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A Comparison of Air Quality in Arid and Temperate Climatic Conditions – A Case Study of Leeds and Makkah

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Abstract**—**In this paper air quality conditions in Makkah and Leeds are compared. These two cities have totally different climatic conditions. Makkah climate is characterised as hot and dry (arid) whereas that of Leeds is characterised as cold and wet (temperate). This study uses air quality data from 2012 collected in Makkah, Saudi Arabia and Leeds, UK. The concentrations of all pollutants, except NO are higher in Makkah. Most notable, the concentrations of PM_{10} are much higher in Makkah than in Leeds. This is probably due to the arid nature of climatic conditions in Makkah and not solely due to anthropogenic emission sources, otherwise like PM_{10} some of the other pollutants, such as CO, NO, and SO_2 would have shown much greater difference between Leeds and Makkah. Correlation analysis is performed between different pollutants at the same site and the same pollutants at different sites. In Leeds the correlation between PM_{10} and other pollutants is significantly stronger than in Makkah. Weaker correlation in Makkah is probably due to the fact that in Makkah most of the gaseous pollutants are emitted by combustion processes, whereas most of the PM_{10} is generated by other sources, such as windblown dust, re-suspension, and construction activities. This is in contrast to Leeds where all pollutants including PM_{10} are predominantly emitted by combustions, such as road traffic. Furthermore, in Leeds frequent rains wash out most of the atmospheric particulate matter and suppress re-suspension of dust. Temporal trends of various pollutants are compared and discussed. This study emphasises the role of climatic conditions in managing air quality, and hence the need for region-specific controlling strategies according to the local climatic and meteorological conditions.

Keywords**—**Air pollution, climatic conditions, particulate matter, Makkah, Leeds.

I. Introduction

In the modern age with the growing energy consumptions in the form of road traffic or other combustion processes, air pollution has emerged as a serious environmental issue globally. Air pollution has resulted in numerous health problems and environmental degradation [1]. World Health Organisation [2] estimated that outdoor atmospheric pollution was responsible for the deaths of 3.7 million people globally during 2012, from heart disease and stroke, respiratory illnesses and cancers. Scientists throughout the world are investigating different aspects of air quality, including air quality monitoring, air quality modelling, and how air quality interacts with other atmospheric parameters to better understand its behaviour, which can help devise an effective air quality management plan. The levels of atmospheric pollutants not only depend on the amount of air pollutant emissions but also on meteorological parameters, such as wind speed and direction, temperature, and relative humidity [3].

Air pollutant levels exhibit considerable temporal variability and the levels of air pollutants change from hour to hour, day to day, season to season, and year to year [4]. Determining temporal trends in air pollutant levels is important as it helps determine the time when air pollutant levels are expected to be high or exceed the air quality standards and pose risk to human health. Furthermore, air pollutant levels vary from one place to another [5]. The spatial variability in air pollutant levels is caused by local meteorological conditions, local emissions, and geographical characteristics. Some air pollutants are emitted locally, while others are transported from other regions [4]. Regional transport of air pollutants depends on the type of pollutants, wind speed and wind direction [6]. Both temporal and spatial comparison of air pollutant levels are important and help us understand the factors responsible for the high episode of air pollutions. In this paper air pollutant levels in Leeds, UK and Makkah, Saudi Arabia are compared and their similarities and dissimilarities are highlighted.

Air quality has improved considerably in the UK in recent decades due to new, cleaner technology and tighter environmental legislations; however NO_2 and particulate matters still exceed air quality standards in many urban areas and roadside locations, including Leeds. Leeds was among nine urban areas in the UK named in a recent report by WHO as failing to meet guidelines on air quality [2]. Strict measures are required to address the causes of air pollution, particularly traffic pollution, which is considered the main culprit for air pollution in urban areas. The measures may include cleaner vehicles, better public transport, alternative transport means including cycling facilities, and ending plans to build more

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roads. For more details on air quality in Leeds see [7] and the references there in.

The Holy City of Makkah is located in the Kingdom of Saudi Arabia (KSA) about 80 km inland from the Red Sea. The average elevation is ~277 m above sea level. Due to religious importance, the City of Makkah has dense population and accommodates about 1,700,000 residents [8]. The city centre is around the Holy Mosque (Al-Haram), which has lower altitude than most of the city. Several authors have reported high levels of air pollutants in Makkah [3], [9]-[12]. Makkah is considered the holiest city in the Muslim world, and millions of Muslims visit the city every year. Clean air is, therefore a particularly sensitive issue in Makkah, especially during Hajj (Pilgrimage) and the month of Ramadan (the fasting month). In this paper the concentrations of several air pollutants are compared between Leeds, UK and Makkah, Saudi Arabia. The two cities have totally different meteorological conditions and emission sources. On average, Leeds has low temperature and high rainfall, whereas Makkah has high temperature and low rainfall. Recent reports show that air quality in both of these cities requires local action plan for air quality management, as several air pollutants exceed air quality standards. The aim here is to compare the air quality levels in these two cities with a view to better understand the factors responsible for air pollution problems in these two different locations, as it is proposed that identification of similarities/dissimilarities will help to identify transferable / non-transferrable air quality management strategies.

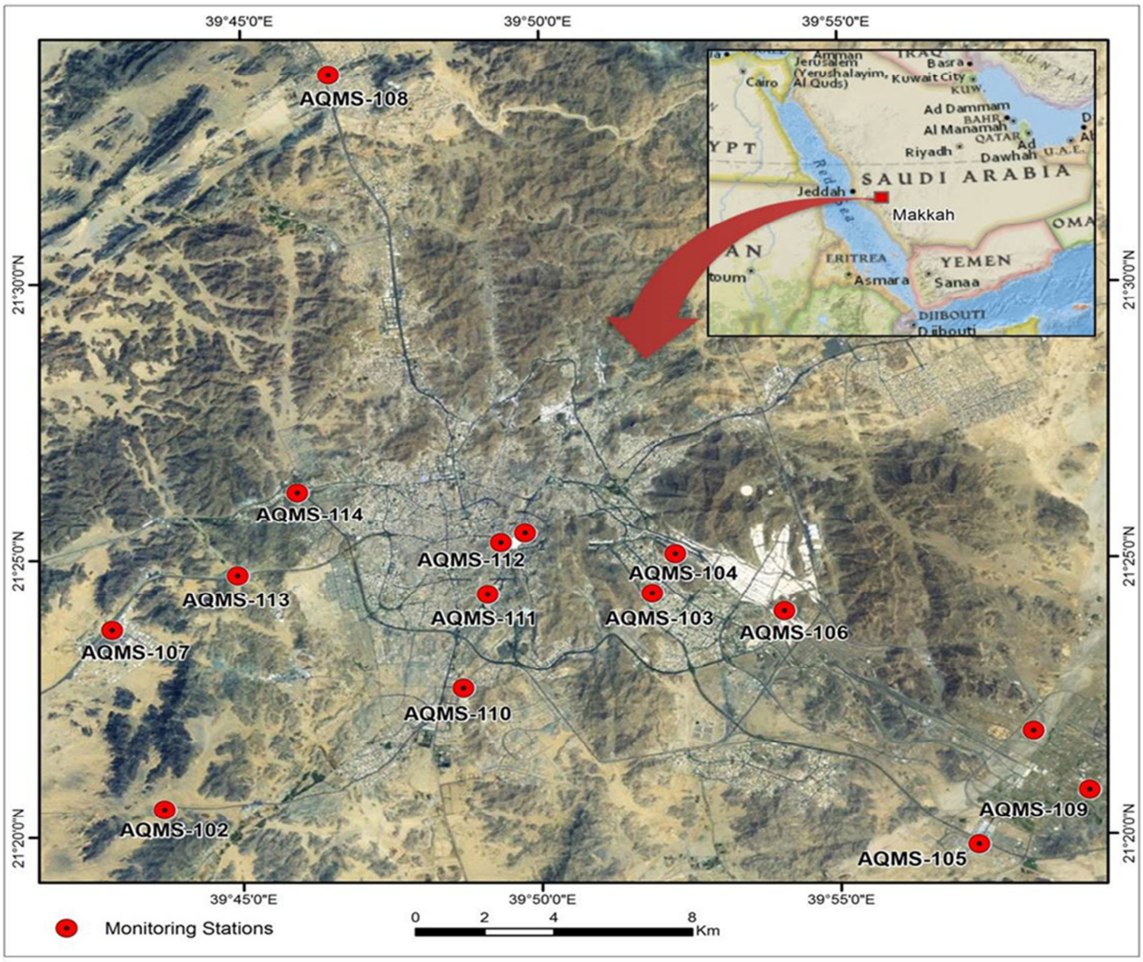


Fig. 1 Map of the air quality and meteorological monitoring sites in Makkah, where AQMS-112 is the PME site, where the data were collected and compared with Leeds centre air quality data for 2012

II. Material and Methods

In this paper the observed concentrations of several air pollutants, including Sulphur Dioxide (SO_2 μg/m^3), Carbon Monoxide (CO mg/m^3), Nitric Oxide (NO μg/m^3), Nitrogen Dioxide (NO_2μg/m^3), Particulate Matters with aerodynamic diameter of 10 μm or less (PM_{10} μg/m^3), and Ozone (O_3 μg/m^3) are compared between Leeds, UK and Makkah, Saudi Arabia. These are both urban background monitoring stations, which are described below.

A. Description of PME Site in Makkah

Fig. 1 shows the monitoring network in Makkah, run by the Custodian of the Two Holy Mosques Institute for Hajj and

Umrah Research, Umm Al-Qura University, Makkah. This is a continuous monitoring station and monitors several air pollutants, such as SO_2, CO, NO, NO_2, PM_{10}, O_3, Wind Speed (WS m/s), Wind Direction (WD degrees from the north), Temperature (T °C), and Relative Humidity (RH %). Data for 2012 are used in this paper. The monitoring site is situated inside the Holy Mosque, situated in the centre of Makkah. The monitoring site is an urban background site (Fig. 1).

B. Description of Leeds Centre Monitoring Site in Leeds

The location of the air quality monitoring site in Leeds is shown in Fig. 2. Leeds Centre is an urban background site, which monitors SO_2, CO, NO, NO_2, PM_{10}, O_3, Particulate Matters with aerodynamic diameter of 2.5 µm or less ($PM_{2.5}$ µg/m^3), 1-3, butadiene and benzene. The monitoring station is located within a self-contained, air-conditioned housing located approximately 30 metres from a busy 4 lane inner-city road (A660), which is subject to periodic congestion during peak periods. The monitoring site is approximately 150 metres from an urban motorway (A58M). The surrounding area is generally open and comprises a busy urban setting road network. For more details, see [13]. Statistical Software R programming language [14], with package openair version 2.13.2 [15] was used for statistical data analysis and graph plotting. Correlation analysis was applied to estimate the extent of the relationship between various air pollutant concentrations.

III. Results and Discussions

Correlation analysis was performed to investigate the association between various air pollutants. The correlation coefficients (R) between various air pollutants in Leeds and Makkah are shown in Table I. Generally the values of R were higher at Leeds than at Makkah, for instance: the R value between NO_2 and NO was +0.67 at Leeds and +0.61 at Makkah; between NO_2 and O_3 was -0.66 at Leeds and -0.39 at Makkah; between NO_2 and PM_{10} was +0.49 at Leeds and -0.07 at Makkah. However, NO_2 vs CO, NO vs CO and O_3 vs CO demonstrated higher R values at Makkah (as shown in Table I). It can be observed in Table I that PM_{10} showed considerably stronger association with other air pollutants in Leeds, for example PM_{10} showed R values of +0.49, +0.57, +0.44 with NO_2, NO and O_3, respectively at Leeds in contrast to -0.07, +0.06, and -0.12 for the same pollutants in Makkah. The association between PM_{10} and other air pollutants is positive and considerably stronger in Leeds, whereas in Makkah the association is weaker and even negative sometimes. This is probably due to the fact that in Leeds most of the PM is primary PM, emitted directly from the same sources (e.g. vehicles) as the gaseous pollutants. While in Makkah primary PM is a much smaller proportion of emissions and other sources such as re-suspension, wind-blow dust, and construction activities etc. most likely dominate [3], [10].

TABLE I
Correlation Coefficients (R) Between Different Air Pollutants At The PME Monitoring Station In Makkah And Leeds Centre Air Quality Monitoring Station In Leeds, UK.

Pollutants	Correlation Coefficients (R)	
	Leeds	Makkah
NO_2 vs NO	+0.67	+0.61
NO_2 vs O_3	-0.66	-0.39
NO_2 vs SO_2	+0.18	+0.13
NO_2 vs PM_{10}	+0.49	-0.07
NO_2 vs CO	+0.23	+0.71
NO vs O_3	-0.45	-0.37
NO vs SO_2	+0.11	+0.09
NO vs PM_{10}	+0.57	+0.06
NO vs CO	+0.31	+0.76
O_3 VS SO_2	-0.08	-0.07
O_3 vs PM_{10}	-0.44	-0.12
O_3 vs CO	-0.07	-0.30
SO_2 vs PM_{10}	+0.26	-0.10
SO_2 vs CO	+0.09	+0.07
PM_{10} vs CO	+0.28	-0.03

TABLE II
Levels of Different Air Pollutants at the PME and Leeds Centre Monitoring Sites In 2012

Air Pollutants	Metrics	Leeds	Makkah
NO_2	Minimum	0	0
	25th percentile	23	27
	Median	33	42
	Mean	36	46
	75th percentile	48	61
	Maximum	184	223
NO	Minimum	0	0
	25th percentile	5	2
	Median	10	5
	Mean	19	12
	75th percentile	20	13
	Maximum	630	299
O_3	Minimum	0	0
	25th percentile	20	29
	Median	40	61
	Mean	30	70
	75th percentile	56	98
	Maximum	156	311
CO	Minimum	0.12	0
	25th percentile	0.35	0.79
	Median	0.47	0.98
	Mean	0.51	1.12
	75th percentile	0.58	1.27
	Maximum	2.21	6.87
SO_2	Minimum	0	0
	25th percentile	0	5
	Median	3	8
	Mean	2	11
	75th percentile	3	15
	Maximum	162	125
PM_{10}	Minimum	0	0
	25th percentile	9	79
	Median	13	124
	Mean	17	180
	75th percentile	19	199
	Maximum	133	5761

In Table II the levels of various air pollutants measured at Leeds and Makkah are compared. Six metrics are calculated for each pollutant: Minimum, 25th percentile, median, mean, 75th percentile, and maximum. Air pollutants levels are significantly higher at Makkah than at Leeds, except NO. PM_{10} shows the highest difference between Leeds and Makkah. For PM_{10} the values for the considered metrics in Makkah were 0, 79, 124, 180, 199, and 5761, respectively, whereas at Leeds the values were 0, 9, 13, 17, 19, and 133, respectively. This is probably because Makkah is located in a hot arid region, where rarely any rainfall occurs and sand and dust storms frequently take place. Large scale construction activities and combustion sources make further contributions to suspended particulate matters in Makkah. Difference between the levels of CO and SO_2 in Makkah and Leeds is not very high, and in addition NO levels are higher in Leeds. This implies that probably the higher levels of PM in Makkah are not because of emission differences but due to meteorological and geographical characteristics.

In Table III correlation coefficients between the same air pollutants monitored at Leeds and Makkah at the same times are shown. Here the R values are very weak and close to zero. The highest R value was found for O_3, which was +0.14. The weak association between various pollutants at Makkah and Leeds probably shows that these two cities have totally different nature in terms of air pollutant emissions, meteorological conditions and geographical characteristics.

TABLE III
CORRELATION COEFFICIENTS BETWEEN THE PME MONITORING SITE MAKKAH AND LEEDS CENTRE.

Pollutants	Correlation Coefficients (R)
NO_2_Leeds vs NO_2_Makkah	-0.08
NO_Leeds vs NO_Makkah	+0.04
O_3_Leeds vs O_3_Makkah	+0.14
CO_Leeds vs CO_Makkah	-0.02
SO_2_Leeds vs SO_2_Makkah	-0.04
PM_{10}_Leeds vs PM_{10}_Makkah	+0.04

In Figs. 3-8, the plots compare the time variations of various air pollutants in Makkah and Leeds during 2012. Time variation plots are important for comparing the daily, weekly and annual cycles of various air pollutants. It is confirmed again that the levels of most of the air pollutants are higher in Makkah than in Leeds, however they have different temporal trends. The differences in temporal trends of air pollutants are probably because of meteorological conditions which are totally different in the two cities, geographical characteristics, and pollutants emission, which is mainly dependent on road traffic. Weekend has a significant effect on the weekly cycles of air pollutants. In the UK and Saudi Arabia we have weekend on different days. In the UK the weekend is on Saturday and Sunday, whereas in Saudi Arabia in 2012 the weekend was on Thursday and Friday, however it was changed to Friday and Saturday in 2013. Due to weekend effect NO and NO_2 show the lowest levels on Friday in Makkah and on Sunday in Leeds. In contrast, O_3 which is negatively correlated with NO_x demonstrates highest concentration on Friday in Makkah and on Sunday in Leeds. This is because on weekend low road traffics result in lower level of freshly emitted NO, which means less O_3 depletion. In the annual cycle O_3 levels are highest in September in Makkah and in May in Leeds. This is explained in detailed by [5]-[7], [16]-[17].

In Fig. 8 (a) time variations of PM_{10} are depicted in Makkah and Leeds, however the difference in the levels of PM_{10} between the two cities is so large that PM_{10}-Leeds looks like a straight line and we cannot observe the variations in Leeds PM_{10}. Therefore in Fig. 8 (b) we have plotted the normalised levels of PM_{10} both in Leeds and Makkah. To get normalised levels the observed levels are divided by the mean. Plotting normalised levels is important when we compare two or more pollutants which are not on the same scale and we want to see only the trend. PM_{10}-Makkah shows two peak values in the diurnal cycle, first in the morning (about 08:00 – 09:00 hour) and second in the evening (about 16:00 – 18:00 hour), whereas PM_{10}-Leeds shows first peak in the morning (about 08:00 – 09:00 hour) and second peak in the mid-night (about 23:00 – 00:00 hour). Furthermore, lowest level of PM_{10}-Leeds can be observed on Sunday and that of PM_{10}-Makkah on Friday, probably due to weekend effect. Similarly, considerable variability in the annual cycle of PM_{10} can be observed in the two cities. The interesting observation here is that most of the other pollutants in Makkah like NO, NO_2, SO_2, and CO demonstrate relative lower levels in the late afternoon (about 15:00 to 18:00 hour), however PM_{10} demonstrate the opposite trend i.e. highest levels are found during this time of the day. This probably shows that the peak in PM_{10} levels is not mostly related to road traffic or other combustion related emissions which tend to be associated with peak human activity times, and rather is caused by meteorological parameters, especially wind speed which increases re-suspension and wind-blown dust-and-sand.

Diurnal cycles of PM_{10} and wind speed in Makkah are shown in Fig. 9, which nicely depicts the positive association between the two variables.

IV. CONCLUSIONS

Different approaches are used to analyse air pollutant levels with a view to better understand the temporal variability and determine the factors responsible for high levels of air pollutants. Comparison of spatially and temporally segregated air pollutants is one of the approaches, which is used here to better understand the sources of air pollutants in Makkah. The comparison has provided a great insight into the behaviour and temporal variability of various air pollutants both in Makkah and Leeds. Particularly, temporal variation of PM_{10} concentrations and its correlation analysis with other air pollutants demonstrated that most of the PM_{10} in Makkah is most likely not emitted directly by combustion sources, such as road traffic and rather comes from re-suspension and wind-blown dust and sand particles.

Fig. 2 The location of the air quality monitoring site in Leeds, where the data were collected and compared with the PME air quality data from Makkah for 2012

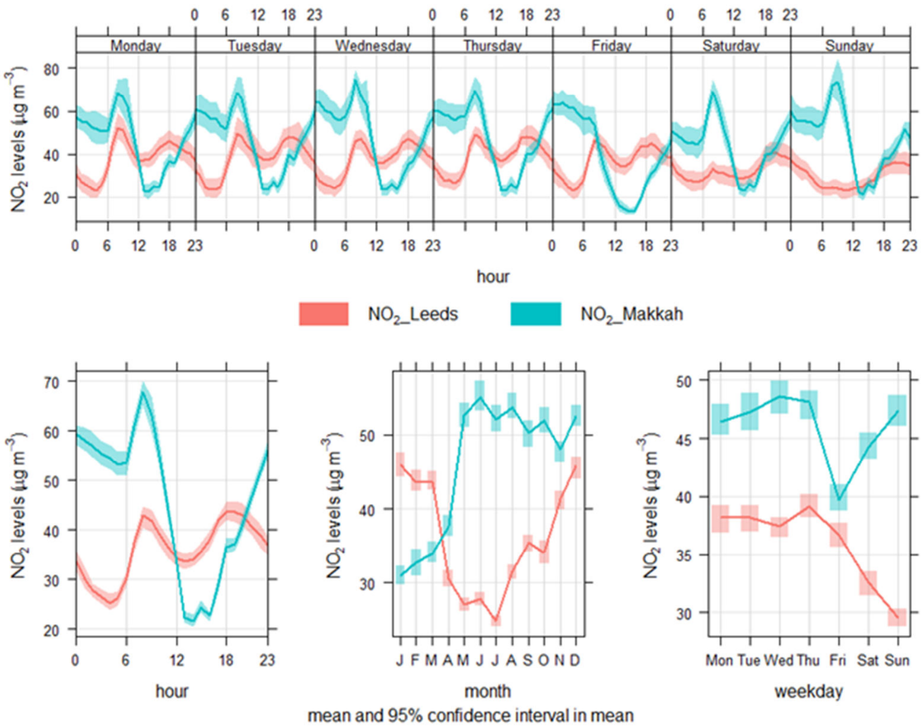


Fig. 3 Time variation plots of NO_2 concentrations (μg/m^3) in Makkah and Leeds for 2012

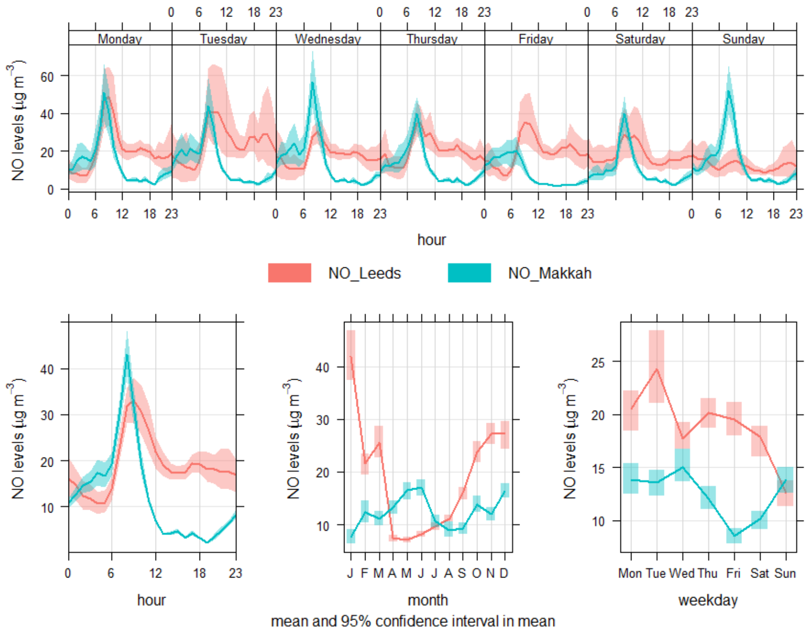


Fig. 4 Time variation plots of NO concentrations (µg/m3) in Makkah and Leeds for 2012

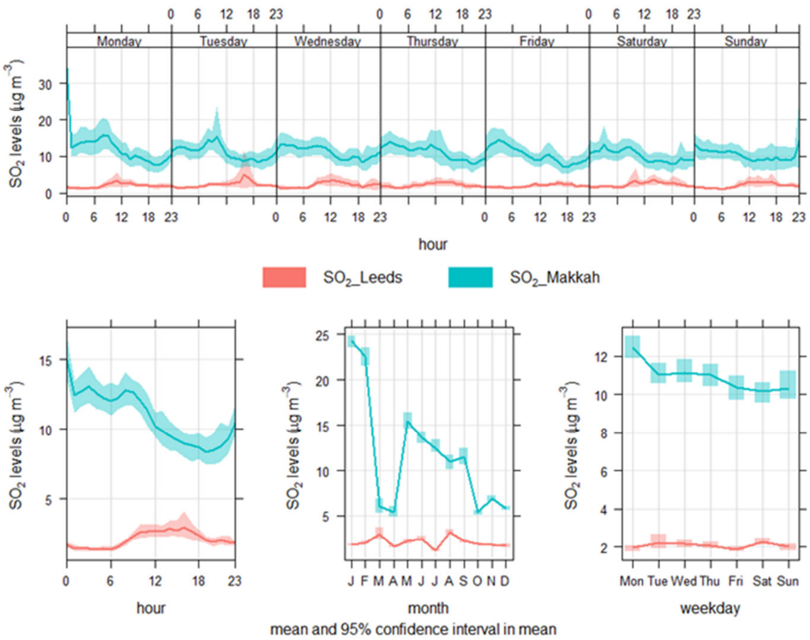


Fig. 5 Time variation plots of SO2 concentrations (µg/m3) in Makkah and Leeds for 2012

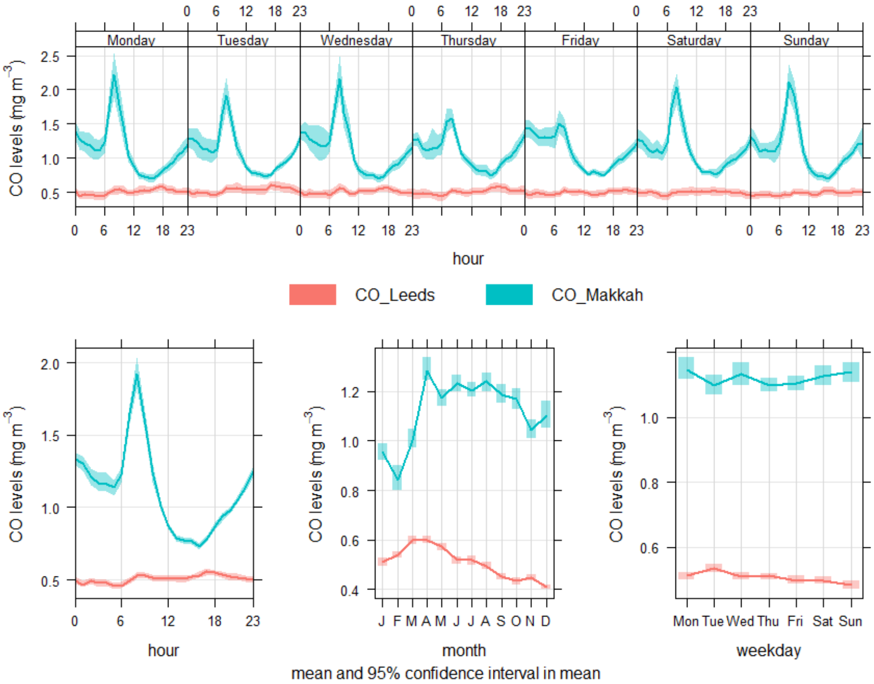


Fig. 6 Time variation plots of CO concentrations (mg/m3) in Makkah and Leeds for 2012

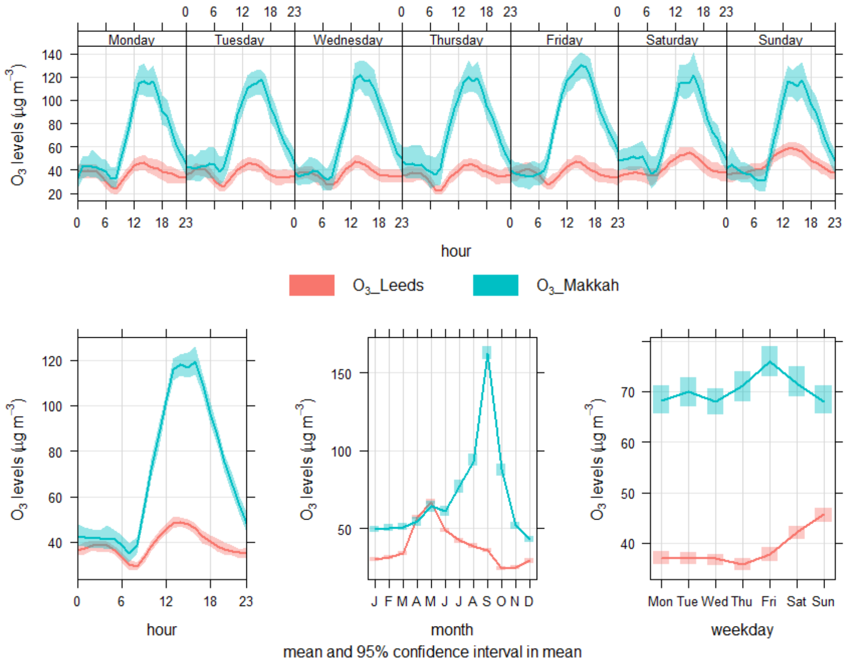
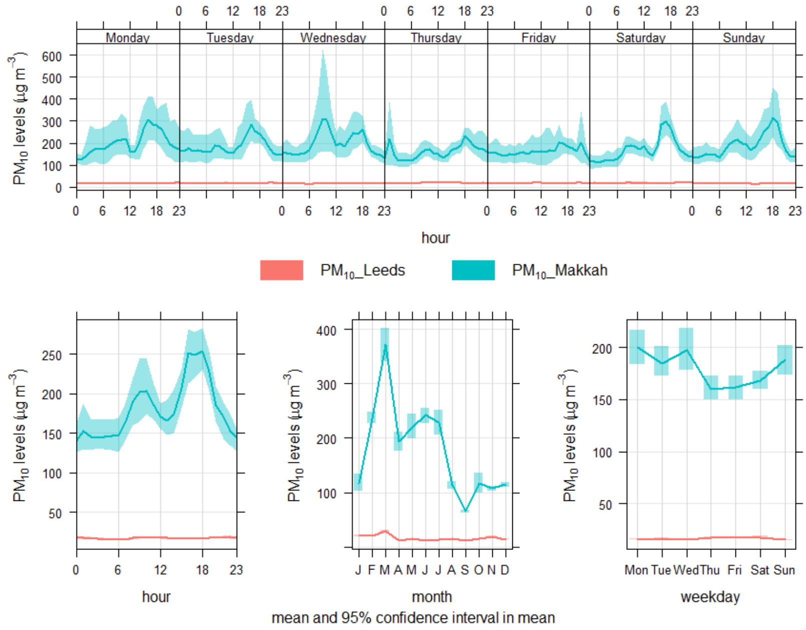
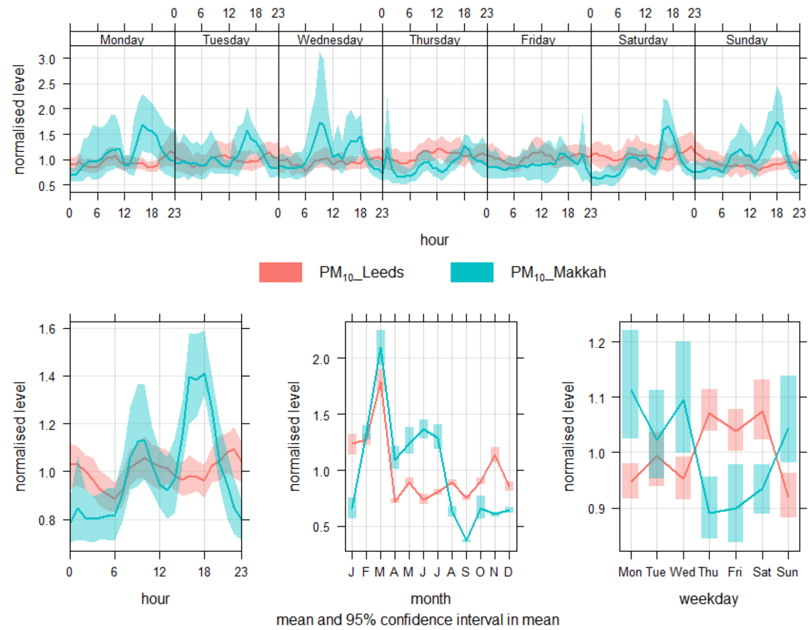


Fig. 7 Time variation plots of O_3 concentrations ($\mu g/m^3$) in Makkah and Leeds for 2012



(a) Observed levels of PM_{10}



(b) Normalised levels of PM_{10}

Fig. 8 Time variation plots of PM10 concentrations (μg/m3) in Makkah and Leeds for 2012: (a) Observed levels; (b) normalised levels. To obtain normalise levels; the observed values of PM10 are divided by the mean

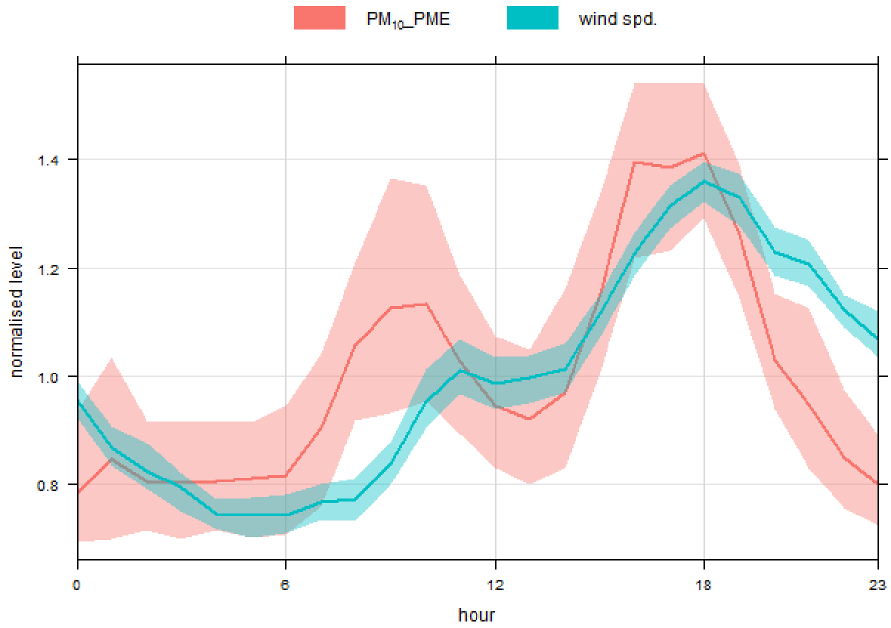


Fig. 9 Daily cycle of PM10 and wind speed at Makkah: The data presented are normalised (divided by the mean)

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