Mohtar *et al. Geosci. Lett.* (2018) 5:21
https://doi.org/10.1186/s40562-018-0122-y

Geoscience Letters

RESEARCH LETTER

Open Access

Variation of major air pollutants in different seasonal conditions in an urban environment in Malaysia

Anis Asma Ahmad Mohtar[1], Mohd Talib Latif[1*], Nor Hafizah Baharudin[1], Fatimah Ahamad[2], Jing Xiang Chung[1], Murnira Othman[1] and Liew Juneng[1]

Abstract

Urban air quality has been deteriorating over time. Pollutant distribution levels in the urban environment may be associated with anthropogenic sources and meteorological conditions. The aim of this study is to determine the variation in concentrations of major air pollutants: carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and particulate matter (PM_{10}), with corresponding seasonal variation in a Malaysian urban environment. Eleven years of data from four selected stations, namely Klang (S1), Petaling Jaya (S2), Shah Alam (S3) and Cheras (S4), were analysed for temporal trend variations (yearly and monthly). Statistical analysis using Openair, an R package open source software, has been conducted to assess pollutants in relation to meteorological conditions. Gas concentrations showed little variation between the study sites apart from NO_2, which recorded its highest concentrations at an industrial site, between 23 and 40 ppb, and is associated with industrial and vehicle emissions. Pollutants that show seasonal variations and frequently exceed the Malaysia Ambient Air Quality Standard (MAAQS) and the National Ambient Air Quality Standard (NAAQS) are O_3 and PM_{10}, predominantly related to the monsoon seasons. High levels of O_3 during the northeast monsoon (January–March) are associated with high levels of the precursors of O_3. The concentration of PM_{10} associated with tropical biomass burning during southwest monsoon. Shipping emissions and power stations are main contributors for higher level of SO_2. This study shows regional and local factors contribute to the different type of air pollutant concentrations in urban environment.

Keywords: Major air pollutants, Urban environment, Air-quality trends, Seasonal variations

Background

The urban environment experiences high levels of air pollutants in almost all parts of the world. Urban air quality is different in different areas and cities, where the contribution of local sources such as anthropogenic emissions is among the contributing factors (Jang et al. 2017; Nerriere et al. 2005). Large emissions of nitrogen oxides (NO_x), carbon monoxide (CO) and volatile organic compounds (VOCs) in the urban atmosphere cause high levels of precursors and reactants, with correspondingly large chemical turnover rates (Monks et al. 2009). According to Fenger (1999), in some cities, increased traffic has produced high emissions of NO_x, organic compounds and particles, where photochemical air pollution is a significant problem.

Meteorological factors are key subjects to be studied to understand the variation in air pollutant concentrations and distributions (Wang et al. 2006). Meteorological driving factors are associated with diurnal concentrations of air pollutants, and also influence aerosol composition (Amil et al. 2016; Khan et al. 2016). Variation and trends of pollutants such as NO_x, particulates with diameters less than 10 μm (PM_{10}) and sulphur dioxide (SO_2) are influenced by land cover and various economies, demographics, and meteorological variables (Rodríguez et al. 2016). A study by Wan

*Correspondence: talib@ukm.edu.my
[1] School of Environmental and Natural Resource Sciences, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
Full list of author information is available at the end of the article

Mahiyuddin et al. (2013) in Klang Valley, Malaysia, found that there was a relationship between air pollutants and meteorological factors (temperature, rainfall, relative humidity), where the highest significant correlation was between ozone (O_3) and temperature. Monsoonal winds are also important when investigating the monsoonal effect on atmospheric pollutants, especially for a tropical country such as Malaysia. According to Malaysian Meteorological Department (2017), there are two monsoon seasons in Malaysia, known as the southwest monsoon (June–September) and the northeast monsoon (November–March). Malaysia also experiences transitional wind periods known as inter-monsoons from April to May and October to November.

This study aims to determine the long-term variation in concentrations of major air pollutants along with corresponding seasonal variation at selected air-quality monitoring stations in an urban environment in Malaysia. The analysed pollutants were CO, O_3, nitrogen dioxide (NO_2), SO_2 and PM_{10}, using data from an 11-year period to assess the pollutant trends, seasonal effects and exceedance levels at each site. The statistical software Openair R version 3.3.1 (Carslaw and Ropkins 2012) was used to conduct a supplementary analysis to assess concentration distributions in relation to meteorological factors. The results from the analysis are then further discussed in relation to the contribution of local sources to the atmospheric pollutant levels at all study sites.

Methods

Study location

Four continuous air-quality monitoring stations were selected for this study (Fig. 1a, b). Klang (S1), Petaling Jaya (S2), Shah Alam (S3) and Cheras (S4) are located in the Klang Valley, Peninsular Malaysia. The Klang Valley is known as the heartland of Malaysia's industry and commerce, and encompasses Kuala Lumpur, its suburban areas, and adjoining cities and towns. The Klang (S1) and Shah Alam (S3) stations lie in the central region of the Klang Valley. The Klang station (S1) is in the most industrialised area with a congested main road, near to a busy port and power plant (Fig. 1c). The Shah Alam station (S3) is located in a residential and commercial area surrounded by extremely busy motorways. The Petaling Jaya (S2) and Cheras (S4) stations are near to industrial, residential and commercial areas and consequently, congested roads. All stations are also close to the major road to Kuala Lumpur and this is affected by heavy traffic, particularly during the morning rush hour.

Data collection

Hourly long-term datasets over a period of 11 years from 1st January 2005 to the 31st December 2015 were used

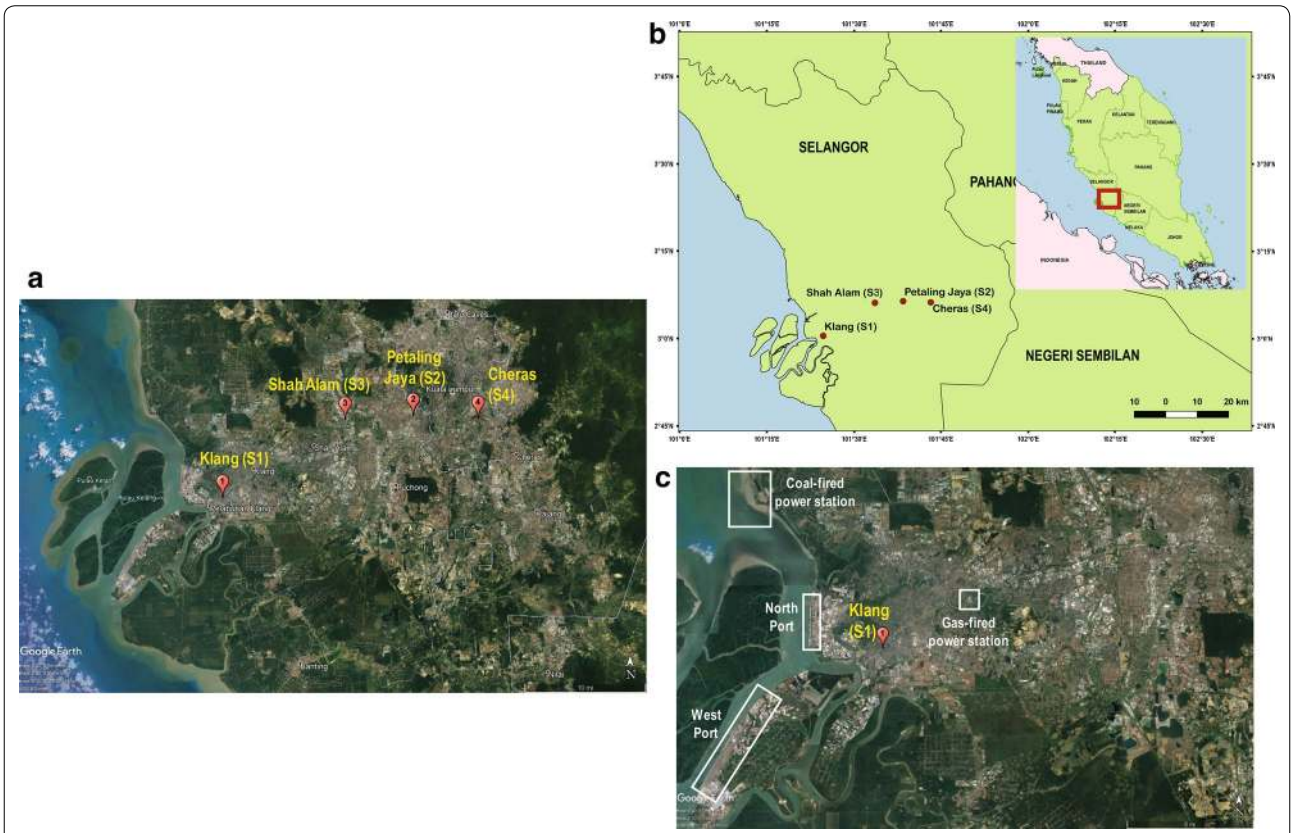

Fig. 1 **a** Station location of four selected continuous air monitoring stations in urban environment **b** Location of selected station situated in Peninsular Malaysia **c** The white boxes in the figure indicate industrial areas surrounding Klang Station

in this study for all stations. Air-quality data along with meteorological data in this study were retrieved from the Malaysian Department of Environment through continuous air monitoring by a private company Alam Sekitar Sdn. Bhd. (ASMA) who were also responsible for calibrating the equipment. Air pollutant parameters used in this study are CO (ppm), NO_2 (ppb), SO_2 (ppb), O_3 (ppb) and PM_{10} ($\mu g/m^3$). In addition, the local meteorological parameters used in this study such as wind speed (km/h) and wind direction were also recorded at the stations.

Data analysis

Time series data of air pollutants at the stations were analysed to study the spatial and temporal variation of air pollutants at four study locations. To study the trend of air pollutants for the study period, monthly mean values were calculated by averaging hourly concentration measurements. The data were smoothed using Locally Weighted Scatterplot Smoothing (LOESS). This method was used to visually examine the non-linearity of trends (Jang et al. 2017). Annual mean concentrations were calculated by averaging hourly values of each year and normalised to the mean concentration of 2005 to investigate the long-term pollution trend.

Daily maximum concentration of pollutants with respect to averaging hour of the Malaysian Ambient Air Quality Standard (MAAQS) and the National Ambient Air Quality Standard (NAAQS) of the United States Environmental Protection Agency (USEPA) were calculated and plotted to study the exceedance level of pollutants during the study period. Running average data for O_3 were 8 h and PM_{10} were 24 h while CO, NO_2 and SO_2 were 1 h. The running times for different air pollutants were based on averaging times suggested by MAAQS and NAAQS of USEPA. In addition, wind speed, wind direction and air pollutant data were computed and analysed using statistical software Openair, R package version 3.3.1 (Carslaw 2015) which can be downloaded free from the website http://www.openair-project.org/.

Results and discussion

Trends and spatial variability in urban environment

The plots in Fig. 2a–e show the monthly mean concentrations of air pollutants and the estimated trend for the 11 years from January 2005 to December 2015. Figure 2f–j shows the normalised annual mean of air pollutants with respect to annual mean value of 2005 to estimate the annual trend. Higher concentrations of CO can be seen at S2 which has an industrial background compared to the other three urban background sites (Fig. 2a) but CO levels for S2 declined from 2007 onwards. All stations experienced the same pattern in CO in the second half of the 2015 due to biomass burning during September and October, leading to a severe haze episode in Malaysia (Field et al. 2016; Shannon et al. 2016; Tacconi 2016). S2 had high concentrations of CO, likely to be due to the incomplete combustion of fossil fuel from industrial sectors (Khan et al. 2015). The normalised plot in Fig. 2f indicates that CO annual levels for S2, S3 and S4 were not significantly different from each other; however, S1 experienced a drop in CO from 2012 to 2015 with values of 1.21–0.89 ppm. The reduction of yearly CO concentrations is mostly due to the reduction of regional biomass-burning occurrences after 2007. Other than motor vehicles and industrial activities, incomplete combustion of biomass contributes to high amounts of CO as well as particulate matter (Latif et al. 2018).

Monthly mean concentrations for O_3 showed (Fig. 2b) almost the same pattern for all stations, where S3 showed the highest concentrations until 2010 when this changed to S4. S3 and S4 recorded high concentrations of O_3 because these stations had low NO levels, meaning the interaction between NO and O_3 via the titration process was less, thus leaving the O_3 level higher compared to S1 and S2. S1 and S2 are located in the city centre in busy locations, leading to higher levels of NO that can titrate O_3 and, therefore, reduce the concentration (Banan et al. 2013; Latif et al. 2012; Wang et al. 2017). In general, the O_3 pattern for all stations showed an increase over the 11-year time period, despite slight decreases. As seen in Fig. 2g, S1 showed a significant decrease in O_3 from 2009 to 2013 (20.27–17.21 ppb) which may be due to its geographic location as S1 is close to the shipping port and main roads. Increase in traffic and shipping activities over a decade is expected to result in increasing NO concentrations and subsequent decreasing O_3 trends due to the ability of NO to titrate O_3 (Song et al. 2010). Continuous higher concentrations of NO have decreased the long-term concentrations of O_3 in this area.

The NO_2 concentrations presented marked spatial variability for S2 as shown in Fig. 2c and Additional file 1. This site with an industrial background showed higher concentrations of NO_2 compared to urban sites of S1, S3 and S4. S2 is an industrial site and there are residential areas near S2 that may increase the NO_2 levels coming from both industrial emissions and residential areas with high vehicle use. According to Dominick et al. (2012), NO_2 levels recorded in industrial and urban environments are high because of the burning of fossil fuels. Based on Fig. 2a, c, the distribution of CO and NO_2 among the study sites was almost the same, with S2 taking the lead in the concentrations of pollutants. Both CO and NO_2 are primary pollutants that are mainly emitted from motor vehicles (Azmi et al. 2010; Dor et al. 1995; Mayer 1999; Morawska et al. 2002). Normalised annual

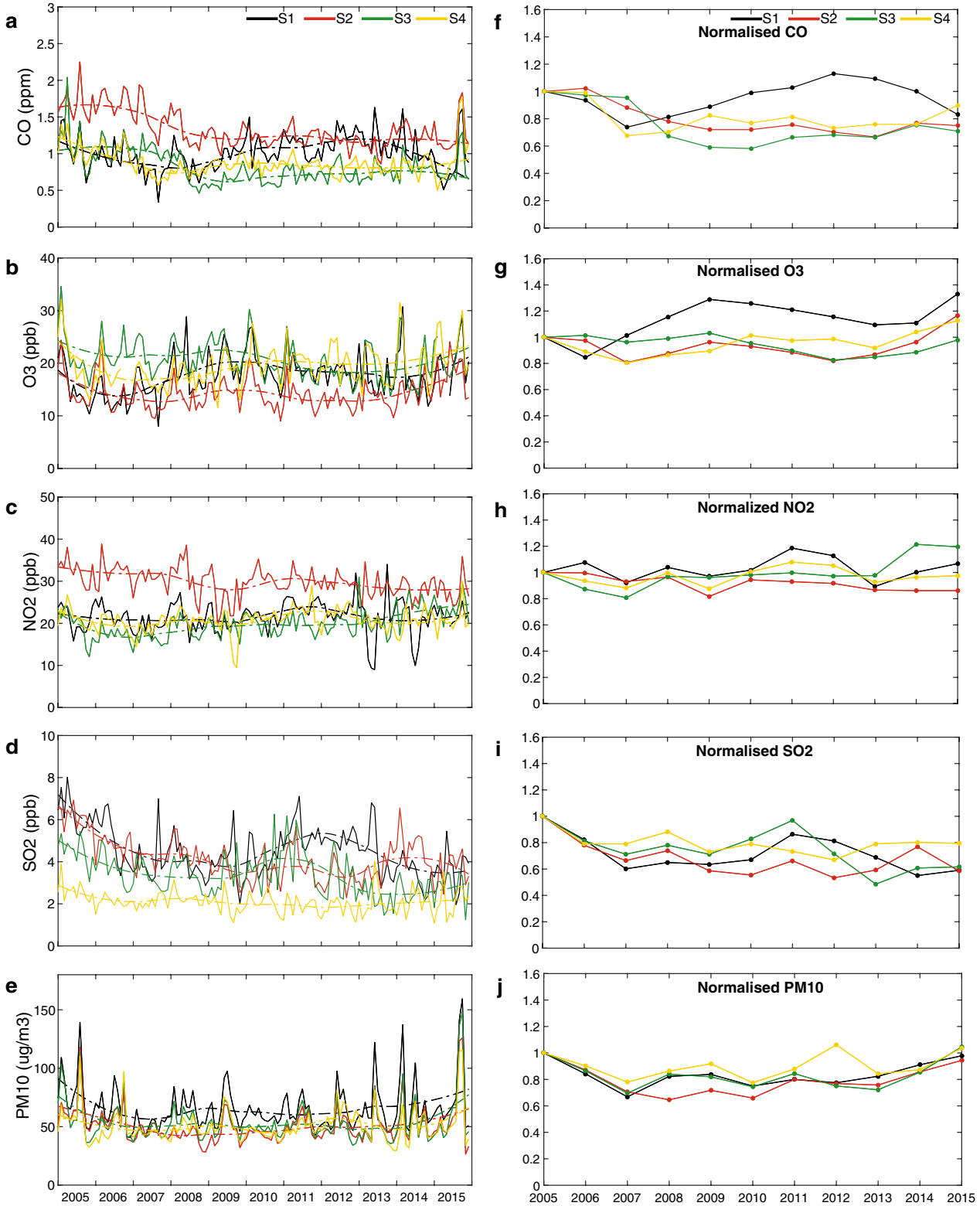

Fig. 2 Monthly mean concentrations with smoothing lines indicate trend of **a** CO **b** O_3 **c** NO_2 **d** SO_2 **e** PM_{10} between 2005 and 2015 and annual trend of **f** CO **g** O_3 **h** NO_2 **i** SO_2 **j** PM_{10} concentration normalised to annual mean of 2005

concentrations in Fig. 2h showed no significant long-term trends in NO_2 levels for all sites.

The long-term trends of SO_2 at S1 and S3 have similar patterns (Fig. 2d, i) with decreased SO_2 levels until 2007 before it continued to elevate until 2011. S2 showed similar patterns and concentrations to S1 and S3 as they are located near each other. Emissions from shipping are the reason why S1 had high SO_2 concentrations because the station is near to a shipping port. However, normalised plots for SO_2 (Fig. 2i) indicated that in general, all stations experienced decreased SO_2 level from 2005 to 2015. Overall, the reduction of SO_2 is due to the reduction of sulphur content in petrol and diesel as indicated by other similar research (Blumberg et al. 2003; Guarieiro and Guarieiro 2013; Lamarque et al. 2010). The fluctuations of SO_2 in the study area may due to the contributions of SO_2 from local and regional sources of biomass burning.

Interestingly, all stations displayed the same pattern with almost the same peak and monthly mean for PM_{10} concentrations (Fig. 2e). This is because when the west coast of Peninsular Malaysia encounters transboundary haze pollution episodes, all those stations will be affected as they are located in the central region of the west coast (Awang et al. 2000; Azmi et al. 2010; Hyer and Chew 2010; Juneng et al. 2009; Khan et al. 2015; Lin et al. 2009). PM_{10} is the main parameter during haze and is decisive in the calculation of the Malaysian Air Pollution Index (Afroz et al. 2003). During haze episode, the smoke from Sumatra will travel to the Peninsular Malaysia. In most cases, all the stations located on the west coast of Peninsular Malaysia have similar patterns of PM_{10} concentration during the haze episode based on the intensity of the smoke and wind direction. The haze peak can be seen in almost every year except 2007 and 2010. In 2007 and 2010, there were no regional biomass-burning episodes to contribute to the high concentration of PM_{10}. In addition to that, an article by Latif et al. (2018) showed that 2007 and 2010 were non-El Niño years and so lower concentrations of PM_{10} were recorded at the study sites. The monthly concentrations were highest in 2015 and followed by 2005 because in these years there were El Niño events that triggered the haze with dry conditions, thus prolonging the drought and intensifying forest fires (Aouizerats et al. 2015; Field et al. 2016; Shannon et al. 2016; Tangang et al. 2010). The intensity of combustion and haze episodes was influenced by dry weather conditions. A strong El Niño event influences regional wind circulation and causes prolonged dry conditions in Southeast Asia. The dry conditions lead to severe haze episodes, particularly due to combustion activities and especially within peat soil areas (Reid et al. 2012). The annual mean concentrations of PM_{10} (Additional file 1) reveal fluctuations over the years with peaks that correspond to haze and El Niño events. S4 showed a sudden increase in 2012 (Fig. 2j) that might be due to emissions from local sources such as open burning and land use changes near the site that contributed to the PM_{10} level (Khan et al. 2015).

The annual mean concentrations of each pollutant from 2005 to 2015 are summarised in Additional file 1. In general, averages of the annual means from 2005 to 2015 showed that S2 recorded the highest concentration of CO (1.34 ppm) compared to S1 (1.02 ppm), S4 (0.88 ppm) and S3 (0.82 ppm). This is likely to be because S2 is located in an industrial area with high traffic emissions. Average annual concentrations of O_3 indicated that S3 experienced high levels with 20.61 ppb, followed by S4 (19.60 ppb), S1 (17.81 ppb) and S2 (14.32 ppb). For NO_2, S2 as the industrial site revealed the highest average during the study period, followed by S1, S4 and S3 with concentrations of NO_2 of 29.86 ppb, 21.43 ppb, 20.74 ppb and 19.80 ppb, respectively. In addition, S1 revealed the highest average annual mean of SO_2 with 4.48 ppb, followed by S2 (4.16 ppb), S3 (3.38 ppb), and S4 (2.10 ppb). S1 recorded high concentrations as the location of S1 is near to the shipping port, where emissions of SO_2 and NO_2 are high. For PM_{10}, S1 had the highest average annual mean concentration with 65.86 μg/m^3 followed by S3 (53.76 μg/m^3), S2 (50.89 μg/m^3) and last S4 (50.75 μg/m^3).

Exceedance levels of air pollutants

Figure 3 shows the daily maximum concentration of trace species from 2005 until 2015 with respect to their averaging time. The averaging time for exceedance levels for CO, NO_2 and SO_2 was 1 h, for O_3 it was 8 h and for PM_{10} 24 h. The exceedance levels of pollutants were compared with the NAAQS and the MAAQS which can be seen in Additional file 2. In general, there were two pollutants (O_3 and PM_{10}) that abundantly exceeded both NAAQS and MAAQS (Fig. 3b, e).

The exceedance level recorded for O_3 (Fig. 3b) was quite high in number for all four stations in every year, especially during the first quarter of the year. The concentrations of O_3 for the 8 h average exceeded both the NAAQS (70 ppb) and the MAAQS (60 ppb). The number of O_3 exceedance events around Klang Valley can be seen from a study by Ahamad et al. (2014), where it was concluded that O_3 exceedance patterns were greatly influenced by localised pollutant emissions. According to a study by Latif et al. (2012), S1 located near the sea and the shipping port may be influenced by sea breezes causing the dispersion of pollutants. In addition to that, S3 and S4 had high O_3 concentrations due to local conditions while S2 had the lowest exceedance due to the titration process of O_3 by NO.

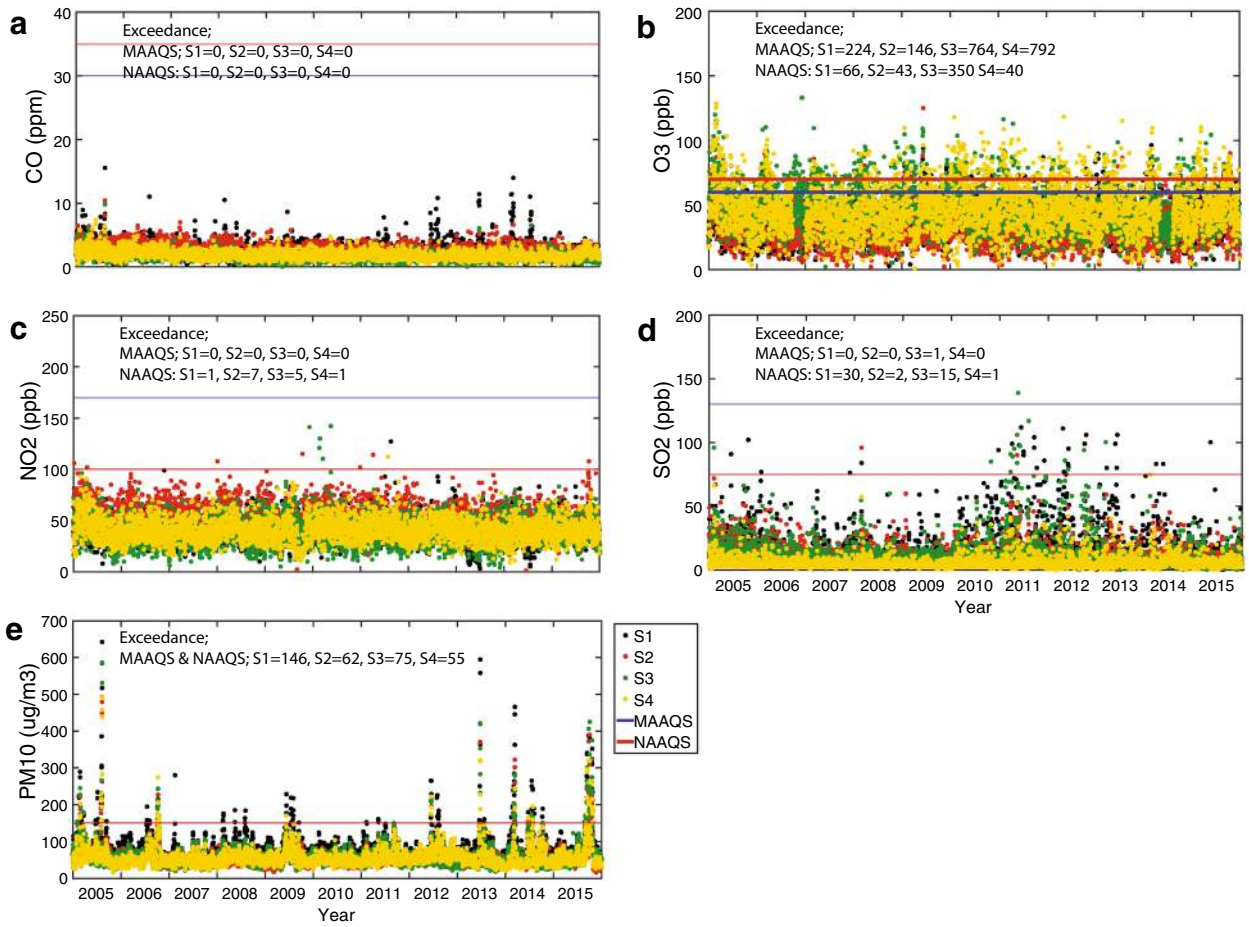

Fig. 3 Daily exceedance level of air pollutants (**a** CO **b** O_3 **c** NO_2 **d** SO_2 **e** PM_{10}) between 2005 and 2015 with respect to averaging time according to Malaysia Ambient Air Quality Standard (MAAQS) and USEPA National Ambient Air Quality Standard (NAAQS). The total occurrence of daily exceedance is stated in the figure for 2005–2015

Both the NAAQS and the MAAQS for PM_{10} are 150 μg/m^3. As shown in Fig. 3e, the exceedance level of PM_{10} can be seen for almost every year except in 2007 and 2010 for all stations. The highest exceedance level recorded for PM_{10} was in mid-2005 and mid-2013 (less than 700 μg/m^3) at S1. In addition to that, there were episodes where PM_{10} levels were high for several days to weeks, for example, in 2005, 2006, 2008, 2009, 2012, 2014 and 2015. A study by Rahman et al. (2015) stated that S1 had the highest number of exceedance events compared to S2, S3 and S4, and these were related to severe haze episodes that transported suspended particulates from Sumatra to the west coast of Peninsular Malaysia.

Monthly variation of air pollutants

Daily mean concentrations of air pollutants were calculated using data measurements from January 2005 to December 2015. Monthly variations shown in Fig. 4 are presented as the number of days from January 1 with a total of 365 data points. Daily mean concentrations for CO (Fig. 4a) were almost consistent throughout the months for S1, S3 and S4 but not for S2, which had slightly higher CO levels but with the same pattern concentration distribution. The highest CO concentrations were recorded at S2 with the range of between 1.0 and 2.0 ppm during the northeast monsoon (November–March), while during the southwest monsoon (June–September), CO concentrations were recorded between 1.0 and 1.6 ppm. The CO monthly trend showed less seasonal influence compared to other pollutants. Emissions from motor vehicles dominated the source of CO compared to other potential sources including biomass burning and industrial activities (Streets et al. 2003; Zhang et al. 2009).

The O_3 concentrations clearly showed the monsoonal effect on O_3 distributions (Fig. 4b). Higher O_3 levels presented from January to March while the lowest O_3 levels were in July to August. A study by Latif et al.

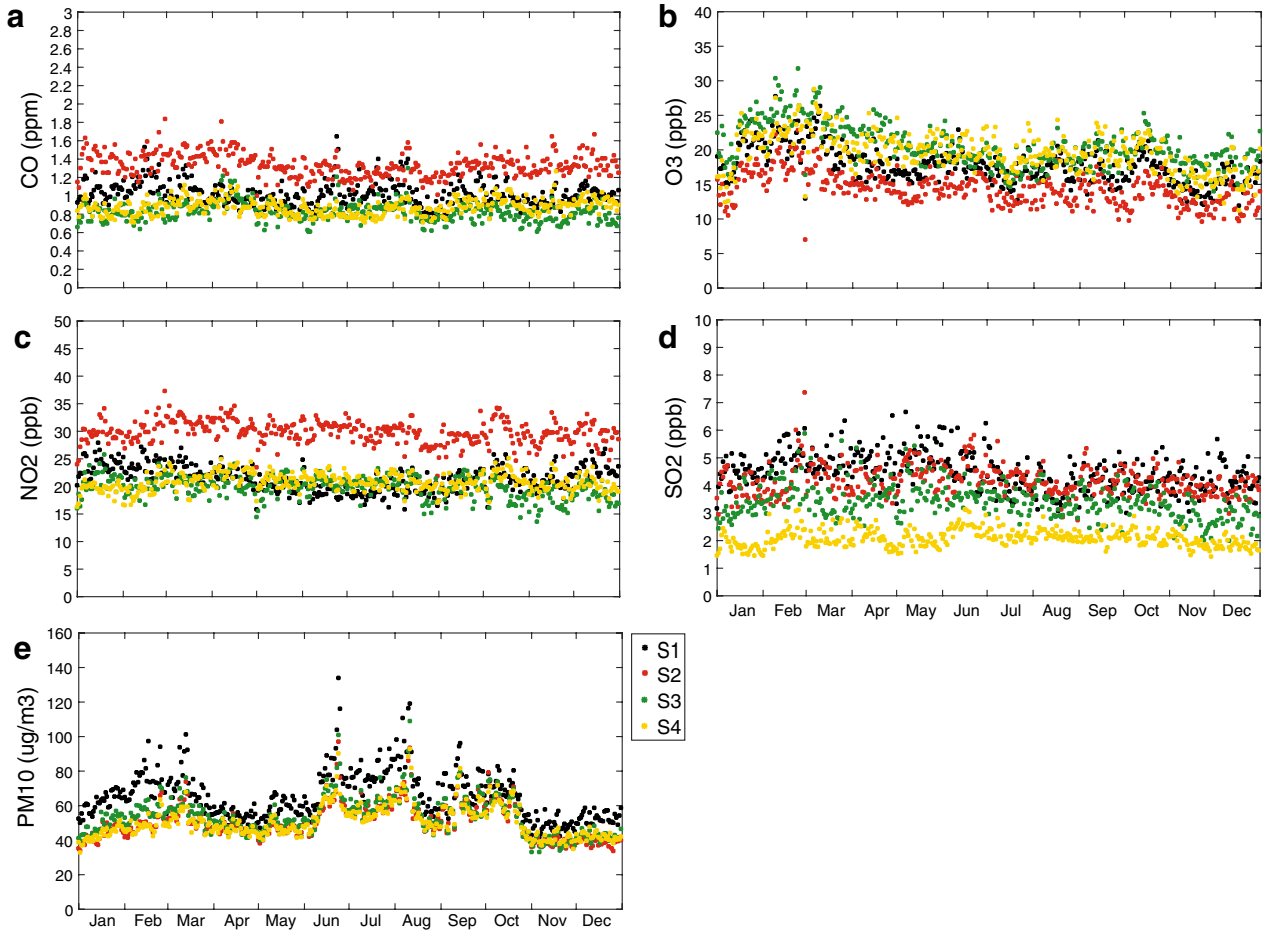

Fig. 4 Monthly variability of daily mean concentration for **a** CO **b** O_3 **c** NO_2 **d** SO_2 **e** PM_{10} concentration from 2005 to 2015

(2012) showed the same result as this study, where O_3 concentrations were high between January and April as the winter monsoon brings pollutants from the area to the northeast of the Malaysian Peninsula including Indochina and the South China Sea. In addition to that, Yonemura et al. (2002) stated that the enhancement of O_3 during December–February in the middle troposphere probably originates from the deep convection of air masses because of the positive temperature anomaly with a negative water vapour anomaly. According to Yamaji et al. (2006), low production of O_3 during the summer monsoon is probably associated with the incursion of monsoon oceanic air carrying less O_3 to the region. Other than that, precipitation will have a washout effect towards pollutants in the air and thus reduce the level of pollutants in the atmosphere (Yoo et al. 2014). However, according to Rahman et al. (2015), high levels of pollutants during this season may not be associated with meteorological factors but are more associated with local environmental factors, for example, emissions from industries, urbanization and motor vehicles.

Figure 4c shows the monthly variation of NO_2 concentrations and the trend is similar to that of CO (Fig. 4a). The industrial site S2 recorded high concentrations of NO_2 in all months but with a consistent trend, and a similar trend was recorded for S1, S3 and S4. The NO_2 concentrations recorded at S2 during the northeast monsoon (November–March) were between 23 and 40 ppb, while during the southwest monsoon (June–September), NO_2 concentrations were recorded between 20 and 35 ppb. Industrial emissions and urban road traffic are the main contributors to the higher concentrations of NO_2 at S2 compared to the other sites. Other than that, the distribution of monthly SO_2 concentrations (Fig. 4d) was scattered and had large ranges even in the same month and same monsoon period. Only S4 exhibited consistent concentrations that did not differ much across the months. The higher ranges of SO_2 recorded at S1, S2 and S3 are due to their locations near to potential sources such as a

shipping port, a coal-fired power plant (S1) and industrial activities (S1, S2, S3). S4 is located in a residential area which is only influenced by motor vehicles as SO_2 contributors. The main sources of SO_2 are from burning of fossil fuel at power plants and industrial facilities (Butler and Whelan 2018; Pereira et al. 2007; Streets and Waldhoff 2000). Based on the Fig. 4c, d, the concentrations of NO_2 and SO_2 showed less monsoonal effects compared to other pollutants (O_3 and PM_{10}).

The monsoonal effect can easily be detected for PM_{10} distributions as all stations revealed the same patterns, with the highest concentrations at S1 followed by S3, S2 and S4 (Fig. 4e). The peak PM_{10} levels can be seen in February, March, June, August, September and October. In addition to that, peak PM_{10} levels were high mostly during June–September, which is during the southwest monsoon (Aouizerats et al. 2015; Heil and Goldammer 2001; Keywood et al. 2003; Khan et al. 2015; Kusumaningtyas and Aldrian 2016; Noor et al. 2015; Rahman et al. 2015; Shannon et al. 2016; Tangang et al. 2010), where low-level winds were associated with long-range transportation of pollutants (Khan et al. 2015; Lee et al. 2017; Noor et al. 2015). Besides, there are several factors that influence PM_{10} variations during summer monsoons and dry seasons. According to Juneng et al. (2011), these factors can be categorised into three groups, namely local meteorological factors, synoptic weather conditions, and hotspot number counts that represent regional emission conditions. The local meteorological factors that affect PM_{10} variation during the summer monsoon are surface air temperature, humidity and wind speed. In our region, the day-to-day variation of aerosol is pretty much modulated by the synoptic circulation which controls the regional moisture convergence and divergence. So, cyclones over the Western North Pacific draw much of the moisture away from Malaysia and elevate the risk of higher air pollution. The number of hotspots represents the numbers of biomass-burning locations based on identification from satellite images. Higher numbers of hotspots contribute high concentrations of smoke that is then transported to the downwind area which is determined by the wind direction.

Meteorological conditions effects on spatial and temporal variability

The compilation of processed data from the different study sites showed variability in both the levels of pollution and the long-term trends of air pollutants. Temporal variability of air pollutant concentrations from 2005 to 2015 leads to the study of local meteorological effects on the concentrations of air pollutants. Subsequently, from previous sections of site-specific temporal variability data, this study specifically focused on three significant issues: (1) monthly mean trends showed high concentrations of NO_2 at S2 (Fig. 2c) compared to the other sites; (2) the trend of normalised mean concentrations marked a reduction in O_3 levels at S1 (Fig. 2g) after a spike in concentrations in 2009; (3) the concentrations of SO_2 for the monthly variation plot were particularly scattered and enhanced at certain times for S1 (Fig. 4d).

High concentrations of NO_2 at S2 (the industrial site) prompted further study of temporal variations and local meteorological effects towards NO_2 levels as shown in Fig. 5. Based on Fig. 5a, the diurnal pattern of NO_2 concentrations had two peaks, one in the morning around 9 am and one in the evening at around 7 pm. Both of these times were during rush hour where people use motor vehicles to travel to and from their workplace. This situation coincides with weekly pattern with higher concentrations on weekdays but not at the weekend. Figure 5b, c shows bivariate polar annulus functions in both monthly and trend variations. Bivariate polar annulus functions can examine the temporal aspects of pollutant concentrations by wind direction. Figure 5b, c exhibits higher NO_2 concentrations dominated by south-westerly winds especially in February–March and June–July. The concentrations of NO_2 are likely to be affected by local vehicle emissions from major roads.

The trend of normalised mean concentrations marked a reduction in O_3 levels at S1 (Fig. 2g) and leads to the study between the lower O_3 period (2005–2009) and higher O_3 period (2010–2015). The temporal patterns of O_3 concentrations and meteorological variations between 2005 and 2009, and 2010–2015 at S1 are shown in Fig. 6. In 2010–2015, the mean hourly O_3 concentrations were slightly higher compared to 2005–2009 with the peak hour at 2.00 p.m. (Fig. 6a). A study by Azmi et al. (2010) experienced the same result for S1 where sunlight had enhanced the formation of O_3. Corresponding to the diurnal plot, the weekly plot (Fig. 6b) also indicated higher mean O_3 concentrations in 2010–2015 compared to 2005–2009. The weekly plot showed no significant difference. As shown in Fig. 6c, the monthly variations of O_3 levels in 2005–2009 showed the highest concentrations in January to March, dominated by westerly winds. The concentrations in 2010–2015 were enhanced from previous years and presented enhancement in June–September with south-westerly winds. Besides, January–April in 2010–2015 (Fig. 6d) showed an enhancement in concentrations with the domination of westerly winds. A study

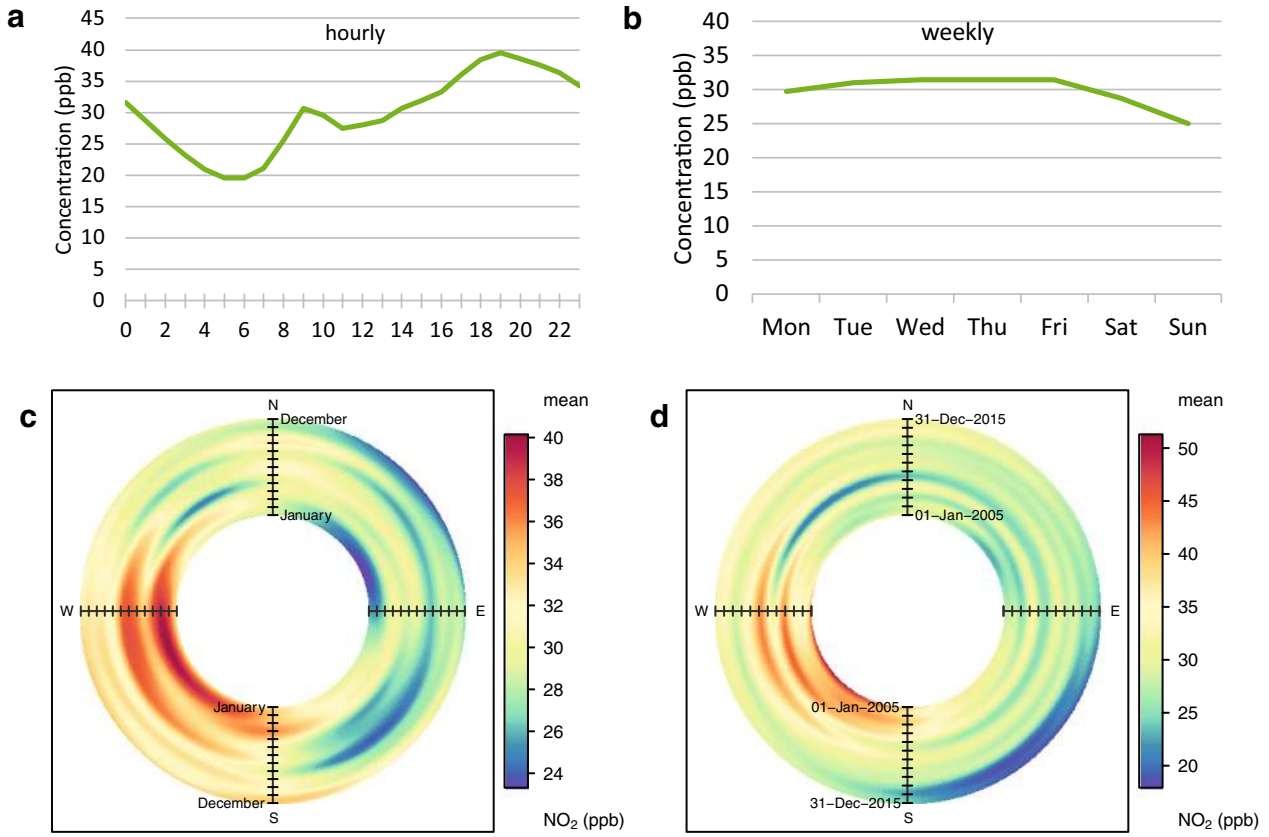

Fig. 5 Variation of NO_2 concentration at S2 station **a** hourly variation; **b** weekly variation; **c** polar annulus of NO_2 variation in monthly aspects with respect to wind direction; **d** polar annulus of NO_2 variation from 2005 to 2015 with respect to wind direction

by Latif et al. (2018) showed that the seasonal O_3 distribution was influenced by the seasonal wind direction and locations of study sites. In that study, January–April also known as the winter monsoon–spring transitional season recorded the maximum distribution of O_3 concentrations in city centre. This is because the advecting of O_3 precursors to the sampling site thus contributed to the high amount of O_3 concentrations.

The scattered and enhanced concentrations of SO_2 in monthly variation plot lead to the study between concentration of SO_2, wind speed and wind direction. The hourly mean SO_2 concentrations as a function of wind speed and wind direction differed between the months (Fig. 7a). Concentrations of SO_2 were highest in May and associated with north-westerly winds with relatively low wind speed (10–15 km/h) while the lowest contributions were in July and August. Generally, the monthly SO_2 distribution observed was high during low-speed north-westerly winds. Figure 7b presents a percentile rose plot that calculated the SO_2 percentile levels and plots by wind direction. This plot is useful in determining the SO_2 concentration distributions by wind direction and reveals various sources. In this case, during May which recorded the highest mean concentration, SO_2 distributions had consistent groups of percentiles from 75th to 85th, 85th to 95th, 95th to 99th and 99th to 99.9th that experienced north-westerly winds. This can bring high concentrations of SO_2 towards the site as there is an industrial area, shipping port and coal-fired power plant from the northwest of S1 as seen in Fig. 1c (North Port Klang). Distributions of SO_2 by winds in July and August were lowest compared to the other months and the concentrations recorded were also the lowest in both months. In July, the distribution of SO_2 was dominated by south-westerly and northerly winds that likely brought SO_2 originating from the shipping port (West Port Klang)

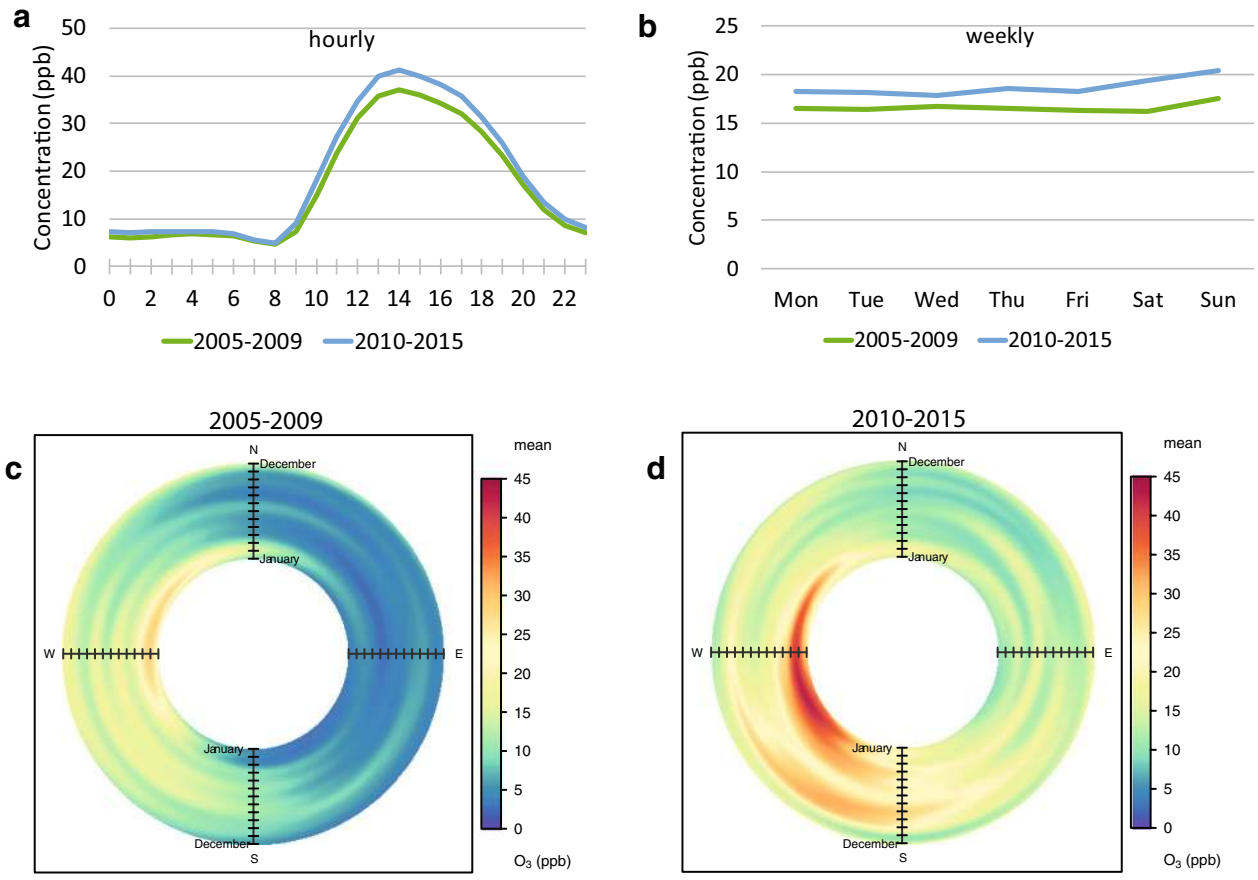

Fig. 6 Comparison of lower O_3 period (2005–2009) and higher O_3 period (2010–2015) at S1 station. **a** Hourly variability; **b** weekly variability; **c** monthly variation of bivariate polar annulus plot for lower O_3 period and **d** for higher O_3 period

and vehicles from the residential area, respectively. However, for August, the 99th–99.99th percentile concentrations (40–60 ppb) were associated with north-westerly winds that estimated to come from the shipping port, North Port Klang and coal-fired power plant direction. From Fig. 7b, it can be concluded that most 99th–99.99th percentile concentrations in every month were correlated with north-westerly wind and south-westerly winds that expected comprised high SO_2 levels coming from the shipping port and power plants. The SO_2 distributions may also be related to emissions from road traffic as S1 is located near a residential area.

Conclusion

The results of this study showed that the application of time series plots can give information on the temporal trends of pollutants at specific study sites. The study revealed that gas concentrations in the Malaysian urban environment did not fluctuate between each site, except for NO_2 with the highest levels recorded at the industrial site S1, ranging between 23 and 40 ppb. In general, CO levels are affected by vehicle emissions while NO_2 levels are affected by both vehicle and industrial emissions. Precursors of O_3 such as NO_x determined the level of O_3 at the different background sites while factors that affected SO_2 distribution levels were related to industrial, shipping and power plant emissions. Other than that, concentrations of PM_{10} were strongly associated with monsoonal effects that bring pollutants from biomass burning. O_3 and PM_{10} showed frequent exceedance of both MAAQS and NAAQS. In addition, these two parameters were also found to be influenced by monsoon seasons.

Local source emissions of pollutants can be identified from the statistical analysis of concentrations with meteorological factors that are imperceptible in a general temporal plot. The pattern of wind direction and NO_2 concentrations showed that the main contributor

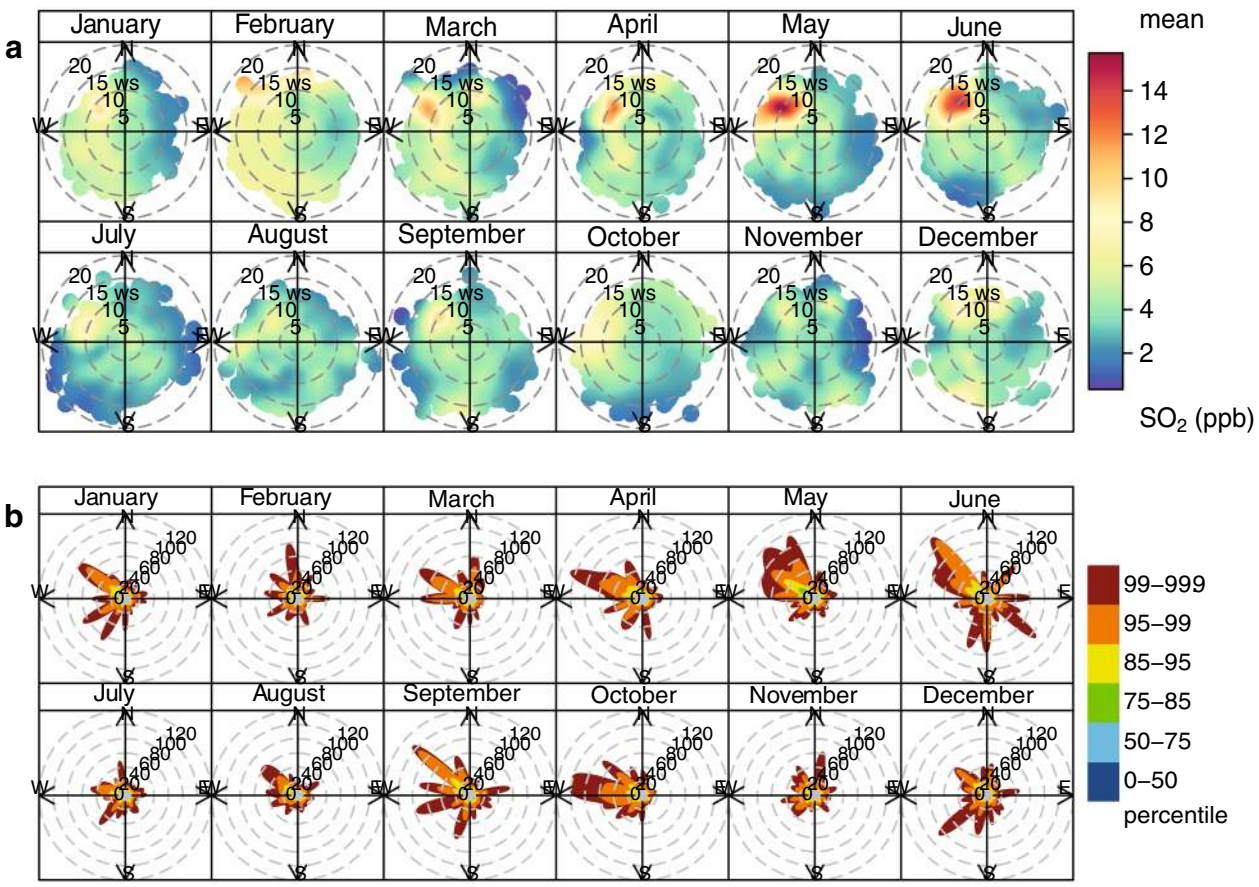

Fig. 7 Bivariate polar plot and percentile rose plot of SO_2 concentrations (ppb) at S1 station; **a** bivariate polar plot of SO_2 concentration with wind speed and wind direction in function of month; **b** percentile rose plots of SO_2 concentrations as a function of month

was vehicle emissions from major roads. The levels of O_3 were associated with its precursors and especially high in January–March with means of 20 ppb and 45 ppb during lower period of O_3 and high period of O_3, respectively. The distribution of SO_2 was distinguishable in the percentile rose plot and predominantly related with north-westerly and south-westerly winds carrying emissions mainly from the shipping port, along with other minor sources of industrial emissions, power plant emissions and road traffic. This study suggests detail information on emission inventory in urban environment especially from motor vehicles and industrial activities.

Additional files

Additional file 1. Annual mean air pollutants concentration from 2005 to 2015.

Additional file 2. Ambient air-quality standard of criteria air pollutants in Malaysia and United States of Environmental Protection Agency.

Abbreviations

MAAQS: Malaysian Ambient Air Quality Standard; NAAQS: National Ambient Air Quality Standard.

Authors' contributions

AAAM conceived the research, conducted data processing and analyses, plotted the figures, interpreted the results and wrote the paper. MTL designed the research, interpretation of the results, provided useful advices and suggested valuable revision on the final draft of the paper. NHB wrote the introduction with MO, plotted the study site, described study site and revised the paper format. FA, JXC and LJ provided useful advice on the draft of the paper. All authors read and approved the final manuscript.

Author details

[1] School of Environmental and Natural Resource Sciences, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia. [2] Centre for Tropical Climate Change System, Institute of Climate Change, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia.

Acknowledgements

The authors would like to express their most gratitude to Malaysian Department of the Environment (DOE) for permitting us to use the air-quality data. We gratefully thank Natural Environment Research Council (NERC) Openair project (http://www.openair-project.org/). Special thanks to Dr. Rose Norman for proofreading this manuscript.

Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
Not applicable.

Ethics approval and consent to participate
Not applicable.

Funding
Universiti Kebangsaan Malaysia, Research University Grants (AP-2015-010).

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 1 March 2018 Accepted: 31 August 2018
Published online: 11 September 2018

References

Afroz R, Hassan MN, Ibrahim NA (2003) Review of air pollution and health impacts in Malaysia. Environ Res 92(2):71–77
Ahamad F, Latif MT, Tang R, Juneng L, Dominick D, Juahir H (2014) Variation of surface ozone exceedance around Klang Valley, Malaysia. Atmos Res 139:116–127
Amil N, Latif MT, Khan MF, Mohamad M (2016) Seasonal variability of PM2.5 composition and sources in the Klang Valley urban-industrial environment. Atmos Chem Phys 16:5357–5381
Aouizerats B, Van Der Werf GR, Balasubramanian R, Betha R (2015) Importance of transboundary transport of biomass burning emissions to regional air quality in southeast Asia during a high fire event. Atmos Chem Phys 15(1):363–373
Awang MB, Jaafar AB, Abdullah AM, Ismail MB, Hassan MN, Abdullah R, Johan S, Noor H (2000) Air quality in Malaysia: impacts, management issues and future challenges. Respirology 5(2):183–196
Azmi SZ, Latif MT, Ismail AS, Juneng L, Jemain AA (2010) Trend and status of air quality at three different monitoring stations in the Klang Valley, Malaysia. Air Qual Atmos Health 3(1):53–64
Banan N, Latif MT, Juneng L, Ahamad F (2013) Characteristics of surface ozone concentrations at stations with different backgrounds in the Malaysian Peninsula. Aerosol Air Qual Res 13(3):1090–1106
Blumberg KO, Walsh MP, Pera C (2003) Low-sulfur gasoline & diesel: the key to lower vehicle emissions. http://www.theicct.org/documents/Low-Sulfur_Exec_Summ_ICCT_2003.pdf
Butler CD, Whelan J (2018) Air pollution and climate change in Australia: a triple burden. Climate change and air pollution. Springer, Berlin, pp 131–149
Carslaw DC (2015) The Openair manual—open-source tools for analysing air pollution data. Manual for Version 1.1–4, King's College London
Carslaw DC, Ropkins K (2012) Openair—an R package for air quality data analysis. Environ Model Softw 27:52–61
Dominick D, Juahir H, Latif MT, Zain SM, Aris AZ (2012) Spatial assessment of air quality patterns in Malaysia using multivariate analysis. Atmos Environ 60:172–181
Dor F, Moullec YL, Festy B (1995) Exposure of city residents to carbon monoxide and monocyclic aromatic hydrocarbons during commuting trips in the paris metropolitan area. J Air Waste Manage Assoc 45(2):103–110
Fenger J (1999) Urban air quality. Atmos Environ 33:4877–4900
Field RD, Van Der Werf GR, Fanin T, Fetzer EJ, Fuller R, Jethva H, Levy R, Livesey NJ, Luo M, Torres O, Worden HM (2016) Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Niño-induced drought. Proc Natl Acad Sci 113(33):9204–9209
Guarieiro LLN, Guarieiro ALN (2013) Vehicle emissions: what will change with use of biofuel? Biofuels-economy, environment and sustainability. InTech
Heil A, Goldammer J (2001) Smoke-haze pollution: a review of the 1997 episode in southeast Asia. Reg Environ Change 2(1):24–37
Hyer EJ, Chew BN (2010) Aerosol transport model evaluation of an extreme smoke episode in southeast Asia. Atmos Environ 44(11):1422–1427
Jang E, Do W, Park G, Kim M, Yoo E (2017) Spatial and temporal variation of urban air pollutants and their concentrations in relation to meteorological conditions at four sites in Busan, South Korea. Atmos Pollut Res 8(1):89–100
Juneng L, Latif MT, Tangang FT, Mansor H (2009) Spatio-temporal characteristics of PM_{10} concentration across Malaysia. Atmos Environ 43(30):4584–4594
Juneng L, Latif MT, Tangang F (2011) Factors influencing the variations of PM_{10} aerosol dust in Klang Valley, Malaysia during the summer. Atmos Environ 45(26):4370–4378
Keywood MD, Ayers GP, Gras JL, Boers CP, Leong (2003) Haze in the Klang Valley of Malaysia. Atmos Chem Phys 3(3):591–605
Khan F, Latif MT, Juneng L, Amil N, Mohd Nadzir MS, Syedul Hoque HM (2015) Physicochemical factors and sources of particulate matter at residential urban environment in Kuala Lumpur. J Air Waste Manage Assoc 65(8):958–969
Khan MF, Sulong NA, Latif MT, Nadzir MS, Amil N, Hussain DF, Lee V, Hosaini PN, Shaharom S, Yusoff NA, Hoque HM, Chung JX, Sahani M, Mohd Tahir N, Juneng L, Maulud KNA, Abdullah SMS, Fujii Y, Tohno S, Mizohata A (2016) Comprehensive assessment of PM25 physicochemical properties during the southeast Asia dry season (southwest monsoon). J Geophys Res Atmos 121:589
Kusumaningtyas SDA, Aldrian E (2016) Impact of the June 2013 Riau province Sumatera smoke haze event on regional air pollution. Environ Res Lett 11(7):075007
Lamarque J-F, Bond TC, Eyring V, Granier C, Heil A, Klimont Z, Lee D, Liousse C, Mieville A, Owen B (2010) Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. Atmos Chem Phys 10(15):7017–7039
Latif MT, Huey LS, Juneng L (2012) Variations of surface ozone concentration across the Klang Valley, Malaysia. Atmos Environ 61:434–445
Latif MT, Othman M, Idris N, Juneng L, Abdullah AM, Hamzah WP, Khan MF, Sulaiman NMN, Jewaratnam J, Aghamohammadi N, Sahani M, Chung JX, Ahamad F, Amil N, Darus M, Varkkey H, Tangang F, Jaafar AB (2018) Impact of regional haze towards air quality in Malaysia: a review. Atmos Environ 177:28-44
Lee H-H, Bar-Or RZ, Wang C (2017) Biomass burning aerosols and the low-visibility events in southeast Asia. Atmos Chem Phys 17(2):965–980
Lin C-Y, Hsu H-M, Lee Y, Kuo C, Sheng Y-F, Chu D (2009) A new transport mechanism of biomass burning from Indochina as identified by modeling studies. Atmos Chem Phys 9(20):7901–11
Malaysian Meteorological Department (2017) General Climate of Malaysia. http://www.met.gov.my/web/metmalaysia/climate/generalinformation/malaysia. Accessed 9 May 2017
Mayer H (1999) Air pollution in cities. Atmos Environ 33(24):4029–4037
Monks PS, Granier C, Fuzzi S, Stohl A, Williams ML, Akimoto H, Amann M, Baklanov A, Baltensperger U, Bey I, Blake N, Blake RS, Carslaw K, Cooper OR, Dentener F, Fowler D, Fragkou E, Frost GJ, Generoso S, Ginoux P, Grewe V, Guenther A, Hansson HC, Henne S, Hjorth J, Hofzumahaus A, Huntrieser H, Isaksen ISA, Jenkin ME, Kaiser J, Kanakidou M, Klimont Z, Kulmala M, Laj P, Lawrence MG, Lee JD, Liousse C, Maione M, Mcfiggans G, Metzger A, Mieville A, Moussiopoulos N, Orlando JJ, O'dowd CD, Palmer PI, Parrish DD, Petzold A, Platt U, Poschl U, Prevot ASH, Reeves CE, Reimann S, Rudich Y, Sellegri K, Steinbrecher R, Simpson D, Ten Brink H, Theloke J, Van Der Werf GR, Vautard R, Vestreng V, Vlachokotas C, Von Glasow R (2009) Atmospheric composition change—global and regional air quality. Atmos Environ 43:5268–5350
Morawska L, Jayaratne E, Mengersen K, Jamriska M, Thomas S (2002) Differences in airborne particle and gaseous concentrations in urban air between weekdays and weekends. Atmos Environ 36(27):4375–4383
Nerriere É, Zmirou-Navier D, Blanchard O, Momas I, Ladner J, Le Moullec Y, Personnaz MB, Lameloise P, Delmas V, Target A, Desqueyroux H (2005) Can we use fixed ambient air monitors to estimate population long-term exposure to air pollutants? The case of spatial variability in the genotox ER study. Environ Res 97:32–42
Noor NM, Yahaya AS, Ramli NA, Luca FA, Abdullah MMAB, Sandu AV (2015) Variation of air pollutant (particulate matter-PM_{10}) in Peninsular Malaysia study in the southwest coast of Peninsular Malaysia. Rev Chim 66(9):1443–1447

Pereira M, Santos R, Alvim-Ferraz M (2007) Air quality improvements using European environment policies: a case study of SO_2 in a coastal region in Portugal. J Toxicol Environ Health Part A 70(3–4):347–351
Rahman SRA, Ismail SNS, Raml MF, Latif MT, Abidin EZ, Praveena SM (2015) The assessment of ambient air pollution trend in Klang Valley, Malaysia. World Environ 5(1):1–11
Reid J, Xian P, Hyer E, Flatau M, Ramirez E, Turk F, Sampson C, Zhang C, Fukada E, Maloney E (2012) Multi-scale meteorological conceptual analysis of observed active fire hotspot activity and smoke optical depth in the maritime continent. Atmos Chem Phys 12(4):2117–2147
Rodríguez MC, Dupont-Courtade L, Oueslati W (2016) Air pollution and urban structure linkages: evidence from european cities. Renew Sustain Energy Rev 53:1–9
Shannon NK, Loretta JM, Miriam EM, Jonathan JB, Patrick SK, Tianjia L, Melissa PS, Ruth SD, Daniel JJ, Joel S, Montira P, Samuel SM (2016) Public health impacts of the severe haze in equatorial asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure. Environ Res Lett 11(9):094023
Song S-K, Shon Z-H, Kim Y-K, Kang Y-H, Oh I-B, Jung C-H (2010) Influence of ship emissions on ozone concentrations around coastal areas during summer season. Atmos Environ 44(5):713–723
Streets D, Waldhoff S (2000) Present and future emissions of air pollutants in China: So_2, NO_x, and CO. Atmos Environ 34(3):363–374
Streets DG, Bond T, Carmichael G, Fernandes S, Fu Q, He D, Klimont Z, Nelson S, Tsai N, Wang MQ (2003) An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. J Geophys Resh Atmos 108(D21):8809
Tacconi L (2016) Preventing fires and haze in southeast Asia. Nat Clim Change 6(7):640–643
Tangang F, Latif M, Juneng L (2010) The roles of climate variability and climate change on smoke haze occurrences in southeast Asia Region. LSE Ideas, London
Wan Mahiyuddin WR, Sahani M, Aripin R, Latif MT, Thach T-Q, Wong C-M (2013) Short-term effects of daily air pollution on mortality. Atmos Environ 65:69–79
Wang Y, Zhuang G, Sun Y, AN Z (2006) The variation of characteristics and formation mechanisms of aerosols in dust, haze, and clear days in Beijing. Atmos Environ 40:6579–6591
Wang T, Xue L, Brimblecombe P, Lam YF, Li L, Zhang L (2017) Ozone pollution in China: a review of concentrations, meteorological influences, chemical precursors, and effects. Sci Total Environ 575:1582–1596
Yamaji K, Ohara T, Uno I, Tanimoto H, Kurokawa J-I, Akimoto H (2006) Analysis of the seasonal variation of ozone in the boundary layer in east Asia using the community multi-scale air quality model: what controls surface ozone levels over Japan? Atmos Environ 40(10):1856–1868
Yonemura S, Tsuruta H, Kawashima S, Sudo S, Peng LC, Fook LS, Johar Z, Hayashi M (2002) Tropospheric ozone climatology over Peninsular Malaysia from 1992 to 1999. J Geophys Resh Atmos 107(D15):4229
Yoo J-M, Lee Y-R, Kim D, Jeong M-J, Stockwell WR, Kundu PK, Oh S-M, Shin D-B, Lee S-J (2014) New indices for wet scavenging of air pollutants (O_3, CO, NO_2, SO_2, and PM_{10}) by summertime rain. Atmos Environ 82:226–237
Zhang Q, Streets DG, Carmichael GR, He K, Huo H, Kannari A, Klimont Z, Park I, Reddy S, Fu J (2009) Asian emissions in 2006 for the Nasa Intex-B Mission. Atmos Chem Phys 9(14):5131–5153