



## Analysing PM<sub>2.5</sub> and its Association with PM<sub>10</sub> and Meteorology in the Arid Climate of Makkah, Saudi Arabia

Said Munir<sup>1\*</sup>, Turki M. Habeebullah<sup>1</sup>, Atef M.F. Mohammed<sup>1,2</sup>, Essam A. Morsy<sup>1,3</sup>,  
Mohammad Rehan<sup>4</sup>, Kawsar Ali<sup>5</sup>

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

<sup>2</sup> *Air Pollution Department, National Research Center, Cairo, Egypt*

<sup>3</sup> *Geophysics Department, Faculty of Science, Cairo University, Giza, Egypt*

<sup>4</sup> *Centre of Excellence in Environmental Studies (CEES), King Abdulaziz University, Jeddah, Saudi Arabia*

<sup>5</sup> *Department of Agriculture, Abdul Wali Khan University Mardan, KPK, Pakistan*

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### ABSTRACT

Atmospheric Particulate Matter (PM) is considered one of the most critical air pollutants in terms of its detrimental health impacts, environmental degradations and visibility. Particles size, their chemical composition and atmospheric levels are important factors for determining their adverse health impacts. In this paper various aspects of PM<sub>2.5</sub> are analysed including PM<sub>2.5</sub>/PM<sub>10</sub> ratios and association with meteorological parameters using data collected from January 2014 to September 2015 in Makkah Saudi Arabia. During the study period, mean PM<sub>2.5</sub>/PM<sub>10</sub> ratio was found to be 0.64, whereas median and maximum ratios were 0.69 and 0.99, respectively. Diurnal, weekly and annual cycles of PM<sub>10</sub>, PM<sub>2.5</sub> and their ratios were analysed, which demonstrated considerable variations during various hours of the day, days of the week and months of the year. PM<sub>2.5</sub>/PM<sub>10</sub> ratios were lower in summer (June and July) and higher in winter (November and December), likewise the ratios were lower during afternoon and higher in the morning and evening. As expected, there was a positive correlation between PM<sub>10</sub> and PM<sub>2.5</sub> ( $r = 0.51$ ) and both PM<sub>10</sub> and PM<sub>2.5</sub> showed negative association with relative humidity and positive with wind speed and temperature. Furthermore, PM<sub>2.5</sub>/PM<sub>10</sub> ratios were lower ( $< 0.45$ ) at lower relative humidity ( $< 16\%$ ) and higher ( $> 0.70$ ) at higher relative humidity (35–90%), indicating a shift towards high PM<sub>2.5</sub> concentrations at higher relative humidity. Polar plots showed lowest ratios at high wind speed ( $> 3 \text{ m s}^{-1}$ ) blowing from west and southwest direction in summer, and highest ratios at low wind speed ( $< 2 \text{ m s}^{-1}$ ) in winter. Polar plots were successfully applied to show the interaction between various meteorological parameters and PM<sub>2.5</sub>/PM<sub>10</sub> ratios. Further work on source apportionment and receptor modelling of PM is required to help develop air quality index and prepare an effective air quality plan for Makkah.

**Keywords:** PM<sub>10</sub>; PM<sub>2.5</sub>; Particulate matter; Air quality; Makkah Saudi Arabia.

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### INTRODUCTION

Air pollution is becoming a growing environmental issue in both developing and developed countries throughout the world (Colls, 2002; Harrison, 2001). Growing urbanisation, transport vehicles on the roads, and biomass and fossil fuels burning to meet the energy needs of growing population have resulted in large amount of emissions of both gaseous pollutants and particulate matter (PM). In this study we focus on PM with aerodynamic diameter of up to 10  $\mu\text{m}$  (PM<sub>10</sub>)

and 2.5  $\mu\text{m}$  (PM<sub>2.5</sub>). PM<sub>10</sub> and PM<sub>2.5</sub> have attracted a vast number of research investigations (e.g., COMEAP, 2009, 2010; Harrison *et al.*, 2010; AQEG, 2012; Barmpadimos *et al.*, 2012; Vu *et al.*, 2015) due to their detrimental impact on public health, visibility, vegetation and other environmental impacts. However, the health impacts of PM over weigh the other environmental impacts, therefore the most concerning fact regarding PM is its health impact (Walters and Ayres, 2001; WHO, 2003). Many scientists have investigated the health impacts of PM and have reported that PM can cause various health issues, including respiratory diseases, rhinosinusitis, cardio-vascular diseases, asthma, and chronic obstructive pulmonary diseases (Walters and Ayres, 2001; WHO, 2003). The health effects of PM are mostly related with the fine fraction (PM<sub>2.5</sub>), which can penetrate deeper into the respiratory system (COMEAP, 2010).

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\* Corresponding author.

Tel.: +966-567349393; Fax: +966-125573282  
E-mail address: saidmunir@yahoo.co.uk

The levels of  $PM_{10}$  and  $PM_{2.5}$  are dependent not only on their emission sources but also on meteorological parameters, such as wind, temperature, relative humidity, atmospheric pressure and boundary layer height (Munir *et al.*, 2013a). Furthermore, the levels and composition of  $PM_{10}$  and  $PM_{2.5}$  are affected by the local geological characteristics and land usage type (Khodeir *et al.*, 2012). The levels and composition of  $PM_{10}$  and  $PM_{2.5}$  vary from one region to another, depending on their background levels and emission sources. It is, therefore, important to conduct monitoring and modelling investigations locally to be able to make informed decision regarding local air quality management. Makkah is situated in an arid hot region and is surrounded by large sandy deserts. The city receives little rain and experiences high temperature throughout the year. The city is expanding rapidly and large amount of construction-and-demolition activities take place, which include expansion of the Holy Mosque, developing a train network inside the Makkah city and from Makkah to other large cities of the countries, mountains digging, and building multi-storeyed building for residents and religious visitors (Munir *et al.*, 2013b). The city also experiences frequent sand-and-dust storms. Furthermore, increasing number of road-traffic vehicles and frequent congestions during the busy hours add to atmospheric pollution in the city. Makkah is one of the densely populated city. Moreover, it receives million of visitors every year to perform Hajj and Umrah. This puts further burden on the local resources and environmental quality, including air quality. Like most of the other Asian and African cities, Makkah also lacks an effective air quality management plan, therefore there is a need for research work into air quality related issues to develop the basic science and characterise temporal and spatial variability of various air pollutants, including PM. Because of the geological characteristics and arid climatic conditions,  $PM_{10}$  and  $PM_{2.5}$  are considered the pollutants of concern in this region as they exceed national and international air quality standards frequently (Othman *et al.*, 2010).

Previously several researchers (e.g., Al-Jeelani, 2008, 2009; Othman *et al.*, 2010; Seroji, 2011) have investigated the levels of PM, especially  $PM_{10}$  in Makkah and have reported that  $PM_{10}$  levels frequently exceeded national and international air quality standards. These studies included both monitoring and modelling investigations and analysed the temporal and spatial variability of  $PM_{10}$  (Munir *et al.*, 2013b), modelled its association with other pollutants and meteorology (Munir *et al.*, 2013a; Munir, 2015), and analysed its potential health effects (Habeebullah, 2013a, b). However no published literature was found regarding  $PM_{2.5}$ . This paper analyses  $PM_{2.5}$  and its association with  $PM_{10}$ , focusing on  $PM_{2.5}/PM_{10}$  ratios. The paper also investigates how the ratios vary during different hours of the day, days of the week and months of the year, plus how the ratios are affected by various meteorological parameters, such as temperature, relative humidity, and wind characteristics. Analysis of the ratio is important as it helps understand the relationship between  $PM_{2.5}$  and  $PM_{10}$  levels and their emissions sources, which may be helpful for developing an effective air quality management plan in Makkah and elsewhere.

## METHODOLOGY

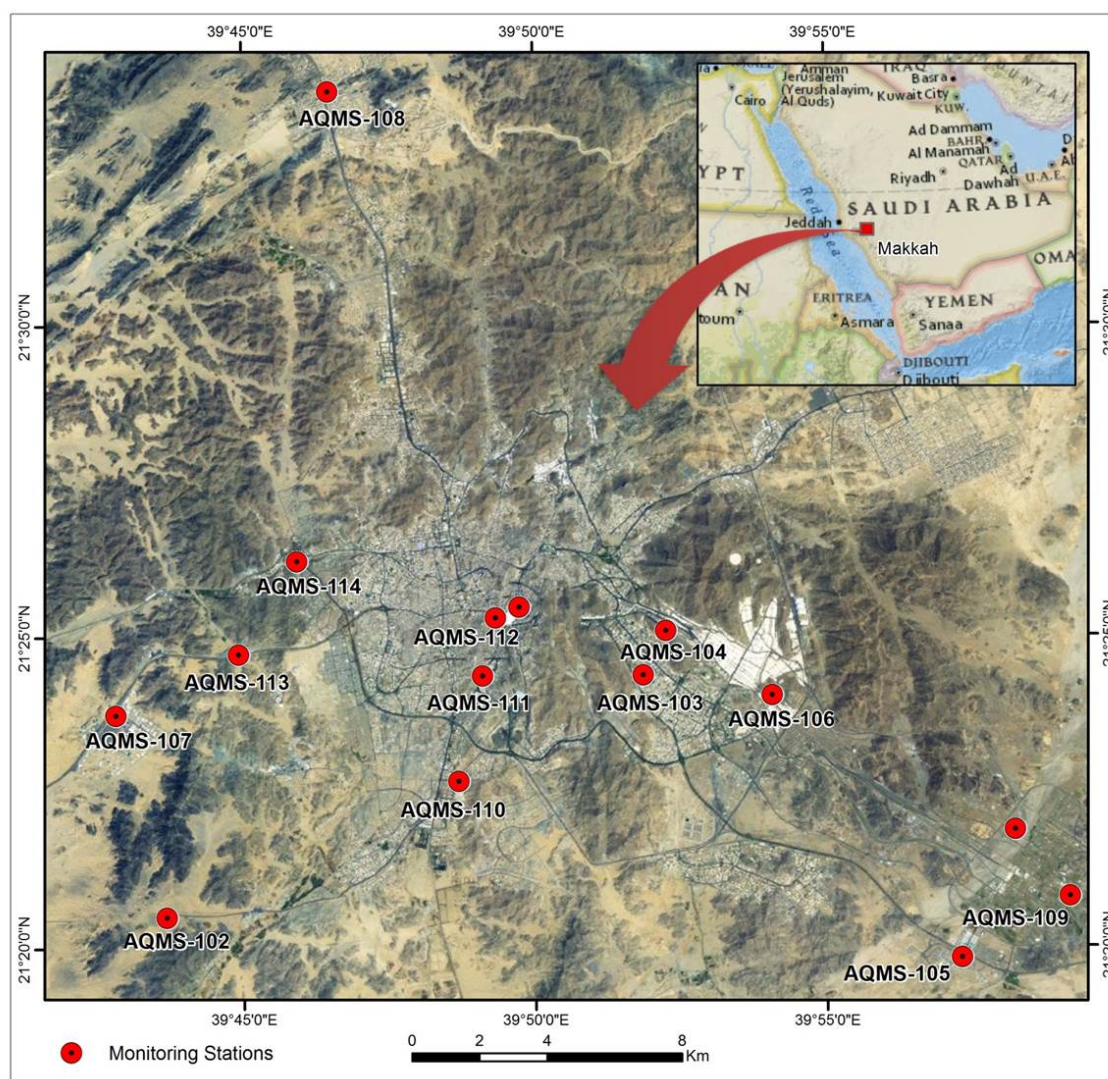
This paper characterises  $PM_{10}$ ,  $PM_{2.5}$  and their ratios in the Holy City of Makkah, Saudi Arabia, which is situated in an arid region, experiencing little rain and hot temperature all year round. Recently an air quality network is developed in the city of Makkah which monitors not only the concentrations of various air pollutants but also meteorological parameters (Fig. 1).

The data used in this study were collected at the Masfalah air quality monitoring station (AQMS111, Fig. 1). The site is classified as an urban traffic site, located near a busy road a couple of kilometre from the Holy Mosque in Makkah (Fig. 1).  $PM_{10}$  ( $\mu\text{g m}^{-3}$ ),  $PM_{2.5}$  ( $\mu\text{g m}^{-3}$ ), temperature ( $^{\circ}\text{C}$ ), wind speed ( $\text{m s}^{-1}$ ), wind direction (degree from the north) and relative humidity (%) hourly data were collected from January 2014 to September 2015. More than 90% data were available for  $PM_{10}$ ,  $PM_{2.5}$  and meteorological parameters for the study period. A summary of these variables are presented in Fig. 2 as a time series and in Fig. 3 as polar plots, which also provide a view of the variations of the various parameters during different seasons. Aeroqual AQM 60 air quality monitoring station was installed to monitor the concentrations of  $PM_{10}$ ,  $PM_{2.5}$  and meteorological parameters. The particles monitor uses a well proven near forward light scattering nephelometer and high precision sharp cut cyclone and has a range of 0–2000  $\mu\text{g m}^{-3}$  with accuracy of  $\pm 2$  for both  $PM_{10}$  and  $PM_{2.5}$ . The optical sensor nephelometer uses light scattering from particles to provide a continuous real-time measurement of  $PM_{10}$  and  $PM_{2.5}$ . In order to make the collected data useful and to provide a sound scientific basis for comparison against air quality standards, public information or policy development, the data need to be accurate and reliable. Strict QA/QC (Quality Assurance and Quality Control) measures were taken to ensure the quality of data. The QA/QC process ensures that the data are representative of atmospheric concentrations in the areas under investigation over the period of measurement. QA included careful selection of monitoring site, proper installment of instruments, selection of instrument and sample system design, and proper training of operators and personnel. QC measures included calibration of instruments, monitoring calibration gases and instrument response, routine site visits and operations, routine data review and validation and data ratification. After the initial calibration, the zero and span responses of the instrument were checked for drift on weekly basis. For both  $PM_{10}$  and  $PM_{2.5}$  the range of measurement was 0–2000  $\mu\text{g m}^{-3}$ , flow rate was 2  $\text{L min}^{-1}$ , and accuracy  $\pm 2 \mu\text{g m}^{-3}$ .

Statistical software R programming language (R Development Core Team, 2014) and its package openair (Carslaw and Ropkins, 2012) was used to perform data analysis and develop various graphs, including polar plots, time variation plots, scatter plots, and time plots (Carslaw and Ropkins, 2012).

## RESULTS AND DISCUSSION

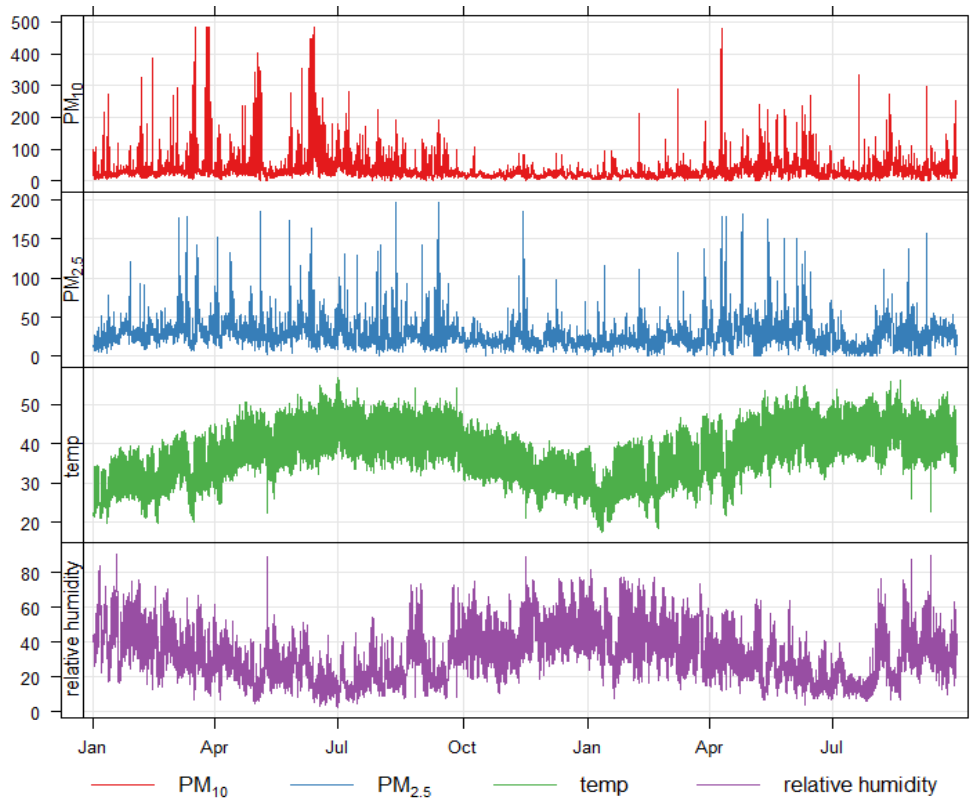
A summary of the data, which include  $PM_{10}$ ,  $PM_{2.5}$ ,



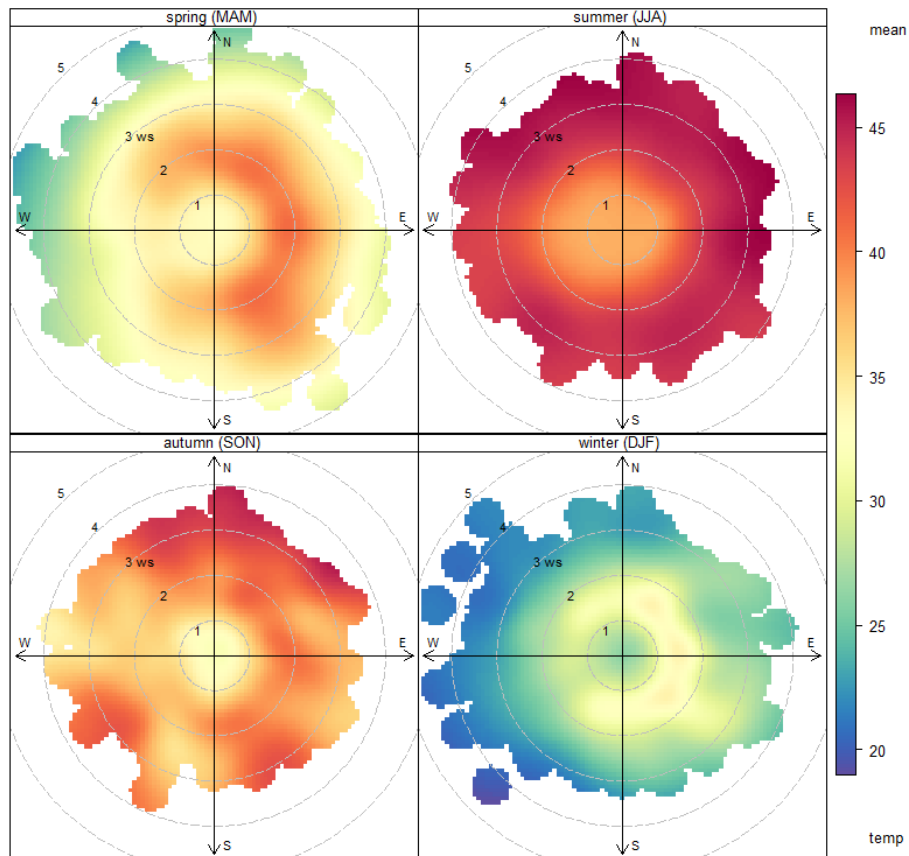
**Fig. 1.** Map of the air quality and meteorological monitoring sites in Makkah Saudi Arabia, where AQMS111 represents the Masfalah Air Quality Monitoring site.

ratios of  $PM_{2.5}/PM_{10}$ , temperature, relative humidity, wind speed and wind direction is presented in Table 1. The Saudi Arabian national annual air quality standards developed by the Presidency of Meteorology and Environment (PME) for  $PM_{10}$  and  $PM_{2.5}$  are  $80 \mu\text{g m}^{-3}$  and  $15 \mu\text{g m}^{-3}$ , respectively. The European Union (EU) annual air quality standards for  $PM_{10}$  and  $PM_{2.5}$  are  $40 \mu\text{g m}^{-3}$  and  $25 \mu\text{g m}^{-3}$ , respectively (EU, 2016). The World Health Organisation (WHO) air quality guidelines for  $PM_{10}$  and  $PM_{2.5}$  are  $20 \mu\text{g m}^{-3}$  and  $10 \mu\text{g m}^{-3}$ , respectively. The annual average of  $PM_{10}$  and  $PM_{2.5}$  during the study period at the Masfalah air quality monitoring station (AQMS111, Fig. 1) was 44 and 23, respectively, indicating that long term  $PM_{2.5}$  levels have exceeded the PME air quality limits, whereas  $PM_{10}$  levels have exceeded the EU limits. Furthermore, the WHO long terms guidelines are exceeded by both  $PM_{10}$  and  $PM_{2.5}$ . In Makkah maximum temperature gets as high as  $56.70^\circ\text{C}$ , and the ratios of  $PM_{2.5}/PM_{10}$  ranged from 0.001 to 0.99 with an average value of 0.64 (Table 1).

Time variations of  $PM_{10}$ ,  $PM_{2.5}$  and their ratios during the study period in Makkah are presented in Fig. 4. As expected  $PM_{10}$  and  $PM_{2.5}$  follow mostly the same trends in their diurnal, weekly and annual cycles. However,  $PM_{2.5}$  levels are significantly lower than  $PM_{10}$  levels. On diurnal basis, lowest levels of both  $PM_{10}$  and  $PM_{2.5}$  were observed in the morning (about 05:00 hour) and at night, whereas highest levels were observed in the late afternoon (about 16:00 hour). In Makkah most of the atmospheric PM comes from resuspended and windblown dust particles, generated by construction-and-demolition activities and raised from the surrounding sandy deserts (Munir et al., 2013b; Habeebullah et al., 2015). The amount of resuspended and windblown dust is greater during daytime due to atmospheric instability and greater vertical and horizontal wind movement. Traffic activities are also greater during daytime, which may play a role in increasing the PM concentrations during daytime. On weekly basis, lowest level of  $PM_{10}$  was observed on Saturday and that of  $PM_{2.5}$  on Friday, whereas highest level



**Fig. 2.** Presenting hourly data of  $PM_{10}$  ( $\mu\text{g m}^{-3}$ ),  $PM_{2.5}$  ( $\mu\text{g m}^{-3}$ ), temperature ( $^{\circ}\text{C}$ ) and relative humidity (%) from January 2014 to September 2015 in Makkah.



**Fig. 3.** Polar plot of wind speed, wind direction and temperature using data from January 2014 to September 2015 in Makkah.

**Table 1.** Summary of various parameters and pollutants hourly data used in this study from January 2014 to September 2015.

Metrics	PM <sub>10</sub> ( $\mu\text{g m}^{-3}$ )	PM <sub>2.5</sub> ( $\mu\text{g m}^{-3}$ )	PM <sub>2.5</sub> /PM <sub>10</sub> Ratios	WS ( $\text{m s}^{-1}$ )	WD (degrees)	RH (%)	Temperature ( $^{\circ}\text{C}$ )
Minimum	1.15	0.01	0.001	0.27	2	2.20	17.49
1st Quartile	20.77	13.32	0.46	1.31	108	15.80	34.51
Median	31.49	20.00	0.69	1.67	224	22.30	38.39
Mean	44.53	23.25	0.64	1.74	196	27.32	38.51
3rd Quartile	49.09	29.12	0.85	2.14	289	34.20	43.37
Maximum	485.36	185.31	0.99	4.62	360	90.74	56.71

of PM<sub>10</sub> and PM<sub>2.5</sub> were observed on Wednesday and Tuesday, respectively. Lower levels of PM<sub>10</sub> and PM<sub>2.5</sub> on Friday and Saturday are most probably due to the weekend, which experiences lower traffic activities. It is worth mentioning that in Saudi Arabia weekend is on Friday and Saturday. Annually, both PM<sub>10</sub> and PM<sub>2.5</sub> demonstrated highest levels in March and lowest in November. Generally both PM<sub>10</sub> and PM<sub>2.5</sub> showed higher levels in summer and during day time and lower levels during winter and night times, which probably highlights the role of high temperature in increasing the levels of PM due to greater turbulence, atmospheric instability and enhanced vertical and horizontal movement of particles. The trend observed in Makkah is different to those observed in colder countries, such as the UK and other European countries. Recently Habeebullah *et al.* (2015) compared several air pollutant levels between Makkah and Leeds UK and reported opposite trends in the diurnal and annual cycles. In Leeds PM<sub>10</sub> concentrations were higher during winter probably due to stagnant atmospheric conditions which hinder the dispersion process, whereas in Makkah higher levels of PM<sub>10</sub> were observed in summer probably due to atmospheric conditions, such as high temperature which encourage re-suspension and windblown dust and sand particles.

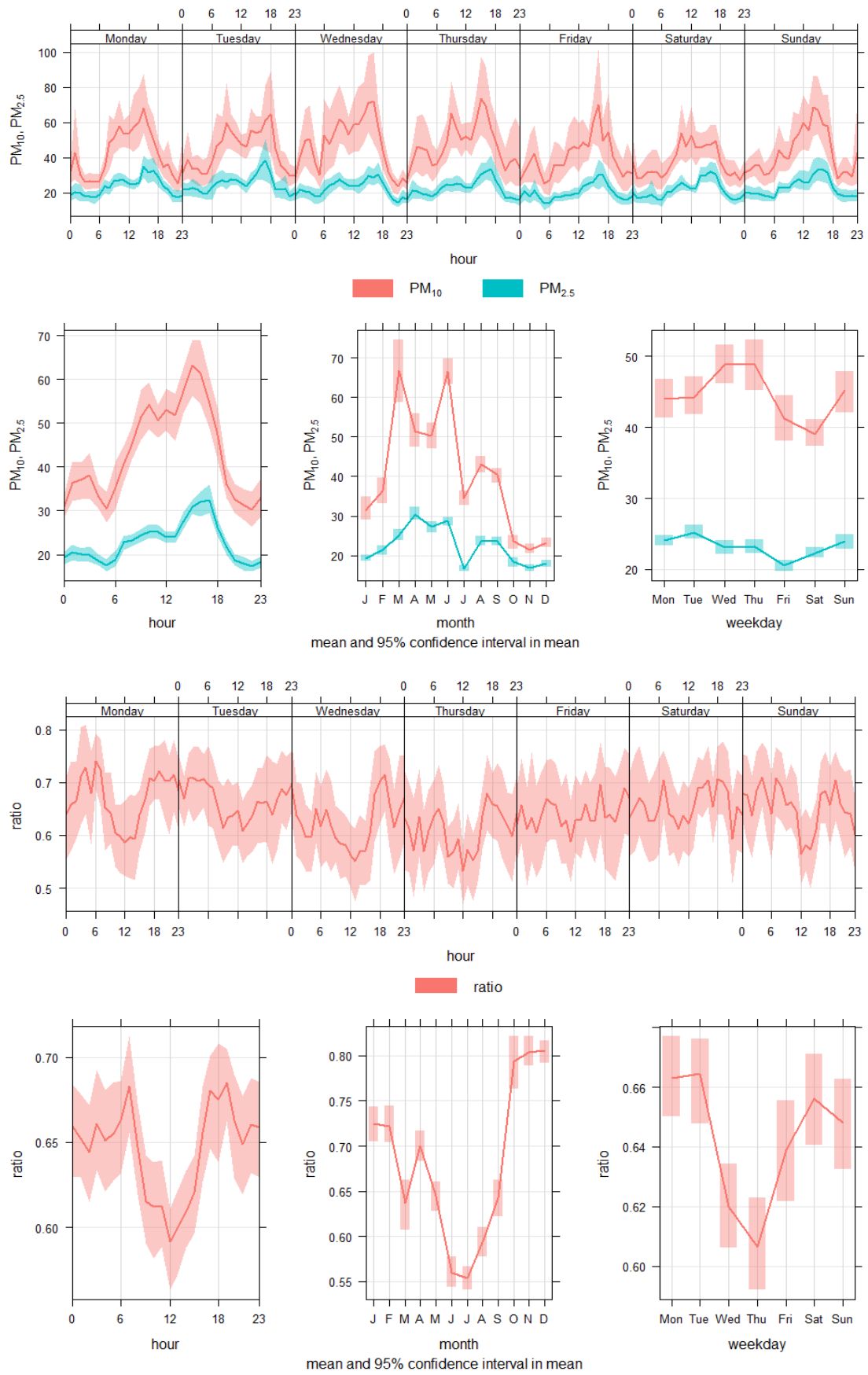
Recently Mohammed *et al.* (2016) observed that PM<sub>10</sub> concentrations were higher in the north western part and lower in the south-eastern part of Makkah city. PM<sub>10</sub> levels ranged from 56 to 391  $\mu\text{g m}^{-3}$  in Makkah. In another study, Mohammed *et al.* (2015) reported that PM<sub>10</sub> and PM<sub>2.5</sub> levels were 145.4 and 13.2  $\mu\text{g m}^{-3}$ , respectively during Hajj days in Makkah. Munir *et al.* (2013b) investigated PM<sub>10</sub> levels in Makkah and reported that PM<sub>10</sub> ranged from 0 to 999  $\mu\text{g m}^{-3}$  having mean concentration of 174.6  $\mu\text{g m}^{-3}$  in 2012. In another investigation Munir *et al.* (2013a) reported that PM<sub>10</sub> concentration had positive trend in Makkah during 1997–2012 and had a mean value of 112.8  $\mu\text{g m}^{-3}$  and maximum value of 821  $\mu\text{g m}^{-3}$ . Several authors have investigated the levels of atmospheric aerosols around the world. Their reported PM<sub>2.5</sub> levels were lower in Turkey (9.7  $\mu\text{g m}^{-3}$ , Kocak *et al.*, 2007) and Brazil (13.8  $\mu\text{g m}^{-3}$ , Mariani and Mello, 2007) and higher in China (451  $\mu\text{g m}^{-3}$ , Wang *et al.*, 2003), India (55.7  $\mu\text{g m}^{-3}$ , Rengarajan *et al.*, 2011) and Pakistan (83.5  $\mu\text{g m}^{-3}$ , Mansha *et al.*, 2011) than those observed in this study in Makkah. Furthermore, PM<sub>10</sub> levels were reported to be lower in Turkey (26.7  $\mu\text{g m}^{-3}$ , Kocak *et al.*, 2007) and Brazil (34.4  $\mu\text{g m}^{-3}$ , Mariani and Mello, 2007) and higher in China (682.0  $\mu\text{g m}^{-3}$ , Wang *et*

*al.*, 2003) and India (171.0  $\mu\text{g m}^{-3}$ , Rengarajan *et al.*, 2011). Nasrallah and Seroji (2008) reported that daily PM<sub>10</sub> concentration ranged from 191 to 262  $\mu\text{g m}^{-3}$  in Makkah, Saudi Arabia. Khodeir *et al.* (2012) estimated that the main sources of PM<sub>2.5</sub> and PM<sub>10</sub> in Jeddah were heavy oil combustion, resuspended soil, industrial sources, traffic sources, and marine aerosols.

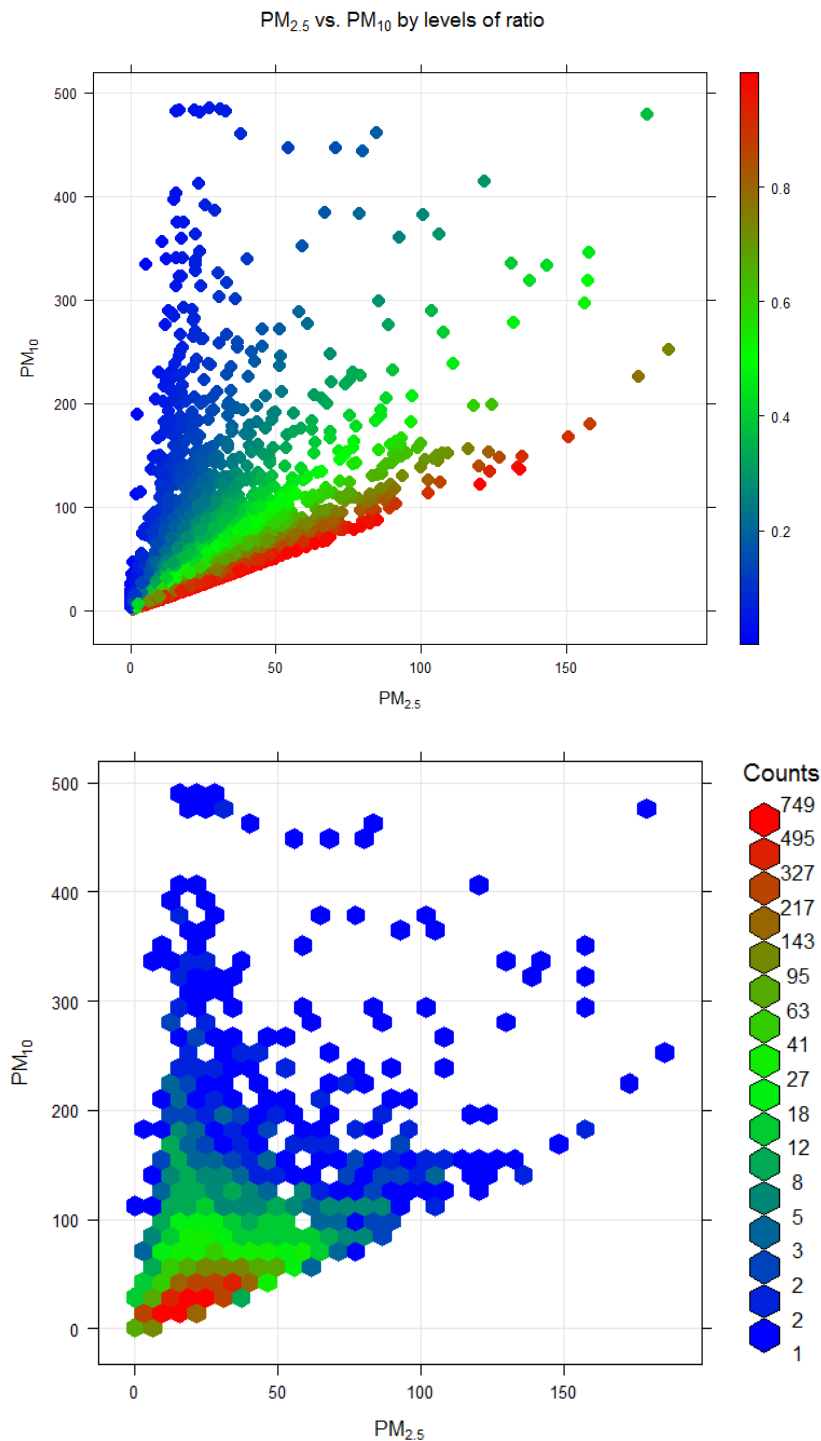
The time variations of PM<sub>2.5</sub>/PM<sub>10</sub> ratios are presented in Fig. 4 (lower-panel). Here it can be observed that lowest ratios are observed at mid-day and in summer months, when re-suspended and windblown dust and sand particles are proportionately in higher quantity. It is important to emphasise that resuspended and windblown dusts are mostly in the coarse range (PM<sub>10</sub>–PM<sub>2.5</sub>), therefore has low PM<sub>2.5</sub>/PM<sub>10</sub> ratio. In contrast PM emitted by combustion processes are mostly in the fine particulate (PM<sub>2.5</sub>) range and have higher PM<sub>2.5</sub>/PM<sub>10</sub> ratio.

A scatter plot of PM<sub>10</sub> versus PM<sub>2.5</sub> in Makkah using hourly data from January 2014 to September 2015 is shown in Fig. 5. The scatter plots are coloured by the ratios of PM<sub>2.5</sub>/PM<sub>10</sub>. Based on the levels of ratios there are 3 distinct regions coloured as red, green and blue in Fig. 5 (upper-panel). Probably the red colour, which represents high ratio of PM<sub>2.5</sub>/PM<sub>10</sub> (> 0.8) are those particles which are emitted by direct combustion processes or are made in the atmosphere, known as secondary particles, such as sulphate and nitrate ions. The blue colour represents coarse particles generated by mechanical means, such as grinding, construction-and-demolition and digging, having very low PM<sub>2.5</sub>/PM<sub>10</sub> ratio (< 0.2). Green colour having moderate ratios from 0.2 to 0.8 (roughly) are a mixture of the fine and coarse particles. Fig. 5 (lower-panel) which shows the counts of particles in each portion of the plot, shows that in the red region (counts > 200), there seems to be a very strong correlation between PM<sub>10</sub> and PM<sub>2.5</sub>, however as concentrations increase and the counts decrease, the plot spreads like a fan and makes a V - sort of shape, which weakens the correlations.

In Fig. 6 the correlation plot shows the association of PM<sub>10</sub> and PM<sub>2.5</sub> with each other and with wind speed, relative humidity and temperature. PM<sub>2.5</sub> is positively correlated with PM<sub>10</sub> ( $r = 0.51$ ), temperature ( $r = 0.27$ ) and with wind speed ( $r = 0.12$ ) and negatively correlated with relative humidity ( $r = -0.17$ ). Similarly, PM<sub>10</sub> is positively correlated with temperature ( $r = 0.24$ ) and wind speed ( $r = 0.19$ ) and negatively correlated with relative humidity ( $r = -0.30$ ). Meteorological parameters, such as wind, temperature and relative humidity play an important role in transport,



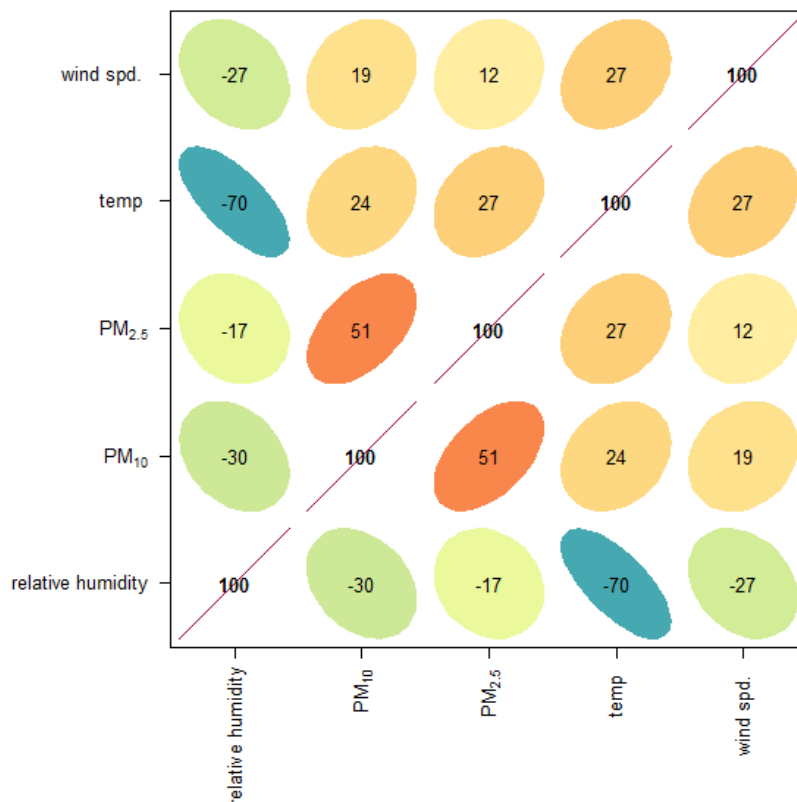
**Fig. 4.** Time variations of PM<sub>10</sub> ( $\mu\text{g m}^{-3}$ ), PM<sub>2.5</sub> ( $\mu\text{g m}^{-3}$ ) (upper-panel) and their ratios (PM<sub>2.5</sub>/PM<sub>10</sub>) (lower-panel) from January 2014 to September 2015 in Makkah Saudi Arabia.



**Fig. 5.** Scatter plots of PM<sub>10</sub> versus PM<sub>2.5</sub> both using data from January 2014 to September 2015 in Makkah.

dispersion, and removal (dry and wet deposition) of PM<sub>10</sub> and PM<sub>2.5</sub> from the atmosphere. They also affect atmospheric chemistry and hence the formation of secondary PM in the atmosphere (Andersson *et al.*, 2006; Munir *et al.*, 2013a). The effect of meteorological parameters varies in different regions of the world. In Makkah, previously Munir *et al.* (2013a) reported a strong positive effect of wind speed and temperature on PM<sub>10</sub> concentrations. High wind speed and temperature play a vital role in the dispersion and

transportation of air pollutants from one place to another, ranging from local to regional or global scale, thus encouraging vertical and horizontal movement of the particles. In addition, in arid region like Makkah high wind speed and temperature may encourage wind turbulence and re-suspension of dust particles. Furthermore, Makkah receives little rain and is surrounded by large deserts, in such conditions wind blowing at high speed may lift dust and sand particles and increase particle concentrations in



**Fig. 6.** Correlation plots of PM<sub>10</sub>, PM<sub>2.5</sub>, relative humidity, wind speed and temperature using hourly data from January 2014 to September 2015 in Makkah.

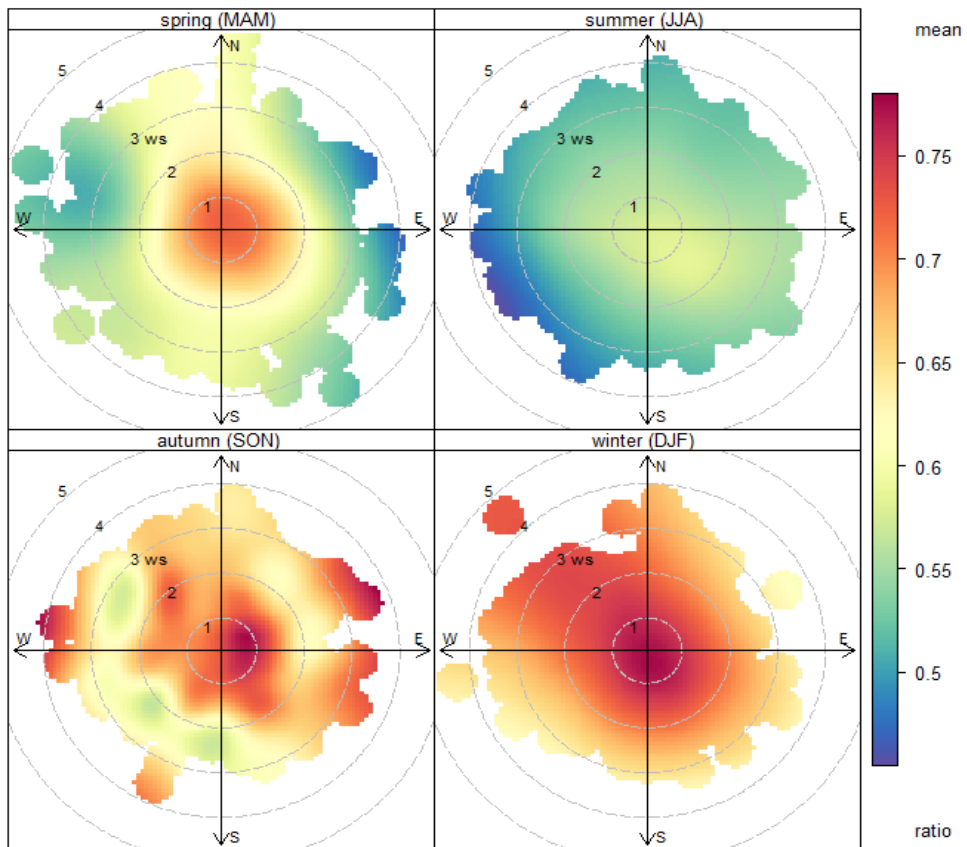
the atmosphere. Previously Munir *et al.* (2013a) in a modelling study on PM<sub>10</sub> reported stronger (than reported in this study) positive correlation between PM<sub>10</sub> concentration and wind speed ( $r = +0.42$ ) and temperature ( $r = +0.38$ ). Relative humidity on the other hand has negative association with both PM<sub>10</sub> and PM<sub>2.5</sub>, probably due to washout effect and wet deposition by rainfall. However, Charron and Harrison (2003) reported that ultrafine particles had higher concentrations during the rainy periods, which might show that relative humidity has different effect on the concentrations of fine and coarse particles. Probably this is the reason that relative humidity showed stronger correlation ( $r = -0.30$ ) with PM<sub>10</sub> than PM<sub>2.5</sub> ( $r = -0.17$ ). The effect of meteorological parameters on the ratios of PM<sub>2.5</sub> and PM<sub>10</sub> is further elaborated by the help of polar plots (Figs. 8 and 9).

Fig. 7 presents the ratios of PM<sub>2.5</sub> and PM<sub>10</sub> associated with wind speed and wind direction in various seasons of the year in Makkah. Generally the values of ratios are lower ( $< 0.6$ ) in summer and higher ( $> 0.6$ ) in winter and autumn at all wind speed and wind direction. In spring high ratios are associated with low wind speed ( $< 2 \text{ m s}^{-1}$ ) from all directions and low ratios are associated with high wind speed blowing mostly from east and west direction. Fig. 7 shows the complex nature of the effect of meteorology on PM, which means the effect of wind direction and wind speed is not the same throughout the year. It rather changes in each season of the year. The Masfalah AQMS, from which the data were obtained, is situated at a roadside in a busy location in the centre of Makkah, therefore at low

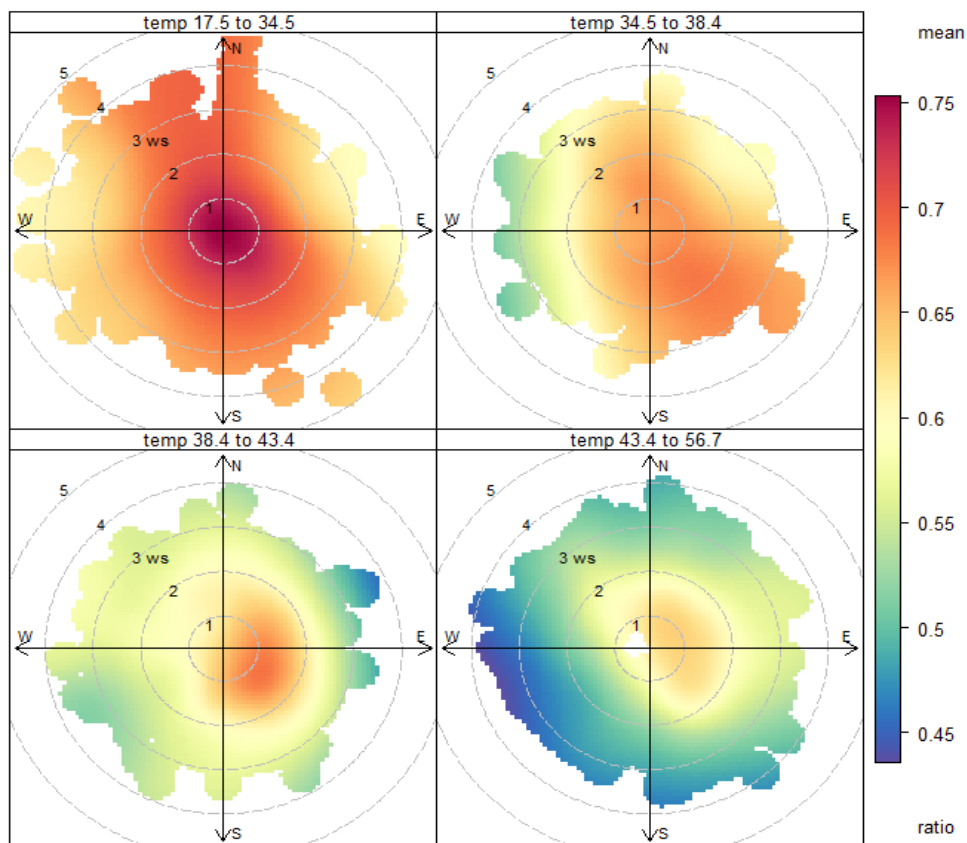
wind speed locally emitted air pollutants are not dispersed quickly. Traffic related PM has a high PM<sub>2.5</sub>/PM<sub>10</sub> ratio, this is the reason why the polar plots show high ratios at low wind speed in Fig. 7. The difference in the ratios observed in winter and summer is mostly due to temperature and atmospheric stability which are responsible for atmospheric turbulence and hence vertical pollutants dispersion. Winter is characterised by low temperature and stable atmospheric conditions, hindering the dispersion of locally emitted pollutants, whereas summer on the other hand is characterised by high temperature and unstable atmospheric conditions which encourage dispersion of locally emitted traffic related air pollutants and enhance resuspension of sand and dust particles, which consist mostly of coarse particles and hence reduce the ratios.

To further elaborate the effect of meteorology on the ratios of PM<sub>2.5</sub> and PM<sub>10</sub>, in Fig. 8 polar plots show the effect of temperature along with wind speed and direction. This figure also confirms that seasonal variations in the ratios are mostly due to the levels of temperature. There is a general negative association between temperature levels and PM<sub>2.5</sub>/PM<sub>10</sub> ratios i.e., higher ratios are linked with low temperature and vice versa. However, this relationship is affected by wind speed and wind direction. At low temperature ( $< 34.5^\circ\text{C}$ ), the ratios are greater than 0.60, whereas at high temperature ( $> 43.4^\circ\text{C}$ ), the ratios are less than 0.60. Furthermore, low wind speed is shown to encourage high PM<sub>2.5</sub>/PM<sub>10</sub> ratios and vice versa. At temperature from  $34.5$  to  $38.4^\circ\text{C}$ , high wind speed ( $> 2 \text{ m s}^{-1}$ ) blowing from the west decreases the





**Fig. 7.** Polar plots showing the ratios of  $PM_{2.5}/PM_{10}$  in various seasons in Makkah.



**Fig. 8.** Polar plots showing the effect of temperature on the ratios of  $PM_{2.5}/PM_{10}$  in Makkah.

ratios. Similarly high wind speed ( $>2 \text{ m s}^{-1}$ ) at temperature range from 38.4 to 43.4°C causes reduction in the ratios almost from all directions. The effect of wind speed is linked with dispersion and re-suspension of the particles, whereas the effect of wind direction is linked with the emission sources. When the wind direction is linked with low ratios, it shows that in that direction probably there is a source of PM dominated by coarse particles. On the other hand when wind direction is linked with high ratios, it shows the presence of fine PM dominated source, such as road traffic or other combustion sources.

Fig. 9 shows the effect of relative humidity on the ratios of  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ . There is a clear positive association between the levels of relative humidity and the ratios of  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ . The interesting thing is that unlike temperature, the association of relative humidity with the ratios of  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  does not seem to be wind speed or direction dependent and the ratios are the same at all wind speed and direction. Although relative humidity has negative correlation with both  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  concentrations (Fig. 6), it seems to have a stronger negative effect on  $\text{PM}_{10}$  than on  $\text{PM}_{2.5}$ . Due to washout effect and wet deposition, rainfall and high relative humidity may cause reduction in the concentration of PM, however due to differential effect fine and ultrafine particles are observed to have higher concentrations in the rainy season (Charron and Harrison, 2003). This shows the importance of meteorological parameters on PM and how meteorological parameters have different effects on smaller

and larger particles and thus affecting the ratios of  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ . The effect of meteorological parameters also vary from place to place (Habeebullah et al., 2015) due to variations in local meteorological conditions and emission sources.

## CONCLUSIONS

In this paper  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$  and their ratios are analysed during the period from January 2014 to September 2015 in the Holy City of Makkah Saudi Arabia. The ratios of  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  are analysed in light of their diurnal, weekly and seasonal cycles. Furthermore, the effects of some meteorological parameters, such as wind speed, wind direction, temperature and relative humidity on  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$  and their ratios are investigated with the help of correlation analysis and polar plots. During the study period, mean  $\text{PM}_{2.5}/\text{PM}_{10}$  ratio was found to be 0.64, whereas median and maximum ratios were 0.69 and 0.99, respectively. Overall, temperature and wind speed had negative associations, whereas relative humidity had positive association with the ratios, which means that the former encourages high levels of  $\text{PM}_{10}$ , whereas the latter encourages high levels of  $\text{PM}_{2.5}$ . The effect of temperature and relative humidity on PM is complicated by wind speed and wind direction, which is demonstrated by the polar plots. Makkah is part of an arid region, which receives little rainfall and experiences high temperature, especially in

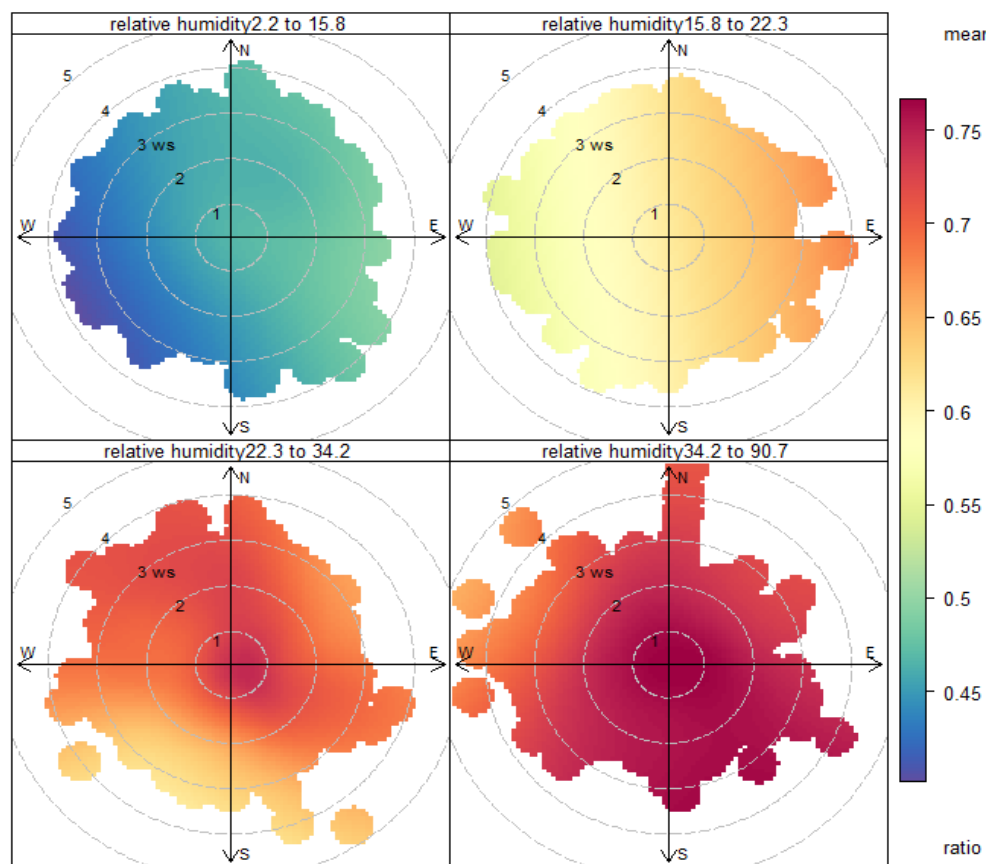


Fig. 9. Polar plots showing the effect of relative humidity on the ratios of  $\text{PM}_{2.5}/\text{PM}_{10}$  in Makkah.

summer when temperature reaches as high as 50°C. Meteorology seems to play an important role in determining the levels of PM<sub>2.5</sub> and PM<sub>10</sub> and their ratios. The ratios are higher in winter and during night-time and lower in summer and during hot hours of the day. Further work is required on source apportionment and receptor modelling of PM<sub>10</sub> and PM<sub>2.5</sub> which will identify the emission sources of PM and help prepare an effective air quality plan in Makkah.

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