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# Modeling Particulate Matter Concentrations in Makkah, Applying a Statistical Modeling Approach

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## ABSTRACT

Particulate matter originates from a variety of sources in Makkah, Saudi Arabia. Since Makkah is situated in an arid region and is a very busy city due to its religious importance in the Muslim world, $PM_{10}$ concentrations here exceed the international and national air quality standards set for the protection of human health. The main aim of this paper is to model $PM_{10}$ concentrations with the aid of meteorological variables (wind speed, wind direction, temperature, and relative humidity) and traffic related air pollutant concentrations (carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide ($NO_2$), sulphur dioxide ($SO_2$) and lag_$PM_{10}$ concentrations), which are measured at the same location near Al-Haram (the Holy Mosque) in Makkah. A Generalized Additive Model was developed for predicting hourly $PM_{10}$ concentrations. Predicted and observed $PM_{10}$ concentrations are compared, and several metrics, including the coefficients of determination ($R^2 = 0.52$), Root Mean Square Error (RMSE = 84), Fractional Bias (FB = –0.22) and Factor of 2 (FAC2 = 0.88), are calculated to assess the performance of the model. The results of these, along with a graphical comparison of the predicted and observed concentrations, show that model is able to perform well. While effects of all the covariates were significant (p-value < 0.01), the meteorological variables, such as temperature and wind speed, seem to be the major controlling factors with regard to $PM_{10}$ concentrations. Traffic related air pollutants showed a weak association with $PM_{10}$ concentrations, suggesting road traffic is not the major source of these. No modeling study has been published with regards to air pollution in Makkah and thus this is the first work of this kind. Further work is required to characterize road traffic flow, speed and composition and quantify the contribution of each source, which is part of the ongoing project for managing the air quality in Makkah.

***Keywords:*** Particulate matter; Air pollution; Generalized additive model; Makkah; Saudi Arabia.

## INTRODUCTION

Fine particles are considered to be responsible for respiratory health effects. There is a strong link between elevated particle concentration and increased mortality and morbidity (WHO, 2004). Exposure to particulate matter can aggravate chronic respiratory and cardiovascular diseases, alter host defenses, damage lung tissue, lead to premature death, and possibly contribute to cancer (WHO, 2004; Hassan, 2006). Particle shape and size are critical factors controlling the extent to which particles can penetrate into the respiratory tract, how and where particles are deposited, and at what rate particles are cleared from respiratory tract. Furthermore, smaller particles have a greater reactive surface area than an equivalent mass of larger particles and have a higher likelihood of reaching the deepest regions of the lungs. Ultrafine airborne particles, below 1 µm in diameter have been related to premature death, aggravated asthma, increased hospital admissions, and increased respiratory problems (Hassan, 2006). Particles also have a range of important non-biological impacts including soiling of man-made materials and buildings, reducing visibility and affecting heterogeneous atmospheric chemistry.

High levels of $PM_{10}$ concentrations in Makkah, especially during the Hajj period when several million people visit the city to perform Hajj, have been reported by several authors (e.g., Al-Jeelani, 2009; Othman *et al.*, 2010; Seroji, 2011; Habeebullah *et al.*, 2012). A brief review of the studies conducted in Saudi Arabia is shown in Table 1. The reasons for the high particulate matter concentrations are most probably high volume of traffic, construction work, resuspension of particles, geographical conditions (Arid Regions) and the role of atmospheric conditions. Most of the area of Saudi Arabia is made of deserts, thus leading to

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**Table 1.** A brief review of previous studies in Saudi Arabia.

| Name, year and location | Main pollutants and results |
|---|---|
| Nasrallah and Seroji, 2008<br>Makkah, Saudi Arabia | TSP, $PM_{10}$ and $PM_{2.5}$<br>Daily $PM_{10}$ concentration ranged 191–262 µg/m$^3$, TSP concentrations reached 665 µg/m$^3$. Chemical analysis showed high levels of sulphate, ammonium, nitrate and chloride. |
| Nasrallah and Seroji, 2007<br>Makkah, Saudi Arabia | $NO_2$, NO, $NO_x$, non-methane hydrocarbon (NMHC) and ozone.<br>Hourly mean $NO_x$ levels reached more than 800 µg/m$^3$ and ozone hourly level reached 160 µg/m$^3$in Makkah. Highest level of ozone was recorded in May and lowest in February. |
| Al-Jeelani, 2009a<br>Makkah, Saudi Arabia | $NO_2$, $SO_2$, CO, ozone, methane ($CH_4$) and total hydrocarbons (THC) as well as some meteorological parameters (temperature, wind speed and wind direction), November 2002 to October 2003 were measured and analyzed. Daily cycles of these pollutants were analyzed. |
| Al-Jeelani, 2009b<br>Makkah, Saudi Arabia | $NO_2$, $SO_2$, CO, ozone, $CH_4$ and THC and WS, WD and temperature. CO, NO, $NO_2$ varied during the day, whereas $SO_2$ concentrations were relatively constant. Ozone concentration was associated with photochemical activities. |
| Othman *et al.*, 2010<br>Makkah, Saudi Arabia | $PM_{10}$<br>$PM_{10}$ was high during Hajj season than other months |
| Kutiel and Furman, 2003<br>Middles East | Dust storms<br>Middle East, Sudan, Iraq, Saudi Arabia and the Persian Gulf, are the regions that reported the greatest occurrence of dust storms. |
| Khodeir *et al.*, 2012<br>Jeddah, Saudi Arabia | $PM_{2.5}$ and $PM_{10}$.<br>The main sources of $PM_{2.5}$ and $PM_{10}$ were (1) heavy oil combustion; (2) resuspended soil; (3) a mixed industrial source; (4) traffic source; (5) other industrial source mixture; and (6) marine aerosol. |
| Sabbak, 1995<br>Jeddah, Saudi Arabia | Iron (Fe), zinc (Zn), cobalt (Co), chromium (Cr), nickel (Ni), lead (Pb), manganese (Mn) and sodium (Na).<br>Fe and Na were the major components of the air dust. |
| Alharbi *et al.*, 2012<br>Saudi Arabia | Saudi Arabian dust storm event and its reasons.<br>Large-scale atmospheric instability, high surface winds, and dry rich dust sources cause dust storms in Saudi Arabia. |

a high concentration of dust in the air as wind blows into inhabited areas from the neighbouring desert lands (PME, 2012). The concentration of $PM_{10}$ in the atmosphere is dependent on the number and strength of the sources (e.g., road traffic), meteorological variables (e.g., wind, relative humidity) and the concentrations of other air pollutants (e.g., $SO_2$, $NO_x$). For effective management of $PM_{10}$ in Makkah, it is vital to quantify the contribution of each source and understand the role of meteorology and other air pollutants.

$PM_{10}$ concentrations have been monitored in Makkah for long time, however no published work on modeling of particulate matter was found. Therefore, this is the first effort to model $PM_{10}$ concentrations in Makkah, where no traffic characteristics and source apportionment data are available. In this study the association of $PM_{10}$ with meteorological variables and other traffic related air pollutants is described and a model is developed for predicting hourly $PM_{10}$ concentrations, using a Generalized Additive Model (GAM). GAM relaxes the assumption of normality and can handle the non-linearity in the association of dependent and independent variables (Wood, 2006). Davis and Speckman (1999), Aldrin and Haff (2005), Carslaw *et al.* (2007), and Westmoreland *et al.* (2007) used GAM for modeling the concentrations of various air pollutants in different countries of the World. More recently, Paciorek *et al.* (2009) applied GAM for modeling the spatio-temporal variation of particulate matter in South Carolina.

## METHODOLOGY

### *Data Source*

This research project was conducted at the Hajj Research Institute (HRI), Umm Al-Qura University in Makkah. The City of Makkah is at an elevation of 277 m above sea level, and approximately 80 km inland from the Red Sea. The city is surrounded by mountains, which define the contemporary expansion of the city with a population of 1,700,000, which gets doubled or even more during the season of Hajj and the month of Ramadhan. The city centers on the Masjid al-Haram area, which is the lowest and most crowded area in the city. The monitoring site used in this project (AQMS-112) is situated near the Holy Mosque (Al-Haram) as shown in Figs. 1 and 2. It is important to note that the AQMS-112 site is run by Presidency of Meteorology and Environment (PME) and shares data with HRI. Fig. 1 shows the monitoring network in Makkah run by HRI and Fig. 2 shows a detailed maps of the AQMS-112 (21°25'28.66"N, 39°49'44.44"E) site and potential sources of emissions in the surrounding area, which include a construction side, a busy road and bus stations (discussed later).

$PM_{10}$ ($\mu g/m^3$) concentration and independent variables (Sulphur Dioxide ($SO_2$ $\mu g/m^3$), Carbon Monoxide (CO $mg/m^3$), Nitric Oxide (NO $\mu g/m^3$), Nitrogen Dioxide ($NO_2$ $\mu g/m^3$), Particles with aerodynamic diameter 10 µm or less

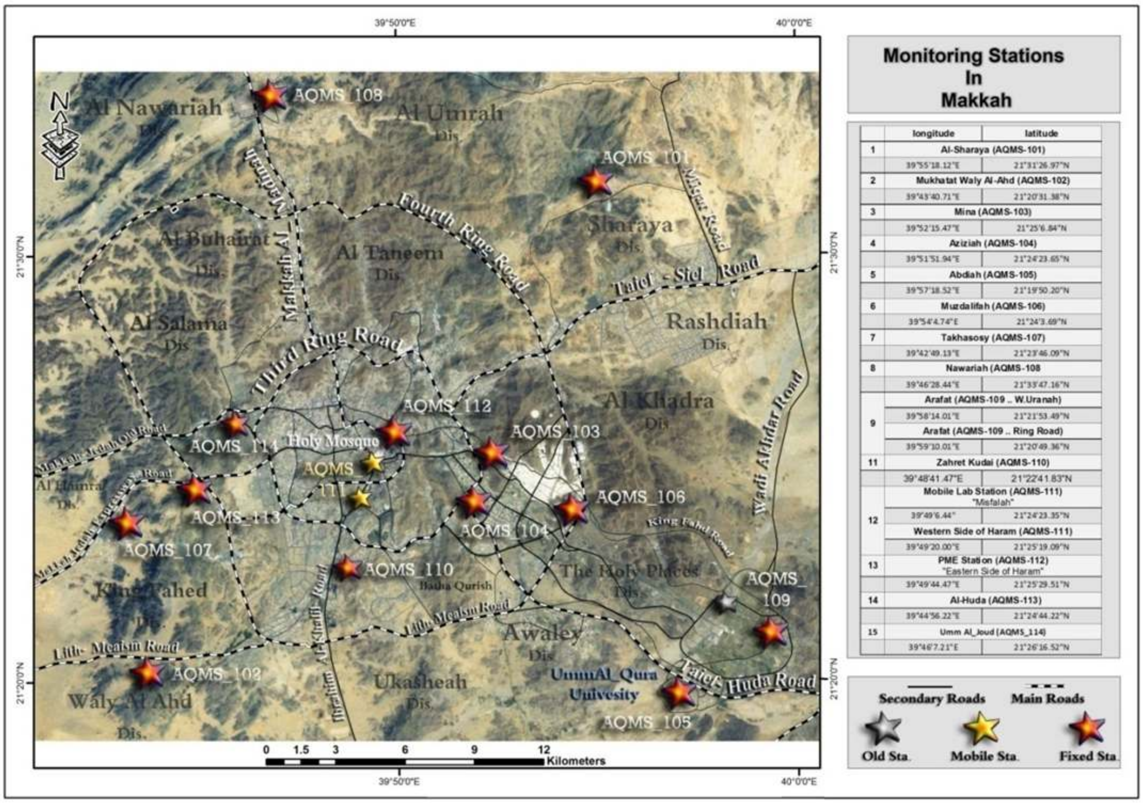


**Fig. 1.** Map of the air quality and meteorological monitoring sites in Makkah, where AQMS-112 shows the site, where the data used in this paper was measured.

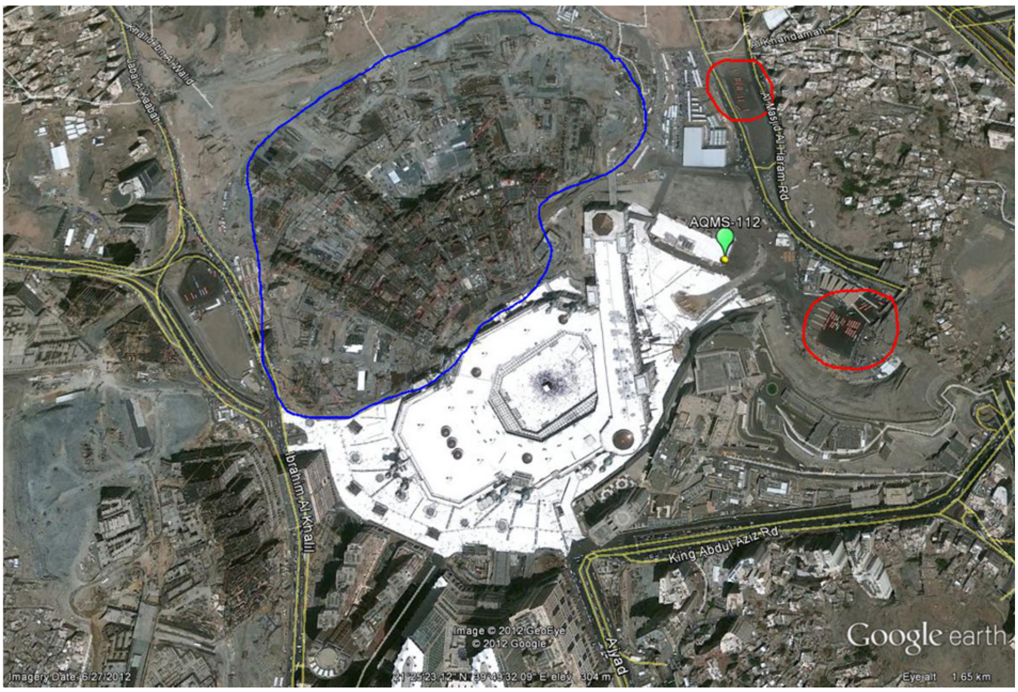


**Fig. 2.** Map of the monitoring site (AQMS-112) showing various sources of emissions. Blue circle shows construction area and red circles show bus stands, along the Masjid Al-Haram Road.

($PM_{10}$ μg/m$^3$), Wind Speed (WS m/s), Wind Direction (WD degrees), Temperature (T °C), and Relative Humidity (RH %) are continuously monitored at PME monitoring site. Hourly mean data of these parameters from November 2011 to July 2012 were obtained, which were further analyzed using the methodology described in below. A summary of these variables is given in Table 2.

Road transport is considered as one of the major sources of traffic related air pollutants including $PM_{10}$ and therefore traffic flow and speed should have been included as explanatory variables in the model. However traffic data for the study area were not available and therefore traffic-related air pollutants (e.g., CO and NO) were included in the model as surrogates for the traffic characteristics (Pont and Fontan, 2000) and as a source of secondary air pollutants (e.g. $SO_2$ and $NO_2$ leading to the formation of $SO_4^{2-}$ and $NO_3^-$).

### *Measurement of $PM_{10}$*

Several methods, such as the Tapered Element Oscillating Microbalance (TEOM) system, the Beta-Attenuation Monitor (BAM) and Partisol are used for measuring the concentration of $PM_{10}$ in the atmosphere. TEOM determines particulate concentration by continuously weighing particles deposited on a filter, whereas BAM consists of a paper band filter located between a source of beta rays and a radiation detector. A pump draws ambient air through the filter and the reduction in intensity of beta-radiation measured at the detector is proportional to the mass of particulate deposited on the filter. The Partisol is a gravimetric sampler that collects daily samples onto a filter for subsequent weighing to determine the $PM_{10}$ concentration.

The standard EU reference method for particulate measurement refers to three devices which might be used for measuring $PM_{10}$ concentrations: (a) Low Volume System: the LVS-$PM_{10}$ Sampler; (b) High Volume System: the HVS-$PM_{10}$ Sampler; and (c) Super-high Volume System: SHVS-$PM_{10}$ also known as Wide Range Aerosol Classifiersampler (WRAC-$PM_{10}$). At HRI two types of monitors are used for measuring the concentrations of $PM_{10}$: BAM 1020 and HVS $PM_{10}$ samplers. Continuous monitoring of $PM_{10}$ is carried out using Dust Monitor (BAM 1020), which provides 30 minutes concentrations in the units of μg/m$^3$. HVS $PM_{10}$ Samplers are used as a portable device for measuring $PM_{10}$ concentrations, providing 24 hr average concentrations. At HRI the later is generally used to monitor $PM_{10}$ concentrations for a short period of time, such as during Hajj and the Month of Ramadan.

### *Data Quality*

A summary of $PM_{10}$ and independent variables is presented in Table 2, where most of the variables have over 95% data capture (%DC), except $SO_2$ (79%) and $PM_{10}$ (88%). EU standard for DC is 75%, suggesting any variable with less than 75% DC should be removed from the analysis. Data for $PM_{10}$ and covariates were obtained from the AQMS-112 monitoring site, near the Haram in Makkah from November 2011 to June 2012 for model training and for July 2012 for model testing.

### *General Statistics*

Correlation analysis is applied to estimate the extent of relationship between $PM_{10}$ concentrations and other variables. Furthermore, graphical presentations (e.g., bivariate polar plots and scatter diagram) are used to present the outputs of the analysis.

Several metrics were calculated to assess the model performance. These metrics are: Root Mean Square Error (RMSE), Normalised Mean Gross Error (NMGE), Correlation coefficient (R), Normalised Mean Bias (NMB), Fractional Bias (FB) and Factor of 2 (FAC2). The RMSE is a commonly used metric that provides a good overall measure of how close modelled values are to predicted values. The Mean Bias (MB) is an indication of the mean over or under

**Table 2.** Presenting a summary of $PM_{10}$ concentrations and independent variables from November 2011 to June 2012 at AQMS-112 site in Makkah.

| Variables | Min | Mean | Median | Max | NA's | DC (%) |
|---|---|---|---|---|---|---|
| [1]$SO_2$ | 0.00 | 15.82 | 16 | 919 | 1224 | 79 |
| CO | 0.00 | 1.10 | 0.95 | 6.87 | 283 | 95 |
| NO | 0.00 | 12.64 | 4.00 | 299 | 262 | 96 |
| $NO_2$ | 0 | 39 | 34 | 320 | 262 | 96 |
| $O_3$ | 0 | 55 | 52 | 270 | 248 | 96 |
| $PM_{10}$ | 0 | 174.6 | 141.0 | 999 | 704 | 88 |
| WS | 0 | 1.15 | 1.1 | 4.4 | 216 | 96 |
| WD | 1 | 239.7 | 279.0 | 360 | 216 | 96 |
| T | 15.6 | 29.5 | 28.7 | 46.2 | 214 | 96 |
| RH | 3.9 | 34.44 | 33.90 | 84.60 | 214 | 96 |
| RF | 0 | 0 | 0 | 2016 | 214 | 96 |
| PR | 649.0 | 974.5 | 976.5 | 984.4 | 214 | 96 |

[1] In the table $SO_2$ stands for sulphur dioxide(μg/m$^3$), CO for carbon monoxide(mg/m$^3$), NO for nitric oxide(μg/m$^3$), $NO_2$ for nitrogen dioxide(μg/m$^3$), $O_3$ for ozone(μg/m$^3$), $PM_{10}$ for particles having diameter less than 10 um(μg/m$^3$), WS for wind speed (m/s), WD for wind direction (degrees), T for temperature (°C), RH for relative humidity (%), RF for rainfall (mm), PR for atmospheric pressure (hPa), Min for minimum, Max for maximum, NA's for missing data (not available), and DC for data capture (valid data in percentage).

estimate of prediction. To estimate NMB the value of MB is divided by the observed concentration. NMGE is the same as NMB, but it ignores whether a prediction is an over or under estimate (absolute value). The correlation coefficient is a measure of the strength of the linear relationship between two variables. Most often correlation coefficient is squared to calculate coefficient of determination ($R^2$). FB is used to identify if the model shows asystematic tendency to over or under prediction. FB value varies between +2 and –2 and has an ideal value of zero. Negative values suggest a model over-prediction and positive values suggest a model under-prediction. FAC2 is the fraction of modeled values within a factor of two of the observed values. In other words FAC2 is a count of the fraction of points within 0.5 and 2 times the observed values and satisfies that $0.5 \leq Mi/Oi \leq 2.0$, where Mi and Oi stand for the modeled and observed values of $PM_{10}$ concentrations. For more details on these metrics and their mathematical formulae see Carslaw (2011) and Derwent *et al.* (2010).

Statistical Software R programming language (R Development Core Team, 2012), with package mgcv, version 1.7–12 (Wood, 2012) and openair version 2.13.2 (Carslaw and Ropkins, 2012) are used for running GAMs, other statistical tests and making graphs.

### *Generalized Additive Model (GAM)*

GAMs are statistical models developed by Hastie and Tibshirani (1990) for blending properties of generalized linear models with additive models. GAMs assume that the mean of the dependent variable depends on additive predictors through a nonlinear link function. GAMs permit the response probability distribution to be any member of the exponential family (e.g., normal, exponential, gamma, Poisson and many other) (Wood, 2006). GAM uses smoothing components to establish the shape of relationship and these are determined by the data itself (i.e., the relationship is not forced to take a particular functional form, e.g., linear or exponential). The additive model in a general form can be described as below (Eq. (1)).

$$Y = s1\ (X1) + s2\ (X2) + s3\ (X3) \qquad (1)$$

where Y is the response variable and s is a smoothing term which corresponds to an associated explanatory variable (X).

#### *Model Development*

In this paper, the main aim is to find the combination of explanatory variables which can describe a high degree of the pollutant concentration variability ($R^2$) in Makkah. $PM_{10}$ was used as response variable and the concentrations of some traffic related air pollutants (Carbon Monoxides (CO mg/m$^3$), Nitric Oxide (NO µg/m$^3$), Nitrogen Dioxide ($NO_2$ µg/m$^3$), Sulphur Dioxide ($SO_2$ µg/m$^3$) and lag_$PM_{10}$ (concentration of $PM_{10}$ from the previous day)); and meteorological variables (Wind Speed (WS m/s), Wind Direction (WD degree from the north), temperature (T °C) and Relative Humidity (RH %) as independent (explanatory) variables. A summary of the parameters is given in Table 2. Traffic data were not available in the study areas, therefore the concentration of other air pollutants were used instead, which provide a surrogate to traffic flow (Pont and Fontan, 2000) and a source for secondary particles formation. Some authors (e.g., Carslaw *et al.*, 2007; Westmoreland *et al.*, 2007) have suggested that wind speed and wind direction should be included in the model as interactive term (u, v), where u is [wind speed] × sine (wind direction) and v is [wind speed] × cosine (wind direction), however this did not improve the model performance significantly and therefore the actual values of wind speed and wind directions, which are easier to follow were used in the model. Precipitation and cloud cover may help reduce $PM_{10}$ concentration by washing out effect and by affecting relative humidity and temperature of the atmosphere; however the values of rain fall and cloud cover were zero for the whole time period considered in this paper and therefore were removed from the model. The final GAM model for $PM_{10}$ is shown in Eq. (2).

$$PM_{10} = s1(CO) + s2(SO_2) + s3(NO_2) + s4(NO) + s5(RH) + s6(T) + s7(WS) + s8(WD) + s9(lag\_PM_{10}) \qquad (2)$$

where s1 to s9 are smoothing terms (Wood, 2006) which correspond to the associated explanatory variables as explained above. Lag_$PM_{10}$ is the concentration of $PM_{10}$ from the previous day, as suggested by several authors (e.g., Baur *et al.*, 2004).

## RESULTS AND DISCUSSIONS

The outputs of the GAM model are depicted in Fig. 3. The p-values being less than 0.01 show highly significant effect of all independent variables included in the model. Coefficient of determination ($R^2$-adjusted) was 0.50, deviance explained was 51%, and GCV score was 8658. Several other metrics were estimated to assess the performance of the model, as suggested by Carslaw (2011) and Derwent *et al.* (2010).

Fig. 3 shows the outputs of GAM model (given in Eq. (2)), where it is shown how the association of $PM_{10}$ concentrations changes with the levels of other variables, for example CO and NO both being primary traffic related pollutants show different effects on $PM_{10}$ concentrations. CO shows negative whereas NO shows positive effect on $PM_{10}$ concentrations and the strength of the effect increases with increasing CO and NO concentrations. This might indicate that a considerable proportion of $PM_{10}$ in Makkah has different sources of emission to these other air pollutants. For example, NO and CO are mainly emitted by road traffic in the surrounded area, whereas $PM_{10}$, in addition to road traffic, is generated by other sources as well, such as construction work and resuspension of the dust particles. Simple correlation analysis showed a strong correlation between CO and NO (R = +0.62) and a weak correlation between $PM_{10}$ and NO (R = +0.02) and $PM_{10}$ and CO (R = –0.11). Correlation coefficients of $PM_{10}$ were –0.08 and –0.11 with $NO_2$ and $SO_2$, respectively. It is well known that $SO_2$ and $NO_x$ are the two important sources of secondary particulate matter (e.g., $NO_3^-$ and $SO_4^{2-}$) and generally have positive contribution to $PM_{10}$ concentrations (e.g., Harrison,

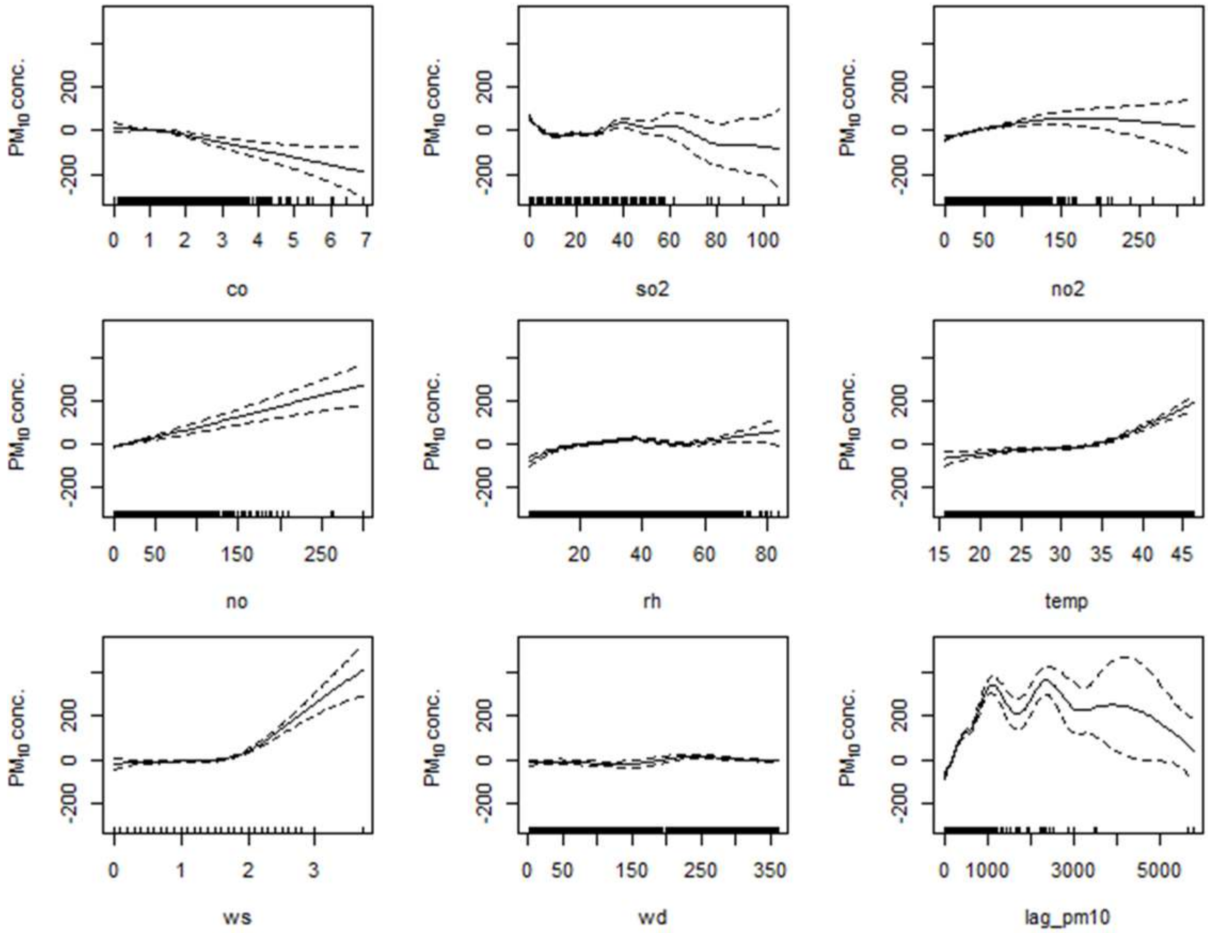


**Fig. 3.** The outputs of the model, where $PM_{10}$ was used as independent variable and concentrations of some other air pollutants, i.e., Carbon Monoxides (CO mg/$m^3$), Nitric Oxide (NO µg/$m^3$), Nitrogen Dioxide ($NO_2$ µg/$m^3$), Sulphur Dioxide ($SO_2$ µg/$m^3$) and lag_$PM_{10}$ (concentration of $PM_{10}$ from the previous day µg/$m^3$) and meteorological variables, i.e., Wind Speed (WS m/s), Wind Direction (WD degree from the north), temperature (T °C) and Relative Humidity (RH %) as independent variables. The data come from the air quality monitoring station near Al-Haram, Makkah Saudi Arabia, November 2011 to June 2012. The dashed lines are the estimated 95% confidence intervals. The vertical lines adjacent to the lower x-axis show the presence of data.

2001b). Here the negative correlation of $PM_{10}$ with these air pollutants might indicate that $PM_{10}$ concentrations are predominantly controlled by construction work and resuspension of dust particles due the arid nature of the regions. Positive association between $PM_{10}$ and lag_$PM_{10}$ is expected and understandable, as fine and extra fine particles stay in the atmosphere for long time and contribute positively to the measured concentration hours or even days later (AQEG, 2005). In Makkah during Hajj season and the month of Ramadhan due to increase in transport and other activities (such as walking), the resuspension of sand and dust is enhanced, which further increases the concentrations of particulate matter in the atmosphere (Seroji, 2011). Modeling and source apportionment of these sources is a challenging task, which may add to uncertainties in the model outputs.

A decrease or increase in air pollution concentration is the result of an imbalance between air pollutants production rates (emission of primary pollutants from sources and formation of secondary pollutants in the atmosphere) and air pollutants removal rates (dilution and loss from the atmosphere) (Andersson *et al.*, 2006). Meteorology plays a vital role in secondary particles formation and their removal from or dilution in the atmosphere. Meteorological factors such as temperature, solar radiations, relative humidity, and wind speed can influence the transport, dispersion and chemical reactions of air pollutants (Harrison, 2001b). Fig. 3 shows strong positive effect of wind speed and temperature on $PM_{10}$ concentrations. Wind speed plays a vital role in the dispersion of air pollutants and transportation of air pollutants from one place to another ranging from local to regional or global scale (Liu *et al.*, 2011 and the references therein). High wind speed and high temperature both increase turbulence and resuspension of the dust particles (Kim *et al.*, 2006). In an arid region like Saudi Arabia which mostly has no rain for months and where most of the area is made of sandy deserts, high wind speed lifting sand and dust particles leads to high concentrations of dust as wind blows into inhabited areas from the neighbouring desert lands (PME, 2012). Simple correlation analysis showed a strong correlation between $PM_{10}$ concentration and wind speed (R = +0.42) and temperature (R = +0.38). Sand and dust storms is a common phenomenon, during high wind speed in Saudi Arabia. High relative humidity increases chemical reactivity in the atmosphere; and is generally linked with night time hours when dust concentration is low and therefore shows negative correlation with $PM_{10}$ concentrations. Duenas *et al.* (2002) has reported that relative humidity plays an important role in air quality, as relative humidity may play a role in the overall reactivity of the atmospheric system, either by affecting chain termination reactions or in the production of wet aerosols, which in turn affect the flux of ultraviolet radiation. Furthermore, relative humidity is also considered to be a limiting factor in the disposition of $NO_2$ because high percentages of humidity favour the reaction of the $NO_2$ with salt particles, e.g., sodium chloride (NaCl).

The effect of wind speed and wind direction is further elaborated in Fig. 4 in the form of a bivariate polar plot. The plots are constructed by averaging pollutant concentration by wind speed categories (0–1 m/s, 1–2 m/s, etc.) as well as wind direction (0–10, 10–20, etc.). In polar plots (Fig. 4) the levels of different variables are shown as a continuous surface, which are calculated through using Generalized Additive Models *s*moothing techniques (Carslaw and Ropkins, 2012). It can be observed in Fig. 4 that high $PM_{10}$ concentration is related with high wind speed from the west direction (between 225 to 360°). Further investigation of the local area revealed that there was a large construction work going on near Al-Haram in southwest to northwest direction (Fig. 2). There are some barriers (e.g., a part of Al-Haram building) between the monitoring site and construction location, however when westerly wind is blowing at speed greater 2 m/s, the dusts manage to reach the Haram and results in high concentrations of $PM_{10}$. On the eastern side, there is a busy road (Masjid Al-Haram Road) and a couple of bus stations (shown in Fig. 2), which probably contribute to the monitored concentration. However this contribution seems considerably lower than the western side contribution, as shown by the colour of the polar plot. Polar plots developed for NO, CO and $SO_2$ showed high concentrations on the eastern side (Habeebullah *et al.*, 2012), indicating high contribution of road traffic. This probably indicates that most of the $PM_{10}$ concentrations come from other sources rather than road traffic, otherwise the pattern of $PM_{10}$ concentrations and other air pollutants would have been the same.

***Assessment of the Model Performance***

Various metrics ($R^2$, RMSE, NMB, FB and FAC2) were calculated to assess the model performance. These metrics have been defined above and their values for the testing dataset (July, 2012) were 0.52, 84, 0.21, –0.22, and 0.88 for $R^2$, RMSE, NMB, FB, and FAC2, respectively. FB (–0.22) shows a tendency towards slightly over predicting the $PM_{10}$ concentrations and therefore an adjustment factor might be required. When the adjustment factor (regression coefficient or slope of the line between observed and predicted $PM_{10}$ concentrations) of 0.75 was applied the FB value changed to 0.06. The values of other metrics improved as well.

Figs. 5 and 6 compare predicted (without any adjustment) and monitored $PM_{10}$ concentrations for the testing dataset (July, 2012). FAC2 value of 0.88 shows that 88% of data-points lie between 0.5:1 and 2:1 lines. Observed and predicted $PM_{10}$ concentrations are also compared in Fig. 6 with the help of a time series plot and a bivariate polar plot, which show closer relationship between the two concentrations. It

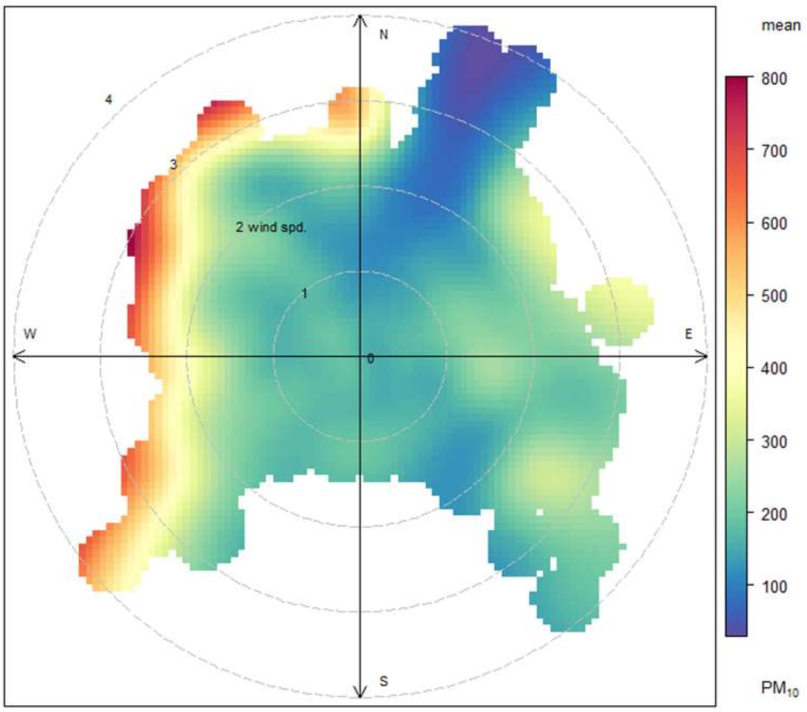


**Fig. 4.** Polar plot of $PM_{10}$ concentration near Al-Haram, Makkah, colour coded by $PM_{10}$ concentrations.

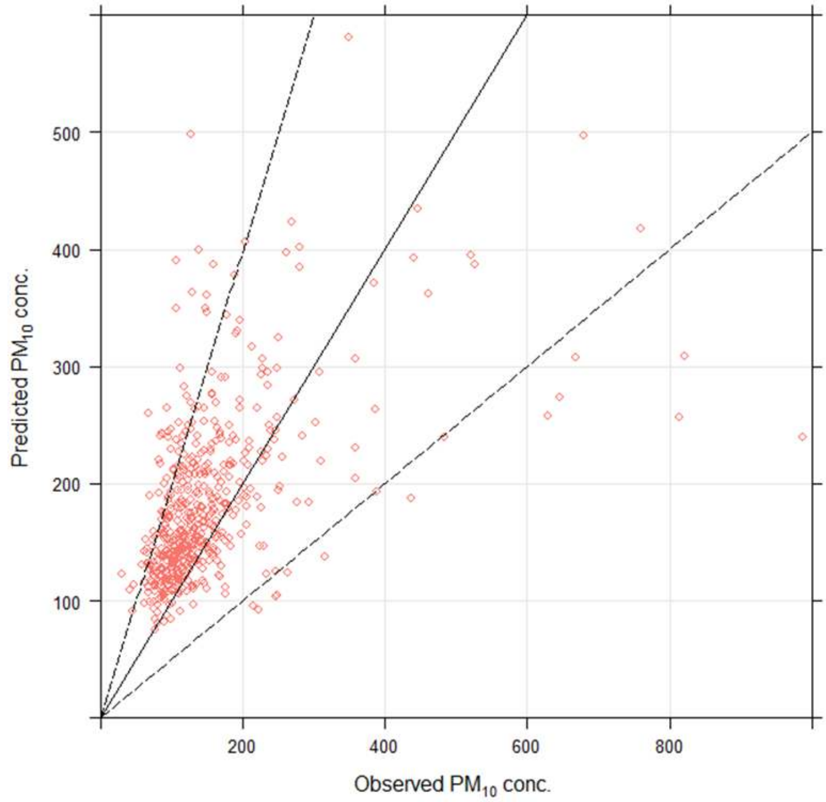


**Fig. 5.** Scatter plot of observed and predicted $PM_{10}$ concentrations. The dashed lines show the within factor of two (FAC2) region. The middle line is 1:1, the above is 0.5:1 line and below is 2:1 line.

should be noted that the right side polar plot, representing the predicted $PM_{10}$ concentrations (p) has considerably larger scale, which again confirms the over prediction of the model, as discussed above. These polar plots have the same characteristics as in Fig. 4 (developed for the training dataset), highlighting the sources towards the west and northwest. However, the model prediction seems slightly biased towards the north but still successfully correlate high prediction with high wind speed, as explained in above.

This is the first effort to model $PM_{10}$ concentration in Makkah, where multiple sources including road traffic, resuspension and construction work contribute to the observed $PM_{10}$ concentrations. Further work is required to quantify the contribution of each source, particularly road traffic, being the main sources of several air pollutants in urban areas, which is part of the ongoing project for improving air quality in Makkah.

## CONCLUSIONS

This study aims to model variations in $PM_{10}$ concentration with the help of meteorological variables and traffic related air pollutants (e.g., CO and $NO_x$). Traffic related air pollutants can provide a surrogate for traffic flow and are sources of secondary particles, such as $SO_4^{2-}$ and $NO_3^{-}$. Meteorological variables play a vital role in particles dispersion, resuspension, and atmospheric reactivity. Using a GAM model, these covariates can explain a considerable amount of variations in $PM_{10}$ concentrations. Predicted and observed $PM_{10}$ concentrations are strongly correlated, with $R^2$ (0.52), RMSE (84), FB (-0.22) and FAC2 (0.88). The values of these metrics and graphical comparison (polar and scatter plots) put confidence in the model performance. The effects of all covariates were significant (p-value < 0.01), however meteorological variables, for instance temperature and wind speed due to their strong positive association seem to play dominant role in controlling $PM_{10}$ concentrations in Makkah. This may suggest that high $PM_{10}$ concentrations in Makkah are as a result of the arid nature of the region. Traffic related air pollutants showed weak association with $PM_{10}$ concentration, which suggests that road traffic is not the major emission source of $PM_{10}$. Further work is required to quantify the contribution of each source of $PM_{10}$ in Makkah, which is part of the ongoing project for improving air quality in Makkah.

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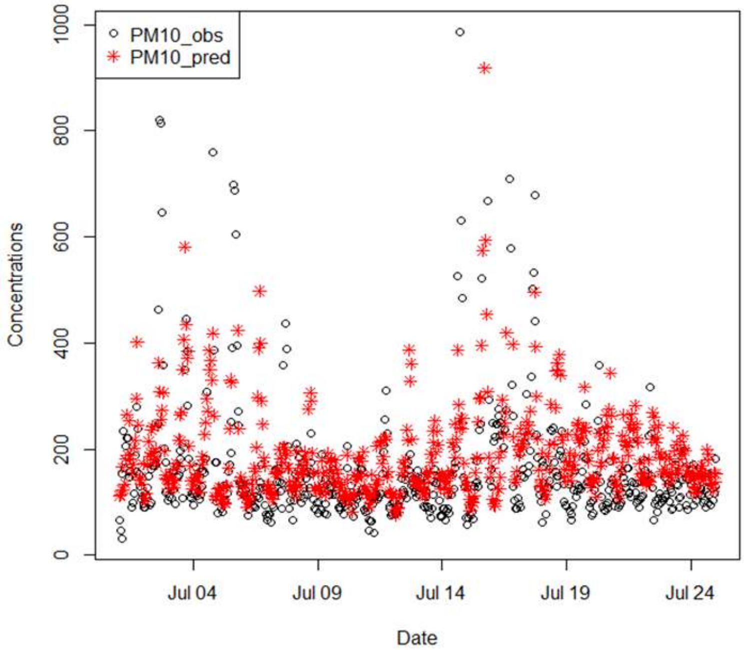
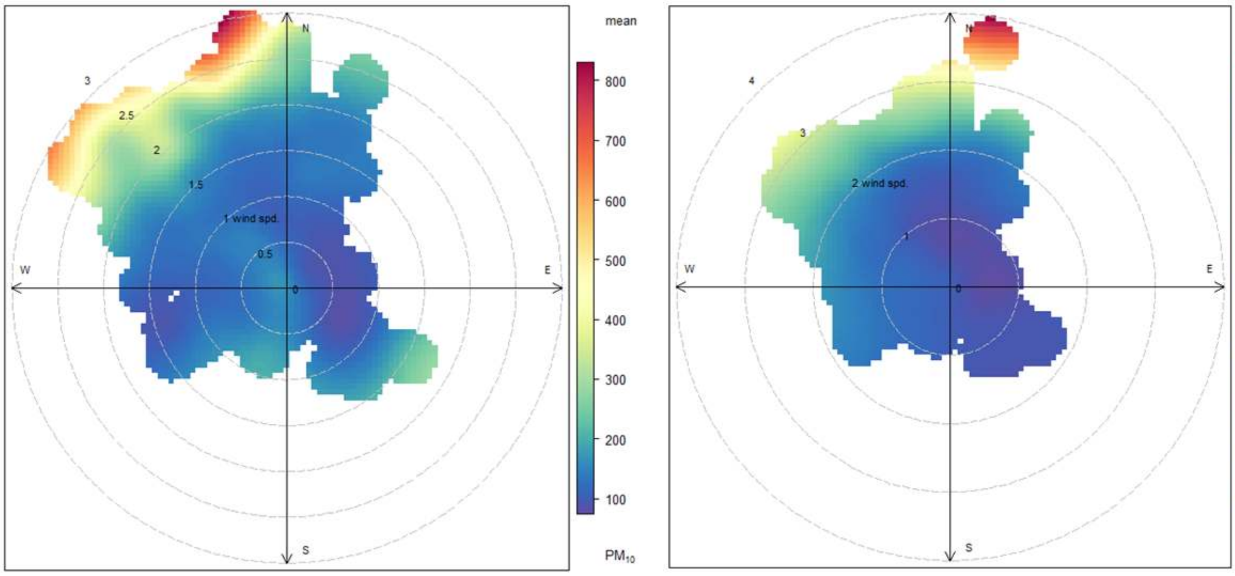



(a)




(b)

**Fig. 6.** Comparison of observed and predicted $PM_{10}$ concentrations for the month of July 2012, in Makkah. (a) shows a time series comparison and (b) shows bivariate polar plot comparison, where $PM_{10}$ shows observed concentrations and p shows predicted concentration.

## REFERENCES

Aldrin, M. and Haff, I.H. (2005). Generalised Additive Modelling of Air Pollution, Traffic Volume and Meteorology. *Atmos. Environ.* 39: 2145–2155.

Alharbi, B., Maghrabi, A. and Tapper, N. (2012). The March 2009 Dust Event in Saudi Arabia: Precursor and Supportive Environment. *Bull. Am. Meteorol. Soc., In Press.*

Al-Jeelani, H.A. (2009a). Evaluation of Air Quality in the Holy Makkah during Hajj Season 1425 H. *J. Appl. Sci. Res.* 5: 115–121.

Al-Jeelani, H.A. (2009b) Air Quality Assessment at Al-Taneem Area in the Holy Makkah City, Saudi Arabia. *Environ. Monit. Assess.* 156: 211–22.

Al-Zahrani, S.A. (2010). The Road to Saudi Arabian Clean Fuels, Downstream Process Engineering Division, Saudi Aramco (http://www.hartfuel.com/0908/f.saudicleanfuels.html).

Andersson, C., Langner, J. and Bergstrom, R. (2006). Interannual Variation and Trends in Air Pollution over Europe Due to Climate Variability during 1958–2001 Simulated with a Regional CTM Coupled to the ERA40 Reanalysis. *Tellus* 59: 77–98.

AQEG (2005). Air Quality Expert Group, Particulate Matter in the United Kingdom, Published by the Department for the Environment, Food and Rural Affairs of the Uited Kingdom.

Baur, D., Saisana, M. and Schulze, N., (2004). Modelling the Effects of Meteorological Variables on Ozone Concentration-A Quantile Regression Approach. *Atmos. Environ.* 38: 4689–4699.

Carslaw, D. (2011). Defra Regional and Transboundary Model Evaluation Analysis – Phase 1. Version: 15th April 2011.

Carslaw, D. and Ropkins, K. (2012). Openair - An R Package for Air Quality Data Analysis. *Environ. Modell. Softw.* 27: 52–61.

Carslaw, D.C., Beevers, S.D. and Tate, J.E. (2007). Modelling and Assessing Trends in Traffic-related Emissions Using a Generalized Additive Modelling Approach. *Atmos. Environ.* 41: 5289–5299.

Davis, J.M. and Speckman, P. (1999). A Model for Predicting Maximum and 8 h Average Ozone in Houston. *Atmos. Environ.* 33: 2487–2500.

Derwent, D., Fraser, A., Abbott, J., Jenkin, M., Willis, P. and Murrells, T. (2010). Evaluating the Performance of Air Quality Models, Issue 3/June 2010.7, 81.

Duenas, C., Fernandez, M.C., Canete, S., Carretero, J. and Liger, E. (2002). Assessment of Ozone Variations and Meteorological Effects in an Urban Area in the Mediterranean Coast. *Sci. Total Environ.* 299: 97–113.

Habeebullah, T.M., Munir, S. and Morsy, E.A. (2012). An Analysis of Air Pollution in Makkah: A View Point of Source Identification, A Report Submitted to the Department of Environment and Health Research, the Custodian of the Two Holy Mosques Institute for Hajj and Umrah Research, Umm Al-Qura University, Makkah, Kingdom of Saudi Arabia, Nov. 2012.

Harrison, R.M. (2001a). *Pollution Causes, Effects, and Control*, 4th Edition, Harrison, R.M. (Ed.) Royal Society of Chemistry, London, ISBN 0-85404-621-4.

Harrison, R.M. (2001b). Chemistry and Climate Change in the Troposphere, In *Pollution Causes, Effects, and Control*, 4th Edition, Harrison, R.M. (Ed.), Royal Society of Chemistry, London, p. 194.

Hassan, S.K.M. (2006). Atmospheric Polycyclic Aromatic Hydrocarbons and Some Heavy Metals in Suspended Particulate Matter in Urban, Industrial and Residential Areas in Greater Cairo, Ph.D. Thesis, Chemistry Department, Faculty of Science, Cairo University, Egypt.

Hastie, T.J. and Tibshirani, R.J. (1990). *Generalised Additive Models*, Chapman & Hall, London.

Khodeir, M., Shamy, M., Alghamdi, M., Zhong, M., Sun, H., Costa, M., Chen, L.C. and Maciejcczyk, P.M. (2012). Source Apportionment and Elemental Composition of $PM_{2.5}$ and $PM_{10}$ in Jeddah City, Saudi Arabia. *Atmos. Pollut. Res.* 3: 331–340.

Kim, J., Yoon, S.C. and Jefferson, A. (2006). Aerosol Hygroscopic Properties during Asian Dust, Pollution, and Biomass Burning Episodes at Gosan, Korea in April 2001. *Atmos. Environ.* 40: 1550–1560.

Liu, N., Yu, Y., Chen, J.B., He, J.J. and Zhao, S.P. (2011). Identification of Potential Sources and Transport Pathways of Atmospheric $PM_{10}$ Using HYSPLIT and Hybrid Receptor Modelling in Lanzhou, China, In *Air Pollution XIX*, Brebbia, C.A., Longhurst, J.W.S. and Popov, V. (Eds.), Wessex Institute of Technology, UK.

Nasrallah, M.M. and Seroji, A.R. (2008). Particulates in the Atmosphere of Makkah and Mina Valley during Ramadhan and Hajj Season of 1424 and 1425 H (2004–2005). *Arab Gulf J. Sci. Res.* 26: 199–206.

Nasrallah, M.M. and Seroji, A.R. (2007). Primary Pollutants and Potential Photochemical smog Formation in Makkah, Saudi Arabia. *Arab Gulf J. Sci. Res.* 25: 153–161.

Othman, N., Mat-Jafri, M.Z. and San, L.H. (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.

Paciorek, C.J., Yanosky, J.D., Puett, R.C., Laden, F. and Suh, H.H. (2009). Practical Large-scale Spatio-temporal Modelling of Particulate Matter Concentrations. *Ann. Appl. Statist.* 3: 370–397.

PME (2012). Presidency of Meteorology and Environment, the Royla Kingdom of Saudi Arabia (http://www.pme.gov.sa/en/en_airpollution.asp).

Pont, V. and Fontan, J. (2000). Comparison between Weekend and Weekday Ozone Concentration in Large Cities in France. *Atmos. Environ.* 35: 1527–1535.

R Development Core Team (2012). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0, URL http://www.R-project.org/. R Version 2.14.

Sabbak, O.A. (1995). Metal Concentration of Atmospheric Inhalable Particles in Jedda. *Environ. Manage. Health* 6: 7–13.

Seroji, A.R. (2011). Particulates in the Atmosphere of Makkah and Mina Valley during the Ramadan and Hajj Seasons of 2004 and 2005, In *Air Pollution XIX*, Brebbia, C.A., Longhurst, J.W.S. and Popov, V. (Eds.), Wessex Institute of Technology, UK.

Westmoreland, E.M., Carslaw, N., Carslaw, D.C., Gillah, A. and Bates, E. (2007). Analysis of Air Quality within a Street Canyon Using Statistical and Dispersion Modelling Techniques. *Atmos. Environ.* 41: 9195–9205.

WHO (2004).World Health Organization, Protection of the Human Environment, Assessing the Environmental Burden of Disease at National and Local Levels, Geneva.

WHO (2008). World Health Organisation, Health Risks of Ozone from Long-range Transboundary Air Pollution, A Report Prepared by WHO Regional Office for Europe, 2008 (http://www.euro.who.int/Document/E91843.pdf).

Wood, S.N. (2006). Generalized Additive Models: An Introduction with R. Chapman and Hall/CRC.

Wood, S.N. (2012). Fast Stable Restricted Maximum Likelihood and Marginal Likelihood Estimation of Semiparametric Generalized Linear Models. *J. R. Stat. Soc. B* 73: 3–36.

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