Modelling PM10 emissions from Fossil Fuels Combustion Using ADMS-Urban in the Holy City of Makkah – A Focus on Hajj and Umrah Seasons

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Abstract

Makkah experiences high levels of atmospheric Particulate Matter (PM) emitted by various sources including re-suspension, construction-and-demolition activities, windblown particles and combustion of fossil fuels. During Hajj and Ramadhan seasons millions of Muslims from around the world visit the Holy City of Makkah to perform Hajj and Umrah, which put extra burden on the available resources. Energy consumptions and the number of road vehicles are increased by several folds, resulting in a large amount of pollutant emissions in the city, which requires effective monitoring and modelling programmes. In this paper the emissions of PM with aerodynamic diameter up to 10 μm (PM10) from the burning of natural gas, petrol, and diesel consumed in residential houses, road traffic and electricity generation are modelled in Makkah for year 2015, applying Urban Atmospheric Dispersion Modelling System (ADMS-Urban). Natural gas is mostly consumed in residential houses and restaurants, whereas petrol and diesel are predominantly used for road traffic and electricity generation. The highest amount of PM10 (tons) was emitted from the combustion of diesel used for electricity generation (330174), followed by diesel used in heavy duty vehicles (171), petrol used in light duty vehicles (48) and natural gas (< 1). Road traffic counts, fleet composition and vehicle speed data were not available in Makkah, therefore emissions were input as grid sources into ADMS-Urban. The outputs of ADMS-Urban are presented as contour maps for various emissions and meteorological scenarios. Modelled and observed PM10 concentrations are compared and discussed. ADMS-Urban model is run for the first time to model the levels of PM10 in Makkah, which will help in determining the emission sources and lead to better air quality management in Makkah, especially during Hajj and Umrah seasons.

Key words: ADSM-Urban, PM10, Air Quality Modelling, Makkah, Air Pollutant Emission, Hajj and Umrah.

Introduction

Particulate Matter (PM) is considered one of the most vital atmospheric pollutants in terms of its detrimental biological and non-biological impacts, including human health, vegetation, visibility, and ecosystem (AQEG, 2005). Atmospheric particles are found in different sizes and have different physical and chemical nature. The effect of PM on human health depends on the particles size, their atmospheric concentrations and chemical composition. The fine PM can penetrate deeply into the lungs, where they may remain embedded for long periods of time or might be absorbed into the bloodstream (AQEG, 2012; COMEAP, 2010). Prolonged exposure to fine PM can be linked to a variety of health problems including irregular heartbeat, aggravated asthma, decreased lung function, increased respiratory symptoms, such as irritation of the airways, coughing or difficulty in breathing, nonfatal heart attacks, and premature death in people with heart or lung disease (TCEQ, 2015; COMEAP, 2010). Furthermore, atmospheric PM can deposit on water bodies and on vegetation harming ecosystems and crops (Harrison, 2001). PM can also stain and damage stone and building materials, including culturally important objects such as statues and monuments (Harrison, 2001).

Recently several investigations have been made in Makkah and other cities of Saudi Arabia to investigate spatial and temporal variability of PM, quantify its emission sources, and determine various factors affecting its concentrations (e.g., Mohammed et al., 2015; Munir et al., 2013 a & b; Khodeir et al 2012). Makkah is one of the busiest cities in the world. Every year millions of people visit the city to perform Hajj and Umrah. This puts extra burden on the resources of Makkah, including energy consumption and road traffic. High fuel consumption for power generation and in road traffic result in large amount of air pollutant emissions during Hajj and Ramadhan seasons (Al-Jeelani 2009; Othman et al. 2010; Seroji 2011; Munir et al. 2013a; Munir et al. 2013b; Habeebullah 2013a; Habeebullah 2013b). PM10 concentrations in Makkah exceed air quality standards set for the protection of human health. The reasons for the high PM concentrations are most probably high volume of road traffic, construction-and-demolition work, resuspension of particles, windblown dust and sand particles, and geographical conditions (arid region) with hot temperature and low rainfall (Khodeir et al. 2012; Munir et al 2013b). Furthermore, it is reported that the concentrations of PM10 in Makkah have increased during the last 15 years or so (Munir et al., 2013b).

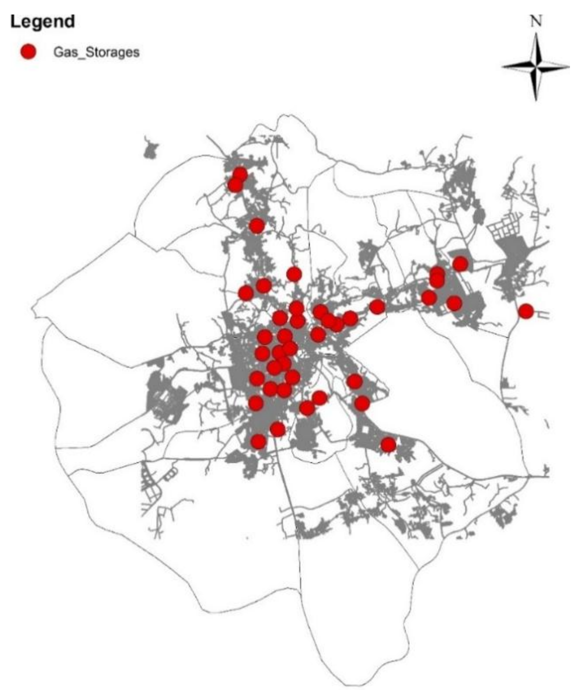
Previously several authors (Munir et al., 2013a; Sayegh et al., 2014) have modelled PM_{10} concentrations in Makkah applying statistical modelling techniques, including Generalised Additive Model, Quantile Regression Model, Multiple Linear Regression Models and Boosted Regression Trees. Further investigations are required to analyse the health impacts of PM_{10} and model its emission sources applying dispersion modelling techniques. In this study Urban Atmospheric Dispersion Modelling System

(ADMS-Urban) has been applied for the first time in Makkah to model PM_{10} emissions from the combustion of fossil fuels, such as natural gas, petrol and diesel consumed in residential houses, road traffic, and electricity generation.

Methodology

Fuel Data

In this paper PM_{10} emissions from combustion sources, including road traffic, electricity generation and residential combustion of natural gas, petrol, and diesel are modelled applying ADMS-Urban. The data of petrol, diesel and natural gas consumed in Makkah during 2015 are collected. Fuel stations (both diesel and petrol) and natural gas storages, where natural gas cylinders are filled (exchanged) are shown in Figure 1. In Makkah there are 137 fuel stations and 40 natural gas storages. Total amount of natural gas, petrol and diesel are determined and the amount of PM_{10} emission was estimated using emission factors. Emission factors were downloaded from the United Kingdom National Atmospheric Emission Inventory (NAEI, 2013) website. Emission are formatted as required by ADSM-Urban model. Road traffic characteristics, such as fleet composition, traffic counts and vehicle speed are not available in Makkah, therefore emissions are modelled as grid sources. Emissions from power plant are firstly entered and modelled as grid sources. However, power plant is also modelled as a point source separately in the second run.



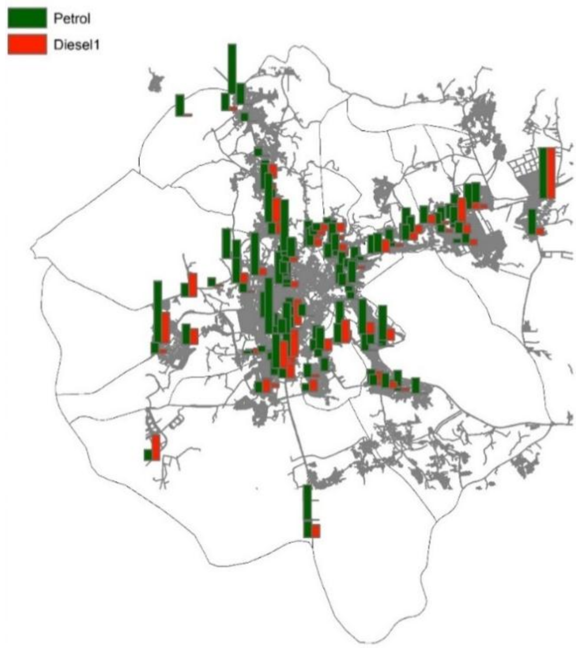


Figure 1. Gas storage sites (upper-panel), petrol and diesel stations (lower-panel) in Makkah

ADMS-Urban

ADMS-Urban has been developed commercially by Cambridge Environmental Research Consultants (CERC) and has been updated regularly since the early 1990s. The most recent version (Version 3.4) has been used throughout this paper. ADMS-Urban models the atmospheric dispersion of pollutants released from industrial, domestic and road traffic sources in urban areas. ADMS-Urban is designed to model dispersion from a single isolated point source or a single road as well as dispersion from a complex urban scenarios having multiple industrial, domestic and road traffic emissions over a large urban area. The ADMS-Urban can be applied in the following cases: (a) Developing and testing policy on air quality; (b) Development of air quality action plans; (c) Investigation of air quality management and planning options for a wide range of sources including transport sources; (d) Source apportionment studies; (e) Air quality and health impact assessments of proposed developments and use of the model for the provision of detailed street-level air quality forecasts (CERC, 2014). To predict the concentrations of pollutants, ADMS-Urban uses: (i) Relevant meteorological parameters, such as wind speed and direction, temperature, relative humidity, cloud cover, boundary layer height and temperature; (ii) Emissions and activity data e.g., traffic, industrial, area and grid sources; (iii) background air pollutants data (optional, unless modelling chemistry); and (iv) Grid or specified points where the model outputs are to be presented.

Emission data from natural gas, petrol and diesel combustion are calculated for the whole Makkah city (see Table 1). Natural gas is mostly consumed in residential house, petrol in light duty vehicles and diesel in heavy duty vehicles and power plants. PM_{10} emissions were calculated (Table 1) and imported to ADMS-Urban as emission inventory. Meteorological data were available in Makkah from several monitoring stations run by the Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research, Umm Al-Qura University Makkah. Several emissions and wind direction scenarios are tested to model their effect on PM_{10} concentrations.

Results and Discussions

The fuel consumption data were collected from various petrol and diesel filling stations in Makkah. Natural gas is mainly used in residential houses and restaurants, petrol in light duty vehicles and diesel in heavy duty vehicles. Diesel is also used for electricity generation in the power plants in Makkah. Makkah has 1.7 million population using annually 7800 kwh electricity per person (Statistical Year Book, 2014), resulting in total of 13260000000 kwh electricity usage per year.

Emissions of PM_{10} from various fuel types are presented in Table 1, which shows that in 2015 PM_{10} emission was 47.52 tons from petrol, 171 tons from diesel, < 1 ton from natural gas, and 330174 tons from power plants using diesel as fuels for electricity generation. It shows that most of the PM_{10} emission come from electricity generations. Total emissions and emission rates are also given in Table 1. Emissions were input as grid sources (0.0000087306 $g/m^2/s$) into the ADMS-Urban model.

Table 1. Emissions of PM_{10} from various sources in Makkah for 2015.

Pollutant	Emission Factor (EF) (Kton/megaton)	Fuel consumption (Mton)	Emission (Kton)	Emission (ton)
PM_{10} from Petrol	0.021	2.254	0.047	47.52
PM_{10} from Diesel	0.249	0.688	0.171	171.04
PM_{10} from Natural Gas	0.00005	0.23998	0.00001	0.01
PM_{10} from Power Generations	0.249	1326	330.174	330174.00
	Total Emissions (in tons)			330392.57
	Emission Rate ($g/m^2/s$)			0.0000087306

Figure 2 shows the output of ADMS-Urban model, using emissions from natural gas, petrol and diesel, which were input as grid source (scenario 1). Annual average PM_{10}

estimated concentrations (µg/m^3) ranged from 11.08 to 12.10. Wind direction 211^o and wind speed (1 m/s) was used in the model as input, which are average values for 2015. Other parameters are shown in the captions of Figure 2. Figure 2, shows the pattern as to how PM_{10} particles are dispersed, affecting the downwind areas of Makah the most, mainly the north-eastern parts of the city. These values are much lower than the European Union (EU, 40 µg/m^3) and Saudi Arabia (80 µg/m^3) annual air quality limits and, therefore are unlikely to have negative impacts on human health. The values are lower because in this model run we modelled only emission from traffic and residential houses, excluding emission from power generation.

Figure 3 shows a contour map as an output of ADSM-Urban model run, using a different emissions scenario (scenario 2). In scenario 2 in addition to scenario 1, emissions from power plant using diesel as fuels are included in the model. Again all emissions are input as a grid source. Meteorological parameters are kept the same as in Figure 2. Here the maximum level of PM10 concentration (µg/m3) has increased up to 350. Because the model uses the same meteorological parameters as earlier, the PM10 spatial trend seems the same, however the levels are much higher. Maximum levels exceed both EU and Saudi Arabia air quality standards. This should be noted the power plants is situated toward the north, outside of the main Makkah city. In real world situation, the emissions from the power plants should be modelled as point source, which will have a different dispersion pattern than using the emissions as a grid source. This is, therefore, over estimating PM10 concentrations in Makkah.

Figure 4, presents the outputs of the ADMS-Urban model using power plant as a point source, and emissions from other sources as grid sources (scenario 3). Here we modelled 2 wind directions: (a) using wind direction 211^o i.e. actual data for 2015 and (b) wind direction 0^o or 360^o i.e. assumed northerly wind. Using wind direction 211^o, the emissions from the power plant are disperse away from the city and most of the city is not affected by the emissions. In this scenario the predicted PM_{10} concentrations (µg/m^3) are below the EU and Saudi Arabia air quality standards. However, when the wind was assumed to be blowing from the north (0^o), the emission are dispersed toward the Makkah city. In this case the main Makkah city is experiencing a high levels of PM_{10} pollution, reaching as high as 960 (µg/m^3).

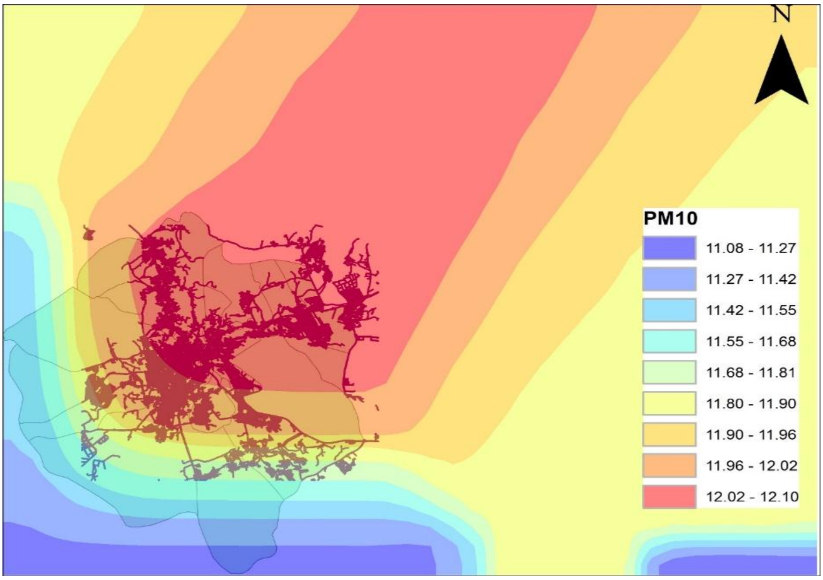


Figure 2. Contour map of modelled PM_{10} (µg/m^3) in Makkah 2015 presenting ADMS-Urban outputs using petrol, diesel, and natural gas emissions and meteorological parameters (WS = 1 m/s, WD = 211^o, Temp = 32^{o}C, Relative Humidity = 51 %, Cloud Cover = 0, and Boundary Layer Height (BLH) = 800 m).

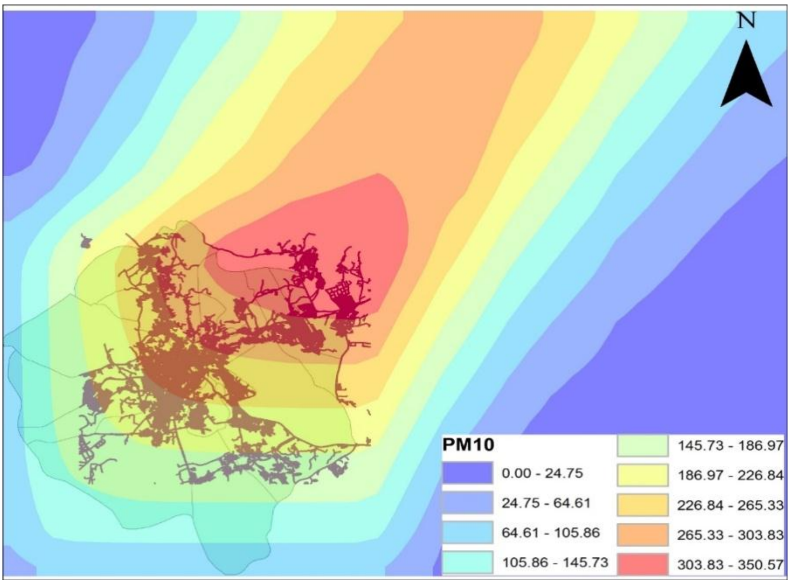


Figure 3. Contour map of modelled PM10 (µg/m3) in Makkah 2015 presenting ADMS-Urban outputs using petrol, diesel, natural gas, electric generation emissions and meteorological parameters (WS = 1 m/s, WD = 211o, Temp = 32oC, Relative Humidity = 51 %, Cloud Cover = 0, and Boundary Layer Height (BLH) = 800 m).

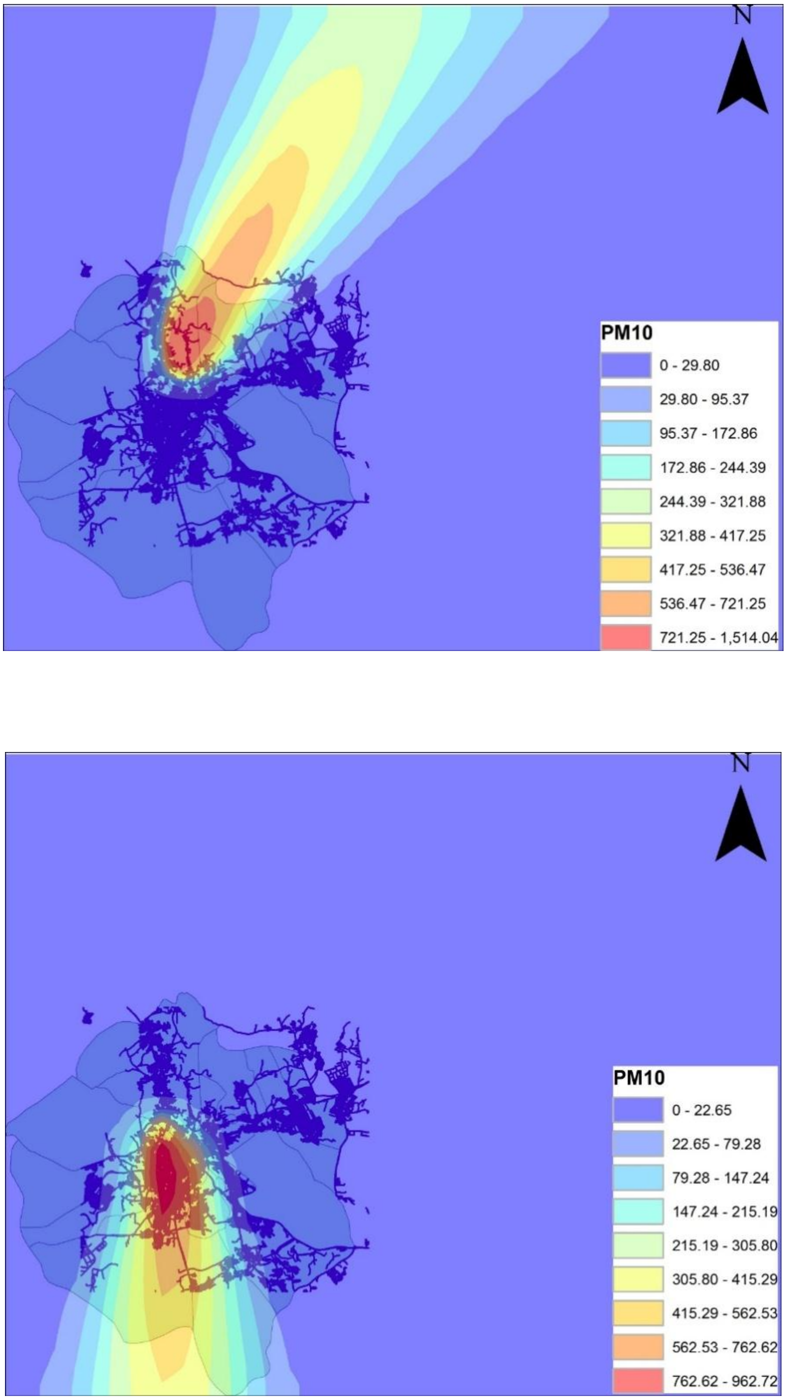


Figure 4. Contour map of modelled PM10 (µg/m3) in Makkah 2015 presenting ADMS-Urban outputs using petrol, diesel and natural gas as grid source and electric generation emissions as point source along with meteorological parameters (WS = 1 m/s, Temp = 32oC, Relative Humidity = 51 %, Cloud Cover = 0 and BLH = 800 m): (a) upper panel - wind direction 211o; lower panel -wind direction 0 or 360o.

The modelled (scenario 2) and observed PM_{10} concentrations (µg/m^3) are compared. The observed data were used from PME (Presidency of Meteorology and Environment) monitoring stations, except for 2015. Data for 2015 came from a background monitoring stations, situated in a rural background location away from the main city of Makkah. PME sites is situated next to the Holy Mosque (Al-Haram) in the centre of Makkah, data for 2015 are not available from this site. Therefore, PM_{10} concentrations are obtained from the background site, where understandably PM_{10} levels are much lower. PM_{10} concentrations for other years (2012 – 2014) are greater than the modelled level, which is expected because the model does not include background concentrations, which come from construction-and-demolition activities, windblown dust particles and resuspensions. Mean and maximum modelled PM_{10} values were 136 and 351, respectively. Observed PM_{10} values varied during different years, where mean value ranged from 27 to 185 and maximum value ranged from 231 to 821 (Table 2).

Table 2. Comparison of modelled (scenario 2) and observed PM_{10} concentrations (µg/m^3).

Year	Min	Mean	Max
2012	3	165	821
2013	8	185	480
2014	6	169	513
2015	0	27	231
Modelled	0	136	351

During the Hajj season the population of Makkah is more than doubled. From 2012 to 2015 the number of pilgrims (in millions) were 3.16, 1.98, 2.08, and 1.95, respectively. The average number of pilgrims during the last 4 years is just over 2 million, which is more than the Makkah population (1.7 million). This is not difficult to comprehend how this would affect the energy, food and transport requirements in Makkah during the Hajj season. Increasing demand for these resources would simply increase the pollutant emissions by a factor of 2, which will double the atmospheric concentrations of PM_{10} in Makkah. Similar situation occurs in Ramadhan. However, further detailed work is required to quantify emission from every individual source, including road traffic, restaurants, construction-and-demolition activities, windblown dust, power plants and other major and minor point, line and area sources.

Conclusions

In this paper the emissions of PM10 have been modelled from combustion of major fossil fuels, such as petrol, diesel and natural gas. Natural gas and petrol are mostly burnt in residential houses and light duty vehicles, respectively, whereas diesel is used in heavy duty vehicles and power plants. Employing ADMS-Urban model the emission of PM10 are modelled to estimate PM10 concentrations under various emission and wind direction scenarios. Makkah experiences highest PM10 concentrations when wind is blowing from the north and emissions from the power plant are treated as point source. In contrast, when the wind direction is changed to south, keeping power plant emission as point source, the levels of PM10 decrease drastically. PM10 concentrations are estimated to be more than doubled during the season of Hajj and Umrah as about 2 million people visit Makkah during the season of Hajj, which more than doubles the requirements of road traffic, energy and food consumptions.

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