



Vehicular emissions on main roads in Makkah, Saudi Arabia—a dispersion modelling study

Said Munir¹ · Turki Muhammad Habeebullah¹

Received: 21 August 2017 / Accepted: 22 August 2018 / Published online: 12 September 2018
© Saudi Society for Geosciences 2018

Abstract

Particulate matter (PM) is the atmospheric pollutant of main concern in Makkah; therefore, there is a need for its effective monitoring, modelling and management. In this study, Atmospheric Dispersion Modelling System (ADMS)-Urban model is employed, which is a well-known atmospheric dispersion modelling system. Traffic data were collected for several years (2007–2012) on six main roads in Makkah during the months of Ramadhan and Hajj. Data analysis showed that on average, there were 83% light-duty vehicles and 17% heavy-duty vehicles on Makkah roads; however, this percentage slightly varied both spatially and temporally. The number of vehicles demonstrated increasing trend from 2007 to 2012 on the six roads. Traffic characteristics, such as vehicle speed, vehicle type and number, were used to calculate the emissions of PM₁₀ and PM_{2.5}. Along with pollutant emissions, ADMS-Urban requires meteorological parameters such as wind speed and direction, temperature, relative humidity, cloud cover and boundary layer height. Concentrations were predicted in three different forms: (a) for six receptors, (b) as diurnal cycles and (c) as contour maps for the whole Makkah City. Modelled concentrations were compared with the observed concentrations at Masfalah and Presidency of Meteorology and Environment (PME) monitoring stations. ADMS-Urban underestimated both PM₁₀ and PM_{2.5} concentrations; however, the difference was much greater at the PME (about 73%) than at the Masfalah station (about 24%). Reasons for the discrepancies are discussed, and various statistical metrics are calculated to assess the model performance. More emission data are required to improve the performance of the model and minimise the gap between observed and predicted concentrations.

Keywords ADMS-Urban · Air pollution modelling · Air quality · PM₁₀ · PM_{2.5} · Makkah

Introduction

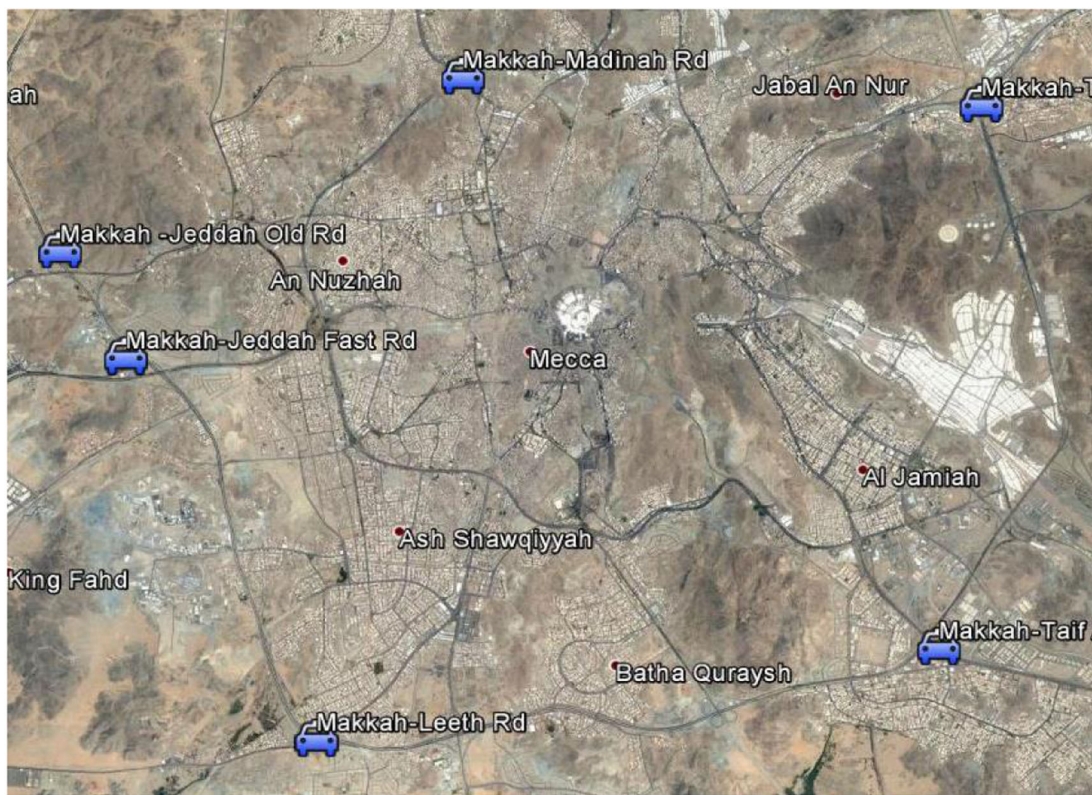
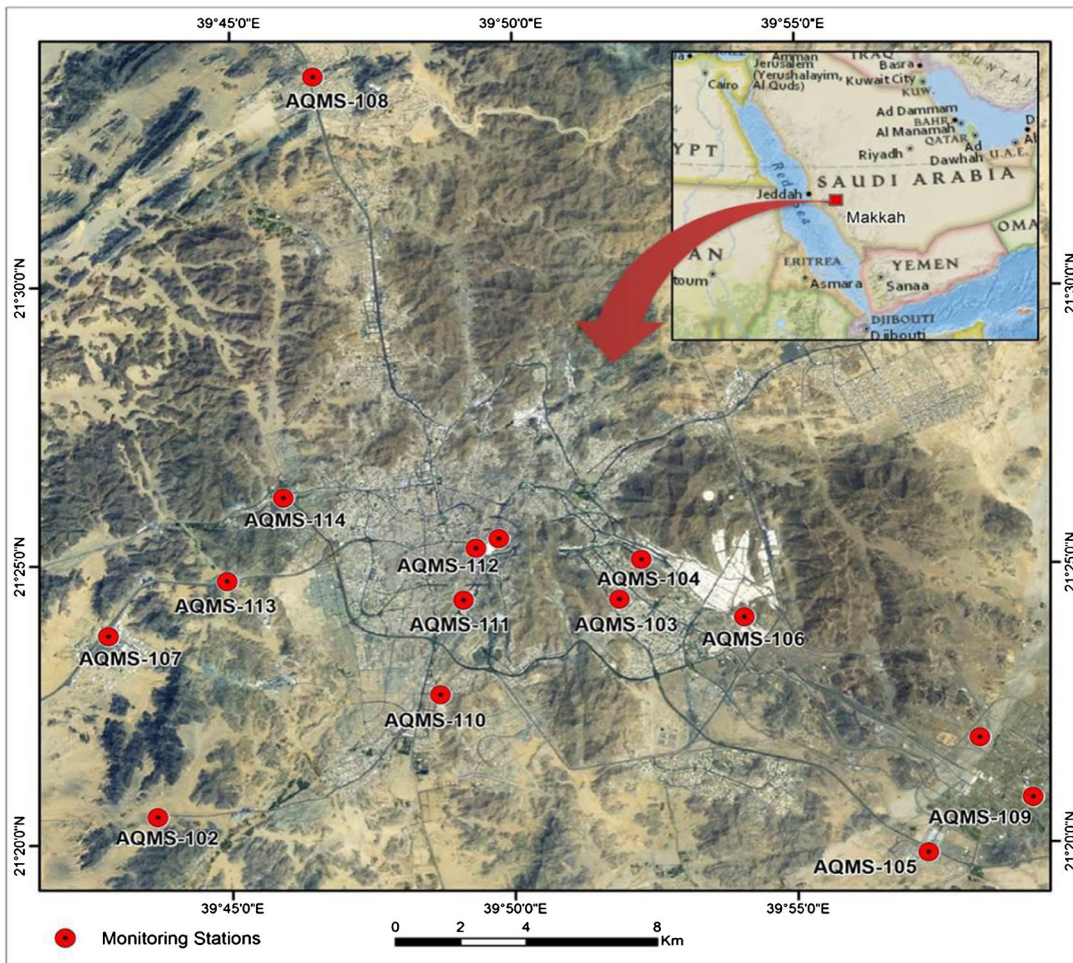
Atmospheric pollution has emerged as a growing environmental concern globally, especially in large urban areas. Atmospheric pollutants are present in the form of both gases (e.g., nitrogen dioxide (NO₂), sulphur dioxide (SO₂) and ground level ozone (O₃)) and particulates (e.g., total suspended particles (TSP), respirable particles (PM₁₀), coarse particles (PM_{10–2.5}) and fine particles (PM_{2.5})). Air pollution not only affects human health in the form of respiratory diseases, cardiovascular diseases and cancer but also has

negative impacts on buildings, historical monuments, plants, biodiversity and visibility (AQEG 2012; COMEAP 2009; Walters and Ayres 2001; WHO 2003). Therefore, monitoring, modelling, management and assessing the environmental and health impacts of air pollution are vital for sustainable development, especially in large urban agglomerations.

Several research projects have been previously conducted in the Holy City of Makkah to assess the levels of various air pollutants, investigate their temporal and spatial variability, determine their long-term temporal trends, model the effects of various controlling factors and analyse their health impacts (Al-Jeelani 2009; Habeebullah 2013; Seroji 2011; Othman et al. 2010; Munir et al. 2013a; Munir et al. 2013b). These researchers have demonstrated that air pollutants, especially PM₁₀ and PM_{2.5}, exceed air quality standards in Makkah and therefore are more likely to adversely affect human health (e.g., Seroji 2011; Habeebullah 2013; Al-Jeelani 2009). Most of the studies on air quality in Makkah are carried out during the seasons of Hajj and Ramadhan (Seroji 2011; Al-

✉ Said Munir
saidmunir@yahoo.co.uk

¹ The Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research, Umm Al-Qura University, Makkah, Saudi Arabia



◀ **Fig. 1** Map of the air quality monitoring stations (upper panel), where AQMS 112 and AQMS 111 show PME and Masfalah monitoring sites, respectively and traffic monitoring locations (lower panel) on six main roads in the Holy City of Makkah, Saudi Arabia

Jeelani 2009). Makkah is a highly populated city, because in addition to the residents, millions of people from all over the world visit Makkah to perform Hajj and Umrah during the seasons of Hajj and Ramadhan. This puts extra pressure on the city resources, leading to further environmental issues.

Previously, Munir et al. (2013a) and Sayegh et al. (2014) have applied statistical approaches to model PM₁₀ concentrations in Makkah. They applied advance statistical models, such as generalised additive models, quantile regression models, multiple linear regression models and boosted regression tree models (BRT) to analyse the levels of PM₁₀ in Makkah. They used PM₁₀ as a dependent variable and meteorological parameters and several air pollutants (e.g., NO_x, SO₂, O₃, CO and lag-PM₁₀) as independent variables. Munir et al. (2013a) applying a generalised additive model showed that temperature and wind speed were controlling most of the variation in PM₁₀ concentrations. In contrast, traffic-related air pollutants were found to have a weak relationship with PM₁₀ concentrations, suggesting high PM₁₀ concentration is mostly due to the arid conditions of the region (including low rainfall, high temperature and large deserts surrounding the city of Makkah) and high-scale construction and demolition projects. Munir et al. (2013b) applying the non-parametric Theil-Sen approach and change point analysis reported positive trends in several air pollutants including PM₁₀ during the period 1993–2012 in the Holy City of Makkah. Temporal

trends were reported at several quantiles of the PM₁₀ distribution, and the results showed that trends ranged from 0.82 to 5.23 µg/m³/year for minimum and maximum PM₁₀ concentrations, respectively. The growing concentration of PM₁₀ was reported to be due to the large-scale construction projects in Makkah, especially near the Holy Mosque during the study period.

More recently, several authors have focused on dispersion modelling and source apportionment of particulates in Makkah (e.g., Munir et al. 2015a; Munir et al. 2016), intending to model PM₁₀ and PM_{2.5} emissions from various sources. However, due to the lack of air pollutants and greenhouse gases emission data, they had to depend on petrol, diesel and natural gas sale data in Makkah. Modelling PM_{2.5} emissions, Munir et al. (2015a) reported that the highest proportion of PM_{2.5} (312,936 tons) in Makkah was emitted by the combustion of diesel fuels used in power plants for electricity generation. The amount of PM_{2.5} estimated from the fuel sale used in heavy-duty diesel vehicles and light-duty petrol vehicles was 162 and 45 tons, respectively, whereas the amounts of estimated PM₁₀ from fuel sale used in power plant, diesel vehicles and petrol vehicles were 330,174, 171 and 48 tons, respectively (Munir et al. 2015a). In this study, the intention is to build on the previous studies, using road traffic data from six main roads in Makkah (Makkah-Jeddah Fast Road, Makkah-Jeddah Old Road, Makkah-Madinah Road, Makkah-Taif Al-Hadda Road, Makkah-Taif Assail Road and Makkah-Leeth Road). The aim is to estimate the amount of PM₁₀ and PM_{2.5} using traffic counts on main roads. The study employs ADMS-Urban model, which is one of the advance dispersion modelling systems employed

Table 1 Hourly traffic flow (vehicles/h) on six main roads in Makkah during Hajj and Ramadhan (1428–1433 AH)

Year	Makkah-Jeddah Fast RD	Makkah-Jeddah Old Rd	Makkah-Madinah Rd	Makkah-Taif Al-Hadda Rd	Makkah-Taif Assail RD	Makkah-Al-Leeth Rd
Hajj						
1428	4474	319	1255		1602	
1429	4663	347	1367		1675	1088
1430	4711	410	1506	837	1163	978
1431	4031	305	1317	1584	1104	339
1432	5255	679	1760	1121	1262	470
1433	5284	1091	2258	1681	1536	893
Average	4736	525	1577	1306	1390	754
Ramadhan						
1428	5498	237	1404		1936	
1429	3069	213			2072	1105
1430	5656	247	1466	981	1060	901
1431	6257	384	1980	1276	1401	629
1432	6180	384	1953	1278	1891	424
1433	6121	1041	2449	1834	1365	824
Average	5463	418	1851	1342	1621	777

Table 2 Summary of PM₁₀, PM_{2.5} and meteorology data at the Masfalah and PME sites, year 1433 A.H. (2012) during both Hajj and Ramadhan

Masfalah-Ramadhan						
Metrics	PM ₁₀ (µg/m ³)	PM _{2.5} (µg/m ³)	WS (m/s)	WD (degree)	Temp (°C)	RH (%)
Minimum	0.37	0.12	0.26	0.00	31.81	7.30
1st quartile	18.24	17.08	1.35	31.90	37.47	17.40
Median	25.15	24.03	1.74	147.90	39.24	23.20
Mean	32.11	28.27	1.794	162.60	40.82	27.50
3rd quartile	36.97	32.48	2.19	315.00	44.45	36.60
Maximum	193.27	182.11	3.58	359.00	53.99	73.70
NA's (missing)	4	4	4	4	4	4
Masfalah-Hajj						
Minimum	4.05	2.07	0.33	0.00	21.11	15.90
1st quartile	13.47	12.55	1.06	35.41	28.56	35.30
Median	19.79	17.26	1.36	108.90	30.88	45.70
Mean	22.02	20.99	1.42	141.72	31.72	45.77
3rd quartile	26.67	24.44	1.74	227.90	34.71	56.25
Maximum	279.73	139.43	3.69	359.12	43.16	88.80
NA's (missing)	1	1	1	1	1	1
PME-Ramadhan						
Minimum	0.11	1.21	0.00	1.00	29.30	11.71
1st quartile	64.12	45.30	0.70	235.11	33.40	22.51
Median	88.12	63.12	1.10	285.00	35.11	32.40
Mean	105.40	58.84	1.05	253.90	35.43	34.15
3rd quartile	125.14	63.21	1.40	317.00	37.40	44.55
Maximum	424.00	244.80	3.40	360.00	41.90	71.12
NA's (missing)	35	25	1	1	1	1
PME-Hajj						
Minimum	6.00	3.60	0.12	1.10	22.90	8.10
1st quartile	55.11	34.20	0.61	117.11	27.20	32.21
Median	74.11	46.80	0.91	262.10	28.80	43.62
Mean	84.46	50.68	0.91	219.20	29.44	43.02
3rd quartile	99.12	57.60	1.20	295.12	31.60	55.11
Maximum	706.12	423.60	2.40	360.12	36.40	68.60
NA's (missing)	6	5	3	3	3	3

WS wind speed, WD wind direction, Temp temperature, RH relative humidity, 1st quartile 25th percentile, 3rd quartile 75th percentile

widely throughout the world for modelling air pollutant emissions. The study will help quantify the emissions from road traffic and help better understand the sources of air pollutants in Makkah.

Methodology

Traffic data

Dispersion modelling requires detailed emission data. In this study, the main aim is to model emissions of PM₁₀ and PM_{2.5} on six main roads in the Holy City of Makkah. Traffic data were collected for several years from 1428 (2007) to 1433

(2012) on the six main roads in Makkah during the month of Ramadhan and Hajj. The road names are Makkah-Jeddah Fast Road, Makkah-Jeddah Old Road, Makkah-Madinah Road, Makkah-Taif Al-Hadda Road, Makkah-Taif Assail Road and Makkah-Leeth Road. These are the six roads which are used for leaving and entering the Holy City of Makkah. The map of the six roads is shown in Fig. 1, and average traffic counts (number of vehicles per hour) are shown in Table 1. Traffic counts were made manually. ADMS-Urban uses a built-in tool known as COPERT 4, which considers not only exhaust emissions covering hot and cold-start exhaust emissions from both light- and heavy-duty vehicles but also non-exhaust emissions from tyre wear, brake wear and road surface wear. Furthermore, road traffic data were divided into two types:

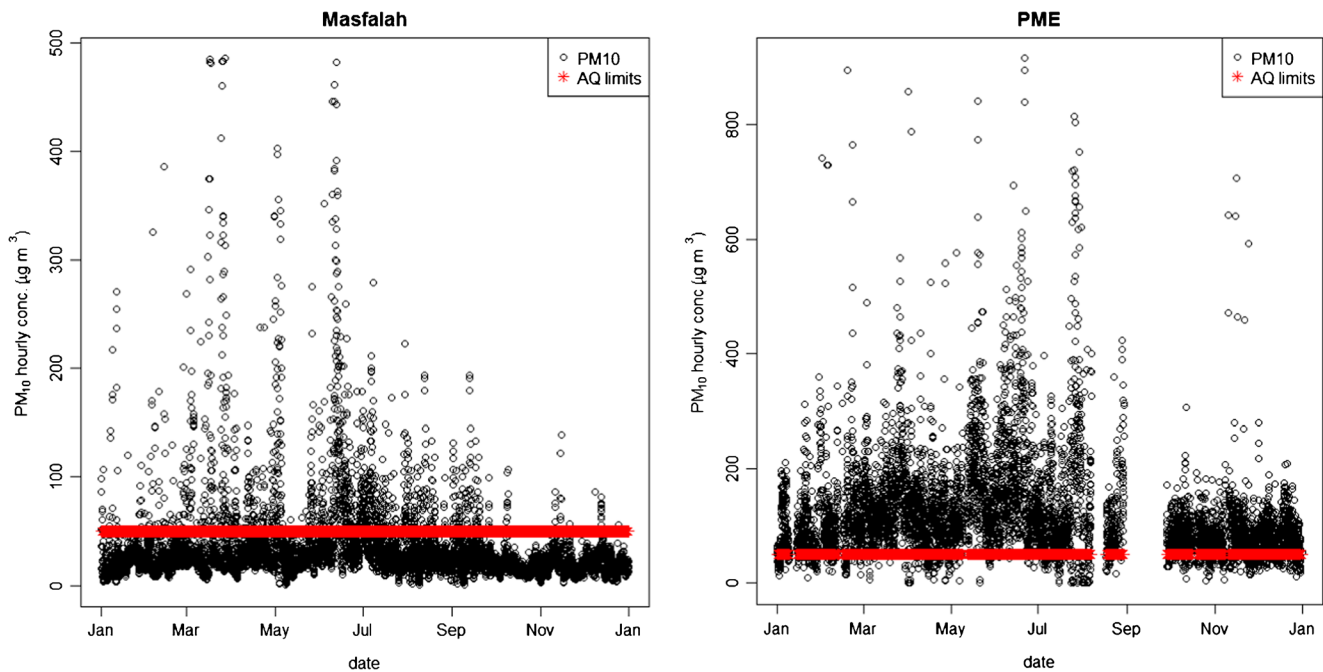


Fig. 2 Comparison of PM_{10} with air quality limits ($50 \mu\text{g}/\text{m}^3$) at the PME and Masfalah site, 2012

light-duty (< 3.5 tons) and heavy-duty (3.5 tons) vehicles. On average, there were about 17% heavy-duty vehicles and 83% light-duty vehicles; however, the percentage slightly varied both temporally and spatially. Based on traffic counts (Table 1), PM_{10} and $PM_{2.5}$ emissions were calculated.

ADMS-Urban

To model the emissions of PM_{10} and $PM_{2.5}$ in Makkah, this study employed ADMS-Urban model, which is one of the advanced dispersion modelling systems. Dispersion models are used to estimate or predict the downwind concentrations of air pollutants emitted from various emission sources, such as industrial plants or vehicular traffic. Numerous atmospheric dispersion modelling systems are available around the world, including AERMOD, ATSTEP, CALPUFF, CMAQ, DISPERSION21, FLACS, FLEXPART, HYSPLIT and ADMS. ADMS-Urban (version 3.4.2.0) is developed by Cambridge Environmental Research Consultants Ltd. (CERC), UK. ADMS-Urban is a PC-based air quality management system, which is fully integrated with GIS (e.g., ArcGIS and MapInfo), allowing easy emission set-up, output presentation and analysis. ADMS-Urban requires emission data, meteorological data, boundary layer height, surface roughness and road geometry. ADMS-Urban is able to model road emissions, industrial emissions (point, area, volume, line) and grid emissions. Full description of the model can be found at the CERC website (CERC 2017). The model is also described by Munir et al. (2015a) and Munir et al. (2016).

In this study, air pollutants emitted by road traffic are modelled at six main roads in Makkah (described in “Traffic

data”). In addition, air quality and meteorological data from the two monitoring stations were used in the model, described in “Air quality and meteorological data”. Background data which cover air pollutant concentrations emitted by emission sources which are not modelled in this study were also added in the model. In simple words, this study models air pollutants emitted by road traffic only; emissions from all other sources such as emissions from restaurants, construction and demolition and some small industries in the city of Makkah are all accounted for by the background concentrations. Background concentrations were taken from an urban background monitoring site near Mina, receiving the same quality assurance and quality control as Presidency of Meteorology and Environment (PME) and Masfalah sites (“Air quality and meteorological data” section).

Air quality and meteorological data

In this study, measured (observed) data from two continuous monitoring stations were used: PME and Masfalah monitoring sites. Both monitoring sites use reference instruments for measuring air pollutant concentrations. These reference instruments are recommended by European Union (EU) and Department of Environment, Food and Rural Affairs (DEFRA) of the UK. PME site is situated just outside the Holy Mosque (Al-Haram). This is an urban background continuous monitoring station, and in addition to PM_{10} and $PM_{2.5}$, it monitors several other air pollutants and meteorological parameters, such as wind speed and direction, temperature, relative humidity and rainfall. Masfalah is also a continuous monitoring

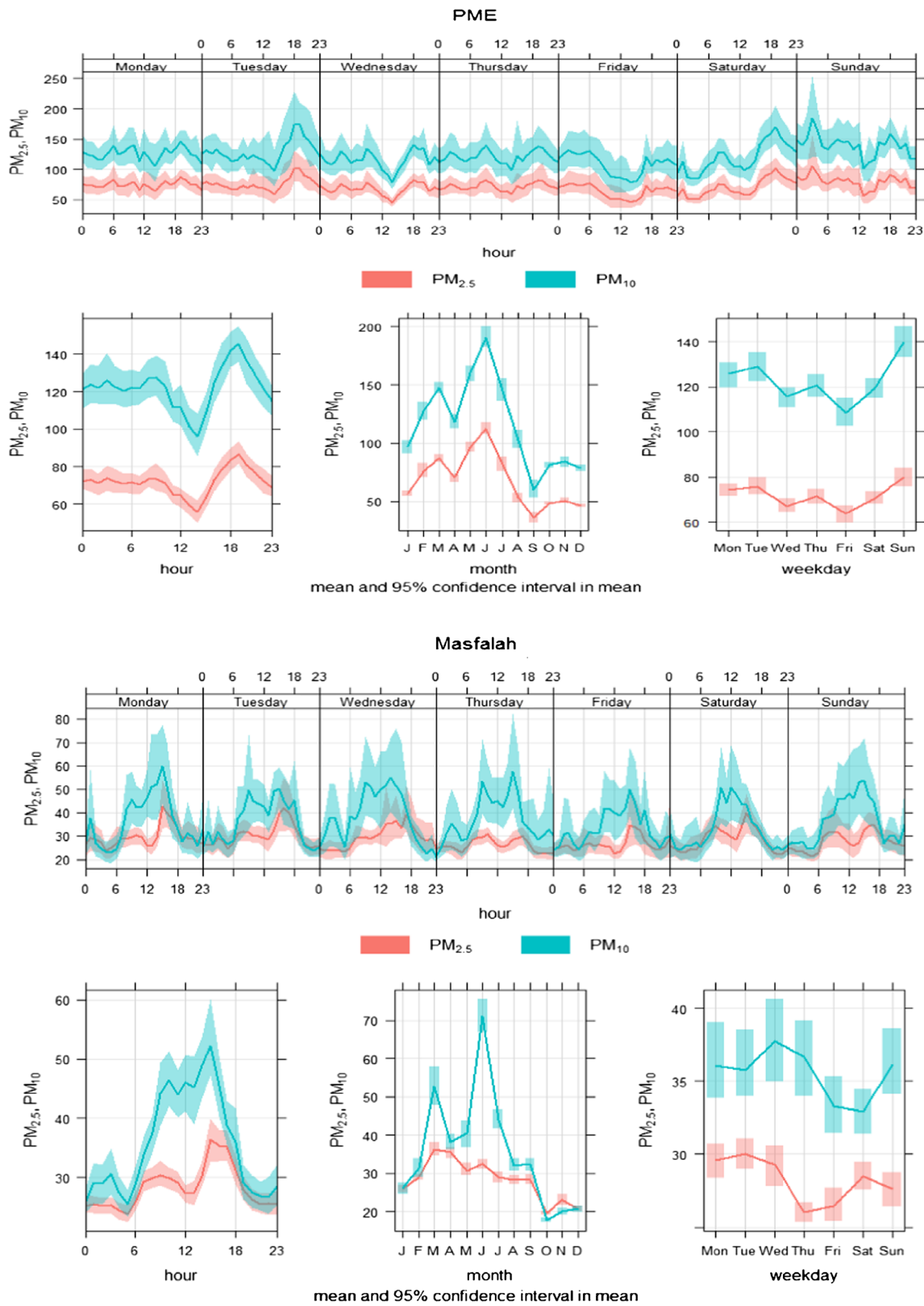


Fig. 3 Time variations of PM_{10} and $PM_{2.5}$ at the PME and Masfalah monitoring stations, 2012

station and is classified as a roadside site, situated a couple of kilometres from the Holy Mosque. This site also monitors various air pollutants including PM_{10} and

$PM_{2.5}$ as well as meteorological parameters, such as wind speed, wind direction, relative humidity, temperature and rainfall.

Table 3 Modelled PM₁₀ and PM_{2.5} concentrations ($\mu\text{g}/\text{m}^3$) in Ramadhan at six receptors located within the roads for year 2012

Road	X	Y	PM ₁₀ _Ram	PM _{2.5} _Ram	PM ₁₀ _Hajj	PM _{2.5} _Hajj
MJ-Fast	563,651.01	2,361,229	33.35	20.01	19.15	11.71
MJ-Old	563,578.77	2,372,452	33.32	19.99	19.13	10.86
M-Leeth	565,480.66	2,358,810	33.34	20.01	19.14	11.22
M-Madinah	579,222.22	2,386,064	33.33	20.01	19.11	11.21
MT-Hadda	605,234.8	2,358,836	33.33	20.00	19.11	11.00
MT-Sail	603,983.32	2,377,018	33.32	19.99	19.09	10.86

At the Masfalah monitoring site, Aeroqual AQM 60 air quality monitoring station was deployed to measure the concentrations of various air pollutants and meteorological parameters. To measure the levels of particulates, the system uses a well-proven near forward light scattering nephelometer and high precision sharp cut cyclone, which has wide range of measurements (0–2000 $\mu\text{g}/\text{m}^3$) and high accuracy (± 2 for both PM₁₀ and PM_{2.5}). At the PME site, beta-attenuation monitor (BAM) was deployed for particulates measurement. BAM has a filter made of paper, which is located between a source of radiation (beta rays) and a radiation detector. BAM also has an air pump drawing air through the paper filter. The mass of particulates in the air is detected from the reduction in intensity of beta-radiation. After collection, the data go through a robust Quality Assurance and Quality Control (QA/QC) process to make sure the data are fit for the purpose of research. QA/QC include careful selection of monitoring site, proper instalment of instruments, selection of instrument and sample system design, proper training of operators and personnel, calibration of instruments, monitoring calibration gases and instrument response, routine site visits and operations, routine data review and validation and data ratification. After the initial calibration, the zero and span responses of the instrument were checked for drift on weekly basis. The data were ratified by air quality experts to check for outliers and non-logical readings. Overall, more than 90% data were available at both monitoring sites.

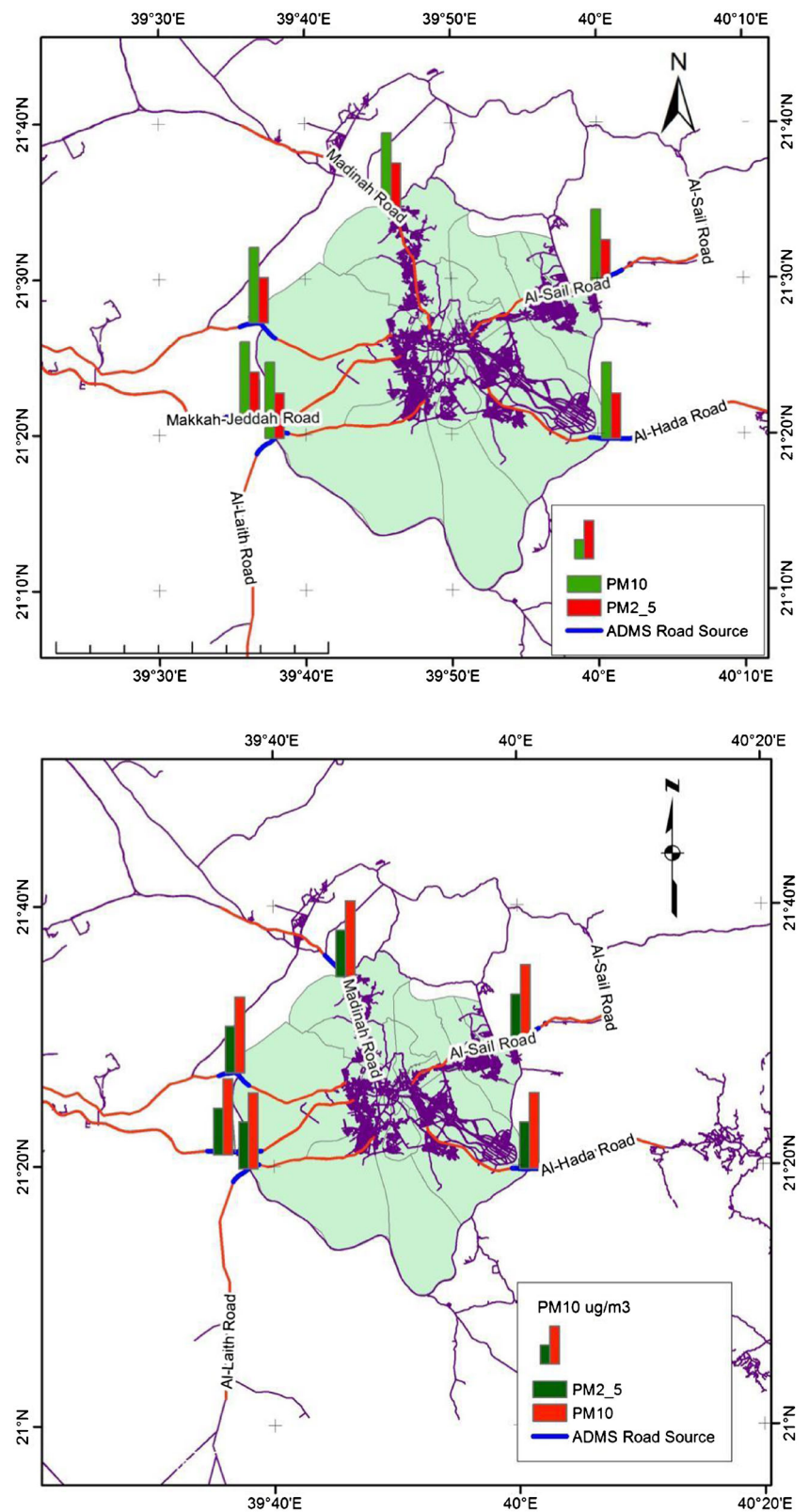
A summary of the data from both monitoring stations is presented in Table 2, where values of minimum, 1st quartile (25th percentile), mean, median, 3rd quartile (75 percentile) and maximum of each parameter are provided. These data were used as inputs for running ADMS-Urban model. PM₁₀ and PM_{2.5} concentrations predicted by ADMS-Urban were compared with the observed concentrations from the two monitoring stations. PM₁₀ concentrations ($\mu\text{g}/\text{m}^3$) from both PME and Masfalah monitoring stations are compared with European Union (EU) air quality limits (50 $\mu\text{g}/\text{m}^3$) (Fig. 2), where it can be clearly observed that PM₁₀ concentrations are exceeding the air quality limits at both monitoring sites. The Saudi Arabian daily air quality standards set by PME for PM₁₀ is 340 $\mu\text{g}/\text{m}^3$, which is also exceeded at the PME sites (Fig. 2, right panel).

Results and discussion

In Fig. 3, a summary of the temporal variations of PM₁₀ and PM_{2.5} is depicted at both PME and Masfalah monitoring stations for year 2012. Generally, PM₁₀ and PM_{2.5} concentrations are higher at the PME monitoring station, which is probably due to the fact that PME monitoring station is situated next to the Holy Mosque and surrounded by several busy roads and restaurants, which add to the observed PM₁₀ and PM_{2.5} concentrations. Furthermore, continuous cleaning, which includes dusting and sweeping, may contribute to the particulate concentrations. Figure 3 shows slightly different patterns of PM₁₀ and PM_{2.5} concentrations at the two monitoring stations; however, generally, the levels are higher in summer and lower during the winter season. Weekly cycle shows lowest level of both PM₁₀ and PM_{2.5} concentrations on Friday at the PME site, whereas at the Masfalah site, PM_{2.5} shows lowest level on Thursday and Friday, and PM₁₀ shows lowest level on Friday and Saturday. Diurnal cycle shows highest level at about 17:00–18:00 h at PME site and at 15:00–16:00 h at Masfalah site. This difference in temporal variations is due to differences in the sources of pollutant emissions at the two sites. Masfalah is a roadside station where PM₁₀ and PM_{2.5} are emitted mostly by road traffic or resuspension of dust particles on the roadside due to vehicle movements; in contrast, PME is an urban background site and the nature of emission is more complex, including a variety of sources. Annual and diurnal cycles seem to be more controlled by changes in meteorological parameters, especially temperature, wind speed and wind direction, whereas the weekly cycle is more controlled by changes in road traffic pattern. Probably, this is the reason that particulate levels are lower during the weekend (Friday). Munir et al. (2015b) and Habeebullah et al. (2014) have also analysed the diurnal, weekly and annual cycles of air pollutants in Makkah and have discussed various reasons responsible for the time variations of air pollutants in Makkah in detail.

The outcomes of the ADMS-Urban model are provided in three forms: (a) at six receptor points inside the roads, where road traffic data were collected, (b) in the form of diurnal cycle and (c) in the form of contour maps for the whole Makkah City. Table 3 and Fig. 4 show PM₁₀ and PM_{2.5} levels at the six

Fig. 4 Monthly average PM_{10} and $PM_{2.5}$ concentrations ($\mu\text{g}/\text{m}^3$) at the six main roads in Makkah during the month of Ramadhan (Aug, 2012) (upper) and Hajj (November) (lower) in the year 1433 AH (2012)



receptors selected inside the roads during the seasons of both Hajj and Ramadhan. Modelled PM_{10} and $PM_{2.5}$ concentrations (Table 3) are significantly higher in Ramadhan than

during Hajj. The difference in both PM_{10} and $PM_{2.5}$ concentrations at various roads in the same season is not significant; however, highest concentrations of PM_{10} and $PM_{2.5}$ in both

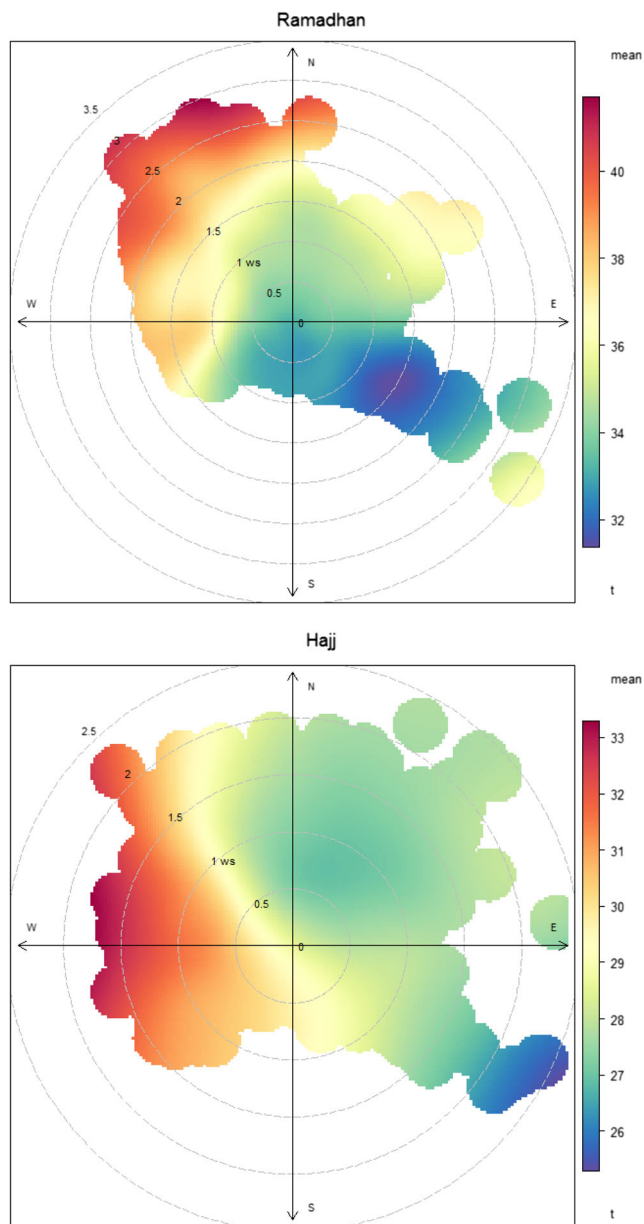


Fig. 5 Polar plots of hourly mean temperature during the months of Ramadhan (upper panel) and Hajj (lower panel), 2012

seasons were predicted at the Makkah-Jeddah Fast Road and lowest at the Makkah-Taif Sail Road followed by Makkah-Jeddah Old Road. ADMS-Urban model predicted significantly higher concentrations during Ramadhan than Hajj due to several factors, which include higher levels of road traffic (average for all roads was 1912 vehicles/h during Ramadhan and 1676 vehicles/h during Hajj) and higher temperature and wind speed in Ramadhan (Fig. 5), which probably resulted in higher levels of PM_{10} and $PM_{2.5}$ concentrations. Positive association of PM_{10} with temperature and wind speed in arid regions is reported by several authors (e.g., Munir et al. 2013a). Furthermore, Bampadimos et al. (2011) reported that high temperature can cause PM_{10} concentrations to increase

due to enhanced re-suspension of soil, roadside dust and formation of secondary aerosols. They also reported that PM_{10} concentrations increased by 4-fold when temperature increased from 10 to 35 °C in summer. Makkah is situated in an arid region, which receives no rain for months and most of the area is made of sandy deserts surrounding the Makkah City. High wind speed lifts sand-and-dust particles from the surrounding deserts and from the house roofs leading to high PM_{10} concentrations (Munir et al. 2013a). Figure 5 shows that the month of Ramadhan (August, 2012) experienced higher temperature and higher wind speed as compared to the Hajj season (November, 2012). Furthermore, high temperature in Fig. 5 is linked with wind blowing from the west or north-west direction, whereas low temperature is linked with south-east direction. This is the general pattern; however, Hajj and Ramadhan seasons exhibit differences in the pattern from each other, which is expected. The north-west and south-east pattern is due to the location of the monitoring stations next to Holy Mosque, where enormous air conditioning systems are running all the times, which seem to affect the nearby surrounding areas.

Table 4 compares observed and modelled concentrations ($\mu\text{g}/\text{m}^3$) at the two sites during Hajj and Ramadhan. Percent difference (% diff) in observed and modelled concentrations is much greater at PME site (about 73% both PM_{10} and $PM_{2.5}$) than at Masfalah site (about 11% for PM_{10} and 36% for $PM_{2.5}$). This probably shows that at PME site, most of the emissions are not related to road traffic, which is leading to much higher difference between predicted and observed concentrations.

Figure 6 shows the diurnal cycles of predicted PM_{10} and $PM_{2.5}$ concentrations ($\mu\text{g}/\text{m}^3$) during both Hajj and Ramadhan 1433 A.H. (2012). Again, it shows that concentrations are much higher during the month of Ramadhan than during the Hajj season. The reasons for the higher concentrations in Ramadhan are explained above. The highest level of PM_{10} during Ramadhan is $50 \mu\text{g}/\text{m}^3$, whereas during Hajj is about $25 \mu\text{g}/\text{m}^3$. In addition, the highest $PM_{2.5}$ level during Ramadhan is $30 \mu\text{g}/\text{m}^3$, whereas during Hajj is about $18 \mu\text{g}/\text{m}^3$. Comparing the diurnal cycles shown in Fig. 3 (observed data) and Fig. 6 (predicted data), it can be seen that the predicted diurnal cycles resemble more closely the Masfalah site. In contrast, the diurnal cycle at the PME site is considerably different than the modelled one. This is probably due to the fact that Masfalah is a roadside monitoring station, where road traffic is considered the main emission source, whereas PME is an urban background site having a variety of emission sources, including road traffic, restaurants and rider floor scrubber. These differences in the emission sources, which display significant temporal variability, are the most probable reasons for differences in the diurnal cycles of PM_{10} and $PM_{2.5}$ at Masfalah and PME sites.

Table 4 Comparison of modelled and observed concentrations ($\mu\text{g}/\text{m}^3$) at PME and Masfalah sites for year 2012

Site	Pollutant	Season	Observed	Modelled	Diff	% diff	Total % diff
Masfalah	PM ₁₀	Hajj	23	19.1	3.9	16.96	10.73
		Ramadhan	34.9	33.33	1.57	4.5	
	PM _{2.5}	Hajj	20.02	11.72	8.3	41.46	
		Ramadhan	29.11	20	9.11	31.3	
PME	PM ₁₀	Hajj	78.24	19.1	59.14	75.59	73.57
		Ramadhan	112.88	33.33	79.55	70.47	
	PM _{2.5}	Hajj	46.25	11.72	34.53	74.66	
		Ramadhan	72.04	20	52.04	72.24	

Figures 7 and 8 show the contour maps of PM₁₀ and PM_{2.5} ($\mu\text{g}/\text{m}^3$) during the months of Ramadhan and Hajj, respectively. The road traffic data used in these model runs are shown in Table 1, whereas meteorological data are presented in Table 3. Due to differences in input variables, especially wind direction, Figs. 7 and 8 show totally different shapes. Wind speed and direction determine the extent and direction of the pollutants dispersion. Areas downwind the emission sources are affected more significantly than the upwind regions. For example, in Fig. 7, the south-eastern regions of Makkah are affected more severely, whereas in Fig. 8, the north-eastern regions are affected more by the emissions of road traffic. Munir et al. 2015a, b, Munir et al. 2016) have used various scenarios to model the emissions of PM₁₀ and PM_{2.5}, applying ADMS-Urban in which they analysed how emissions were affected when meteorological data, especially wind direction, was changed.

The performance of the ADMS-Urban model is assessed by comparing average modelled (averaged over the six receptor points) and observed PM₁₀ and PM_{2.5} concentrations. The modelled values from both Hajj and Ramadhan are compared with observed values collected at Masfalah and PME monitoring stations. To evaluate the model performance, various metrics are recommended by various researchers (e.g., Sayegh

et al. 2014; Munir et al. 2013a; Caslaw, 2015). The metrics used in this study are provided in Table 5, which include root mean squared error (RMSE), normalised mean gross error (NMGE), correlation coefficient (R), normalised mean bias (NMB), factor of 2 (FAC2), coefficient of efficiency (COE) and coefficient of determination (R^2). Definitions and methods of calculation of these metrics are provided by Sayegh et al. (2014), Munir et al. (2013a) and Caslaw (2015). In this study, modStats function of the openair was used to calculate these metrics. By comparing the model performance at the two sites (Masfalah and PME), it can be observed that model performance is much better at Masfalah than PME site. For instance, FAC2, R, COE and R^2 values are greater, whereas NMB, NMGE and RMSE values (absolute values) are smaller at Masfalah site, which indicate better performance of the model. Furthermore, the model performance is better for predicting PM₁₀ than PM_{2.5}.

The reason as to why the model performs better at Masfalah site is that the model uses traffic data as inputs for predicting PM₁₀ and PM_{2.5} concentrations, which are closely related to the traffic conditions near Masfalah site. As mentioned above, Masfalah is a roadside monitoring station, whereas PME is a background station. PME site is a complex one receiving emissions from different sources, which are not

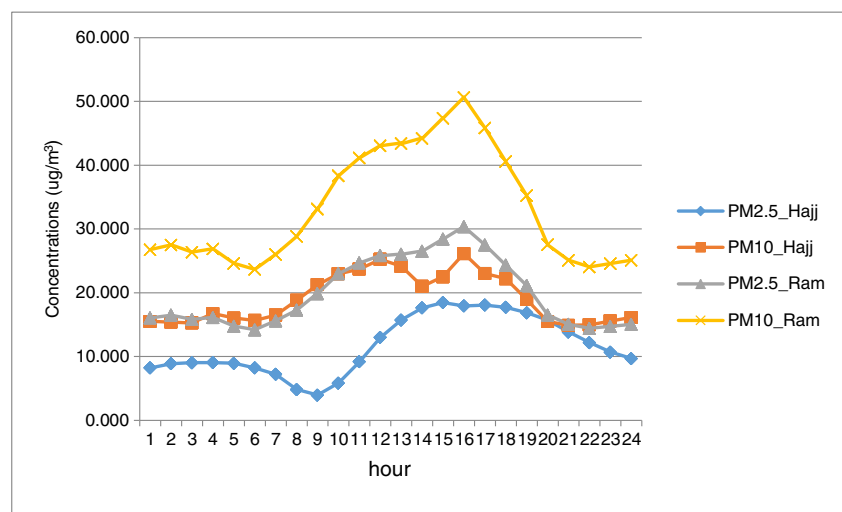
Fig. 6 Comparing the average diurnal cycles of modelled PM₁₀ and PM_{2.5} during Hajj and Ramadhan 1433 AH (2012) in Makkah

Fig. 7 Contour map of monthly average PM_{10} (lower) and $PM_{2.5}$ ($\mu g/m^3$) (upper) during the month of Ramadhan in Makkah 1433 AH (2012)

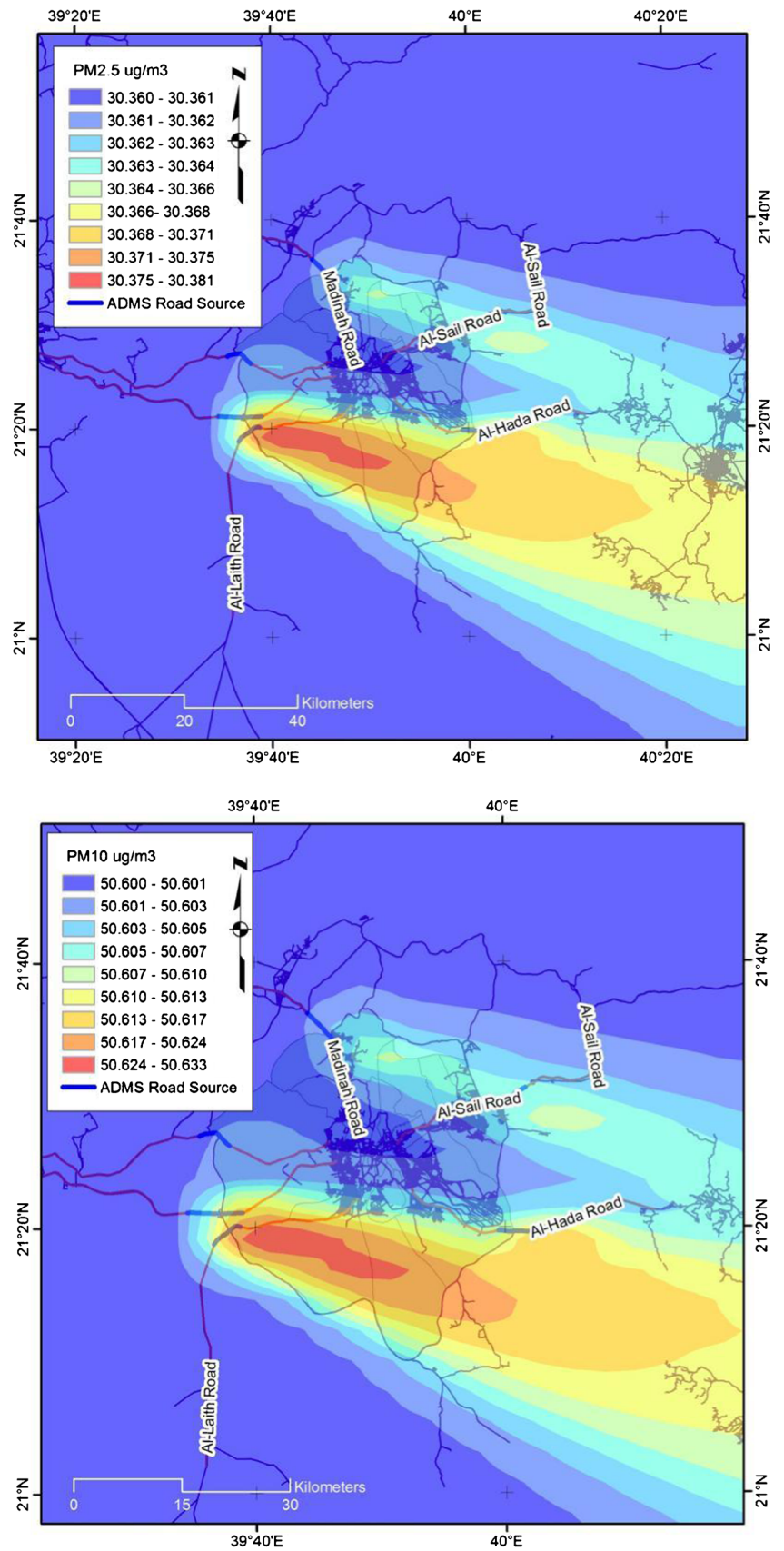


Fig. 8 Contour map of monthly average PM_{10} (lower) and $PM_{2.5}$ ($\mu g/m^3$) (upper) during Hajj in Makkah 1433 AH (2012)

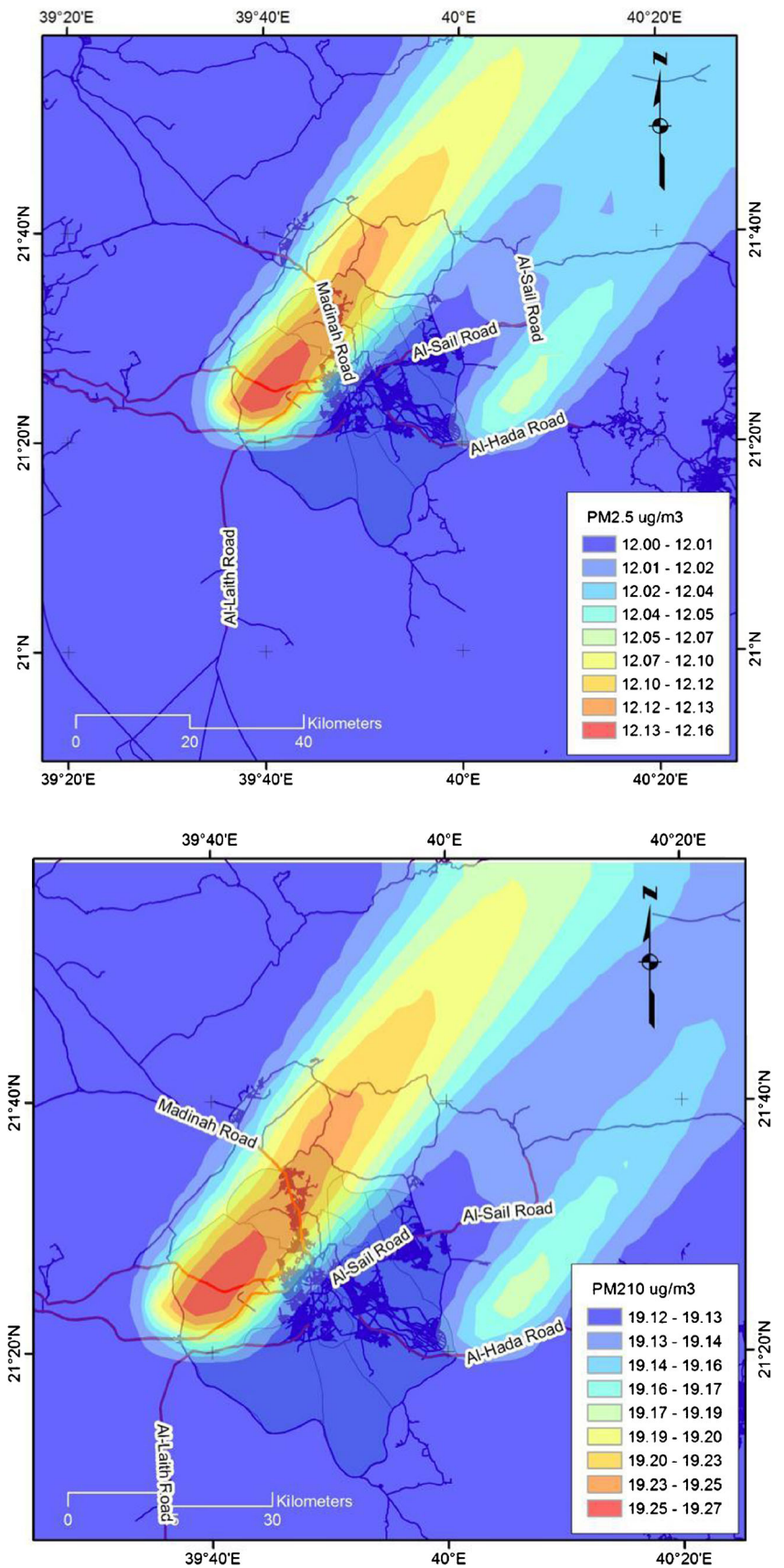


Table 5 Comparison of observed and modelled PM₁₀ and PM_{2.5} during Hajj and Ramadhan 1433 AH (2012)

Metric	Hajj		Ramadhan		Site
	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀	
FAC2	1.00	1.00	0.37	1.00	Masfalah
NMB	-0.41	0.04	-0.31	-0.04	
NMGE	0.41	0.11	0.31	0.08	
RMSE	8.30	4.78	9.11	1.57	
COE	-0.79	0.47	-2.45	0.23	
R	0.53	0.85	0.38	0.89	
R ²	0.28	0.72	0.14	0.79	PME
FAC2	0.29	0.13	0.00	0.00	
NMB	-0.74	-0.75	-0.72	-0.70	
NMGE	0.74	0.75	0.72	0.70	
RMSE	34.53	59.14	41.04	69.02	
COE	-1.94	-4.88	-4.01	-3.52	
R	-0.50	-0.40	-0.34	0.08	
R ²	0.25	0.16	0.11	0.01	

accounted for in the model; therefore, its performance is better at the Masfalah site. Model is generally under predicting both PM₁₀ and PM_{2.5} concentrations; however, prediction is much lower than the observed concentration at the PME site, which results in poor model performance in terms of the metrics shown in Table 5. To improve the model performance at PME site, further emission data are required including emission data from the surrounding restaurants and construction and demolition activities around the Haram areas.

Westmoreland et al. (2007) reported that ADMS-Urban underestimated NO_x and NO₂ concentrations by 11% and 21%, respectively, at a busy street canyon location in York, UK. The authors carried out several sensitivity tests to improve the model performance, including increasing the amount of primary NO₂ by 10%, which had a positive effect on the model performance. However, there were still major differences in predicted and measured concentrations. The results of Westmoreland et al. (2007) agree with this study, which also shows underestimation of PM₁₀ and PM_{2.5} by ADMS-Urban model. Munir et al. (2016) employed ADMS-Urban to predict PM₁₀ concentrations in Makkah estimated from the consumption of petrol, diesel and natural gases. They compared predicted and measured PM₁₀ concentrations at the PME monitoring site. The model underpredicted PM₁₀ concentrations, which again agree with the present study. This might indicate that there is a tendency of ADMS-Urban model to slightly under predict air pollutant concentrations. However, this difference might be due to error in emission sources or measured concentrations. In Makkah, no work has been done to compile a detailed air pollutants and greenhouse gases emission inventory, which is required to determine the emission sources and quantify their emissions. The

data used in this study were collected by University students manually counting vehicles as they pass by, which might have introduced a factor of error. Therefore, further work is required to fine tune the model and reduce error in air pollutant emission sources.

It is probably important to mention that the concentrations measured by monitoring stations are total concentrations (PM₁₀ emitted by natural sources plus anthropogenic sources), whereas for air quality compliance, it is recommended by Jones and Harrison (2006) to subtract the natural component from the total concentrations. We are not able to control the emission of PM₁₀ and PM_{2.5} from the natural sources, such as sea sprays, sand storms and volcanoes. We can only address emissions from anthropogenic sources, such as road traffic and power plants; therefore, for the air quality compliance purposes, only man-made emissions should be considered (Jones and Harrison 2006). In Makkah, a considerable amount of emissions comes from the natural sources which are not accounted for in the model; therefore, model prediction is considerably lower than the measured concentrations.

Conclusions

In this paper, road traffic emissions are modelled employing ADMS-Urban modelling system in the Holy City of Makkah. PM₁₀ and PM_{2.5} concentrations exceed air quality limits and, therefore, are considered the pollutants most likely to affect human health in Makkah. Modelled PM₁₀ and PM_{2.5} levels are considerably lower than the observed levels, especially at PME site, where observed concentrations of both PM₁₀ and PM_{2.5} were about 73% greater than the modelled concentrations, compared to about 24% at Masfalah site. In the model, only road traffic emissions were considered; therefore, further work is required to compile a detailed emission inventory of various emission sources. In addition to emission sources, meteorology plays a vital role in the higher levels of dust pollution in Makkah, especially temperature and wind. This study highlights the need for such modelling studies which can lead to effective air quality management leading to reduction in the impacts of air pollutants, especially of particulate pollution on human health.

Acknowledgments I greatly appreciate the institute for supporting and funding projects on environmental issues.

Funding information This study was sponsored by the Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research, Umm Al-Qura University Makkah, Saudi Arabia.

References

- Al-Jeelani HA (2009) Evaluation of air quality in the Holy Makkah during Hajj season 1425 H. *J Appl Sci Res* 5:115–121
- AQEG (2012) Air Quality Expert Group, Fine particulate matter (PM_{2.5}) in the United Kingdom. Website: https://ukair.defra.gov.uk/assets/documents/reports/cat11/1212141150_AQEG_Fine_Part particulate_Matter_in_the_UK.pdf (accessed: 09.08.2017)
- Barnpadimos I, Hueglin C, Keller J, Henne S, Prevot A (2011) Influence of meteorology on PM₁₀ trends and variability in Switzerland from 1991 to 2008. *Atmos Chem Phys* 11:1813–1835
- Caslaw D (2015) The openair manual, open-source tools for analysing air pollution data. Version: 10th June 2014, page: 230–237. Website: http://www.openair-project.org/PDF/OpenAir_Manual.pdf (accessed: 08.08.2017)
- CERC (2017) Cambridge Environmental Research Consultancy Ltd. <http://www.cerc.co.uk/environmental-software/ADMS-Urban-model.html> (accessed: 23/07/2017)
- COMEAP (2009) Long-term exposure to air pollution: effect on mortality. The Committee on the Medical Effects of Air Pollutants
- Habeebullah TM (2013) Health impacts of PM₁₀ using AirQ2.2.3model in Makkah. *J Basic Appl Sci* 9:259–268
- Habeebullah TM, Munir S, Morsy EA, Mohammed AMF (2014) Spatial and temporal analysis of air pollution in Makkah, the Kingdom of Saudi Arabia, 5th International Conference on Environmental Science and Technology. International Proceeding of Chemical, Biological and Environmental Engineering, ISSN: 2010–4618, vol. 69: 65–70. May 14–16, 2014, Gdansk, Poland
- Jones AM, Harrison RM (2006) Assessment of natural components of PM₁₀ at UK urban and rural sites. *Atmos Environ* 40(2006):7733–7741
- Munir S, Habeebullah TM, Seroji A, Morsy E, Mohammed A, Saud W, Abdou A, Awad A (2013a) Modeling particulate matter concentrations in Makkah, applying a statistical modeling approach. *Aerosol Air Qual Res* 13:901–910
- Munir S, Habeebullah TM, Seroji AR, Gabr SS, Mohammed AMF, Morsy EA (2013b) Quantifying temporal trends of atmospheric pollutants in Makkah (1997–2012). *Atmos Environ* 77:647–655
- Munir S, Habeebullah TM, Gabr S, Morsy E, Mohammed AMF, El-Saoud WA (2016) Application of ADMS-Urban in the Holy City of Makkah—modelling particulate matter (part-2). *Int J Agri Environ Res* 2(1):24–36
- Munir S, Habeebullah TM, Gabr S, Morsy E, Mohammed AMF, El-Saoud WA (2015a) Application of ADMS-Urban in the Holy City of Makkah—modelling particulate matter (part-1). *Int J Agri Environ Res* 1(1):30–39
- Munir S, Habeebullah TM, Mohammed AMF, Morsy EA, Awad AH, Seroji AR, Hassan IA (2015b) An analysis into the temporal variations of ground level ozone in the arid climate of Makkah applying k-means algorithms. *EnvironmentAsia* 8(1):53–60
- Othman N, Mat-Jafri MZ, San LH (2010) Estimating particulate matter concentration over arid region using satellite remote sensing: a case study in Makkah, Saudi Arabia. *Mod Appl Sci* 4:11–20
- Sayegh AS, Munir S, Habeebullah TM (2014) Comparing the performance of statistical models for predicting PM₁₀ concentrations. *Aerosol Air Qual Res* 14:653–665
- Seroji AR (2011) Particulates in the atmosphere of Makkah and Mina Valley during the Ramadan and Hajj seasons of 2004 and 2005. In: Brebbia CA, Longhurst JWS, Popov V (eds) *Air pollution XIX*. Wessex Institute of Technology, Ashurst
- Walters S and Ayres J (2001) The health effects of air pollution. In *Pollution causes, effects and control*, Harrison, R.M. (Ed.), Chapter 11, pp. 275, ISBN 0-85404-621-6, fourth editions, Royal Society of Chemistry, Cambridge
- Westmoreland EM, Carslaw N, Carslaw DC, Gillah A, Bates E (2007) Analysis of air quality within a street canyon using statistical and dispersion modelling techniques. *Atmos Environ* 41:9195–9205
- WHO (2003). Health aspects of air pollution with particulate matter, ozone and nitrogen dioxide. Report on a WHO Working Group Bonn, Germany 13–15, January 2003