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Temperature and air pollution relationship during heatwaves in Birmingham, UK

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ABSTRACT

While temperature has long been known as a catalyst for pollutants to be more airborne, it is unclear how an increase in temperature affects air pollution during heatwaves. Through a regression analysis of 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 levels of O_3 and PM_{10}. These findings established that the influence of temperature on air pollution did not change according to rural or urban locations although air pollutants (O_3, PM_{10}, and NO_2) increased with increasing temperatures, particularly during heatwaves. Levels of ozone were found to increase by more than 50% with increases in temperature. This supports studies where the incidence of high levels of pollutants has conclusively been found to be much more prevalent during prolonged heatwaves. The implications of these findings are important to the establishment of long-term prevention measures in heatwave plans. When a heatwave is forecast, additional measures to reduce air pollutant concentrations may be appropriate when commencing emergency responses.

1. Introduction

Worsening air quality and extreme weather events, such as heatwaves, are increasingly affecting people worldwide. Heatwaves have long been known as an important driver of air pollutant levels, resulting in various health, environmental, and economic impacts (Cheval, Dumitrescu, & Bell, 2009; García-Herrera, Díaz, Trigo, Luterbacher, & Fischer, 2010). Air pollutants whose concentrations and impacts are known to be affected by heatwaves include ozone (O_3), particulate matter (PM) and nitrogen dioxide (NO_2). These pollutants, when emitted into the 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 level 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, PM_{10}, and NO_2) are the result of a mixture of various meteorological effects and chemical reactions. These pollutants are of the greatest health concern, as their emissions may be exacerbated during heatwaves (Analitis et al., 2014; Fouillet et al., 2006; Johnson et al., 2004). As a result, sensitive individuals may not only be stressed by high temperatures, but may be more subject to mortality due to air pollution during heatwaves (Analitis et al., 2014). Unusually hot weather during summer led to elevated levels of air pollutants during the heatwaves that occurred in Athens, Greece, between June and July 2007 (Fischer, Brunekreef, & Lebret, 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 was implicated in the increase in urban heat islands (UHIs) and air pollution in London, England (McMichael et al., 2003; Rooney, McMichael, Kovats, & Coleman, 1998).

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Heatwaves are particularly intense in urban areas, where surface characteristics alter the temperature differences between urban and rural areas. The differences are generated by low levels of vegetation in cities, and the production of anthropogenic heat and air flow caused by urban infrastructure such as buildings and asphalt streets (Bibri & Krogstie, 2017). Mirzaei (2015) indicated that extreme air temperatures in cities (UHIs) increase heat- and air pollution-related mortality and raise the energy demands for cooling buildings, which in turn leads to a further increase in air pollutants and greenhouse gas emissions. Despite this, several studies have shown that sustainable urban planning, and smart city design including green roofs and cool pavements could significantly reduce both UHIs 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 investigating temperature and air pollution during heatwaves (Fischer et al., 2004; Fouillet et al., 2006) have only explored the role of air pollution in modifying the effects of heatwaves on mortality. There is a dearth of research studies examining the relationship between temperature and air pollution during heatwaves, without considering mortality. In addition, there seems to be no research into the spatial relationships 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 (specifically ozone (O_3), particulate matter (PM_{10}) and nitrogen dioxide (NO_2)); and (3) investigate the difference in 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 Birmingham, a metropolitan city in the West Midlands region of the United Kingdom. Birmingham was selected as a study location because it is representative of typical population exposure as the largest and most populous British city outside London. This study used an 11-year data series (2003–2013) of O_3, PM_{10}, and NO_2 and meteorological data (temperature). Birmingham Tyburn (52.51 N, -1.83 W) and Harwell (51.57 N, -1.325283 W) air quality monitoring stations provided urban and rural data respectively (Fig. 1). Edgbaston (52.46 N, -1.91 W) and Coleshill (52.48 N, -1.689 W) weather stations provided the respective urban and rural meteorological data used in this study.

2.2. Air quality data

Historical air quality data (O_3, PM_{10}, and NO_2) from both the 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 part of England. The site is surrounded by fields and is considered representative of a rural location monitoring station (Charron, Birmili, & Harrison, 2007). The nearest road is to the east of the science park with access only to buildings. The nearest trees are 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 it 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 for the United Kingdom. The first assessment was of the availability of daily concentrations of O_3 (maximum 8-hour running average), NO_2 (the daily maximum value of the 1-hour mean) and PM_{10} (mean, 24 h). There were no air quality data for NO_2 for 2013 at Harwell monitoring station and for 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 Birmingham city centre, representing a rural environment) and Edgbaston (approx. 4 km from Birmingham city centre, representing an urban background) (see British Atmospheric Data Centre (http://badc.nerc.ac.uk)). The weather stations (urban and rural) were chosen based on data availability over the 11-year period, with reference to the literature that has previously used similar stations (Johnson, 1985; Tomlinson, Chapman, Thornes, & Baker, 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 close to the definition provided by the World Meteorological Organization (WMO), with some modification. According to the WMO, a heatwave is a phenomenon during which the daily maximum temperature for at least five consecutive days exceeds the average daily 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 analyzed the historical trend for ozone seasons, typically from May 1 to September 30 (U.S. EPA, 2009), these being the extended summer months (Shen, Mickley, & Gilleland, 2016), during which the probability of observing a heatwave is highest (Air Quality Expert Group, 2005). In this study, a heatwave was defined as a phenomenon during which the daily maximum temperature, for at least five consecutive days, exceeded the average daily maximum temperature by 6 °C. In addition to heatwaves identified in rural and urban areas, this study also noted some hot day episodes observed during the hottest years in Birmingham. We define a hot day episode as an episode of one to four consecutive days that occurred before or after a heatwave period, with temperatures greater than 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, SAS Institute, Cary, NC).

3. Results and discussion

This investigation focused only on severe heatwaves (2003, 2006 and 2013) where a high intensity and long duration of elevated temperatures were observed (Tables 1 and 2). In all heatwaves identified in rural and urban areas, the temperatures ranged from 26.9 to 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. Most hot days observed during the 11 years occurred in July for both sites, followed by June and August, respectively. Based on the heatwave definitions applied in this study, 8 heatwave periods were identified in the rural

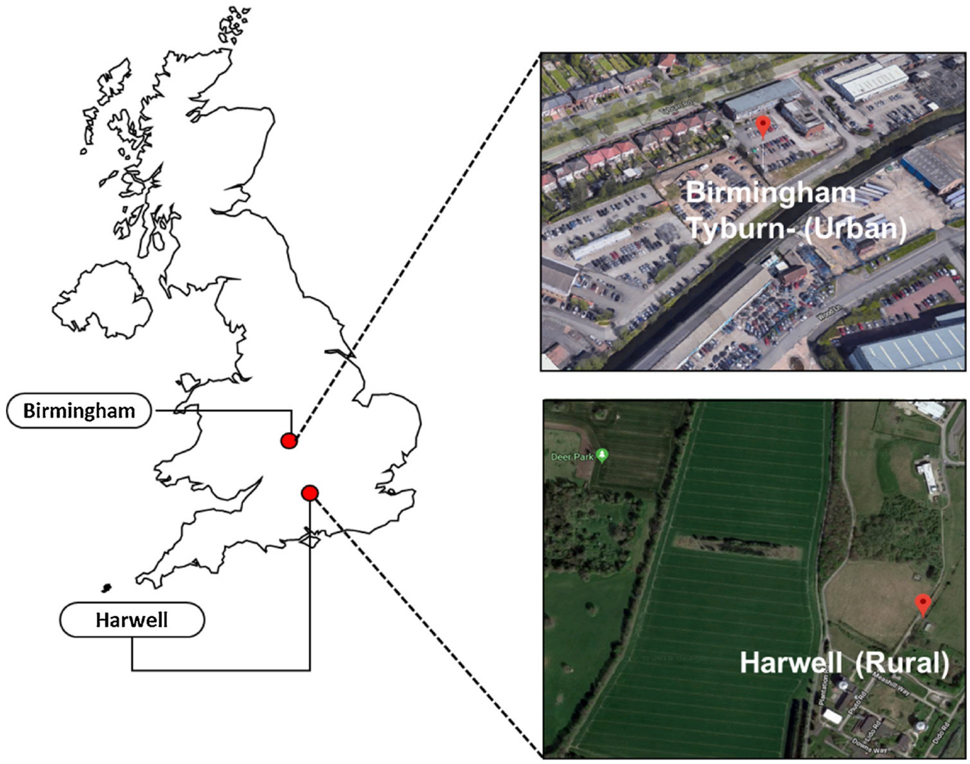


Fig. 1. Map of the United Kingdom and Ireland showing the location of the two UK air quality stations, Birmingham Tyburn (Urban) and Harwell (rural).

Table 1
Heatwave periods, corresponding annual maximum temperatures and concentration of air pollutants (O_3, 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 [$\mu g/m^3$]	PM_{10} [$\mu g/m^3$]	NO_2 [$\mu g/m^3$]
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 (O_3, 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 [$\mu g/m^3$]	PM_{10} [$\mu g/m^3$]	NO_2 [$\mu g/m^3$]
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

area (Table 1) and 7 heatwaves in the urban area (Table 2). The most severe heatwaves with the 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 frequencies of hot days (more than 5 days in a month) observed between 2003 and 2013 were in August 2003 (45.5%), July 2006 (55.2%) and July 2013 (88.2%) in both rural and urban areas (Table 5). 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; 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). Heatwave duration and intensity can be important factors for a significant increase in the concentration of air pollutants, particularly O_3 (Theoharatos et al., 2010). The results (Table 3) show that daily maximum temperatures were significantly higher in rural areas than in urban areas ($p = 0.0156$) during the summer months (May 2003–September 2013). Pearce, Beringer, Nicholls, Hyndman, and Tapper (2011) state that urban areas are warmer than their surrounding areas due to the characteristics of urban surfaces, radiative trapping effects, significant human activity, heat release, high heat capacity and the lack of green space (vegetation and moisture). However, the use of the daily maximum temperature metric may explain why high temperatures were not observed in urban areas in this study, because of the behaviour of urban heat islands (UHIs), which is normally most apparent during the night. In addition, summer temperatures dry the ground in rural areas, which enhances the amount of solar radiation reflected back to the atmosphere and increases the daytime temperature. Research in the UK showed that the UHI effect enhances night-time temperatures, especially during heatwaves (Oke, 1973; Tomlinson et al., 2012). Many cities like Birmingham reported night-time air temperatures that were warmer in urban areas than surrounding rural areas. Tomlinson et al. (2012) indicated that the Birmingham UHI created an increase in night-time temperature of more than 4.5 °C on a heatwave day in 2006 and Heaviside, Cai, and Vardoulakis (2015) showed an increase 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 surfaces absorb

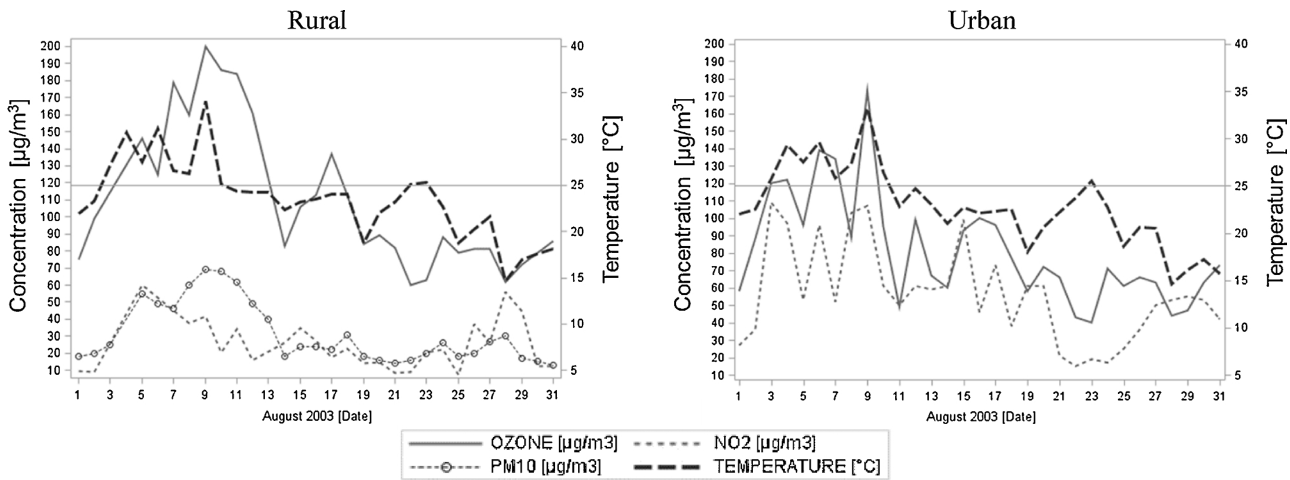


Fig. 2. Mean concentrations of air pollutants (O_3, NO_2, and PM_{10}) and temperature during heatwaves in August 2003.

Table 3
The mean concentration of air pollutants (O_3, NO_2, and PM_{10}) and temperatures in rural and urban locations from May 2003 to September 2013.

	RURAL		URBAN		p-value
	Mean	Std	Mean	Std	
Daily max NO_2 [µg/m^3]	17.5	12.4	50.6	21.7	< 0.0001
Daily max O_3 [µg/m^3]	76.2	24.8	69.1	25.0	< 0.0001
Daily mean PM_{10} [µg/m^3]	18.4	8.1	19.1	8.1	0.0765
Daily max temperature [°C]	19.4	4.1	19.0	4.0	0.0156

more energy from the sun. Rural areas tend to have a high albedo because the daytime temperature becomes high once incoming radiation is reflected in the atmosphere, while urban areas (urban materials) absorb heat during the day and release it during the night. Furthermore, Johnson (1985) indicated that the level of heating and cooling in urban and rural areas could be explained by the sky view factor (SVF), which is the amount of sky visible from the ground. For example, the sky view factor controls the radiation balance in Birmingham city centre because of the tall buildings. 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 regarding the Birmingham UHI (Tomlinson et al., 2012). Unwin (1980) also used a similar weather station (Edgbaston) in a study comparing daily minimum and maximum temperatures at two sites, Edgbaston and Elmdon. The results showed that the average temperature (daily maximum) was lower at Edgbaston, which represents an urban area, compared to Elmdon, a rural area, where the heat island effect caused a higher nighttime minimum temperature than at Edgbaston. The current research supports Unwin's (1980) study, which indicated that a daytime cool urban island exists in Birmingham City.

3.1. Air pollution and heatwaves

3.1.1. Temperature and air pollution relationship during heatwaves of August 2003

Over the 11 years covered by the data in this study, the mean concentration of O_3 ($p < 0.0001$) and the peak daytime temperature ($p = 0.0156$) (Table 3) were significantly higher in rural than urban areas. However, the mean concentrations of NO_2 were significantly higher in the urban environment compared to the rural area ($p < 0.0001$). Only PM_{10} did not show a statistically significant difference in mean concentration between rural and urban areas ($p = 0.0765$). The comparisons of mean concentrations of air pollutants (O_3, PM_{10}, and NO_2) and temperatures between urban and rural sites for all 11 years are shown in Table 3. Details for each year (2003–2013) for mean concentrations of air pollutants (O_3, PM_{10}, and NO_2) and temperatures in rural and urban areas are presented in Table 4. During 2003 the mean concentrations of O_3 and NO_2 were significantly different between urban and rural areas (Table 6). Temperature, O_3, PM_{10}, and NO_2 concentrations on days with heatwaves were significantly higher than those on non-consecutive "hot" days. Additionally, O_3 concentrations rose at both urban and rural sites and coincided with the peak maximum temperatures. The peaks in temperature coincided with the peak of O_3, NO_2, and PM_{10} on 9 August 2003, in both rural and urban areas (Fig. 2). During the same month, 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, but not for PM_{10}. These findings are consistent with those previously reported for heatwaves in the US (Lee et al., 2006) and the Netherlands (Tomlinson et al., 2012). Previous studies report an indirect relationship between air pollution and temperature during heatwaves, by comparing the effects of air pollution and temperature on mortality during heatwave periods (Analitis et al., 2014; Filleul et al., 2006; Stedman, 2004) and non-heatwave periods (Carslaw, Beevers, & Tate, 2007; Pearce et al., 2011). These studies support our present findings.

3.1.2. Temperature and air pollution relationships during the 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 and 2013. Generally, the O_3, PM_{10}, and NO_2 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 correlations between temperature and air pollution were significant and positive for 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 pattern, with peaks situated in periods of high temperature. Statistically significant variations and positive correlations

Table 4
May to September averages of air pollutants and temperatures in rural and urban locations from 2003 to 2013.

Year		RURAL		URBAN		p-value
		Mean	± SD	Mean	± SD	
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/m³]	15.6	11.5	53.3	24.7	< 0.0001
	O_3 [μg/m³]	74.9	17.5	65.6	19.3	< 0.0001
	PM_{10} [μg/m³]	13.0	3.5	–	–	–
	Temperature [°C]	18.9	4.1	18.2	3.8	0.1082
2011	NO_2 [μg/m³]	13.3	8.3	44.8	18.0	< 0.0001
	O_3 [μg/m³]	75.2	16.8	64.0	15.7	< 0.0001
	PM_{10} [μg/m³]	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/m³]	16.0	9.6	44.8	16.0	< 0.0001
	O_3 [μg/m³]	75.0	20.1	61.5	20.0	< 0.0001
	PM_{10} [μg/m³]	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/m³]	10.1	7.8	46.9	21.8	< 0.0001
	O_3 [μg/m³]	66.9	20.6	66.6	22.1	0.9088
	PM_{10} [μg/m³]	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 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)

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 indicate that the 2006 heatwaves were much longer in terms of duration, and the large number of mortalities recorded in Birmingham during the 2006 heatwave compared to the August 2003 heatwave may be attributable to this (Vardoulakis & Heaviside, 2012). Heatwave duration and intensity can be important factors in significant increases in the concentration of air pollutants, particularly O_3 (Theoharatos et al., 2010).

Table 6
Comparison of the mean concentration of air pollutants (O_3, NO_2, and PM_{10}) and temperatures in urban and rural sites during the 2003, 2006 and 2013 heatwaves combined.

Heatwaves Year		RURAL Mean ± SD	URBAN 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
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
2013	NO_2 [μg/m³]	10.1 ± 7.8	46.9 ± 21.8	< 0.0001
	O_3 [μg/m³]	66.9 ± 20.6	66.6 ± 21.1	0.9088
	PM_{10} [μg/m³]	24.4 ± 8.3	15.5 ± 6.5	0.0006
	Temperature [°C]	19.1 ± 4.6	19.2 ± 4.5	0.7894

3.1.3. Temperature and air pollution relationship during the 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 indicates that pollution changes were not instantly linked to variations in temperature. In fact, there was a time lapse between an increase or decrease in temperature and an increase or decrease in air pollution. This suggests an effect of both the current and previous days' temperatures on air pollution readings.

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

Based on simple linear regression analysis, the relationships between air pollutants (O_3, PM_{10}, and NO_2) and temperature during all intense heatwaves in 2003, 2006 and 2013 are presented in Fig. 6. Observation-based statistical analysis showed that temperature affects all three air pollutants, particularly O_3 and PM_{10}. Strong correlations were also found between these pollutants and temperatures 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 that for PM_{10} (R^2 = 0.32, $p < 0.0001$) or NO_2 (R^2 = 0.04, p = 0.0566) during intense heatwaves identified in rural areas (Fig. 6). Fig. 4 indicates that temperature strongly correlated with NO_2 during the heatwave of July 2006 ($R^2 > 0.50$). A peak in NO_2 was observed at the beginning of the heatwave, on 5 August 2003 in rural areas and 3 August 2003 in urban areas. The annual number of exceedances of air quality standards (40 μg/m³ annual mean), matched the annual number of heatwave days. This may be attributable 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). A comparison of the 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 rural and urban areas.

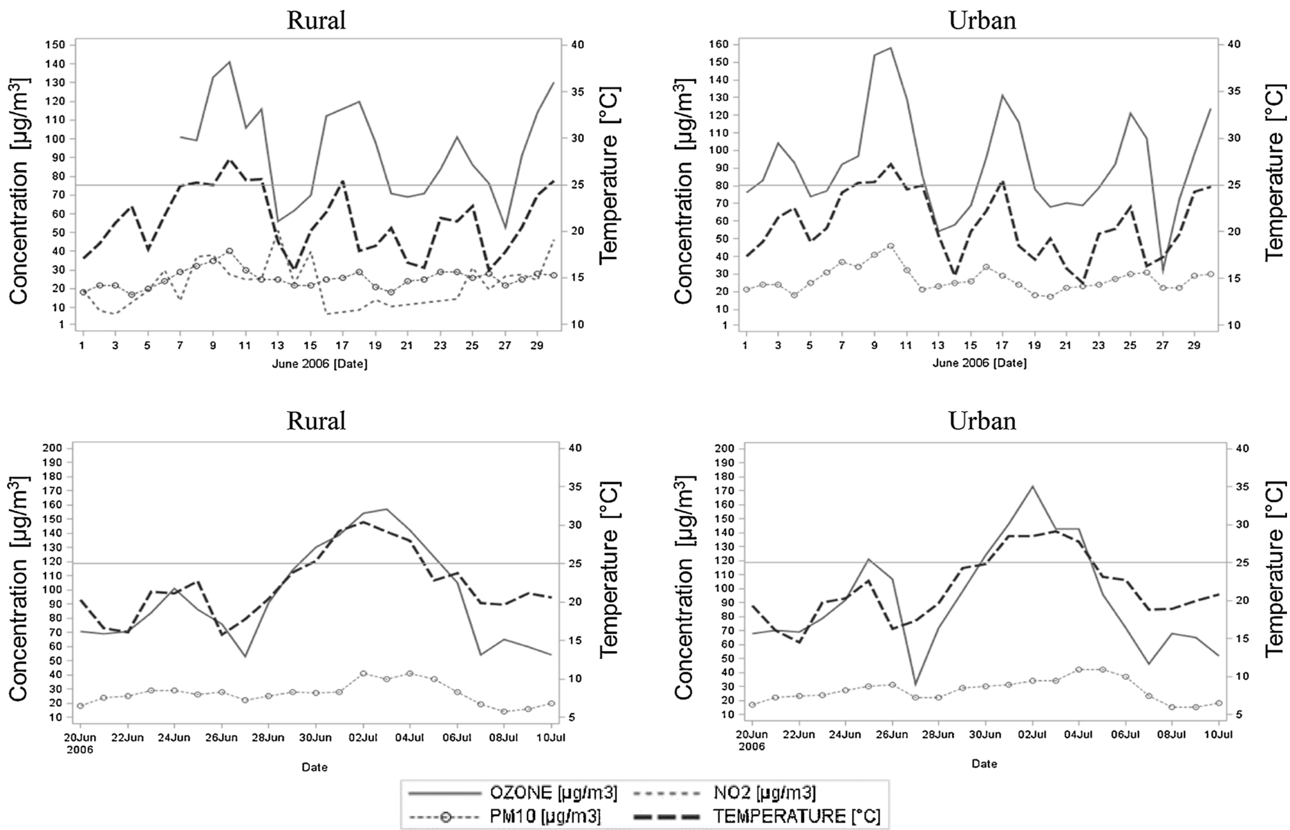


Fig. 3. Mean concentrations of air pollutants (O_3, NO_2, and PM_{10}) and temperature during heatwaves spanning June to July 10th, 2006.

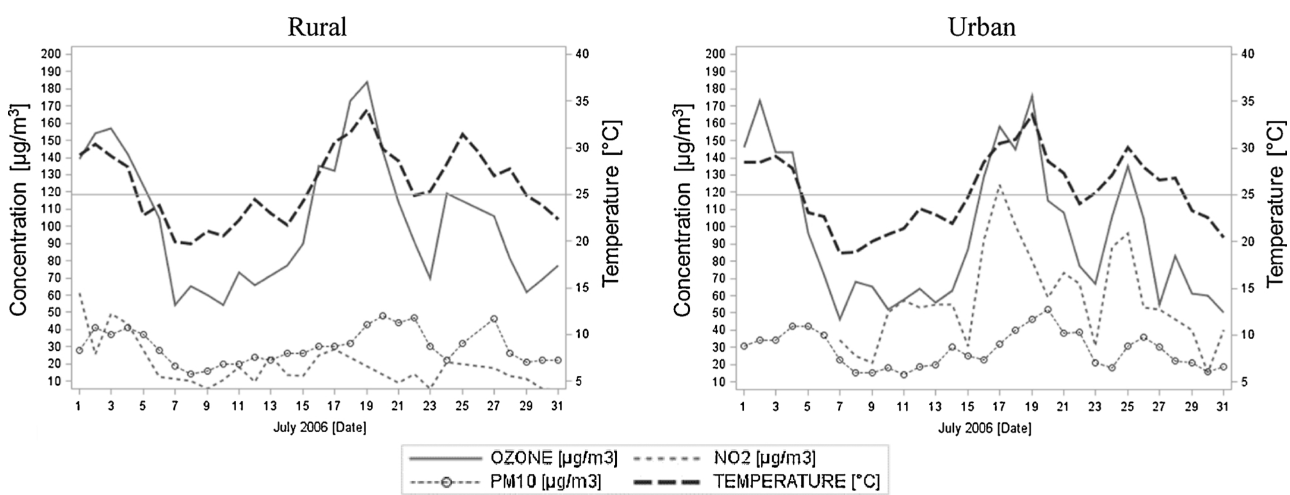


Fig. 4. Mean concentrations of air pollutants (O_3, NO_2, and PM_{10}) and temperature during heatwaves in July 2006.

3.2.1. 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 (33.2 °C) areas. 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 only moderate in the urban area. The fact that ozone levels were more commonly higher in rural areas than in cities can be explained by ozone degradation by its precursors (NO_x) (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 is formed on hot days by the influence of solar radiation and becomes airborne. Ozone degradation occurs more often in cities than in rural areas, because there is more NO_x 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 of nitrogen oxides helps the removal of OH radicals, through reaction with NO_2 (Qian, Hospodsky, Yamamoto, Nazaroff, & Peccia, 2012). In addition, the peaks of O_3 during heatwaves are due to favourable temperatures and plenty of sunlight, which promote photochemical reactions (Katsouyanni et al., 2001). Furthermore, UHIs can also contribute to the production and dispersion of O_3 (Chaxel & Chollet, 2009). We found

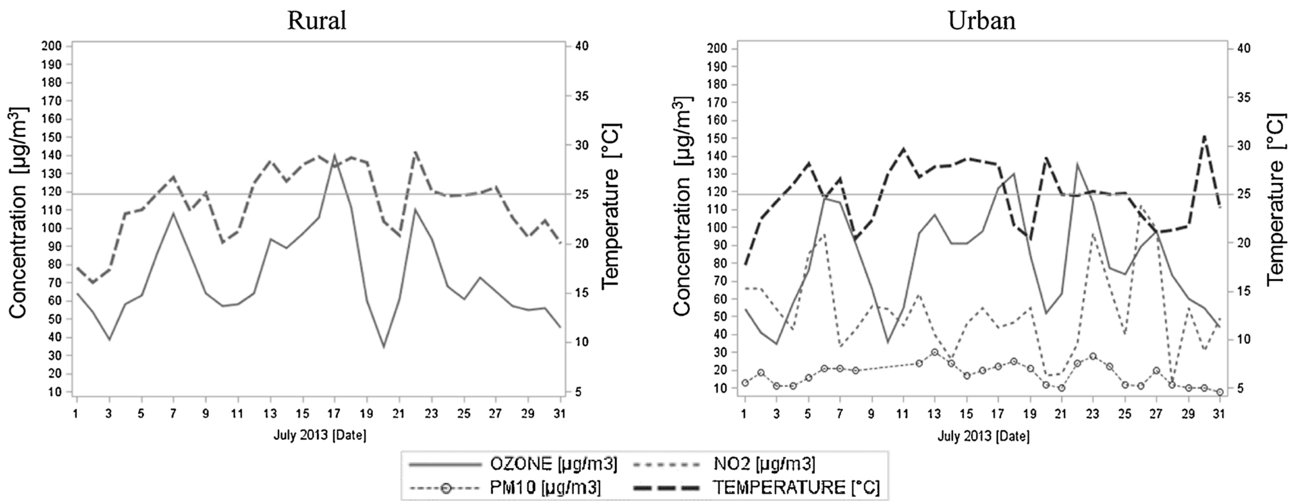


Fig. 5. Mean concentrations of air pollutants (O_3, NO_2, and PM_{10}) and temperature during heatwaves in July 2013.

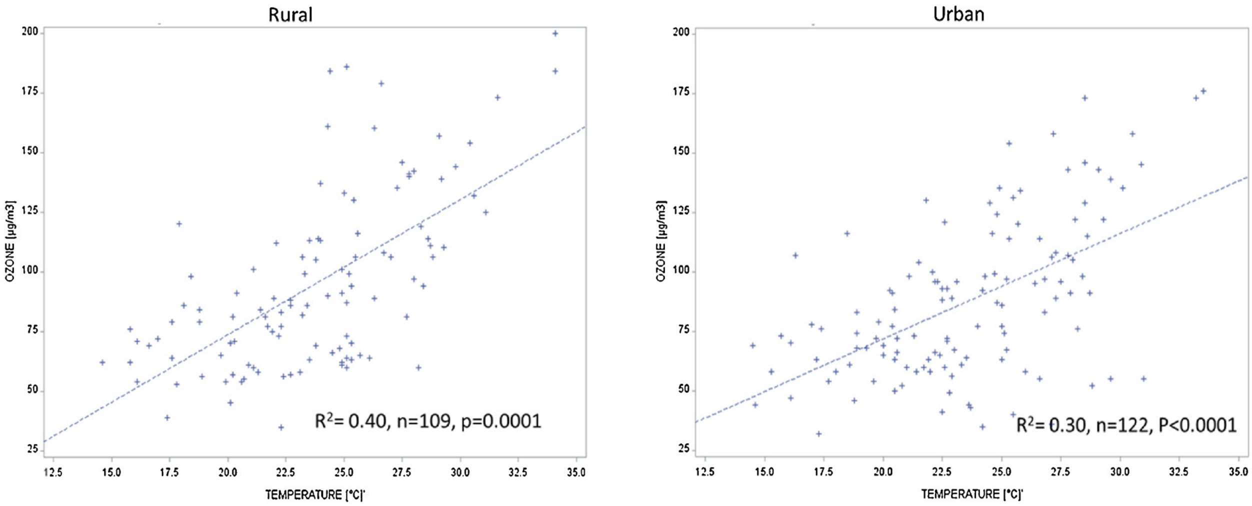
that when the temperature was lower, especially during non-heatwave periods, O_3 concentration did not correlate with the air temperature. However, a strong correlation was observed during heatwave periods of a longer duration (Fig. 4). There are various plausible explanations for a synergistic association 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 (Monks et al., 2015; Solberg et al., 2008). These findings are consistent with previous studies that reported strong correlations between pollutants and temperature during heatwaves (Chaxel & Chollet, 2009; Dawson, Adams, & Pandis, 2007; Heal et al., 2013; Huang et al., 2010; Johnson et al., 2004).

3.2.2. Particulate matter (PM_{10})

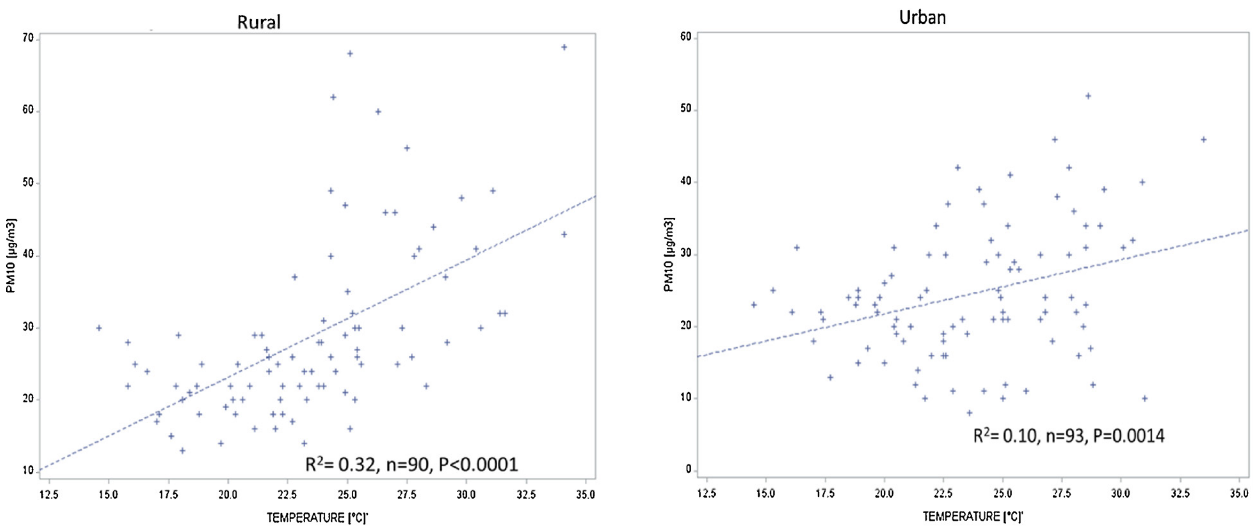
Air pollutants are generally more concentrated in urban areas than in rural areas due to large emissions caused by human activities (Hewitt & Jackson, 2009; Jacobson, 2012). This study found that the average concentration of PM_{10} was higher in urban than in rural areas during heatwave years recorded in Birmingham (Table 1). Temperature increases led to increased levels 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; Massey, Kulshrestha, Masih, & Taneja, 2012; Tai, Mickley, & Jacob, 2010). The higher concentration of PM_{10} in urban areas than in rural areas is probably due to there being more emission sources in urban areas. This results in turbulent flow and elevated PM_{10} levels in congested areas with tall buildings, which stop air movement and trap pollutants. Birmingham city centre has many tall buildings, which thus contribute to increases in ground-level concentrations of PM_{10}. In addition, PM_{10} increases in urban areas because of vehicle emissions and road transport-related emissions (tyre wear and brake wear), (Barlow et al., 2007; Dore et al., 2003). These findings are in agreement with previous studies (Air Quality Expert Group, 2005; Analitis et al., 2014; Elminir, 2005; Pearce et al., 2011; Vardoulakis & Kassomenos, 2008). Mues et al. (2012), investigating the effect of meteorological conditions on the concentration of PM_{10} in the extreme European summer of 2003, observed that the concentrations of PM_{10} increased during weather conditions with high daily maximum temperatures. Pollution levels can therefore be further increased during heatwaves because of the atmospheric conditions that prevail, leading to the accumulation of pollutants (Tressol et al., 2008). This suggests that during summer episodes when hot weather is associated with slow wind speeds, high temperatures increase the likelihood of O_3 and NO_2 emissions. High ambient temperatures support the production of secondary aerosols. Thus, the increased concentration of NO_2 and O_3 during the summer can be attributed to the production of secondary aerosols (Elminir, 2005). Furthermore, in Birmingham, the concentration of PM_{10} was found to be higher during periods of low wind speed (poor dispersion conditions) and this is thought to be a result of atmospheric stability and a reduced mixing of air (Vardoulakis & Kassomenos, 2008). Typically the increased concentration of PM_{10} during warm seasons in Athens has been attributed to the relative contribution of secondary and natural particles during hot, dry days (Kassomenos et al., 2014).

3.2.3. Nitrogen dioxide (NO_2)

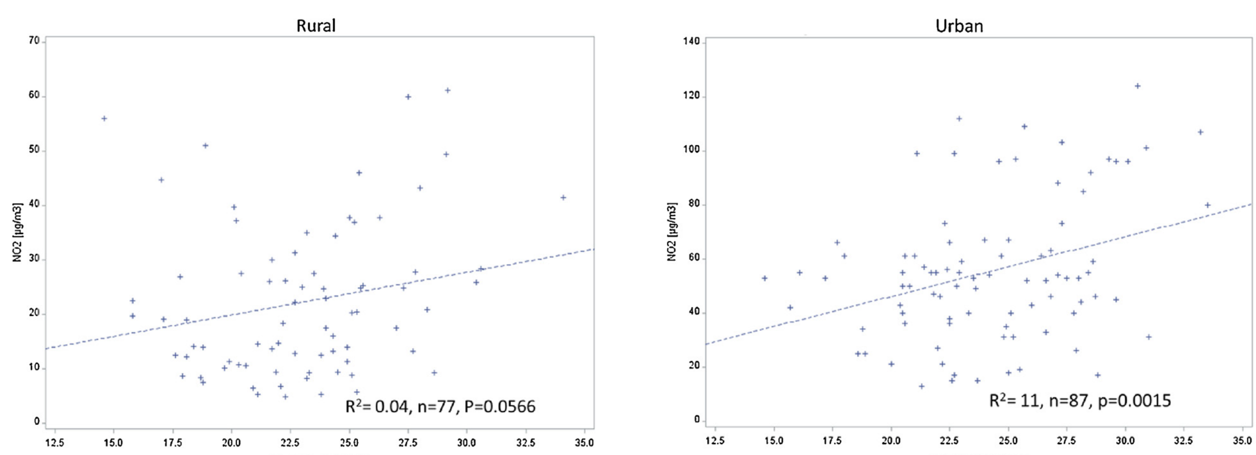
The results of this study, as shown in Tables 1 and 2, show that the mean concentration of NO_2 was significantly higher in urban (51.7 µg/m^3) than in rural areas (18.4 µg/m^3). The higher concentration in urban areas was largely due to emissions from traffic congestion, which is greater in urban than in rural areas. DEFRA (2004) and the US EPA (2009) have indicated that throughout the UK, 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) with NO_2 levels during heatwave events. Pearce et al. (2011) report that when the temperature rises above 35 °C, NO_2 increases by about 120%. It has been reported that in Cairo (Egypt) the annual monthly average concentration of NO_2 levels peaks during the summer, particularly in July, at around 103 µg/m^3, and from August to December, the monthly average concentration of NO_2 decreases from about 82 to 62 µg/m^3 (Elminir, 2005). In Fig. 4 the temperature strongly correlates with NO_2 levels during the heatwave of July 2006 ($R^2 > 0.50$). A peak in NO_2 was observed at the beginning of the 2003 heatwave, on 5 August in rural areas and 3 August 2003 in urban areas. The annual number of exceedances of the air quality standards (40 µg/m^3 annual mean) matches the annual number of heatwave days. This may 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 during heatwaves than on other hot days, due to the higher temperature range. However, the influence of temperature on NO_2 during a heatwave is low compared to its effect on ozone and PM_{10}. In conclusion, NO_2



(a) Correlation analysis between O_3 and heatwaves.



(b) Correlation analysis between PM_{10} and heatwaves.



(c) Correlation analysis between NO_2 and heatwaves.

Fig. 6. Correlation analysis of air pollutants (O_3, PM_{10}, and NO_2) and all intense heatwaves identified in 2003, 2006 and 2013.

concentration increases with increasing temperature during heatwave events, which strongly agrees with previous related studies (Pearce et al., 2011; Rooney et al., 1998; Stedman, 2004).

4. Conclusion

This study 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 a positive correlation between temperature and air pollution during heatwaves and that the relationship between temperature and air pollution was more apparent for high intensity and long duration heatwaves. The variation in average air pollution levels in relation to heatwave duration exhibited a peak that was more pronounced for O_3. The implications of these findings are important for policy development; for example, when there is a heatwave forecast, additional measures to reduce air pollutant concentrations may be appropriate when commencing emergency responses, and these measures may be applicable in both urban and rural environments. Based on our findings, it would seem unwise to attempt to include health effects such mortality in assessing the correlation between temperature and air pollution. However, assessment of the health effects of high temperatures and air pollution should be conducted during heatwave periods. Air pollution is so closely related to temperature that removing one variable (either 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 the incidence of health effects.

Conflicts of interest

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

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