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AN INVESTIGATION OF THE EFFECTS OF METEOROLOGY ON AIR POLLUTION IN MAKKAH

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ABSTRACT:

Air pollutant concentrations are not only affected by emission sources but also by meteorological variables. Meteorological variables play an important role in the dispersion, transport, photochemical reactions and formation of secondary air pollutants. In this study, the effect of meteorological variables on different air pollutant concentrations has been analyzed using correlation analysis and graphical presentation in Makkah, Saudi Arabia during the month of Ramadan (20 July to 18 August, 2012), which is the busiest month of the year after the Hajj season. PM_{10}, had relatively weaker correlation with other air pollutants, most probably suggesting different sources of emission. Among meteorological variables, as expected temperature showed strong positive correlation with ozone (0.74), and negative correlation with NOx, CO, SO2, and PM10, whose concentrations are rather dependent on the emission sources. Wind speed disperses local pollutants, which probably explains why it was negative correlation with NOx, SO2 and CO, however it was positive correlation with ozone and PM10, probably because higher wind speed encourages sand storms and resuspension of particles from roadsides and bared deserts and transport of ozone from the surrounding rural areas. Relative humidity is positively correlated with PM10 and negatively correlated with the

rest of the air pollutants. The effect of rainfall was negligible because no rain occurred during the study period. The effects of meteorological variables have also been analysed using polar plots and pollution roses, which provide further insight into the association between air pollutants and meteorology. Factors responsible for the high concentrations during the PM10 episode from 26 to 28 July 2012 were analyzed. Unexpectedly, atmospheric pressure and relative humidity seemed to be responsible for the episode, and not the sources of emissions, which are higher during the last 10 days of Ramadan (08 to 18 August).

Keywords: Air pollution, Meteorology, Polar plots, Pollution roses, Makkah

INTRODUCTION:

Air pollution in urban areas in both developed and under developing countries adversely affects human health, urban ecosystem, building materials and visibility (e.g., Harrison, 2001; WHO, 2008; Bell and Treshow, 2008; Air pollution in the UK, 2011). In this paper we consider five of the most common air pollutants, which are sulphur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NO_x): the sum of nitric oxide (NO) and nitrogen dioxide (NO_2), ozone (O_3) and particulate matter with aerodynamic diameter of 10 um or less (PM_{10}). Individually and in combination with other air pollutants, these Pollutants can cause different health problems. For example, SO_2 is a respiratory irritant and can cause constriction of the airways of the lung, particularly in people suffering from asthma and chronic lung disease. NO_2 acts as an irritant, causing inflammation of the airways and increasing susceptibility to respiratory infections. Fine particulate matter can penetrate deep into the airways, carrying surface-absorbed harmful compounds into the lungs, increasing the risk of health effects, including cancer. Ozone is an oxidising agent and acts as an irritant, causing inflammation of the respiratory tract

and irritating the eyes, nose, and throat, causing coughing and discomfort whilst breathing (Harrison, 2001; WHO, 2008; Air pollution in the UK, 2011; AQEG, 2005; AQEG, 2009).

Air pollutant concentrations are not only affected by the sources of emission but also by meteorological variables (e.g., Elminir, 2005; Ordonez et al., 2005; Cheng et al., 2007; Beaver and Palazoglu, 2009; Pearce et al., 2011). Meteorological variables playan important role in the dispersion, transport, photochemical reactions and secondary pollutants formation, including ozone, NO_2 and particulate (e.g., sulphate and nitrate ions), however in spite of the presence of a vast body of literature, many aspects of the association between air pollutants and meteorology are still not clear (Pearce et al., 2011). This is due to the interaction between various meteorological variables, for example the dependency of boundary layer height on surface temperature, the link between surface temperature and radiation or the association between relative humidity and temperature, which make separating the effects of individual parameter a highly complex task. Meteorological variables can affect the concentrations of air pollutant directly (e.g., affecting photochemical ozone formation or dispersing locally emitted pollutants) or indirectly by affecting other meteorological parameters or affecting some pollutants which in turn affect other pollutants (Ordonez et al., 2005; Jacob and Winner, 2009). Furthermore, the effects of meteorological variables the concentration of pollutants vary both temporally and spatially (Baur et al., 2004). See Schlink et al. (2006), Camalier et al. (2007), Thompson et al. (2001), Baur et al. (2004) and Pearce et al., 2011 for various approaches used to investigate the association of meteorological variables on air pollutant concentrations.

National and international policies, demanding for clean air have resulted in great interest in air pollution In Saudi Arabia. Numerous studies have

been conducted in Saudi Arabia to report the levels of different air pollutants in many regions, especially in Jeddah, Makkah and Madinah (Kadi et al., 2009; Aburas et al., 2011; **Al-Zahrani, 2010; Othman et al., 2010).A research into identifying various sources of air pollutants and quantifying their contribution to the observed levels of air pollutants has also been carried out (Khodeir et al., 2012). Most of these studies are related to particulate matters (PM_{10}, $PM_{2.5}$, and heavy metals), probably because the concentrations of particulate matters observed in Saudi Arabia are generally high (Seroji, 2011; Othman et al., 2010) and exceed the air quality limits set for the protection of human health. It has been reported that in Saudi Arabia, being an arid region a significant amount of particles are generated by natural sources, including windblown dust and sand and resuspension of particles (e.g., Aburas et al., 2011 and Khodeir et al., 2012). However, no published work was found intending to investigate the effect of meteorological variables on the concentrations of air pollutants.**

The objechve of their study is to analyse the effect of meteorological variables (wind speed, wind direction, temperature, relative humidity, atmospheric pressure and rain fall) on the concentrations of five major pollutants (SO_2, NO_x, CO, ozone and PM_{10}) in Makkah using exploratory data analysis techniques. The study was conducted during the month of Ramadhan, 1433 H (18 July to 20 August, 2012), when millions of people come to Makkah to perform Umrah. This is the second busiest month of the year after Zulhijjah (the month of Pilgrimage - Hajj), which further signifies the need for clear air.

1. METHODOLOGY:

In this study The data related to the concentration of the considered air pollutants and meteorology parameters were collected at the Presidency of Meteorology and Environment (PME) air quality monitoring station (AQMS 112) situated near Al-Haram (the wholly Mosque) in Makkah, the Kingdom of

Saudi Arabia. Figure 1 shows the location of PME (AQMS 112) and other air quality monitoring sites in Makkah.

The au collected during data considered here are for the month of Ramadan 1433 H (20th July to 18th August, 2012), when millions of people come to Makkah to perform Umrah. This is the second busiest time of the year after Hajj. In this study the following parameters were considered: Sulphur Dioxide (SO_2 µg/m^3), Carbon Monoxide (CO mg/m^3), Nitrogen Oxides (NO_x µg/m^3), Nitric Oxide (NO µg/m^3), Nitrogen Dioxide (NO_2 µg/m^3), Particulate Matter with aerodynamic diameter of 10 um or less (PM_{10} µg/m^3), Ozone (O_3 µg/m^3), Wind Speed (WS m/s), Wind Direction (WD Degrees from the north), Relative Humidity (RH %), Temperature (T ^{o}C), Rain Fall (RF mm), and atmospheric Pressure (P hPa), where hectopascal (hPa) is the same as wkilopascal (kPa) and is equivalent to the older unit millibar (mbar).

Statistical data analysis was carried out in R-programming language (R-development team, 2012) and one of its package open air (Carslaw and Ropkins, 2012). Correlation analysis and graphical presentations (scatter plots, polar plots, and time series plots) were used to investigate the association of various air pollutants with each other and with meteorological variables. A summary of the parameters is presented in Table 1.

Table 1: A summary of the parameters for the month of Ramadan 1433 H (20th July to 18th August, 2012), number of observations for each parameters were 715.

Parameters	Units	Minimum	Median	Mean	Maximum	[1]NA's	DC, %
CO	mg/m^3	0.34	1.09	1.28	5.56	5	99
SO_2	$\mu g/m^3$	1	7	9.12	105	26	96
NO_2	$\mu g/m^3$	8	50	52.73	130	5	99
NO	$\mu g/m^3$	0	66	14.25	178	103	86
NO_x	$\mu g/m^3$	0	54	64.58	300	0	100
O_3	$\mu g/m^3$	0	71.5	79.3	290	6	100
PM_{10}	$\mu g/m^3$	31	133	195	1708	6	100
P	hPa	965	969.5	969.5	973.1	0	100
RF	mm	0	0	0	0	0	100
RH	%	10.5	25.3	27.14	74	0	100
T	^oC	31.2	36.2	36.6	42.9	0	100
WS	m/s	0	1.2	1.2	4.5	0	100
WD	Degree	1	298	264.8	360	0	100

[1]NA represents missing data and DC represents data capture.

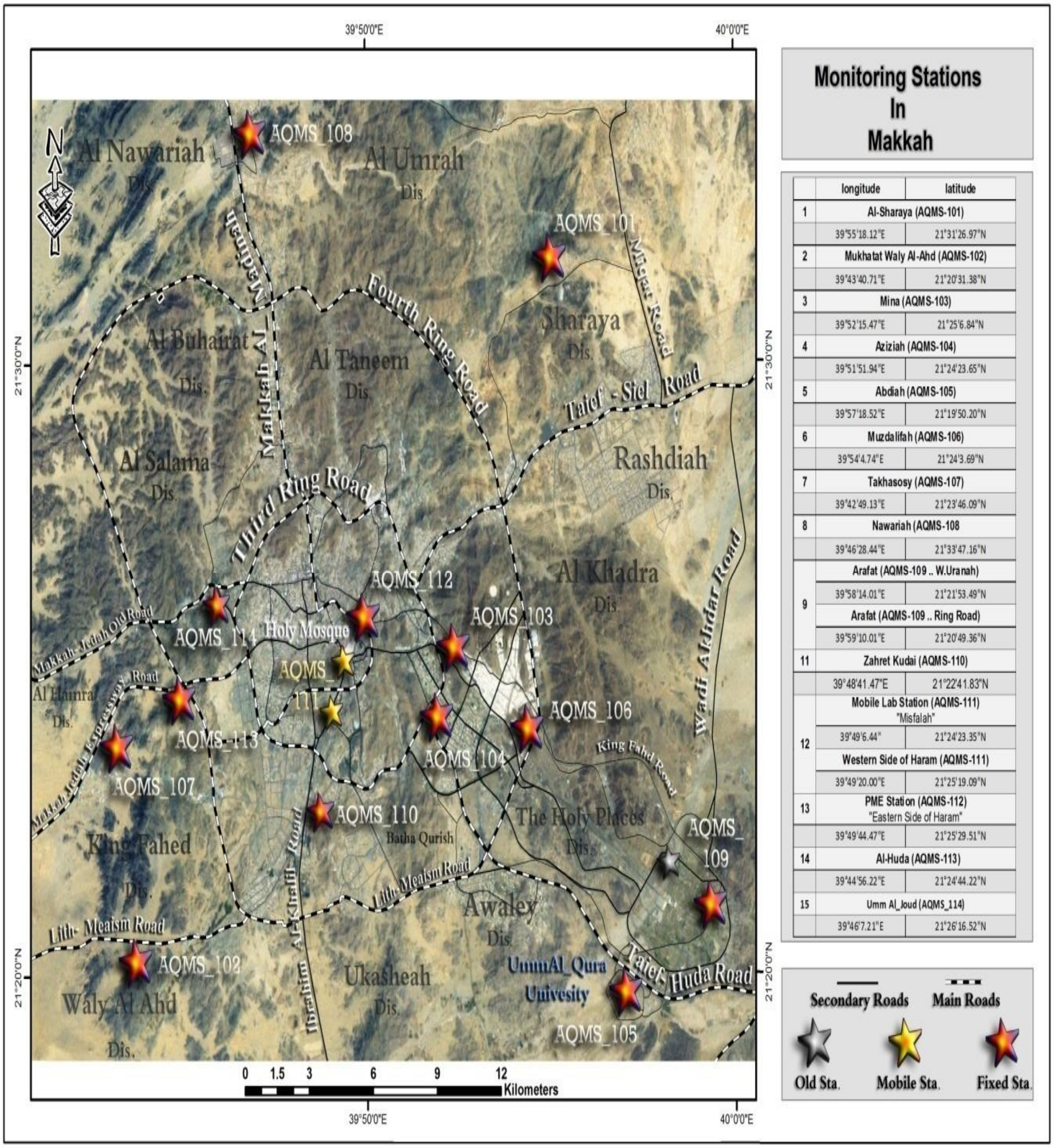


Figure 1: Map showing the locations of the air quality and meteorological monitoring sites in Makkah.

2. RESULTS AND DISCUSSIONS:

2.1. Coirrelation analysis:

Knowing the association of different variables is important and can be helpful in identifying the emission sources of various air pollutants. In this paper correlation matrix plot (Carslaw and Ropkins, 2012) is used, which provides correlation between all pairs of the data. Correlation plot shows the correlation coded in three ways: by shape (ellipses), colour and the numeric value. The ellipses are similar to scatter plot. A perfect positive correlation is represented by a line at 45 degrees, whereas no correlation is shown by a circle of points. Furthermore, hierarchical clustering is applied to the correlation matrices to group variables that are most similar to one another. The numerical values are shown from -100 to 100, where zero indicates no correlation and 100 indicates perfect positive and 100 indicates perfect negative correlation.

Figure 2 shows the correlation matrix plot of various air pollutants and meteorological variables. Several clusters can be clearly observed. For example NO_x and CO show very strong positive correlation, whereas NO_x and ozone show strong negative correlation, which is expected as NO_x and CO have the same sources of emissions in Makkah, predominantly road traffic; and the negative correlation of ozone and NO_x is due to the chemical coupling between these species (Jenkin, 2004). SO_2 is positive correlated with CO and NO_x, however the strength is weaker, indicating SO_2 has different sources of emissions (e.g., burning of crude oil and diesel vehicles) (Habeebullah et al., 2012). PM_{10} has relatively weak correlation with other air pollutants, most probably because most of the PM_{10} in Saudi Arabia, being an arid region, is generated by non-combustion sources, such as

construction work and windblown dust and sand.

Among meteorological variables, temperature show strong positive correlation with ozone, which is due to the fact that ozone is a secondary air pollutant and is formed in the atmosphere by photochemical reaction of hydrocarbons and NO_x in the presence of sunlight. Generally high temperature accelerates photochemical formation of ozone molecules, due to this reason ozone level are higher in summer than in winters seasons (AQEG, 2009). In contrast temperature has negative correlation with NO_x, CO, SO_2, and PM_{10}, whose concentration is more dependent on the emission sources. However, the negative correlation indicates that probably high temperature results in greater dispersion and dilution of the air pollutants, probably linked with vertical and horizontal turbulence (EPA, 2010). The effect is negligible on PM_{10}. It is important to highlight that in the case of PM_{10} greater turbulence can generate more dust particles in a region like Makkah, which may offset the effect of pollutants dispersion. Wind speed help disperse local pollutants, which probably explains why it has negative correlation with NOx and CO, however it has positive correlation with ozone and PM_{10}, most probably due to raising particles from bared surfaces and road sides and transport of ozone from the surrounding rural areas. The effect of wind speed is generally related to its direction, which is further elaborated in later sections with the help of polar plots.

Relative humidity is positively correlated with PM_{10} and negatively correlated with the rest of the air pollutants. Duenas et al. (2002) have reported that relative humidity plays an important role in air quality, through its effect an 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, the relative humidity is also considered to be a limit-

ing factor in the disposition of NO_2 because high percentages of humidity favour the reaction of the NO_2 with particles of sodium chloride salt (Duenas et al., 2002). Relative Humidity can also act on air pollutants to create secondary aerosols, such as sulphate and nitrate ions, which contribute positively to PM_{10} concentrations. Rain washout most of the dust from the atmosphere and may encourage wet deposition of some of the gaseous pollutants, however in this analysis rain fall has shown weak association with all air pollutants, because Makkah being part of an arid region receives very limited rain throughout the year.

Differences in atmospheric pressure cause air to move from high pressure areas to low pressure areas, resulting in wind. Wind speed can greatly affect the pollutant concentration in a local area (as described above). Furthermore, high-pressure systems often combine with stable atmospheric conditions and low wind speeds, which can lead to episodes of severe air pollution (EPA, 2010).

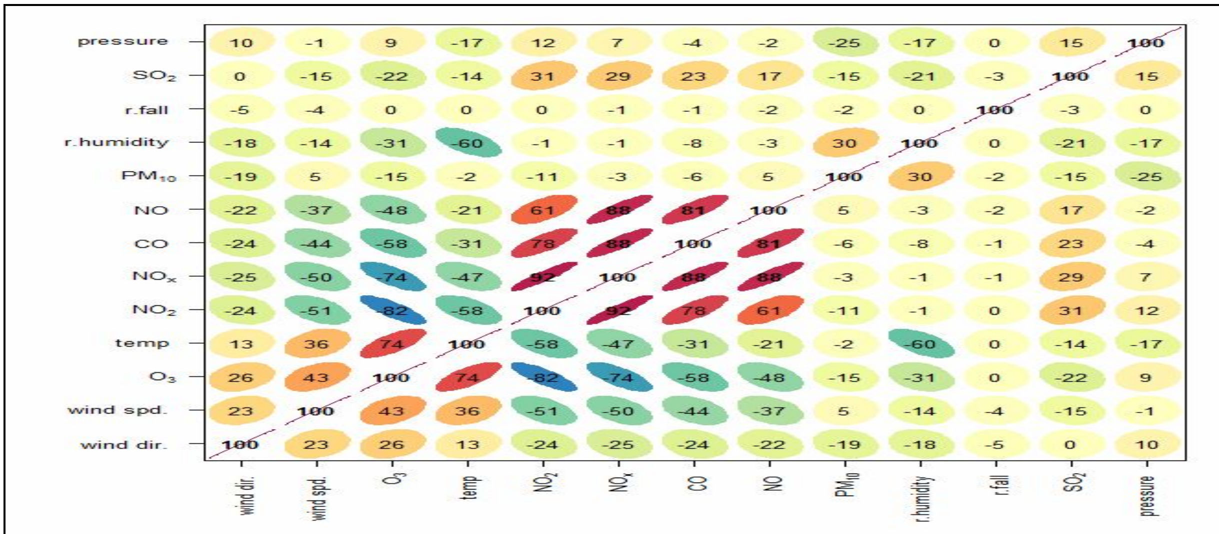


Figure 2: Correlation matrix plot of various parameters from 20th July to 18th August, 2012.

2.2 Polar plot:

The bivariate polar plot is a useful diagnostic tool for quickly gaining an idea of potential sources (Carslaw and Ropkins, 2012). 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.). The principal aim of polar plot is as a graphical rather than quantitative analysis 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). Figure 3 shows the polar plots of various air pollutants for the study period (20 July to 18 August, 2012) at PME monitoring site, Near Al-Haram, Makkah. In Figure 3, polar plot for CO (top-left), NO (top-right), SO_2 (middle-left) and NO_2 (middle-right) with slight variation show high concentrations at low wind speed, however high concentrations of NO_2 are also linked with high wind speed from the southeast direction. High concentrations at low wind speed suggest local sources of these air pollutants, which may disperse at high wind speed. In contrast, high levels of ozone and PM_{10} concentrations are kinked with high wind speed from northwest and southeast, respectively and at low wind speed their levels are low, which may suggest these air pollutants are transported from the surrounding areas. Ozone is inversely proportion to NO and NO_2 and hence the polar plots show the opposite pattern of these pollutants. There is a construction site towards west and northwest of Al-Haram, however the PM_{10} polar plot does not shows significant contribution from it, which is further investigated in later sections. There are some local roads, bus stations, and parking places in the surrounding areas, which probably contribute to the emissions of traffic related air pollutants, however the levels of these air pollutants have not exceeded the air quality standards during the

study period. PM_{10} was the only pollutants which exceeded 24hr PME air quality guideline on 26 – 28 July. This is further discussed in section 3.3.

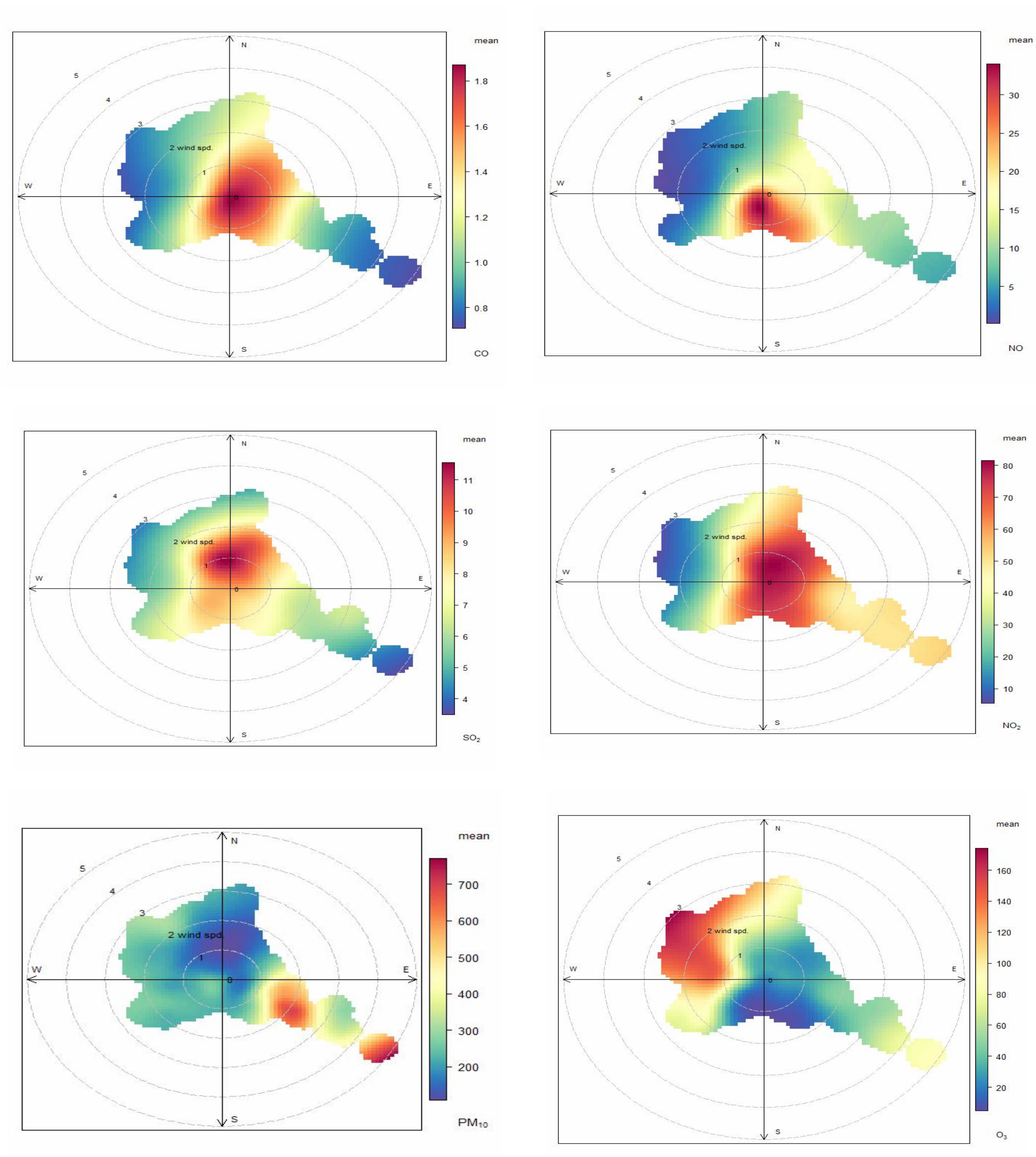


Figure 3: Polar plots of various air pollutants for the study period at PME site near Al-Haram, Makkah.

2.3 PM_{10} episode (26 to 28 July, 2012)

Statistical analysis shows that the concentrations of the air pollutants during the study period were below the air quality standards set by World Health Organization (WHO) and the Presidency of Meteorology and Environment (PME) of the Saudi Arabia. The only exception was PM_{10} concentrations, which exceeded the 24 hour average air quality limit of 340 µg/m^3 set by PME for the protection of human health. On 26 to 28 July 2012, the 24 hour average concentrations of PM_{10} were 518, 790 and 389 340 µg/m^3, respectively, which are given in Table 2 along with some other air pollutant concentrations. In this section, these three days have been further investigated to determine the causes of high PM_{10} concentrations.

Table 2: Daily average concentrations of various air pollutants during the period from 26 to 28 July 2012.

Date	CO	SO_2	NO_2	NO	Ozone	PM_{10}
26/7/12	1.11	7.96	44.30	10.00	47.23	518.33
27/7/12	0.95	4.79	34.75	7.88	41.00	790.29
28/7/12	1.33	5.50	52.17	17.05	58.63	389.17

Pollution roses (Fig. 4) are used to show the effect of wind on PM_{10} concentrations. Pollution rose is a variant of wind rose and is useful for considering pollutant concentrations by wind direction, or more specifically the percentage time the concentration is in a particular range. These plots are very useful for understanding which wind directions control the overall mean concentrations (Carslaw and Ropkins, 2012). It is worth mentioning that polar plot shows pollutant concentrations by wind speed and wind direction, while pollution rose depicts pollutant concentrations by wind frequency (the number of hours wind is blowing from a certain direction) and wind direction. Figure 4

(top-left) shows that during the study period, wind is predominantly blowing from the northwest direction, however high PM_{10} concentrations (shown by the colour and width of the paddles) are linked with westerly and south-easterly winds. Figure 3 has also shown high PM_{10} concentrations linked with south-easterly wind, where wind speed reach up to 4 m/s. Figure 4 (top-right) shows PM_{10} concentrations during the three days (26 to 28 July, 2012), when the PME air quality standards were violated. In this panel high PM_{10} concentrations are linked with south, south-easterly and south-westerly wind. When the data was divided into two subsets: (a) PM_{10} concentration > 500 (μg/m^3); and (b) PM_{10} concentrations < 500 (μg/m^3), dataset (a) clearly linked high concentrations with south-easterly wind. High concentration of PM_{10} from the south-easterly direction either could be due to the high wind speed, as shown in Fig. 3 or there might be an emission source in this direction, or both. It is a fact that Makkah being part of an arid region receives low precipitations and has large barren sandy land, therefore when wind blows it can generate considerable amount of atmospheric dust. The large heavy particles quickly deposit due to gravity, however smaller particle can stay in the atmosphere and travel long distances. The contributions from road traffic in the surrounding areas might add a significant amount, however on this occasion it was not considered as the main source, otherwise highest PM_{10} concentrations would have been observed during the last 10 days of the study period (08 to 18 August, 2012), when the number of visitors to the Makkah and hence traffic flow reach the peak level.

Time plots of the various air pollutants and meteorological variables (24 hour average) are shown for the period of study (20 July to 18 August, 2012) in Fig. 5. It can be observed in Fig. 5 (top panel) that pollutant concentrations show considerable variations in their levels during the study period, however

the pattern in PM_{10} concentrations is significantly different than that of other pollutants, which suggest that the effect of different factors (emission sources and meteorological variables), controlling their concentrations varies on each pollutant. When PM_{10} concentration is the highest (26 to 28 July), ozone concentration is the lowest and vice versa. During these three days, the concentrations of other pollutants (SO_2, NO_2 and CO) are pretty low as well. Fig. 5 (bottom panel) shows the levels and variations in meteorological variables, and it can be observed from the Figure 5 that atmospheric pressure is low and relative humidity is high during the 3 days period. Other meteorological variation do not show any distinct characteristics, except wind direction which seems to be blowing at about 200^o (southern direction), however it does not correlate well with Fig. 4 (top-left), where the wind direction during the three days vary considerably. The dissimilarities are due to different averaging time and the circular nature of wind direction. Therefore, the wind direction in Fig. 4 is considered here, which associates high PM_{10} concentrations with the southeast directions. Hence we conclude that low pressure and high relative humidity, are probably the main reasons for the high PM_{10} concentrations, where the former might have encouraged the moving-in of the particles from the surrounding areas as wind blow from high to low pressure areas (EPA, 2010), whereas the latter might have encouraged secondary aerosols formation by the process of coagulation and condensation (Harrison, 2001).

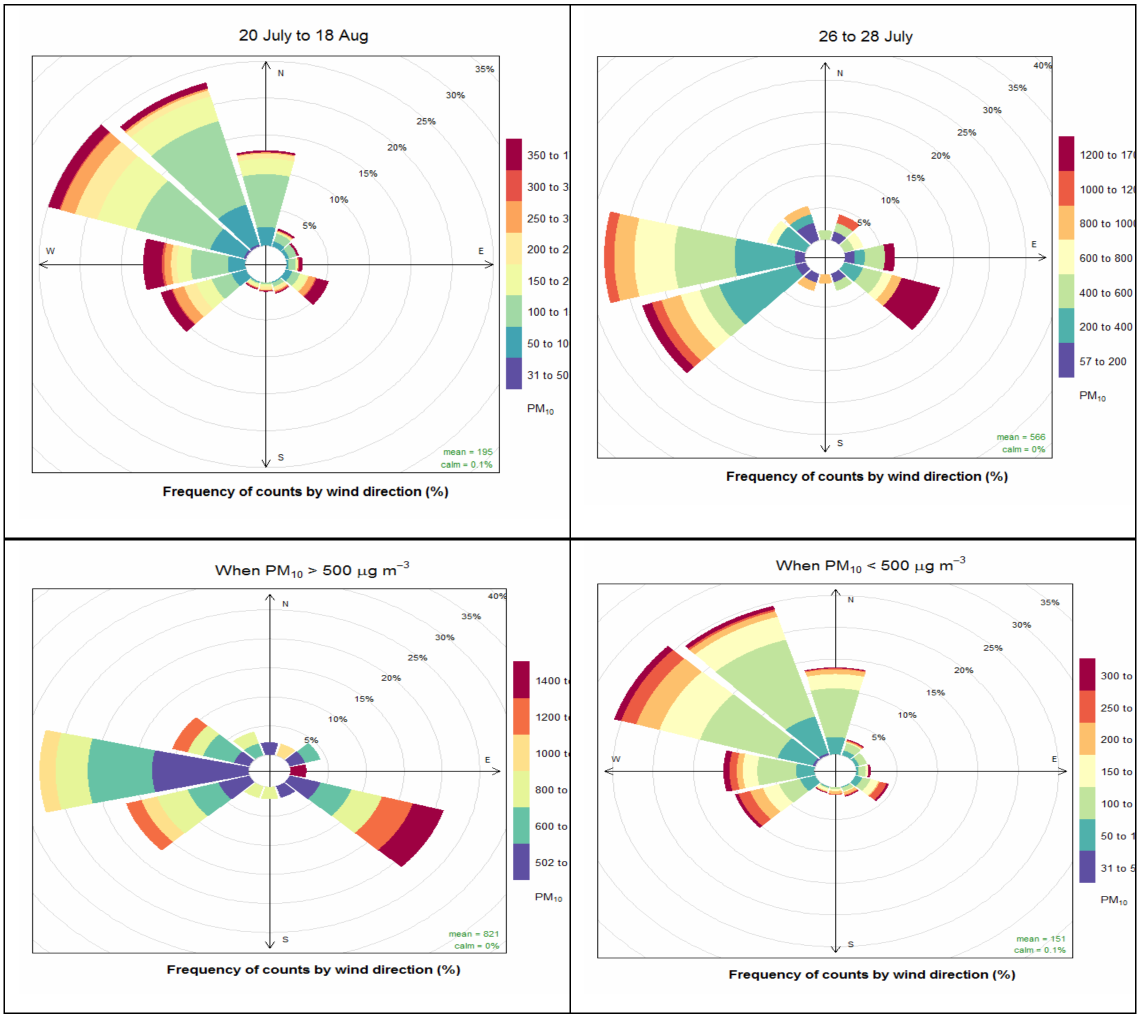
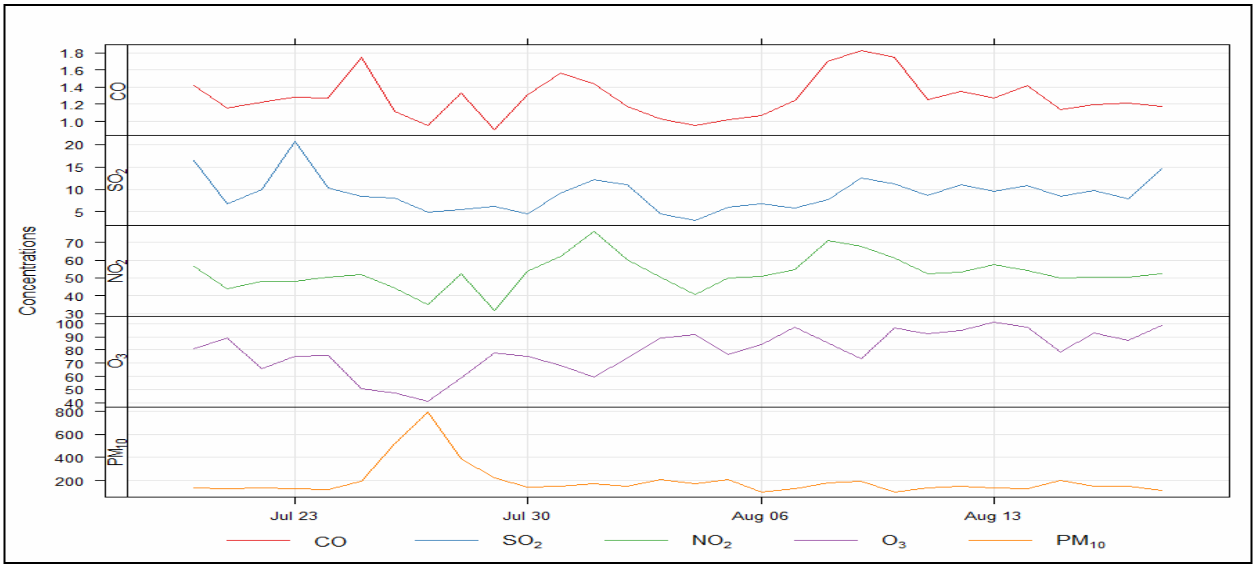


Figure 4: Pollution Roses, colour coded by the levels of mean hourly PM_{10} concentrations (µg/m^3): Top-left panel shows the whole month data (20 July to 18 August, 2012); Top-right panel shows three days data (26 to 28 July, 2012); Bottom-left shows when PM_{10} concentrations > 500 µg/m^3; and Bottom-right shows when PM_{10} concentrations < 500 µg/m^3.



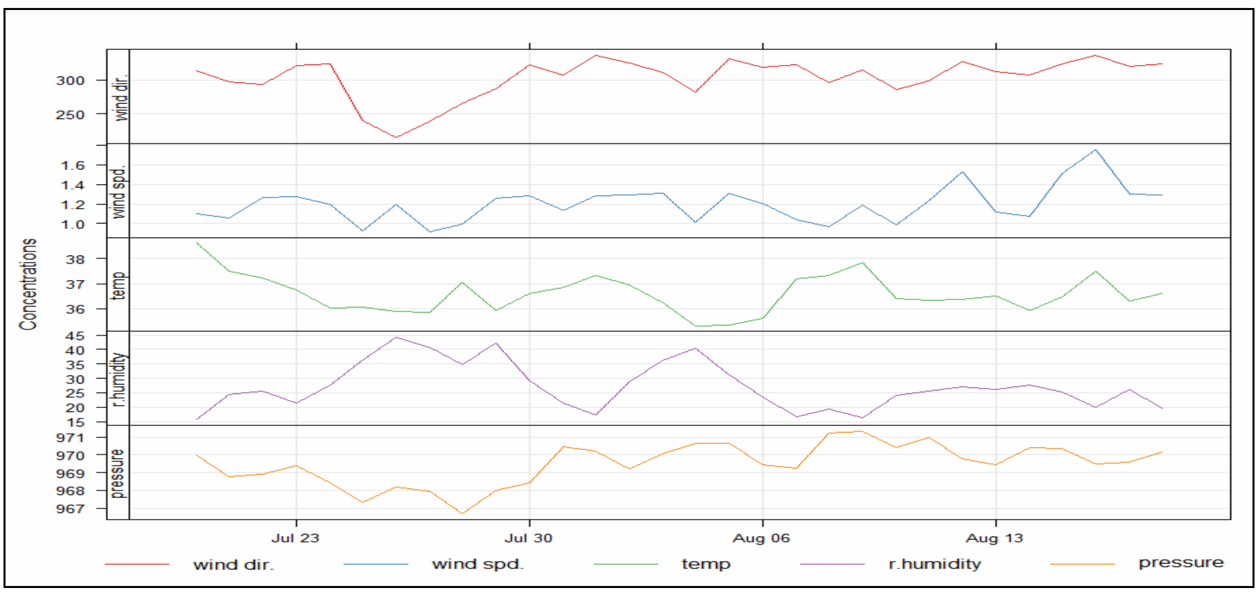


Figure 5: Time plots of various air pollutants (top-panel) and meteorological variables (bottom-panel), showing 24 hour average at the PME monitoring site, from 20 July to 18 August, 2012.

3. Conclusions:

In this study the effects of meteorological variables on the concentrations of various air pollutants, including SO_2, CO, NO_x, PM_{10} and ozone have been investigated during the month of Ramadhan (20 July to 18 August, 2012) in Makkah near Al-Haram. Correlation analysis has been used to investigate the association of air pollutants with each other and with meteorological variables. PM_{10} has relatively weaker correlation with other air pollutants, most probably because most of the PM_{10} in Saudi Arabia, being an arid region is generated by non-combustion sources, such as construction work and windblown dust and sand, whereas the other pollutants like SO_2, CO and NO_x are mainly emitted by combustion sources, including road traffic.

Among meteorological variables, temperature show strong positive correlation with ozone (0.74), which is probably due to the fact that ozone is a secondary air pollutant and is formed in the atmosphere by photochemical reaction of hydrocarbons and NO_x in the presence of sunlight. In contrast temperature has negative correlation with NO_x, CO, SO_2, and PM_{10}, whose concentration is more dependent on the emission sources. However, the negative correlation indicates that probably high temperature results in greater dispersion and dilution of the air pollutants, probably linked with vertical and horizontal turbulence (EPA, 2010). Wind speed help disperse local pollutants, which probably explains why it has negative correlation with NO_x and CO, however it has positive correlation with ozone and PM_{10}, most probably due to raising particles from bared surfaces and road sides and transport of ozone from the surrounding rural areas. Relative humidity is positively correlated with PM_{10} and negatively correlated with the rest of the air pollutants. The effect of rainfall was negligible most probably due to the fact that no rain

occurred during the study period. The effects of meteorological variables have also been analysed using polar plots and pollution roses, which provide further insight into the association between air pollutants and meteorology.

Factors responsible for the high concentrations of pollutants, particularly during the PM_{10} episode from 26 to 28 July 2012 are analysed. Unexpectedly, atmospheric pressure and relative humidity seem to be responsible for the episode, and not the sources of emissions, which are higher during the last 10 days of Ramadhan (08 to 18 August).

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التحقق من تأثير الأرصاد الجوية على تلوث الهواء في مكة المكرمة

تركي محمد حبيب الله

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لا يتأثر تركيز ملوثات الهواء فقط بمصادر التلوث، وإنما تتأثر كثيراً بمتغيرات عناصر الأرصاد الجوية والتي تلعب دوراً هاماً في تشتت وإنتقال المركبات والتفاعلات الكيميائية للملوثات الثانوية في الغلاف الجوي. تم في هذه الدراسة تحليل أثر تغير عناصر الأرصاد الجوية على تراكيز مختلفة من الملوثات الهوائية بإستخدام معادلات تحليل الإرتباط والعروض الرسومية لمكة المكرمة خلال شهر رمضان ١٤٣٣هـ (٧/٢٠ – ٢٠١٢/٨/١٨)، والذي يعد أزحم شهور السنة بعد شهر ذي الحجة. تبين من خلال التحليلات بأن الأتربة الصدرية أقل إرتباطاً بالملوثات الأخرى بسبب تغير مصادر التلوث. بينما هناك علاقة وثيقة بتغير درجة الحرارة مع الأوزون والتي وصل فيها معامل الإرتباط إلى (٠,٧٤)، في حين إنخفض معامل الإرتباط مع الملوثات الأخرى وهي أكاسيد النيتروجين وأول أكسيد الكربون وثاني أكسيد الكبريت والأتربة الصدرية، وهذه الملوثات مرتبطة إرتباطاً وثيقاً بمصادر التلوث. سرعة الرياح أيضاً ساعدت في تشتت الملوثات الهوائية، وهذا يفسر أن معامل الارتباط مع أكاسيد النيتروجين وثاني أكسيد الكبريت وأول أكسيد الكربون سالباً، بينما كان معامل الإرتباط موجباً مع الأوزون والأتربة الصدرية بسبب زيادة سرعة الرياح والذي ساعد على عدم ثبات العواصف الترابية في الشوارع والمناطق الصحراوية، وأيضاً إنتقال الأوزون من المناطق البعيدة عن مدينة مكة المكرمة. الرطوبة النسبية هي بالتالي سجلت علاقة قوية وموجبة مع الأتربة الصدرية وسالبة مع بقية ملوثات الهواء. كما أن معامل الإرتباط لتأثير سقوط الأمطار كان ضئيلاً بسبب عدم وجود تساقط للأمطار فترة إجراء الدراسة. كذلك تم تحليل تأثير عناصر الأرصاد الجوية بواسطة الرسمة القطبية ووردة الرياح. كما تم تحليل العوامل المسئولة في زيادة تراكيز الأتربة الصدرية عن الحدود المسموح بها خلال الفترة من ٢٦–٢٨ يوليو ٢٠١٢.