Temperature and air pollution relationship during heatwaves in Birmingham, UK

Egide Kalisa [a, b], Sulaiman Fadlallah[c*], Mabano Amani[d], Lamek Nahayo[e], and Gabriel Habiyaremye[f]

[a]School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, West Midlands B15 2TT, United Kingdom

[b]School of Sciences, University of Rwanda, College of Science and Technology, Kigali-Rwanda

[c]Mechanical Engineering Department, Auckland University of Technology, New Zealand

[d]Centre for Functional Ecology, Department of Life Sciences, University of Coimbra, Largo Marquês de Pombal, 3004-517 Coimbra, Portugal

[e]State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, 818 South Beijing Road

[f]Lancaster Environment Centre, Lancaster University – Lancaster LA1 4YQ, United Kingdom

Abstract

While temperature has long been known as a catalyst for pollutant to be more airborne, it is unclear how an increase in temperature impacts on air pollution during heatwaves. Through a regression analysis the relationship between ozone (O_3), particulate matter (PM_{10}, particles less than 10 μm in diameter), nitrogen dioxide (NO_2), and temperatures in urban and rural areas of Birmingham, it was found that during heatwaves, all pollutant levels rose at each site, with the maximum temperature coinciding with the peak of O_3 and PM_{10}. These findings established that the influence of temperature on air pollution did not change according to rural and urban locations although air pollutants (O_3, NO_2, and PM_{10}) increased with increasing temperatures particularly during heatwaves. However the variation in the amount of ozone, altered by more than 50% according to increases in temperature. This matches studies where the incidence of high levels of pollution have conclusively been found to be much more prevalent during heatwaves of a long duration. The implications of these findings are important to long-term prevention in the framework of heatwave plans and when there is a heatwave forecast, additional measures to reduce air pollutant concentrations may be appropriate to trigger emergency response.

Keywords: Heatwave; Temperature; Ozone; Nitrogen dioxide; Particulate matter less than 10μm.

*Address correspondence to Sulaiman Fadlallah, Auckland University of Technology, Mechanical Engineering Department, New Zealand. E-mail: sulaiman.fadlallah@aut.ac.nz
Phone: +64 2108242625.

1. Introduction

The impact of worsening air quality and extreme weather events, such as heatwaves, are increasingly affecting people in both hemispheres. Heatwaves have long been known as an important driver of air pollutants, inducing various health, environmental, and economic impacts (Cheval et al., 2009; García-Herrera et al., 2010). Air pollutants whose concentrations and impacts are known to be affected by heatwaves include particulate matter (PM), ozone (O_3) and nitrogen dioxide (NO_2). These pollutants being emitted into atmosphere from a variety of natural and anthropogenic sources, are a major threat to human health (World Health Organization, 2010). The concentration of these pollutants in ambient air, depends on the amount of emission and the ability of the atmosphere to absorb or disperse these pollutants (World Health Organization, 2010).

Since meteorological variables such as temperature and concentrations of air pollutants vary on a daily basis, it is important to consider their relationship in the planetary boundary layer, since the atmosphere is the medium in which air pollutants are transported away from the source. Lee et al. (2006) indicated that during photochemical pollution episodes, air pollutants (O_3, NO_2, and PM_{10}) are the result of a mixture of various meteorological effects and chemical reactions. These pollutants are of the greatest health concern, as they may be exacerbated during heatwaves (Analitis et al., 2014; Fouillet et al., 2006; Johnson et al., 2004), and not only cause sensitive individuals to be stressed by high temperatures, but be the cause of mortality during heatwaves (Analitis et al., 2014). Unusual hot weather during summer led to elevated air pollutants during the heatwaves that occurred in Athens, Greece between June and July 2007 (Fischer et al., 2004). Theoharatos et al. (2010) found a significant correlation between heatwaves and average hourly concentrations of O_3, NO_2 and SO_2 in Athens. Similarly the combination of elevated air pollution

levels and high temperatures has been implicated in the increase of urban heat island (UHI) and air pollution in London, England (McMichael et al., 2003; Rooney et al., 1998).

Heatwaves are particularly intense in urban areas, where surface characteristics alter temperature difference between urban and rural areas. This changes is due to low vegetation in cities production of anthropogenic heat and air flow caused by urban infrastructures such as buildings and asphalt street (Bibri & Krogstie, 2017). Mirzaei, (2015) indicated that extreme air temperature of a city (UHI) increases the heat and air pollution related mortality and raised energy demand of building for cooling, which in turn leads to an increase in air pollutants and greenhouse gases. Despite this, several studies have shown that the sustainable urban planning or smart city such as green roofs and cool pavements could significantly reduce both UHI and air pollution especially O_3, NO_2, and PM_{10} (Bibri & Krogstie, 2017; McDonald et al., 2007; Silva, Khan, & Han, 2018; Yang, Yu, & Gong, 2008).

Previous studies between temperature and air pollution during heatwaves (Fouillet et al., 2006; Fischer et al., 2004) have only explored the role of air pollution in modifying the effects of heatwaves on mortality. There is a dearth of research studies that investigated the relationship between temperature and air pollution during heatwaves without the consideration of the effects of mortality. In addition, there seems to be no research into the spatial relationship of temperature and air quality during heatwaves, such as between urban and rural areas in England. The objectives of this study are to: (1) assess the relationship between temperature and air pollution during heatwaves, (2) quantify the impact of temperature on air pollutants (namely ozone (O_3), particulate matter (PM_{10}) and nitrogen dioxide (NO_2) and finally, (3) investigate the difference of that impact

between urban and rural areas of Birmingham in the United Kingdom during heatwave events identified between 2003 and 2013.

2. Materials and Methods

2.1. Study location

Data used in this study were collected in the Birmingham metropolitan city in the United Kingdom. Birmingham was selected as study location to be representative of a typical population exposure as the largest and most populous British City outside London located in the West Midlands region. This study employed eleven years data series (2003-2013) of O_3, NO_2, and PM_{10} and meteorological data (Temperature). Birmingham Tyburn (52.51 N, -1.83W) and Harwell (51.57 N, -1.325283 W) air quality monitoring stations provided respectively urban and rural data (Fig. 1). Edgbaston (52.46 N, -1.91 W) and Coleshill (52.48 N, -1.689 W) weather stations provided respectively urban and rural meteorological data used in this study.

2.2. Air quality data

Historical air quality data (O_3, NO_2, and PM_{10}) data with both urban and rural backgrounds required for this study were obtained from the Department for Environment, Food and Rural Affairs (DEFRA) (www.defra.gov.uk). Birmingham Tyburn is an urban background air quality monitoring station situated to the North-East of Birmingham City centre, near the Tyburn Road (A38) within 6 km of the city centre, a site typical of the urban environment. This station was chosen because a comprehensive range of measurements had been reliably collected over time. Harwell is located in a rural location, Harwell Science Centre in Oxfordshire, in the South Eastern

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part of England. The site is surrounded by fields and is considered as representative of a rural location monitoring station (Charron et al., 2007). The nearest road is on the east of the science park with access to only buildings. The nearest trees are at a distance of 200–300 m from the monitoring station. Harwell is situated at an altitude of 126 m in the South East of England. Although Harwell air quality station is not located in the Birmingham metropolitan area, it was chosen for this study because Harwell was seen as the best choice to provide rural air quality data for this 11-year period - previous studies have used data from Harwell station to represent reliable rural data over the United Kingdom. The first assessment was of the availability of daily concentrations of ozone (maximum 8-hour running average), nitrogen dioxide (the daily maximum value of the 1-hour mean) and particulate matter (mean, 24 hours). There was no air quality data for NO_2 for 2013 at Harwell monitoring station and NO_2 and PM_{10} at Birmingham Tyburn in 2006.

2.3. Temperature data

The daily maximum temperature data from 1 January 2003 to 31 December 2013 were obtained from two synoptic weather stations situated in Coleshill (approx. 12 km from city centre, representing a rural background) and Edgbaston (approx. 4 km from city centre, representing an urban background) (see British Atmospheric Data Centre (http://badc.nerc.ac.uk)). The weather stations (urban & rural) were chosen based on data availability over the 11-years period, with reference to the literature that has previously used similar stations (Johnson, 1985; Tomlinson et al., 2012).

2.4. Heatwave definition

One of the challenges in this study was to define a heatwave day, as the concept of a heatwave has no universal definition (Meehl et al., 2000), being dependent on the average climate for each region in question. In this study, the definition of a heatwave was much closer to the definition by the World Meteorological Organization (WMO) with some modification. According to the WMO, a heatwave is the phenomenon during which the daily maximum temperature for at least five consecutive days exceeds the average maximum temperature by 5 °C, considering the period between 1961 and 1990 as the normal measuring period (Frich et al., 2002). Heatwaves are likely to occur during summer months, thus, we have analyzed the historical trend of an ozone season typically from May 1st to September 30th (U.S. EPA, 2009). The data analysis focused on the extended summer months starting from May to September (known as summer months) (Shen et al., 2016), during which the probability to observe a heatwave was highest (Air Quality Expert Group, 2005). In this study, heatwave was defined as phenomenon during which the daily maximum temperature for at least five consecutive days exceeds the average maximum temperature by 6 °C. In addition to heatwaves identified in rural and urban areas, this study has also noted some hot day episodes observed in hottest years in Birmingham. We define hot day as an episode of one to four consecutive days that occurred before or after the heatwave period with temperature above or equal to 25 °C.

2.5. Data analysis

The relationship between daily mean temperature and air pollution levels during heatwave periods for Birmingham was determined using a simple linear regression model (linear correlation model) to highlight the possible correlation between temperature and each of the air pollutants. Statistical analysis was performed using Statistical Analysis Software (SAS, version 9.4 by SAS institute Inc. Cary.INC. USA).

3. Results and Discussion

3.1. Hot days and heatwave days

In this paper, the discussion presented only focused on severe heatwaves (2003, 2006 and 2013) where high intensity and long duration of heatwaves were observed (Table 1 and Table 2). In all heatwaves identified in rural and urban areas, the temperatures ranged from 26.9 -34.1 °C. Based on a hot day definition, 135 hot days were observed in rural areas and only 109 hot days were observed in urban areas (Table 5). Most hot days observed during the eleven years occurred in July for both sites, followed by June and August, respectively. Based on heatwave definitions applied in this study, 8 heatwave periods were identified in the rural area (Table 1) and 7 heatwaves in the urban area (Table 2). Most severe heatwaves with highest intensity and longest duration were found in August 2003, July 2006 and July 2013 in both urban and rural areas (Table 5). The highest frequency of hot days (more than 5 days in a month) observed between 2003 and 2013 was in August 2003 (45.5%), July 2006 (55.2%) and July 2013 (88.2%) in both rural and urban areas (Table5). Comparing the most intense heatwaves (2003, 2006 and 2013) observed, August 2003 displayed the highest maximum temperatures for both urban and rural areas (Fig. 2). The heatwave in 2003 was the hottest heatwaves year, however, in terms of duration; the 2006 heatwave included 21 consecutive days with a temperature above 25 °C compared to 8 days in 2003 and 11 days in 2013 for rural areas (Table 1).The heatwave duration and intensity can be important factors for a significant increase in the concentration of air pollutants particularly on O_3 (Theoharatos et al., 2010). The results (Table 6) show that temperature levels were significantly high in rural areas rather than urban areas (p=0.0156) during summer months (May 2003 to September 2013). This is likely due to urban areas being considerably warmer than the surrounding suburban areas due to the so-called Urban Heat Island (UHI). Pearce et al. (2011) state that urban areas are warmer than

their surrounding areas due to the characteristics of urban surface, radiative trapping effect, significant human activity, heat release, high heat capacity and the lack of green space (vegetation and moisture space). However, the use of this metric (daily maximum temperature), may explain why high temperatures were not observed in urban areas, as it might be expected due to the behaviour of urban heat island (UHI) which occurs normally during night time. In addition, summer temperatures dry the ground in rural areas, which enhances the radiation from the sun to be reflected back to the atmosphere and increases the daytime temperature. Research in the UK showed that UHI enhances night-time temperatures, especially during heatwave periods (Tomlinson et al., 2012; Oke, 1973). Many cities like Birmingham reported air temperatures that are warmer in urban area than surrounding areas. Tomlinson et.al (2012) indicated that Birmingham UHI presented a magnitude of more than 4.5 °C on a heatwave day in 2006 and Heaviside et al. (2015) showed a magnitude of up to 7 °C in August 2003. Again, the albedo (the amount of incident radiation or light that is reflected by a surface) can have a significant effect on air temperature, with high temperatures associated with dark, low albedo surfaces such as tarmac (Mirzaei, 2015). High albedo surfaces reflect back much of the incoming light from the sun into the atmosphere while low albedo absorbs more energy from the sun. Rural areas have high albedo because the daytime temperature becomes high once reflected in the atmosphere while urban areas (urban materials) absorb heat during the day and release it during the night. Furthermore, Johnson (1985), has indicated that the level of the heating and cooling of urban and rural areas could be explained by the sky view factor (SVF), which is the amount of the sky visible from the ground. For example, the sky view factor controls the radiation balance in Birmingham City centre because of the tall buildings. The cooling rates reduce with a decrease in SVF (r = -0.83). Therefore, Birmingham was found to heat up and cool down more than its surrounding rural areas. In addition,

most of the rural areas of Birmingham are partially similar to urban areas, thus there is not much variation between the two areas. These findings are consistent with a recent study published by the Royal Meteorology Society on Birmingham UHI (Tomlinson et al., 2012). Unwin (1980) also used a similar weather station (Edgbaston) in a study comparing daily minimum and maximum temperature at two sites, Edgbaston and Elmdon. The results showed that the average temperature (daily maximum) was cooler at Edgbaston, which represents an urban area compared to Elmdon that represents rural area where the heat island effect was due to nighttime minimum temperature at Edgbaston. This research supports similar findings in this study that a daytime cool urban island pervades through Birmingham (Unwin, 1980).

3.2 Air pollution and heatwaves

3.2.1 Temperature and air pollution relationship during heatwaves of August 2003

During the past 11 years, the mean concentration of O_3 (p<0.0001) and temperature (p = 0.0156) (Table 3) were significantly higher in rural than urban areas. However, the mean concentrations of NO_2 was significantly higher in the urban than rural area (p<0.0001). Only PM_{10} did not show a statistically significant difference of mean concentration between rural and urban areas (p = 0.0765). The comparison of mean concentration of air pollutants (O_3, NO_2, and PM_{10}) and temperature between urban and rural sites for all 11 years are shown in the Table 3. Details by each year (2003 to 2013) on the comparison of mean concentration of air pollutants (O_3, NO_2, and PM_{10}) and temperature in rural and urban areas are presented in the Table 4. During 2003 the mean concentration of O_3 and NO_2 were significantly different between urban and rural areas (Table 6). Temperature, O_3, NO_2, and PM_{10} concentrations on days with heatwaves are significantly higher than those non-consecutive "hot" days. Additionally, O_3 concentrations rose at both urban and rural sites and coincided with the peak of the maximum temperature. The peaks

of temperature coincided with the peak of O_3, NO_2, and PM_{10} during 9th August in both rural and urban areas (Fig. 2). During the same month, the results of the correlation between temperature and air pollution was only significant for O_3 ($R^2 = 0.44$, n = 28, p<0.0001) and PM_{10} ($R^2 = 0.39$, p = 0.0001) in rural areas. In the urban area the influence of temperature on NO_2 ($R^2 = 0.20$, n = 31, p = 0.0068) and O_3 ($R^2 = 0.54$, n = 30, p<0.0001) was significant with a positive correlation except for PM_{10}. These findings are consistent with those previously reported in the heatwaves of the US (Lee et al., 2006) and Netherlands (Tomlinson et al., 2012). Previous studies report an indirect relationship between air pollution and temperature during heatwaves, by comparing effects of air pollution and temperature on mortality during heatwave periods (Analitis et al., 2014; Filleul et al., 2006; Stedman, 2004) and not heatwave periods (Carslaw et al., 2007; Pearce et al., 2011). These studies support our present findings.

3.3.2 Temperature and air pollution relationship during heatwaves of June –July 2006

During 2006, 3 episodes of heatwaves were observed in each urban and rural area (Tables 1 and 2). The year 2006 was characterised by long duration heatwaves compared to 2003 & 2013). Generally, the O_3, NO_2, and PM_{10} concentrations on days with heatwaves were elevated compared to other hot days, where heatwaves were not observed (Fig. 3). This reflects the build-up effect from the extended period of high temperature during heatwave events. During June 2006, in rural areas, increased temperatures resulted in increased air pollutants. The results on the correlation between temperature and air pollution showed a significant and positive correlation between temperature and O_3 ($R^2 = 0.54$, p<0.0001) and PM_{10} ($R^2 = 0.30$, n = 30, p<0.0001). During July 2006 in the rural area, similar findings were observed with a positive correlation between temperature and PM_{10} ($R^2 = 0.40$, p<0.0001); and O_3 ($R^2 = 0.80$, p<0.0001). In the urban area,

June and July 2006 showed the same evolution with peaks situated in periods of high temperature. Statistically significant variation and positive correlation were observed between temperature and O_3 (R = 0.48, p<0.0001) and PM_{10} (R^2 = 0.36, n = 30, p = 0.0002) in June 2006 and similar findings were observed in July 2006 for O_3 (R^2 = 0.76, n = 31, p<0.0001), PM_{10} (R^2 = 0.38, n = 31, p = 0.0001) and NO_2 (R^2 = 0.54, n = 25, p = 0.0015). Figs. 3 and 4 show that 2006 heatwaves were much longer in terms of duration, which can be attributed to the large number of mortalities recorded in the Birmingham during the 2006 heatwave, than August 2003 (Vardoulakis and Heaviside, 2012). The heatwave duration and intensity can be important factors for a significant increase in the concentration of air pollutants particularly on O_3 (Theoharatos et al., 2010).

3.3.3 Temperature and air pollution relationship during heatwaves of July 2013

The heatwave period observed in 2013 occurred during July. However, the influence of temperature on air pollution was only significant on O_3 in rural areas (Fig. 5) (R^2 = 0.51, n = 31, p<0.0001. Figs. 5 shows that pollution variation was not instantly linked to the variation of temperature. In fact, there was a time lapse between the increase or decrease of temperature and the increase or decrease of air pollution. This suggests the effect of both current and previous day's temperature on air pollution readings.

3.3 Correlation analysis of air pollution and all intense heatwaves identified in 2003, 2006 and 2013

Based on the analysis of simple linear regression, the relationship between air pollutants (O_3, NO_2, and PM_{10}) and temperature during all intense heatwaves that happened in 2003, 2006 and 2013 are presented in Fig. 6. In all intense heatwaves during the three years (2003, 2006 and 2013), the maximum temperatures positively correlated with most air pollutants (Fig. 6). However, this

correlation was weak for NO_2. Observation-based statistical analysis showed that temperature affects all three-air pollutants, particularly for O_3 and PM_{10}. Strong correlation was also observed between these pollutants and temperature during heatwaves in both urban and rural areas. The results of this study indicated that the correlation of O_3 with daily maximum temperature ($R^2 = 0.40$, $p = 0.0001$) was much higher than PM_{10} ($R^2 = 0.32$, $p<0.0001$) and NO_2 ($R^2 = 0.04$, $p = 0.0566$) during intense heatwaves identified in rural areas (Fig. 6). In Fig.4 the temperature strongly correlates with NO_2 during the heatwave of July 2006 in which the correlation coefficient R^2 was larger than 0.50. In all intense heatwaves during the three years, the maximum temperatures positively correlated with most air pollutants (Fig. 6). However, this correlation was weak for NO_2. A peak in NO_2 was observed at the beginning of the heatwave, on 5 August in rural areas and 3 August 2003 in urban areas. The annual number of the exceedances of the air quality standards (40 µg/m^3 annual mean), matching the annual number of heatwave days. This could be attributed to the atmospheric conditions that usually prevail during heatwave days. Stagnation of air masses is usually observed during heatwaves, favouring the accumulation of particles and O_3 precursors (NO_2) (Tressol et al., 2008).The comparison of influence of temperature on air pollution, between rural and urban areas during all intense heatwaves identified in 2003, 2006 and 2013 indicated that there was no significant difference between both areas.

3.3.1 Ozone (O_3)

The maximum O_3 concentration was recorded at Harwell rural air quality station during the 2003 heatwave (200 µg/m^3) rather than at the Birmingham Tyburn station (urban) (173 µg/m^3). These concentrations coincide with the daily maximum temperature in rural (34.1 °C) and urban areas (33.2 °C). The concentration of O_3 was significantly lower in the urban than in the rural area

(p<0.0001). Statistically significant positive correlations were found between temperature and O_3 in all the heatwaves identified in the rural area, but the level of correlation was found to be moderate in the urban area. The fact that most of the times ozone levels are higher in rural areas than in cities can be explained by ozone degradation by its precursors (NOx) (Simon, Reff, Wells, Xing, & Frank, 2015). Ozone is a secondary pollutant, which means it is not directly emitted by traffic or industry emissions in cities, but it is formed on hot days by the influence of solar radiation to become more airborne. This degradation occurs more often in cities than in rural areas, because there is more NO in cities (Wałaszek, Kryza, & Werner, 2018). The O_3 concentrations were found to increase with increasing daily maximum temperature. This phenomenon exists because the elevated concentration for nitrogen oxides helps the removal of OH radicals, through the reaction with NO_2 (Qian et al., 2012). In addition, the peaks of O_3 during the heatwave are due to favourable temperatures and plenty of sunlight that promote the photochemical reaction (Katsouyanni et al., 2001). Furthermore, UHI can also contribute to the production and the dispersion of O_3 (Chaxel and Chollet, 2009). We found that when the temperature was lower especially during no heatwave periods, O_3 concentration did not correlate with the air temperature. However, strong correlation was observed during heatwave periods of a longer duration (Fig. 4). There are various plausible explanations for a synergistic association between elevated temperature, and air pollutants. Processes in the atmosphere in the presence of sunlight, generate ozone and a proportion of particles (secondary particles) and primary emitted pollutants. Since Sunlight is associated with high temperatures, there is likely to be increased production of secondary pollutants during warm seasons (Elminir, 2005; Tressol et al., 2008). During heatwaves, the air becomes stagnant, and traps emitted pollutants, often resulting in increases in ground level O_3 (Solberg et al., 2008; Monks et al., 2015). These findings are consistent with previous studies that reported strong correlation

with temperature during heatwaves (Johnson et al., 2004; Chaxel and Chollet, 2009; Heal et al., 2013; Huang et al., 2010; Dawson et al., 2007).

3.3.2 Particulate matter (PM$_{10}$)

Air pollutants are generally more concentrated in urban areas than in rural areas due to large emissions from human activities (Hewitt and Jackson, 2009; Jacobson, 2012). This study found that the average concentration of PM$_{10}$ were higher in urban than in rural areas during heatwave years recorded in the Birmingham (Table1). Temperature increase led to the increase of the level of PM$_{10}$. In this study, the mean concentration of PM$_{10}$ increased with rising temperatures during heatwaves in both urban and rural areas. This occurs because warm weather induces the formation of secondary fine particles, therefore increased temperatures result in increased PM$_{10}$ (Dawson et al., 2007; Tai et al., 2010; Massey et al., 2012). The higher concentration of PM$_{10}$ in urban areas than in rural areas is more likely due to more emission sources in urban areas. Consequently, this results in turbulence flow and elevated PM$_{10}$ levels in congested areas with tall buildings, which stop air and trap pollutants. For example, Birmingham city centre has many tall buildings, which stop airflow and trap pollutants often resulting in increases in ground level of PM$_{10}$. In addition, PM$_{10}$ increases in urban areas because of heavy road traffic emissions and road transport emissions (tyre pipe, brake wear, and re-suspension) (Dore et al., 2003; Barlow et al., 2007). These findings are in agreement with previous studies (Analitis et al., 2014; Vardoulakis and Kassomenos, 2008; Air Quality Expert Group, 2005; Pearce et al., 2011; Elminir, 2005). Mues et al. (2012) investigating the effect of the meteorological conditions in the extreme European summer 2003 on the concentration of PM$_{10}$, observed that the concentrations of PM$_{10}$ increased during weather conditions with high daily maximum temperature. Pollution levels can therefore be further increased during heatwave because of the atmospheric conditions that prevail leading to the

accumulation of pollutants (Tressol et al., 2008). This infers that during the summer episodes when the hot weather is associated with slow wind speed, the presence of high temperatures increases the likelihood of O_3 and NO_2 emissions. High ambient temperatures support the production of secondary aerosols. Thus, the increase of the concentration of NO_2 and O_3 during the summer can be accredited to the production of secondary aerosols (Elminir, 2005). Furthermore, in Birmingham, the concentration of PM_{10}, was found to be higher during low wind speed (poor dispersion conditions) and this is thought to be a result of atmospheric stability and a reduced mixing of air (Vardoulakis and Kassomenos, 2008). Typically the concentration of PM_{10} during warm seasons in Athens has been attributed to relative contribution of secondary and natural particles during hot and dry days (Kassomenos et al., 2014).

3.3.3 Nitrogen dioxide (NO_2)

The results of this study as shown in Table 1 and 2 show that the mean concentration of NO_2 was significantly higher in urban (51.7 $\mu g/m^3$) rather than rural areas (18.4 $\mu g/m^3$). The main reason for this higher concentration in urban areas was due to large emissions from traffic congestion, which is greater in the urban than surrounding areas. Defra (2004) and US EPA (2009) have indicated that over the UK, the high concentration of NO_2 is elevated in most urban areas particularly at kerbside locations. It has been reported that local dispersion and temperature play an important role (Carslaw et al., 2007). However, less research has been directed to the meteorological link (temperature) for NO_2 during heatwave events. Pearce et.al (2011) report that when the temperature rises above 35 °C, nitrogen dioxide increases by about 120 %. It has been reported that in Cairo (Egypt) the yearly distribution of the monthly average concentration of nitrogen dioxide levels, peaks during the summer, particularly in July 103 $\mu g/m^3$, and from August to December, the monthly average concentration of NO_2 decreases from about 82 to 62 $\mu g/m^3$ (Elminir, 2005). In Fig.4 the temperature strongly correlates with NO_2 during the heatwave of July

2006 in which the correlation coefficient R^2 was larger than 0.50. A peak in NO_2 was observed at the beginning of the heatwave, on 5 August in rural areas and 3 August 2003 in urban areas. The annual number of the exceedances of the air quality standards (40 µg/m^3 annual mean), matching the annual number of heatwave days. This could be attributed to the atmospheric conditions that usually prevail during heatwave days. Stagnation of air masses is usually observed during heatwaves, favouring the accumulation of particles and O_3 precursors (NO_2) (Tressol et al., 2008). These findings indicate that the influence of temperature on NO_2 is much more effective in heatwaves than other hot days, due to the higher temperature range. However, the influence of temperature on NO_2 during a heatwave is low compared to ozone and PM_{10}. In conclusion, nitrogen dioxide concentration increases with increasing temperature during heatwave events, which strongly agrees with previous related studies (Rooney et al., 1998; Stedman, 2004; Pearce et al., 2011).

5. Conclusion

This article has examined the relationship between temperature and air pollution during heatwave periods in Birmingham. A heatwave was defined by taking both intensity and duration into account. Overall, the results indicate that there was a linear relationship and positive correlation between temperature and air pollution during the heatwaves and that the relation between temperature and air pollution was more evident for high intensity and long duration heatwaves.

The variation of average air pollution levels in relation with heatwave duration, exhibited a peak that was more pronounced for O3. The implications of these findings are important for policy measures; for example, when there is a heatwave forecast, additional measures to reduce air pollutant concentrations may be appropriate to trigger emergency response, and this measure can be applicable either in urban or rural environments. Based on our findings, it would seem unwise to attempt to relate health effects such mortality for assessing the correlation between temperature and air pollution. However, when assessing health effects of high temperature and air pollution, this should be assessed during heatwave periods. Air pollution is so closely related to temperature, removing one variable (air pollutants or temperature), could reduce the effect of the other variable substantially. Thus, the correlation between temperature and air pollution cannot be assessed based on cases of health effect.

Acknowledgments

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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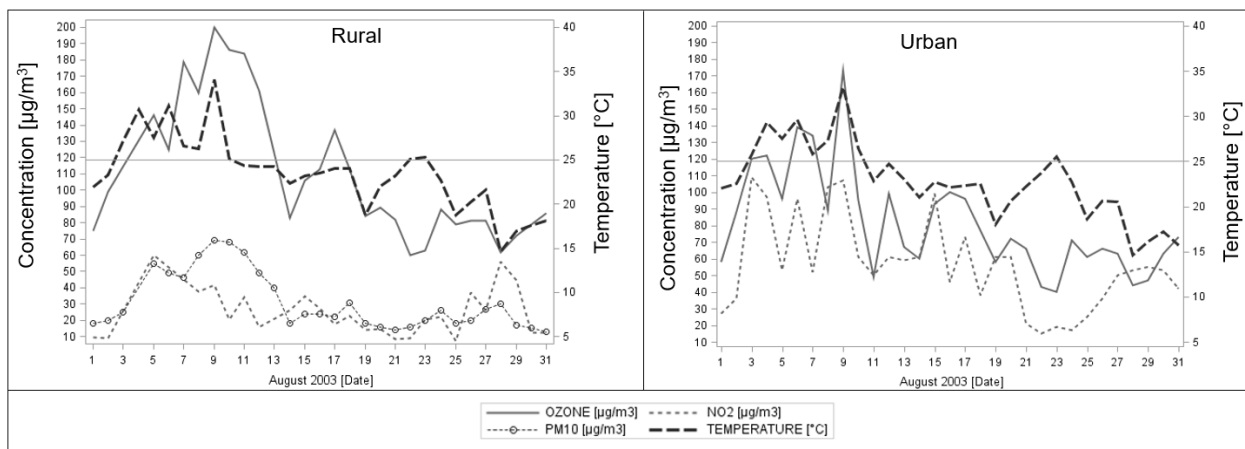
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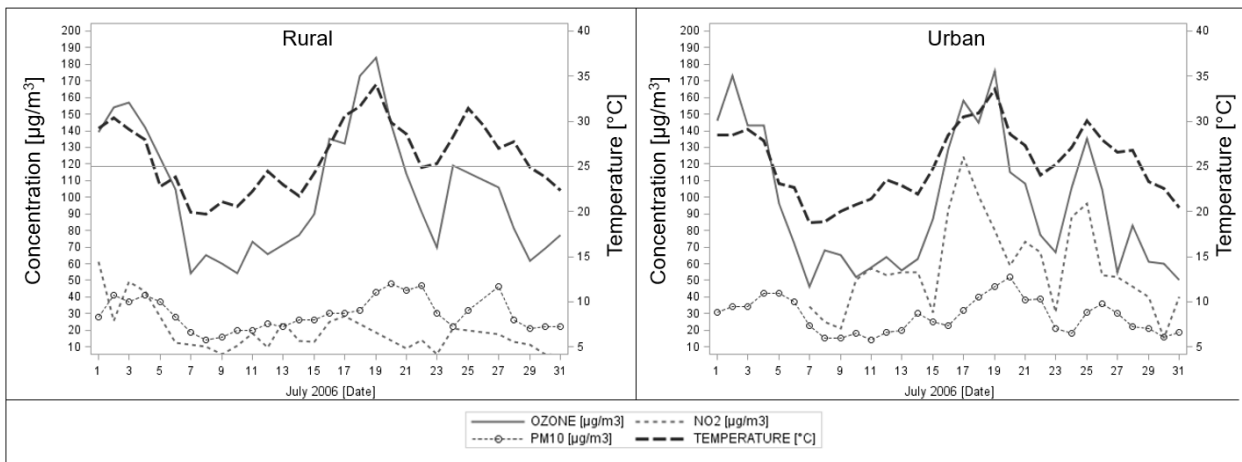

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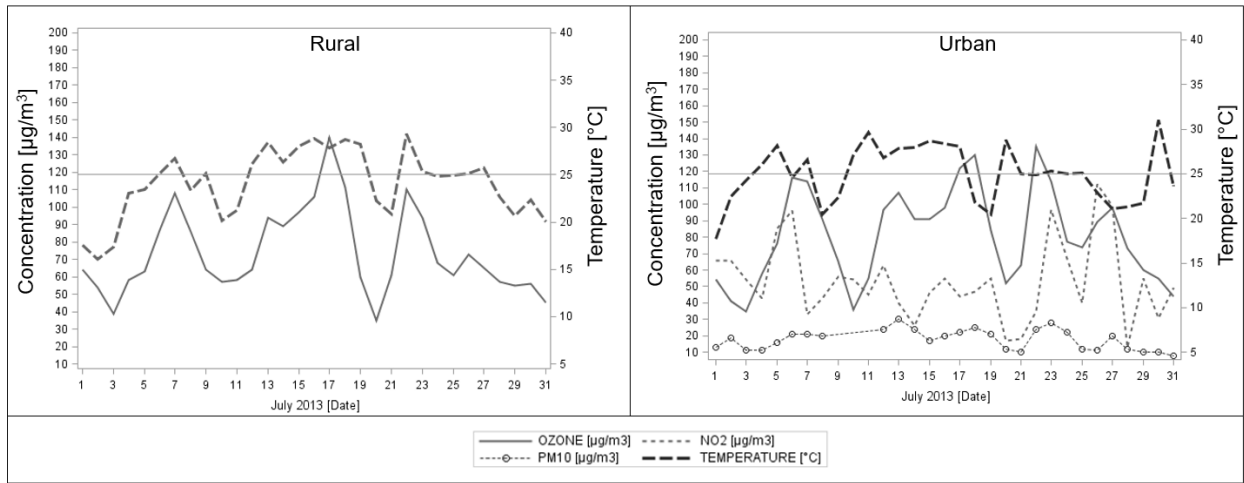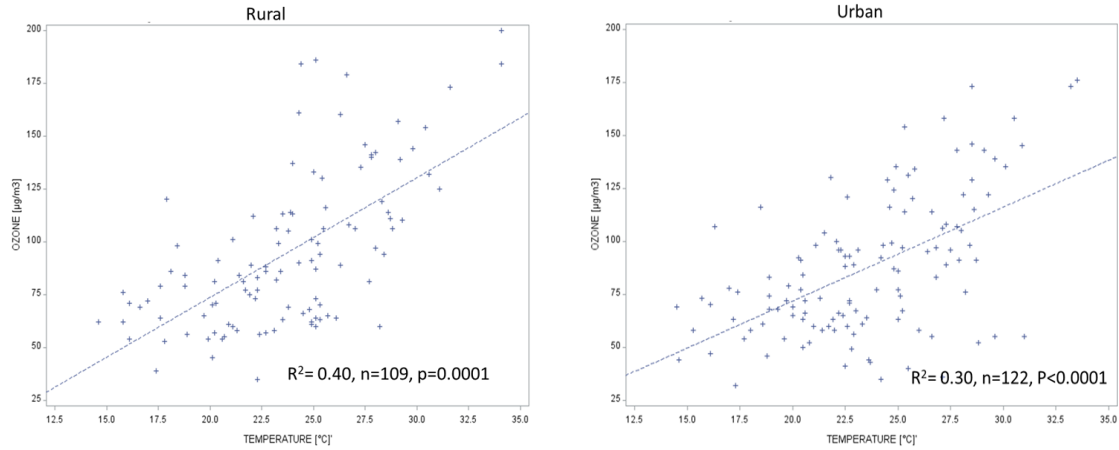
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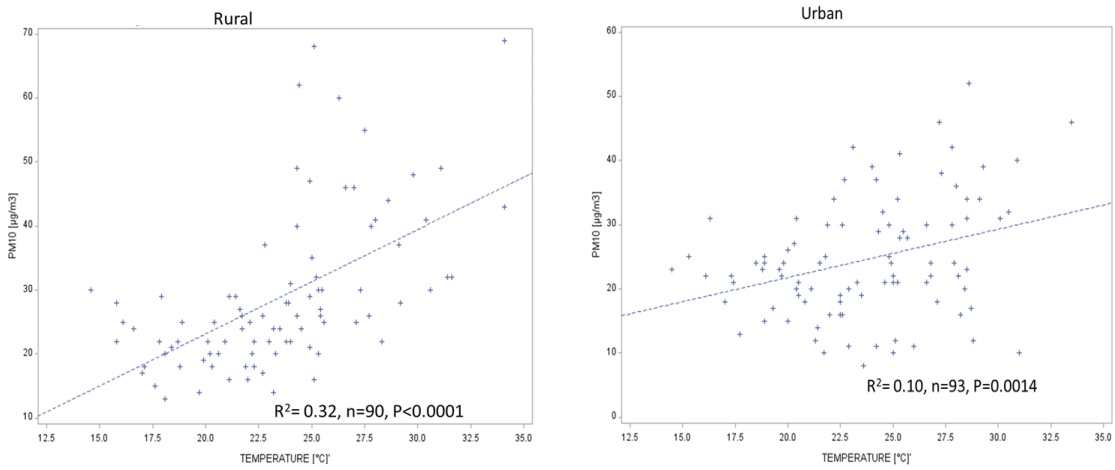

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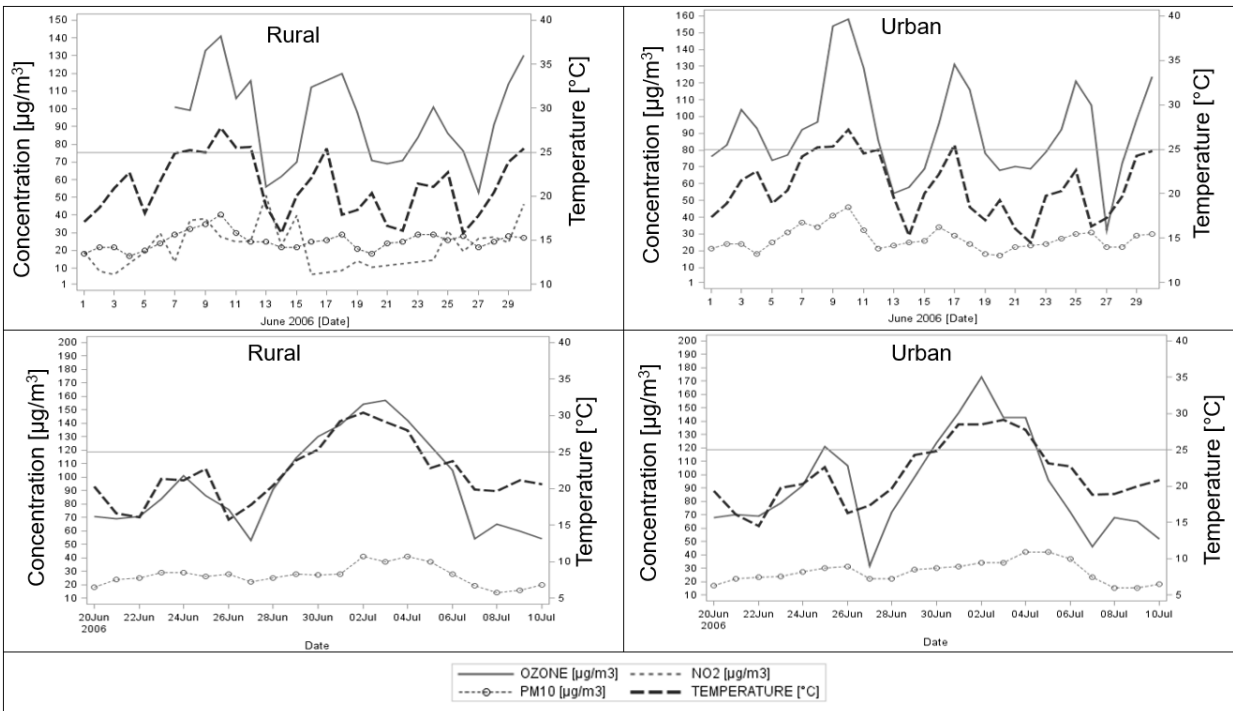
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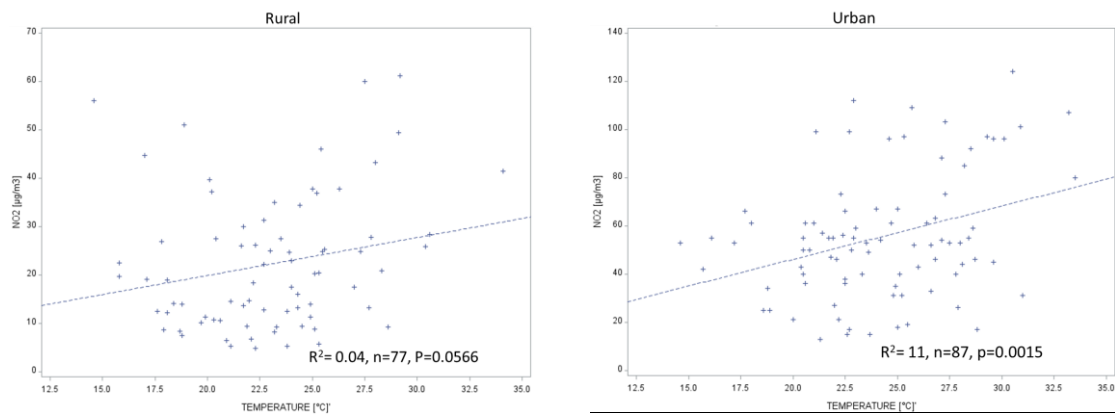
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Table 1
Heatwave periods, corresponding annual maximum temperatures and concentration of air pollutants (Ozone, NO_2 and PM_{10}) identified in 2003, 2005, 2006, 2008, 2010 and 2013 in rural areas

Year	Month	Period	Max. Temp [°C]	O_3 [μg/m³]	PM_{10} [μg/m³]	NO_2 [μg/m³]
2003	August	03-10th	34.1	200	69	41.4
2005	July	10-14th	28.7	107	27	14.5
2006	June	08-12th	27.8	141	40	27.7
	June-July	30-04th	30.4	154	41	25.8
	July	17-29th	34.1	184	43	-
2008	July	24-28th	27.1	108	21	26.4
2010	June	26-30th	26.9	130	20	40.1
2013	July	9-19th	28.8	106	-	-

Table 2
Heatwave periods, corresponding annual maximum temperatures and concentration of air pollutants (Ozone, NO_2 and PM_{10}) identified in 2003, 2005, 2006, 2008, 2010 and 2013 in urban areas

Year	Month	Period	Max. Temp [°C]	O_3 [μg/m³]	PM_{10} [μg/m³]	NO_2 [μg/m³]
2003	August	02-10th	33.2	173	-	107
2005	July	10-14th	28	103	28	56
2006	June	12-17th	27.2	158	46	-
	June-July	30-04th	29.1	143	34	-
	July	16-28th	33.5	176	46	80
2008	-	-	-	-	-	-
2010	-	-	-	-	-	-
2013	July	10-17th	28.7	91	17	46
		20-25th	28.8	52	12	17

Table 3
The mean concentration of air pollution (O_3, NO_2, and PM_{10}) and temperature in rural and urban spanning from May 2003 to September of 2013

	RURAL		URBAN		
	Mean	Std	Mean	Std	p-value
Daily max NO_2 [μg/m³]	17.5	12.4	50.6	21.7	<0.0001
Daily max O_3 [μg/m³]	76.2	24.8	69.1	25.0	<0.0001
Daily mean PM_{10} [μg/m³]	18.4	8.1	19.1	8.1	0.0765
Daily max temperature [°C]	19.4	4.1	19.0	4.0	0.0156

Table 4
May to September averages of air pollution and temperature in rural and urban areas from 2003 to 2013

	Year	RURAL		URBAN		
		Mean	± SD	Mean	± SD	p-value
2003	NO_2 [µg/m³]	21.3	15.2	50.4	24.0	<0.0001
	O_3 [µg/m³]	97.5	31.3	80.9	27.5	<0.0001
	PM_{10} [µg/m³]	21.5	11.2	20.7	7.8	0.5093
	Temperature [°C]	20.4	4.4	19.7	4.3	0.2211
2004	NO_2 [µg/m³]	17.0	12.6	51.5	19.5	<0.0001
	O_3 [µg/m³]	82.6	19.5	63.2	16.2	<0.0001
	PM_{10} [µg/m³]	20.5	7.8	21.1	8.2	0.4928
	Temperature [°C]	19.2	3.6	18.7	3.5	0.2097
2005	NO_2 [µg/m³]	17.2	11.1	50.2	18.9	<0.0001
	O_3 [µg/m³]	72.7	18.5	66.1	21.8	0.0052
	PM_{10} [µg/m³]	19.4	5.3	20.6	5.9	0.0708
	Temperature [°C]	19.6	4.1	19.0	4.0	0.2550
2006	NO_2 [µg/m³]	19.8	11.3	57.3	23.4	<0.0001
	O_3 [µg/m³]	82.6	28.3	73.5	31.0	0.0107
	PM_{10} [µg/m³]	20.2	7.9	24.1	8.9	0.3451
	Temperature [°C]	20.8	4.5	20.3	4.4	0.2378
2007	NO_2 [µg/m³]	17.0	12.6	51.5	19.5	<0.0001
	O_3 [µg/m³]	82.6	19.6	63.2	16.2	<0.0001
	PM_{10} [µg/m³]	20.5	7.8	21.1	8.2	0.4928
	Temperature [°C]	19.2	3.6	18.7	3.5	0.2097
2008	NO_2 [µg/m³]	18.8	13.7	53.5	19.2	<0.0001
	O_3 [µg/m³]	70.1	21.4	69.6	25.1	0.8660
	PM_{10} [µg/m³]	16.4	7.5	18.0	9.9	0.1309
	Temperature [°C]	18.6	3.1	18.4	3.0	0.6182
2009	NO_2 [µg/m³]	13.2	9.7	44.1	17.4	<0.0001
	O_3 [µg/m³]	69.6	19.3	62.7	22.1	0.0044
	PM_{10} [µg/m³]	15.3	4.9	16.1	5.5	0.1883
	Temperature [°C]	18.8	3.3	18.3	3.3	0.1806

2010	NO$_2$ [µg/m^3]	15.6	11.5	53.3	24.7	<0.0001
	O$_3$ [µg/m^3]	74.9	17.5	65.6	19.3	<0.0001
	PM$_{10}$ [µg/m^3]	13.0	3.5	-	-	-
	Temperature [°C]	18.9	4.1	18.2	3.8	0.1082
2011	NO$_2$ [µg/m^3]	13.3	8.3	44.8	18.0	<0.0001
	O$_3$ [µg/m^3]	75.2	16.8	64.0	15.7	<0.0001
	PM$_{10}$ [µg/m^3]	15.3	5.1	15.6	6.9	0.7379
	Temperature [°C]	19.3	3.1	18.4	3.0	0.0099
2012	NO$_2$ [µg/m^3]	16.0	9.6	44.8	16.0	<0.0001
	O$_3$ [µg/m^3]	75.0	20.1	61.5	20.0	<0.0001
	PM$_{10}$ [µg/m^3]	16.5	6.6	17.0	6.6	0.4970
	Temperature [°C]	17.8	4.1	17.5	4.1	0.4175
2013	NO$_2$ [µg/m^3]	10.1	7.8	46.9	21.8	<0.0001
	O$_3$ [µg/m^3]	66.9	20.6	66.6	22.1	0.9088
	PM$_{10}$ [µg/m^3]	24.4	8.3	15.5	6.5	0.0006
	Temperature [°C]	19.1	4.6	19.2	4.5	0.7894

Table 5

Hottest month of the year and the frequency of hot days observed from 2003 to 2013 in rural and urban areas in Birmingham

Year	RURAL		URBAN	
	Hottest month	**Frequency: n (%)**	**Hottest month**	**Frequency: n (%)**
2003	August	10 (45.5)	August	9 (47.4)
2004	August	5 (45.5)	August	4 (40.0)
2005	July	6 (23.5)	July	6 (42.9)
2006	July	16 (55.2)	July	16 (50.0)
2007	September	2 (100)	August	2 (100)
2008	July	6 (85.7)	July	3 (75.0)
2009	June	3 (50.0)	June	3 (60.0)
2010	June	7 (58.3)	June	3 (75.0)
2011	August	4 (44.4)	August	2 (40.0)
2012	July	2 (100)	July	2 (66.7)
2013	July	15 (88.2)	July	17 (94.4)

Table 6

Comparison of the mean concentration of air pollutants (O_3, NO_2, and PM_{10}) and temperature between urban and rural sites during 2003, 2006 and 2013 heatwaves combined

Heatwaves		RURAL	URBAN	p-value
Year		Mean ± SD	Mean ± SD	
2003	NO_2 [µg/m^3]	21.3 ± 15.2	50.4 ± 24.0	**<0.0001**
	O_3 [µg/m^3]	97.5 ± 31.3	80.9 ± 27.5	**<0.0001**
	PM_{10} [µg/m^3]	21.5 ± 11.2	20.7 ±7.8	0.5093
	Temperature [°C]	20.4 ± 4.4	19.7 ± 4.3	0.2211
2006	NO_2 [µg/m^3]	19.8 ± 11.3	57.3 ± 23.4	**<0.0001**
	O_3 [µg/m^3]	82.6 ± 28.3	73.5 ± 31.0	**0.0107**
	PM_{10} [µg/m^3]	20.2 ± 7.9	24.1 ± 8.9	0.3451
	Temperature [°C]	20.8 ± 4.5	20.3 ± 4.4	0.2378
2013	NO_2 [µg/m^3]	10.1± 7.8	46.9 ± 21.8	**<0.0001**
	O_3 [µg/m^3]	66.9 ± 20.6	66.6 ± 21.1	0.9088
	PM_{10} [µg/m^3]	24.4 ± 8.3	15.5 ± 6.5	**0.0006**
	Temperature [°C]	19.1± 4.6	19.2 ± 4.5	0.7894