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An Analysis of Air Pollution in Makkah - a View Point of Source Identification

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Abstract

Makkah is one of the busiest cities in Saudi Arabia and remains busy all year around, especially during the season of Hajj and the month of Ramadan when millions of people visit this city. This emphasizes the importance of clean air and of understanding the sources of various air pollutants, which is vital for the management and advanced modeling of air pollution. This study intends to identify the major sources of air pollutants in Makkah, near the Holy Mosque (Al-Haram) using a graphical approach. Air pollutants considered in this study are nitrogen oxides (NOx), nitrogen dioxide (NO_2), nitric oxide (NO), carbon monoxide (CO), sulphur dioxide (SO_2), ozone (O_3) and particulate matter with aero-dynamic diameter of 10 um or less (PM_{10}). Polar plots, time variation plots and correlation analysis are used to analyse the data and identify the major sources of emissions. Most of the pollutants demonstrate high concentrations during the morning traffic peak hours, suggesting road traffic as the main source of emission. The main sources of pollutant emissions identified in Makkahwere road traffic, re-suspended and windblown dust and sand particles. Further investigation on detailedsource apportionment is required, which is part of the ongoing project.

Keywords: air pollution; source identification; Makkah; sources of air pollution

1. Introduction

Air quality in Saudi Arabia has improved significantly sincethe installment of several sulphur recovery plants in Saudi Aramco refineries and the beginning of emission monitoring by the Presidency of Meteorology and Environment (PME) and Saudi Aramco Air Quality and Meteorological Monitoring Network stations. However, during the last decade due to the rising per capita income the number of registered vehicles in Saudi Arabia has increased by 45%. It is predicted that during the next decade, annual demand for diesel and gasoline fuels might grow at an average rate of 4%, reaching about 1.5 million barrel per day in 2018. This may increase the emission of traffic related air pollutants. At present generally the concentrations of traffic related gaseous air pollutants (e.g., nitrogen oxides (NOx), carbon monoxide (CO), sulphur dioxide (SO_2)) are below the air quality standards set by World Health Organisation (WHO) and PME (Habeebullah *et al*., 2012), however the concentrations of particulate matter (PM) and ozone (O_3) sometimes violate the air quality limits.

High levels of particulate matter with aero-dynamic diameter of 10 micronor less (PM_{10}) in Makkah, especially during the Hajj period have been previously reported by several authors (Nasralla, 1983; Othman *et al*., 2010; Khodier *et al*., 2012). The reasonsfor the high PM_{10} concentrations are most probably high volume of traffic, construction work, re-suspension of particles, windblown dust and sand particles and geographical conditions (Arid Regions) (Khodier *et al.*, 2012). Most of the area of Saudi Arabia is made of deserts, which leads to a high concentration of dust in the air as wind blows onto inhabited areas from the neighboring desert lands (PME, 2012). The government of Saudi Arabia is continuously working on improving the air quality in Makkah. Steps undertaken for the reduction of air pollutant concentrations include the development of electric train system, continuous water spray program in the Holy Mosque, which has shown positive effect on PM_{10} concentration and reducing the number of vehicles in the Holy Sites (Mina, Muzdalifah and Arafat), especially during the Hajj period.

Identifying the sources of emissions and quantifying their contribution are vital for effective management and advanced modeling of the air pollution; however no published literature was found regarding the source apportionment of air pollutants in Makkah. In this study the authorintends to analyseair pollutants data in a view to investigate their temporal variations and identify different sources of air pollutants in Makkah near Al-Harm using correlation analysis and graphical presentations.

2. Methodology

This study uses mean hourly air quality data from January 2012 to August 2012, collected at Air Quality Monitoring Station (AQMS 111), which is situated near the Holy Mosque (Al-Haram), as shown in Fig. 1. The site is a continuous monitoring site and measures the concentrations of NOx, NO, NO_2, SO_2, CO, O_3 and PM_{10}. Percent data capture was over 90% for this site. The site has no facilities for monitoring meteorological variables, therefore air pollutants and meteorology data for the month of November 2011 from the PME monitoring site (AQMS 112) arealso used in this study. Data capture for PME site was over 95% for all variables. In addition to correlation analysis, graphical presentations (scatter plots, polar plots, wind rose and time variation plots) were employed to depict the effect of meteorology andinvestigate the association of pollutants with each other. Statistical data analysis was carried out in statistical software R programming language (R Development Core Team, 2012) and one of its package openair (Carslaw and Ropkins, 2012).

3. Results and Discussions

3.1. Temporal variations

This section describes the temporal variations (e.g., weekly cycles, diurnal cycles and seasonal cycles) of various air pollutants (NOx, NO, NO_2, SO_2, CO, O_3, and PM_{10}). All pollutants are expressed in $\mu g/m^3$, except CO which is expressed in mg/m^3. The aim is to analyse the temporal trends in air pollutant concentrations in a view to identify the major sources of air pollutants. Fig. 2 shows time variation plots of NOx, O_3, CO, and SO_2, which represents the normalised levels of pollutant concentrations. Normalised levelis obtained dividing each observation by the mean of the each variable and is an easy way of showing pollutants at different scales in the same plot.

The negative correlation of O_3 and NOx is clearly visualised in the diurnal, weekly and seasonal cycles. The diurnal cycle of NOx seems to follow the pattern in daily traffic flow, which is normally higher in the morning hours and lower during mid-day and night hours. Lowest NOx concentration in the afternoon is likely to be due to both low traffic activities and atmospheric conditions. During this time of the day the atmosphere is very turbulent and pollutants emitted get dispersed quickly, compared to night time when atmosphere is relatively stable, resulting in poor ventilation (low pollutants dispersion). NO and NO_2 (data not shown due to brevity) follow a similar pattern to that of NOx, however NO_2 seems to lag by an hour probably because most of the NO_2 is secondary (formed in the atmosphere as a result of NO and O_3 reactions: $NO + O_3 \rightarrow NO_2 + O_2$).

O_3 concentrations are lower during nighttime, early morning and evening hours and higher in the afternoon (12:00 to 17:00 hrs). O_3 is one of the secondary air pollutants and is formed in the atmosphere by photochemical reactions of NOx and volatile organic compounds (VOCs) in the presence of solar radiation. During night time due the absence of solar radiation

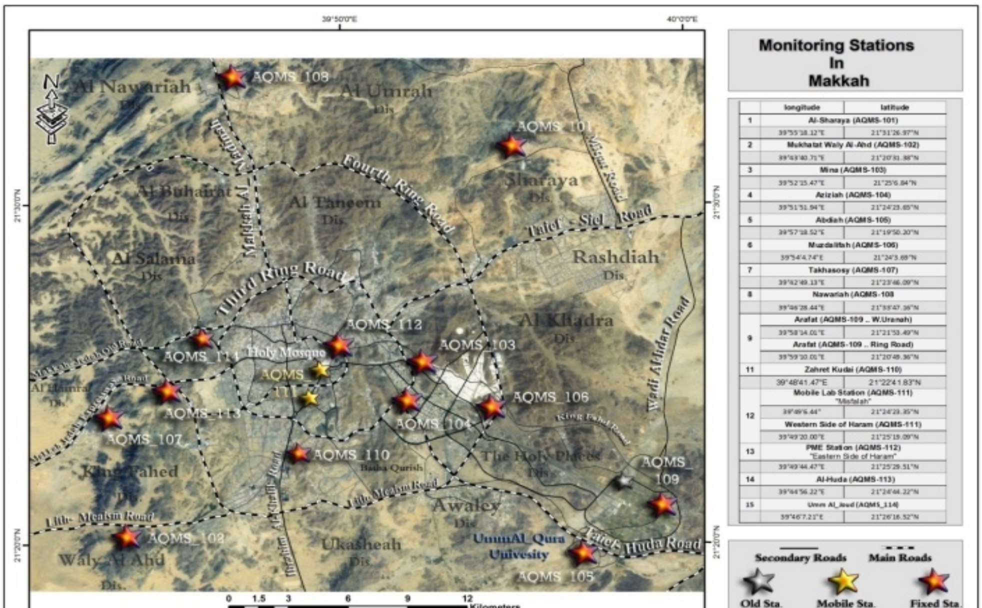

Figure1. Map of the air quality and meteorological monitoring sites in Makkah (Munir *et al*., 2013)

photochemical O_3 formation stops and its level decreases further by dry deposition and titration by NOx. The concentrations of traffic related air pollutants are lower during Thursday and Friday and higher during the weekdays, most probably because traffic flow is lower during the weekend (Thursday and Friday, note that in Saudi Arabia weekend is on these two days in contrast to many other countries, where weekend is on Saturday and Sunday), whereas O_3 show the opposite trend, which is understandable due to its negative correlation with NOx. Generally NOx show higher concentration during January and February and their concentration decrease from March onwards, reaching the lowest level in August. During different months the negative correlation of O_3 with NOx is not asclear as it was observed in the diurnal and weekly cycles, probably due to the predominant role of meteorology. Diurnal and weekly cycles of various pollutants (Fig. 2) seem to be more closely linked with traffic flow rather than with meteorological variables. This is probably because variations in meteorological variables are not as much as during different seasons. Furthermore, various months (seasons) do not show much variation in traffic flow and hence in pollutant emissions. Probably, therefore, O_3 concentration during different seasons is more affected by meteorological variables and shows weak association with NOx. Meteorological variables play an important role in pollutant dispersion and chemical reactions, however the effect varies during different seasons, climatic conditions (e.g., temperate or arid), and geographical conditions (such as altitude and proximity to sea-side) (See for details Munir *et al.*, 2013 and the references therein).

Apart from some minor differences, SO_2 and CO concentrations generally follow the same temporal trends as discussed above for NOx, however PM_{10} (data not shown) shows considerably different diurnal and weekly cycles. PM_{10} shows two peaks in the diurnal cycle (morning and evening) and highest concentrations are observed on Friday and Saturday. It is worth mentioning that particulate matters in Makkah, which is situated in an arid region have various emission sources, the most dominant are the re-suspendedand windblown dust and sand particles. Therefore particulate concentration is more related to wind speed and wind direction rather than traffic flow, which is further elaborated latter in this paper (section 3.3).

3.2. Correlation analysis

NO shows very strong correlation with NOx ($R=0.96$), whereas NO_2 has relatively weaker

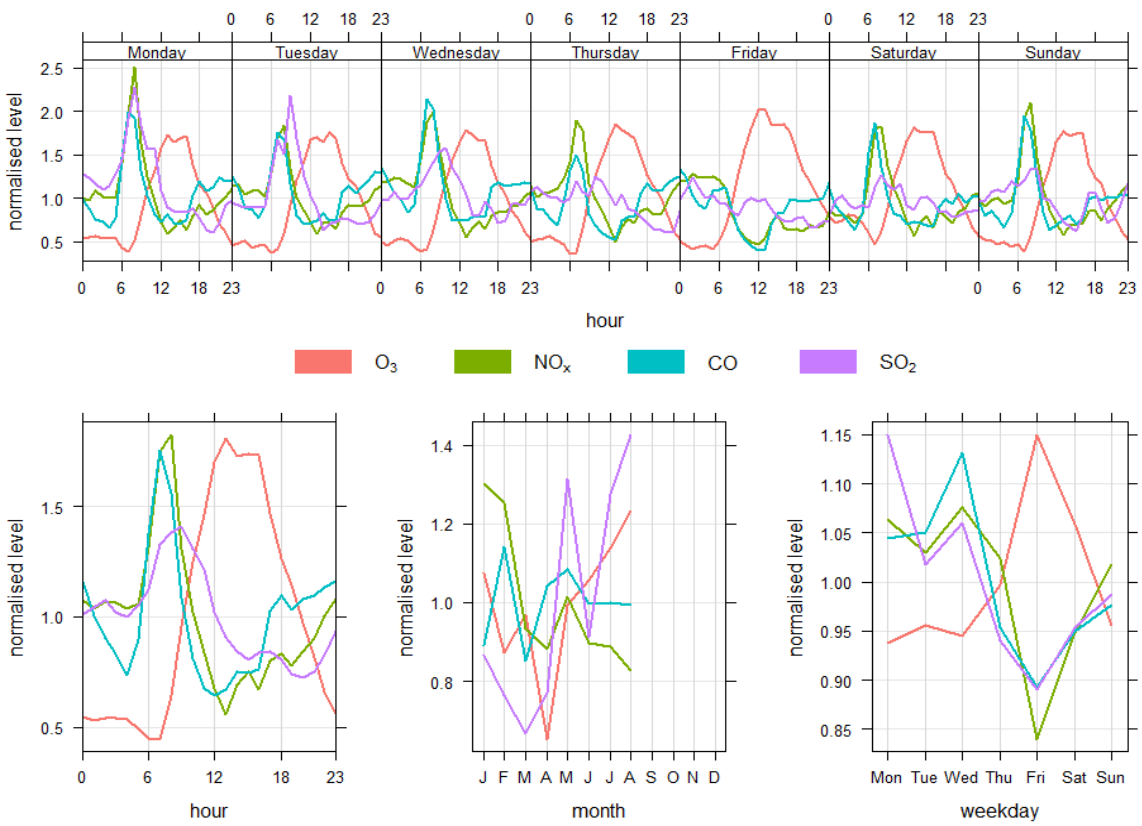

Figure 2. Time variation plots of NOx (µg/m^3), O_3 (µg/m^3), CO (mg/m^3), and SO_2 (µg/m^3) using January to August 2012 data from the Mobile Lab Station (AQMS 111) in Makkah.Normalised levels of pollutants are used which are calculated dividing each observation by the mean of the variable.

correlation with NOx (*R=0.39*). Most probably because NO and NOx both have the same source, mainly road traffic, whereas NO_2 is predominantly a secondary air pollutant and is formed in the atmosphere. Therefore NO_2 does not correlate well with NOx. Moreover, NO was about 60% and NO_2 about 40% in total NOx, which means NOx is predominantly as NO and therefore has strong correlation.

Scatter plots of various air pollutants are shown in Fig. 3 in a view to investigate their association with each other. This sort of analysis can be useful in identifying the sources of pollutants emissions (Khodeir *et al*., 2012). If 2 pollutants have strong correlation, then it can be deduced that most probably they have the same emission source, for example CO and NOx on roadside locations normally have a strong correlation and are believed to be emitted by road traffic (Fig. 3, *R=0.66*). NOx and CO do not seem to have strong correlation with either SO_2 or PM_{10} and their correlation coefficients are weaker (as shown in Fig. 3), probably suggesting different sources of emissions. As discussed above that most of the PM_{10} in Makkah comes from the windblown dust and sand, construction work and re-suspension of particles and therefore do not associate well with traffic flow or traffic emitted pollutants. Emissions of SO_2 have decreased drastically in the last couple of decades due to national and international policies, therefore SO_2 level in Makkah is well below the air quality standards of WHO and PME. The mains source of SO_2 in Saudi Arabia is burning of crude oils and emissions from diesels vehicles; whereas the bulk of CO and NOx are emitted by light vehicles, such as taxis and cars (PME, 2012). Most probably this is the reason why SO_2 does not correlate well with these air pollutants. O_3 is negatively correlated with all these pollutants (NOx, CO, SO_2 and PM_{10}), however the correlation is stronger with NOx (*R=-0.61*), followed by CO (-0.48) (Fig. 3). For more details regarding the chemical coupling of these species readers are referred to Jenkin (2004) and Clapp and Jenkin (2001).

3.3. Polar plots

In this section polar plots areused to identify the sources of emissions of NOx, CO, SO_2 and PM_{10}. The bivariate polar plot is a useful diagnostic tool for

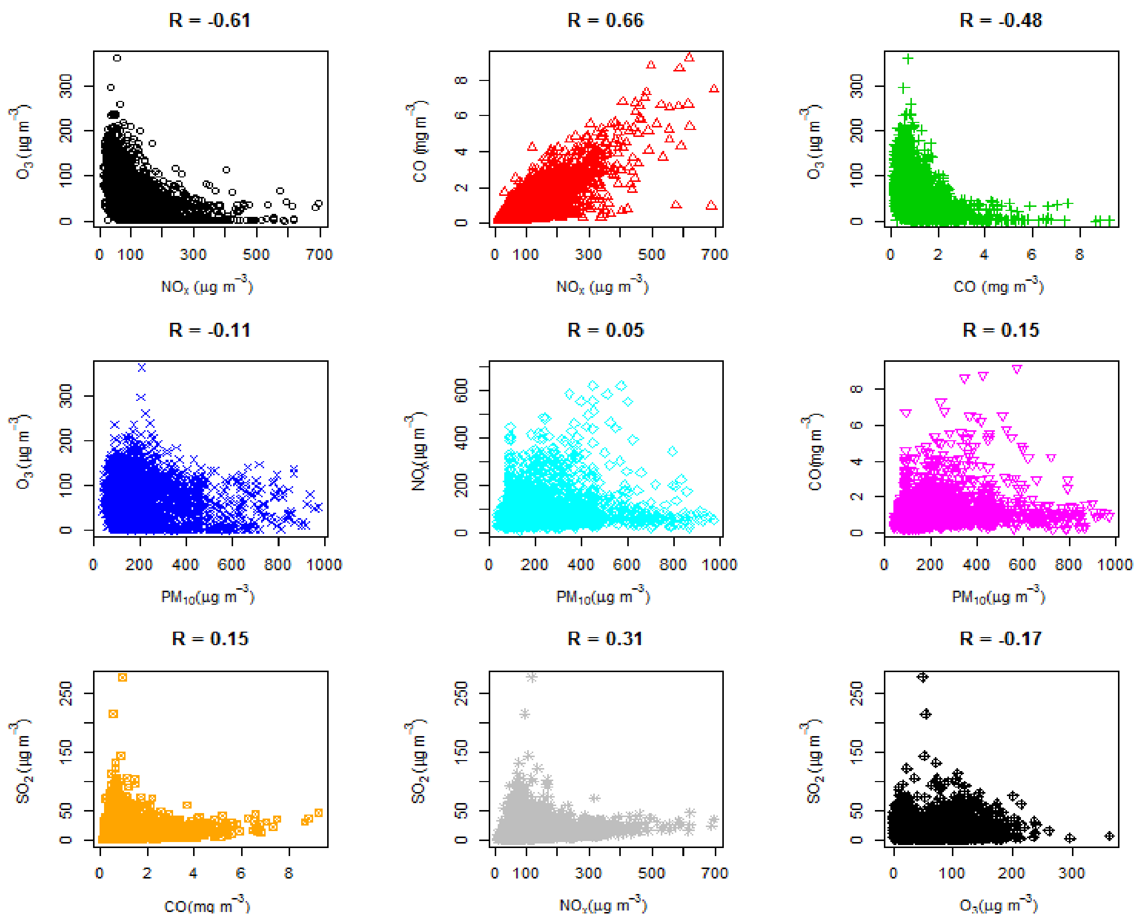

Figure 3. Scatter plots of various pollutants (NOx, O_3, CO, SO_2, PM_{10}) using January to August 2012 data from the Mobile Lab Station in Makkah.

quickly gaining an idea of potential sources (Carslaw and Ropkins, 2012). The principal aim of polar plot is as a graphical analysis rather than for quantitative purposes and it uses generalised additive model (GAM) for smoothing purposes (for details on GAM see Wood, 2006; and on the use of polar plot for sources identification see Westmoreland *et al*., 2007).

It can be observed in Fig. 4 that NO and CO concentration are higher when the wind speed is about 1–2 m/s from the east or northeast, but when wind direction is from the south the higher concentration is linked rather with lower wind speed (up to 1 m/s). NO_2 shows almost the same trend but here the highest concentration is from the south, in contrast to NO where the highest concentration is shown from the east to northeast. PM_{10} shows the highest concentration linked with the west and southwest direction at wind speed 2 m/s or slightly greater. Polar plot of SO_2 shows a uniform contribution from all direction, except from west and northwest direction. O_3 shows lower concentration when the wind

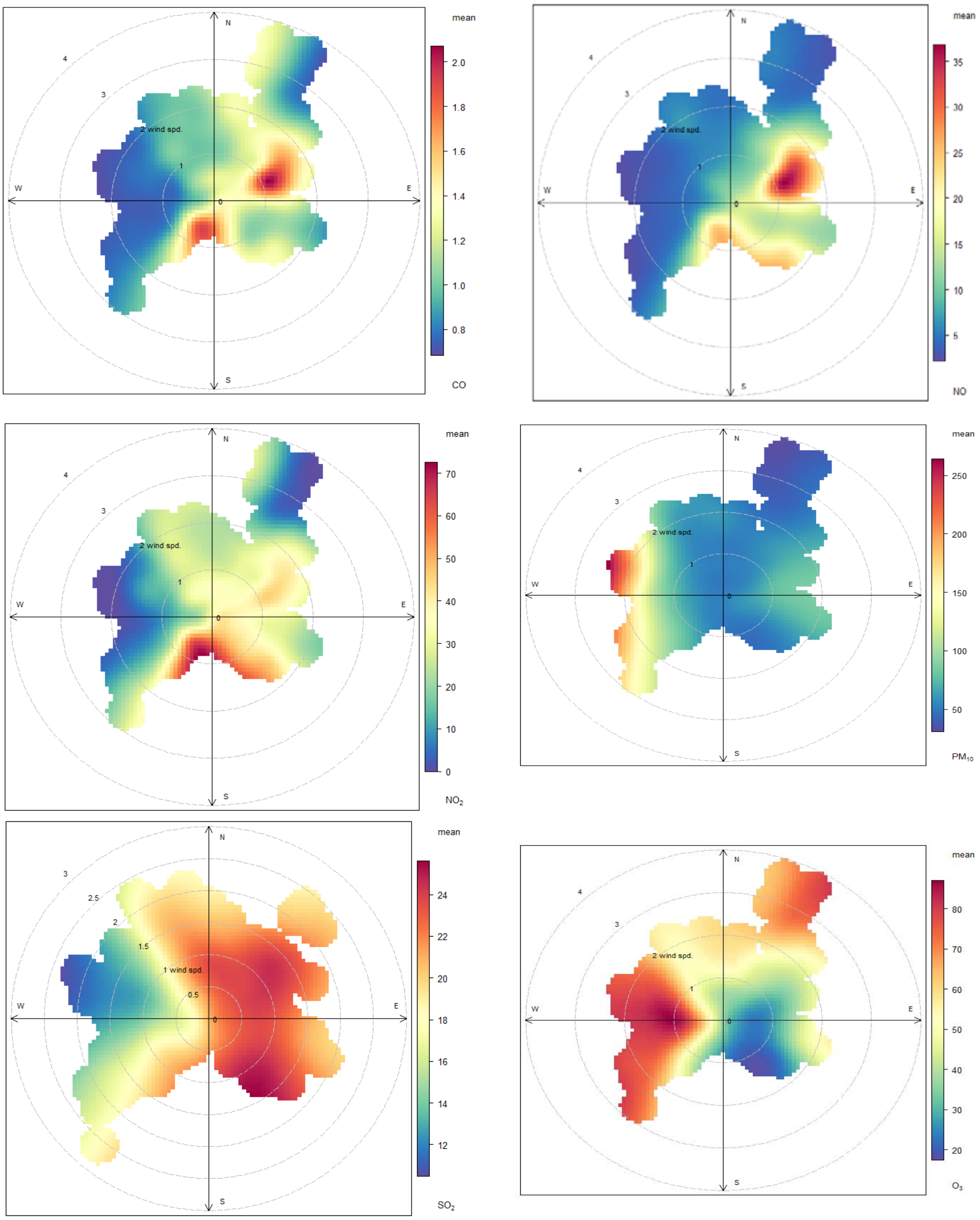

Figure 4.Polar plots of various air pollutants for the month of November, 2012 at PME monitoring site in Makkah.

is blowing from the south, southeast and east direction, presenting an opposite pattern to that of NO, which is expected due to their negative correlation.

These observations indicate a potential emission source of traffic-related pollutants towards the east and southdirection, except for PM_{10}, where the emission source is shown towards the west. There is a busy road towards the southeast, east, and northeast of the monitoring site. Furthermore, there are two bus stations along the same road and a long tunnel in the southeast. Most of the NOx and CO probably comes from the road emissions, whereas most of the SO_2 is probably emitted by the buses and burning of crude oil. In the west and southwest of the monitoring site, there is large construction site, which explains why high PM_{10} concentration is linked with this direction. It is worth mentioning that there are some buildings between the construction site and the monitoring site that may act as a barrier for pollutants, however at high wind speed the dust manages to reach the monitoring site. O_3 being a secondary air pollutant is not emitted by any combustion source and rather is formed in the atmosphere. However, its concentration seems to be affected by the emission sources of NOx, which acts as a sink for O_3 and reduces its concentrations; therefore these pollutants show opposite patterns.

A most recent study in Jeddah, Saudi Arabia by Khodeir *et al*. (2012) on source apportionment of particulate matter (PM_{10} and $PM_{2.5}$) reported that re-suspension of soil particles and oil combustion were the two major sources of particulate matter in Jeddah and contributed 77% and 82% to the observed concentrations, respectively. Other minor sources of particles included industrial emission, road traffic, and marine aerosols (Khodeir *et al*., 2012). Particulate matters demonstrate significant temporal and spatial variations and are affected by local emission sources, local topography and meteorology, therefore it is expected that percent contribution of each source in Makkah will be different to that in Jeddah, however generally the nature and types of emission sources will probably be the same due to the regional climatic and topographical effects. This study successfully identifies the main sources of PM_{10}, in agreement with Khodeir *et al*. (2012), as re-suspension of particles and windblown dust and sand, however further work is required to quantify their percent contribution. No source apportionment literature was found regarding the other air pollutants (CO, NOx, SO_2), however this study identifies combustion sources, especially road traffic as the main source of their emission. Further work is required to quantify accurately the contribution of each combustion source, including point sources, aerial sources and line sources (e.g., road traffic).

4. Conclusions

This study analyses the temporal variations of various air pollutants and intends to graphically identify the emission sources of the major pollutants in Makkah, using data from two monitoring sites, situated near Al-Haram. Temporal variations of various air pollutants (NOx, NO, NO_2, SO_2, CO, PM_{10} and O_3) have been analysed and it is shown that pollutant concentrations associate well with the daily flow of road traffic. Most of the pollutants demonstrate high concentrations during the morning traffic peak hours, except O_3 that shows highest level during the afternoon as expected due to high solar radiation. Polar plots were developed to graphically identify the sources of emissions. The main sources identified near the monitoring site were road traffic, bus stands, construction work and re-suspension of dust and sand particles. Further work is recommended, which includes advance modeling, source apportionment, and characterising the spatiotemporal variations of air pollutions in the Holy City of Makkah and Madinah.

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