sulfur was the major element in ambient $PM_{2.5}$ (with a weight ratio of about 75%, whereas Si composed 10% only). They also observed strong correlations between S, N, and O for the same particle aggregates, indicating the existence of ammonium sulfate. They concluded that the natural sources of PM originating from dust storms, sea salts and crustal materials, interacting with anthropogenic emissions (SO_2) and (NO_x) to form secondary $PM_{2.5}$. The PM_{10} was composed of Si (40% weight ratio), Ca, Al, Mg, Cl, K, Fe, and Ti indicating natural sources of aerosols (dust storms, building and crustal materials, and sea salts) (Hamdan et al. 2015).

Population-weighted mean of $PM_{2.5}$

Assessment of population-weighted exposure to $PM_{2.5}$ is of vital importance to delineate vulnerable areas where the population is exposed to higher concentrations of $PM_{2.5}$. Based on the long-term annual average concentrations of $PM_{2.5}$ and population data, the population-weighted average of $PM_{2.5}$ in the UAE is 63.9 $\mu g/m^3$, which is more than three times greater than the global population-weighted mean of 20 $\mu g/m^3$ (van Donkelaar et al. 2010). van Donkelaar et al. (2010) also argued that about half the population-weighted decadal mean of $PM_{2.5}$ concentrations in the Middle East, including the UAE, are related to dust and sea salts of $PM_{2.5}$, with increasing annual trends of about 0.38 ± 0.21 $\mu g/m^3$ (1.5 ± 0.8% per year) driven by mineral dust (Chin et al. 2014).

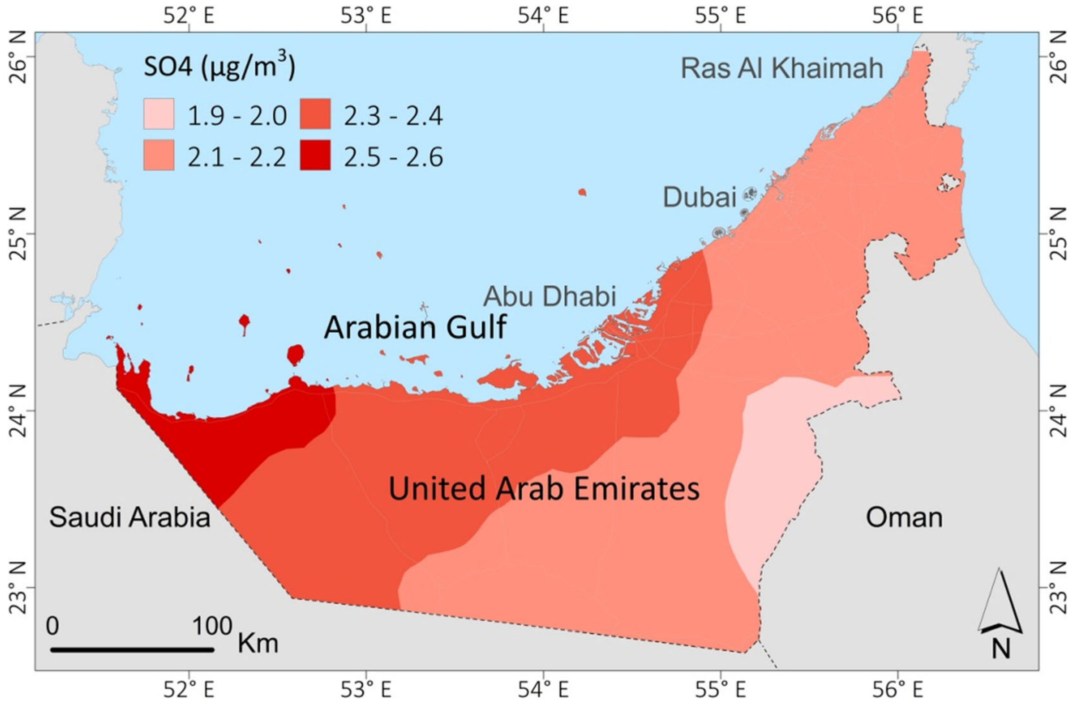


Fig. 11 Spatial changes of ambient sulfate concentrations in the UAE from 1980 to 2016

The cumulative population distribution in UAE shows that all the population live in areas with annual average $PM_{2.5}$ concentrations of higher than the WHO and EPA air quality guidelines (Fig. 12).

The UAE population is approximately 9 million, of which about 3% live in a relatively clean area with annual $PM_{2.5}$ levels of 38.44 μg/m^3, especially in the northeastern part. 35.6% of the UAE's populations are exposed to the highest concentrations with an annual average of 67.8 μg/m^3, where they reside in the western and southern regions. Residents of Abu Dhabi (occupying the western and southern regions of the UAE) constitute about 35.6% of the total population, and are exposed to the highest levels of $PM_{2.5}$. People living in Dubai in the northern UAE, with about 31.3% of the country's total population, are exposed to long-term ambient $PM_{2.5}$ of 48.3 μg/m^3. These values highlight the importance of fine particulate matter as a

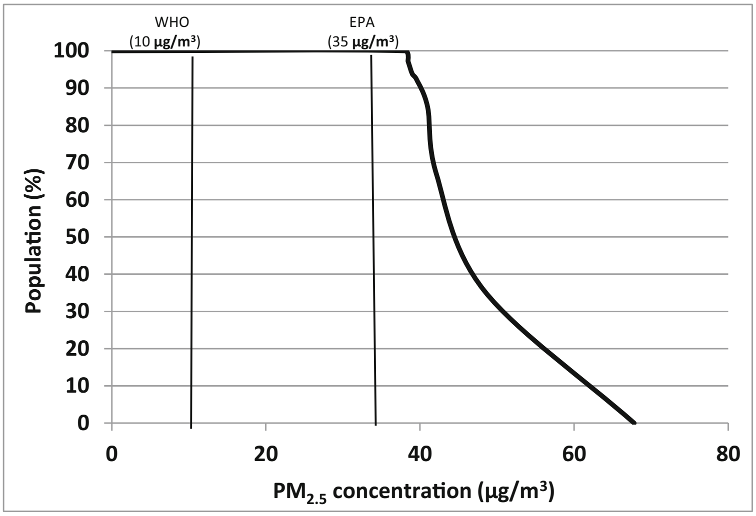


Fig. 12 Cumulative population distribution in UAE in terms of exposure to long-term annual average $PM_{2.5}$ from 1980 to 2016

contributing factor to the adverse public health. It has been estimated that a 6.2% increase in mortality is expected with 10 μg/m^3 increase in long-term $PM_{2.5}$ exposure (Hoek et al. 2013).

Conclusions

Airborne particles are a significant health and environmental problem in the UAE. This work attempted to investigate the spatiotemporal distribution and the potential sources of $PM_{2.5}$ in the UAE from 1980 to 2016. The annual average $PM_{2.5}$ levels (ranging between 77 and 49 μg/m^3) were in excess of the EPA and WHO guidelines for ambient $PM_{2.5}$, with an increasing trend, especially, over the last 14 years. Strong seasonal trends were evident, where greatest values have been observed in summertime and the lowest during autumn. Seasonal changes of $PM_{2.5}$ levels were primarily related to variations in energy demands, dust events, and weather conditions (which enhance/ reduce the secondary formation of $PM_{2.5}$). Higher values of $PM_{2.5}$ concentrations were found in the southern and western regions, concurrent with abundant oil and gas fields. Evaluation of $PM_{2.5}/PM_{10}$ ratio suggested that ambient aerosols are principally associated with anthropogenic sources. $PM_{2.5}$/CO ratio showed higher values during summertime, indicating that secondary formation plays an important role in $PM_{2.5}$ (due to stronger photochemical activities in this period). The lowest $PM_{2.5}$/CO ratios found during autumn suggested a considerable contribution from primary emissions (especially vehicular emissions). $PM_{2.5}$ concentrations in the UAE coastal region were linked to sea spray, fossil fuel burning from power plants, oil and gas fields, and oil industries. About 3% of the UAE populations live in a relatively clean (especially in the northeastern part), whereas 35.6% are exposed to the highest concentrations (with an annual average of 67.8 μg/m^3) and are resided in the western and southern regions. These values highlight the importance of fine particulate as a contributing factor matter to the adverse public health.

Funding information This project was funded by the Research Office, Zayed University in United Arab Emirates (Project No. R 17081).

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