The influence of meteorology and air quality on parkrun athletic performance

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Abstract

Background: Despite increased awareness of climate change and urban air pollution, little research has been performed to examine the influence of meteorology and air quality on athletic performance of the general public and recreational exercisers. Anecdotal evidence of increased temperatures and wind speeds as well as higher relative humidity conditions resulting in reduced athletic performance has been presented in the past, whilst urban air pollution can have negative short- and long-term impacts on health. Furthermore, pollutants such as Ozone, Nitrogen Dioxide and Particulate Matter can cause respiratory and cardiovascular distress, which can be heightened during physical activity. Previous research has examined these impacts on marathon runners, or have been performed in laboratory settings. Instead, this paper focuses on the potential impacts on the general public. With the rise of parkrun events (timed 5 km runs) across the UK and worldwide concerns regarding public health in relation to both air quality and activity levels, the potential influence of air quality and meteorology on what is viewed as a 'healthy' activity has been investigated. A weekly dataset of parkrun participants at fifteen events, located in London UK, from 2011-2016 alongside local meteorological and air quality data has been analysed.

Results[JH(G+ESLF1] **:** The biggest influencer on athletic performance is meteorology, particularly temperature and wind speed. Regression results between parkrun finishing times and temperature predominantly show positive relationships, supporting previous laboratory tests (p=0[JH(G+ESLF2] .01). Increased relative humidity also can be associated with slower finishing times but in several cases is not statistically significant. Higher wind speeds can also be related to slower times (p=<0.01) and in contrast to temperature and relative humidity, male participants are more influenced than female by this variable. Although air quality does influence athletic performance to an extent, the heterogeneity of pollutants within London and between parkrun events and monitoring sites makes this difficult to prove decisively.

Conclusions: It has been determined that temperature and relative humidity can have the largest detrimental impact on parkrun performance, with ozone also being detrimental in some instances[JH(G+ESLF3] . The influence of other variables cannot be discounted however and it is recommended that modelling is performed to further determine the extent to which 'at event' meteorology and air quality has on performance. In the future, there results can be used to determine safe operating and exercise conditions for parkrun and other public athletics events.

Key Points

- Temperature and relative humidity have the largest detrimental impact on parkrun participants in the Greater London area.
- Air quality impacts are less clear but it is shown that ozone, as an irritant to the cardiorespiratory system, can lead to slower times.
- Modelling 'at event' air quality is recommended to improve data resolution and influence on participants.

Introduction

Urban air quality (UAQ) has become a widespread and serious issue and focus for countries worldwide, with poor air quality having detrimental impacts on the environment and human health [1-5]. This includes cardiovascular and respiratory distress, for example, contributing to the incidence of acute lower respiratory infections, and also particularly for those with pre-existing conditions such as asthma, which can also be aggravated by poor air quality [6, 7]. Poor air quality also contributes to premature deaths [6, 7]. Furthermore, research has recently started to identify links between poor air quality and cognitive functions, with results suggesting negative impacts across a range of demographics [8-12]. It has been suggested that exercising in poor air quality can reduce exercise-induced cognitive improvements [13]. With continuing development, urbanisation and increasing pollutant sources, especially vehicles, urban air quality and associated health impacts are expected to worsen in the coming years [14-16].

The impact of UAQ on human health is a cause for concern, with nitrogen dioxide (NO_2), ozone (O_3) and particulate matter (particles with a diameter of 10 μm (PM_{10}) and 2.5 μm ($PM_{2.5}$) or less) being the main influencers. These pollutants can have detrimental respiratory and cardiovascular impacts, including irritation of the eyes, nose, throat and respiratory system, leading to breathing difficulties [17]. In a time when medical professionals are encouraging patients and the general public to be more active, there is the question as to whether increasing outdoor physical exercise may be doing more harm than good, or whether poor UAQ is hindering exercise performance [18, 19]. Despite this, research has suggested that the benefits of exercise outweigh the negative effects of poor air quality and therefore does not contribute to early mortality [18, 20-22].

Future predictions for global warming and increasing temperatures suggest that activity levels will be reduced due to thermal stress as well as reduced competitive levels at events [23, 24]. This is due to exercise altering the bodies thermoregulatory, circulatory and endocrine systems and a reduced capability to maintain a suitable internal body temperature, especially in warmer and more humid conditions [23]. These impacts have also been demonstrated under current climate conditions for temperature, relative humidity and wind speed, with increased values often resulting in slower or reduced performances [25].

This work investigates the role of UAQ and meteorology on amateur athletic performance using parkrun as a natural experiment. parkrun events provide free, timed 5km runs on Saturday mornings, starting at 9 am, and have developed from an individual event in Bushy Park, London, UK in 2004 into a UK phenomenon with a rapidly increasing international reach. Events are open to all abilities and ages and promote physical activity within local communities [26, 27]. The wide popularity of parkrun events, twinned with their mental and physical health benefits has resulted in there being over 100,000 weekly participants in the UK along with others in twenty additional countries [26, 28-31]. Consequently, this provides a high quality, weekly UK dataset to determine the influence of local air quality and meteorology on the athletic performance on the general population.

Background

2.1 The Influence of Temperature on Athletic Performance

The impact of meteorology on parkrun performance is often anecdotal information, however, the influence of temperature on performance has been explored in a number of marathon and laboratory studies, which have found that athletic performance decreases as temperature increases [25, 32, 33]. Exercising in warmer temperatures can alter the bodies circulatory, endocrine and thermoregulatory systems, increasing the risk of adverse effects including dehydration, hyperthermia and heat stress due to reduced internal body temperature regulation [23]. This is due to the cardiovascular system having to meet the demands of blood flow to vital organs, skin and contracting muscles, the former of which, along with maintaining blood pressure, takes precedence and leads to a reduced ability to regulate internal body temperature, increased blood lactate levels within muscles and reduced maximal oxygen uptake [34, 35]. These all lead to increased fatigue and reduced power output or speed during athletic performances or time trials [23, 36, 37]. In contrast, cold temperatures can help maintain an optimum core temperature if suitable clothing is worn and heat is produced, but extreme cold can reduce blood supply and cardiorespiratory capacity [38, 39].

The majority of research on the impact of temperature on athletic performances has been focused on marathons. Vugts [40] determined that the quickest finishing times at the Beijing and Boston marathons were recorded in during temperatures of 8°C. Meanwhile Ely *et al*. [32] and Brotherhood [41] highlighted reduced performance in increasing temperatures, particularly for the slower finishers who experience greater heat stress when running in larger groups. More recently, Helou *et al*. [25] further confirmed the work of Vugts [40] by determining that temperatures of 3.8-9.9°C resulted in the quickest times registered at several major international marathons.

Age and gender are can also influence the extent to which temperature impacts performance, albeit with differing results. Sandsund *et al*. [42] and Renberg *et al*. [43] suggest that ambient air temperature has little to no impact on female short-duration exercise performance whilst male athletes have an optimum range. In contrast, Maffetone *et al*. [44] showed that both genders have been equally impacted by temperature fluctuations at the Boston marathon. Middle-aged and older demographics have also shown reduced athletic performance under increased temperature, likewise with children who experience increased heat gain and then reduced dissipation due to their lower sweating capacity and cardiac output [45, 46].

2.2 The Influence of Relative Humidity on Athletic Performance

Humidity can also impact athletic performance. Helou *et al*. [25] showed that after temperature, humidity had significant impacts on both male and female athletic performance as heat dissipation is limited under higher humidity conditions because of reduced sweat evaporation [34, 35]. Maintenance of an optimal core body temperature and thus performance requires heat loss to equal heat production during exercise, therefore high relative humidity levels can reduce performance due to limited amounts of heat dissipation [34, 35]. There is also an increased risk to health in cases of high relative humidity and temperature due to the combined stress this puts on the body [47].

2.3 The Influence of Wind on Athletic Performance

Wind direction, wind speed and wind chill are all variables that can, to an extent, influence athletic performance. In high temperatures, the cooling effect of wind can be beneficial, with a wind speed of 4 ms^{-1} providing double the cooling level as a 1 ms^{-1} wind [40]. However, in colder conditions, this cooling can be detrimental as it can lower core the core body temperature below optimal levels for performance and greater levels of blood flow are diverted to maintaining vital core functions and temperature rather than muscular contractions required for performance. Despite the potential influence of wind speed, Vihma [33] showed that it does not always result in significant results on performance. This is likely due to wind direction. As parkrun courses generally start and finish near the same location and consist of some form of loop, it is expected that there will not be a consistent dominant head- or tailwind. However, Davies [48] showed that headwinds will reduce finishing times to a greater extent than a tailwind can aid performance, thus completing an event half into a headwind and half into a tailwind will result in a finishing time that is slower on average by 3.6 s/km.

2.4 The influence of Air Quality upon Athletic Performance

The influence of air pollution on athletic performance and cardiovascular and respiratory health has been examined in several studies; often in laboratory settings [reviewed by Giles and Koehle, 18]. Higher intensity exercise sees a switch from nasal to oral breathing and reduced respiratory defences, thus greater potential for increased pollution exposure [18, 50-52]. Despite this, studies have failed to unanimously show that poor air quality is detrimental to performance [18, 53-56].

However, there have been numerous studies that highlight air pollution, notably O_3, can decrease lung function and potentially contribute to reduced athletic performance [57-60]. Additionally, it has been noted that air pollution can trigger asthma attacks due to its irritant qualities. Asthma is a respiratory condition prevalent in both the general population and elite athletes and it is believed that physical exercise can enhance the negative effects of O_3 pollution [58, 60-64]. Pre-exposure to and performance in poor air quality has also been shown to reduce VO_2 max (maximal oxygen uptake) performance in tests [65, 66].

Particulate matter has also been identified as being detrimental to performance, reducing lung and cardiovascular function, arterial pressure, arterial vasodilation and athletic performance, including those who are not asthmatic [59, 60, 67, 68]. Importantly, a pre-test ‘accumulation’ session was performed, suggesting that exposure prior to exercise, or a warm up, can hinder later performance [59, 60, 68].

Limited real world examination of pollution influencing athletic performance has been conducted. Most notably Marr and Ely [69] and Helou *et al.* [25] both examined yearly marathon finishing times. The former determined that increases in PM_{10} resulted in decreased female performance whilst Helou *et al.* [25] showed that increases in temperature above an optimal range also resulted in slower finishing times. Additionally, O_3 was determined to be also detrimental to marathon performances, although this was linked potentially to covariance with meteorological effects [25]. Although not focused on athletics, a long-term study of the professional German football league showed a causal relationship between local air quality and productivity, whilst it has also been shown that large deviations from an ideal walking speed of 2-6 km/h for minimal pollution uptake can more than double the inhalation dose [70, 71].

Based upon previous research, there has been limited real-world examination of air quality and /or meteorology on athletic performance. Where studies exist, they have focused on either elite athletes or a small number of finishers. It is important to acknowledge that meteorology and air quality are not separate parameters for investigation. Notably, NO_2 and O_3 levels alter in response to sunlight and temperature, whilst relative humidity and wind speed can influence PM concentrations [16, 72-75]. Indeed, the importance of climate and air quality has been highlighted with an estimated additional 423-769 deaths occurring during the 2003 UK heatwave as a result of elevated temperature, O_3 and PM_{10} [76, 77]. With deaths in recent Belfast and London marathons also being attributed to extreme temperatures, the response of the wider public and athletic participants to both general and adverse weather and air quality conditions needs to be examined, particularly with climate change predicted to increase mean and extreme temperatures [78-80]. Furthermore, under future climate change predictions of increased temperatures, rising levels of thermal discomfort may also lead to reduced physical activity participation and thus community and public well-being [80, 81]. Therefore, as public knowledge of UAQ and parkrun events and popularity spreads, the relevance of this research is increased and could be used to educate the general public when and where might be best to exercise outdoors.

Materials And Methods

The parkrun events examined in this study are all located within Greater London. This location was chosen because of the relatively high spatial coverage of air quality monitoring stations and parkrun events. Furthermore, London often breaches European air quality limits with poor UAQ contributing to an estimated 9,400 premature deaths, which costs between £1.4 and £3.7 billion per year [82-85]. Finishing times for participants of fifteen parkrun events (Fig 1) from 2011-2016 were provided by the parkrun research board. These were selected due to their close proximity to Department for Environment, Food and Rural Affairs (DEFRA) monitoring stations (<15 km) to utilise as accurate 'at event' readings as possible due to the high spatial variability of air quality [86-89]. The parkrun dataset contains details of the parkrun location, event date, individual run times of each participant on that corresponding date, their gender and age group. The parkrun finishing time data was anonymised prior to research access being given in accordance with the completed and agreed ethics procedures (ERN_17-1583).

For each parkrun event, the weekly mean finishing time was calculated and then used for further analyses. This was for the complete participant list before being broken down into male and female times. It is important to note that due to the increasing success of parkrun events, average finishing times continue to increase due to growing participation levels. Therefore, decomposition of the run times was performed and the remainder value was used for analysis against the explanatory variables of temperature, relative humidity, wind speed, O_3, NO_2 and $PM_{2.5}$ (Fig 2).

The removal of long term trend and seasonality is determined to be required due to the variation in parkrun numbers over time as a result of parkrun gaining popularity and changes in participants over the course of the year. The decompose function in the R package 'forecast' was used to determine the seasonal, long term and random components within the data via an additive model. This is used because the seasonality variation remains relatively constant despite an increase in participation.

Meteorological data was obtained from the British Atmospheric Data Centre (BADC) using the Met Office Integrated Data Archive System (MIDAS). Seven stations (Fig 1) were used due to their proximity to the parkrun events being examined. Observations were downloaded for 09:00 on Saturdays to match the starting time of parkrun events and ensure that the values used in analyses were as accurate as possible to those the parkrun participants were exposed to. Air temperature, relative humidity and wind speed variables were downloaded. The worldmet package within R was utilised to import meteorological data for analyses [90]. This was quality checked against the MIDAS datasets and it was shown that temperature values were the same but relative humidity in some cases varied by up to 2%, although this is likely due to the formatting algorithms used in processing the data [91].

Air quality data for Greater London was retrieved from the DEFRA Automatic Urban and Rural Network (AURN) SITES, between 08:00 and 10:00 local time at background monitoring sites. This includes hourly readings for NO_2, O_3, $PM_{2.5}$ and PM_{10}. PM_{10} was subsequently removed from analyses due to its high correlation to $PM_{2.5}$, while the latter was retained due to the greater association of smaller particles with deleterious health effects. Locations of the monitoring sites can be seen in Fig 1 and were selected due to them being urban background sites, i.e. not in direct proximity to roadsides and vehicular pollution, measuring all or most of the above pollutants and their proximity to parkrun events. The mean 08-10:00 air quality values were found and used for analysis to capture the air quality participants were potentially exposed to before and during the events.

Each parkrun site was paired with the closest DEFRA AURN and Met Office locations (Table 1). Although some are not optimally placed, they are indicative of the local air quality. Due to not all measurement sites recording all of the desired explanatory variables, some events have been analysed against a reduced times series as dates containing missing data have been removed from analysis. Likewise, with discrepancies in the meteorological data. Prior to analysis, parkrun finishing times over ninety minutes were discarded, as these were technical issues indicated by parkrun [92]. Additionally, correlation and regression analysis shows that there is no statistical relationship between the parkrun's distance from air quality or meteorological stations and finishing times ($p>0.11$).

Table 1. The analysed parkrun events and their corresponding air quality and meteorological monitoring location along with distances between the sites.

parkrun	DEFRA AURN	Distance (km)	Meteorological Station	Distance (km)
Bedfont	Harlington	5.3	Heathrow	3.0
Brockwell	Westminster	5.2	St James Park	6.1
Bromley	Eltham	7.8	Biggin Hill	8.9
Bushy	Teddington	1.4	Hampton W WKS	2.2
Crystal Palace	Eltham	10.2	Biggin Hill	14.1
Finsbury	Haringey	2.2	St James Park	7.3
Greenwich	Eltham	0.6	London City Airport	4.3
Grovelands	Haringey	5.3	St James Park	14.4
Hackney	Haringey	7.2	London City Airport	7.8
Kingston	Teddington	0.8	Hampton W WKS	4.9
Lloyd	Eltham	14.3	Biggin Hill	9.5
Old Deer	Teddington	4.4	Kew Gardens	0.9
Richmond	Teddington	3.7	Kew Gardens	3.6
Roundshaw	Teddington	17.0	Kenley Airfield	3.5
Wimbledon	Teddington	6.9	Kew Gardens	7.8

Correlation analyses between the decomposed finishing times and the explanatory variables were performed for the whole data set as well as the male and female sex subsets provided by parkrun, and were used by Helou *et al*. [25]. Each of the parkrun events was also examined separately to determine whether certain locations were more influenced by the measured variables. Linear regression analyses, the common technique used in aforementioned marathon studies [44], was used to compute the R^2 value, showing the total percentage of variance in finishing times explained by the control variables.

Analysis to determine the influence of UAQ and meteorology on the average weekly parkrun finishing time was achieved by two multiple linear regression analyses. One considered the combined influence of NO_2, O_3 and $PM_{2.5}$ on finishing times whilst for meteorological impacts, temperature, relative humidity and wind speed were used as the independent variables. Air quality and meteorological data was not included in the sample analysis model due to the risk of multicollinearity between variables, in particular temperature, NO_2 and O_3. For the multiple linear regression models, variable inflation factors (VIFs) were checked post-test to ensure that they were below the threshold of 3. This analysis method also reintroduces a form of natural seasonality that is initially striped from the time series. This is done to remove the 'slowing' influence of New Year's resolution runners and general loss of physical fitness over the Christmas period, rather than leaving the long term trend and seasonality in from the beginning of analyses. It also allows for a more representative insight into real world processes and influences. Post-test analysis was also performed using the following diagnostic tests; Quantile-Quantile, Scale-Location, Fited vs Residuals, Cooks-Distance and ACF plots and histograms of residuals (Fig 3).

It needs to be noted that this research follows a time series rather than space-time series analysis. Although there could be variation between parkrun finishing times and the local air quality and meteorology, there are other factors that would also need to be considered such as differences between event surfaces and elevation profiles that could lead to false conclusions. However, controlling these factors over a spatial analysis would prove challenging and probably a paper in its own right.

For reference within the rest of the manuscript, a positive relationship between an explanatory variable and finishing time would see an increase in run time and thus a slower performance. In contrast, a negative relationship means that performances have improved whilst the associated explanatory variable has increased in value.

Results

4.1. Meteorology

Basic descriptive statistics for the data used in this work are shown in Table 2.**Table 2.** Descriptive statistics for the parkrun finishing times and meteorological conditions encountered during the study period.

	Minimum	Maximum	Mean
parkrun time (minutes)	14.42	90.50	26.62
Temperature (^{o}C)	-6.60	26.00	11.38
Relative humidity (%)	42.50	100.00	78.30
Wind Speed (ms^{-1})	0.00	12.86	3.61

4.1.1 Temperature

Initial analysis shows that the distribution of run times are predominantly between 20 and 30 minutes, with temperatures between 8-15^{o}C. Linear regression analysis across all parkrun events resulted in the regression equation (Equation 1) below, where t is run time in s, and T is temperature in °C. The linear regression gives Equation 1, which is significant at the 99% confidence interval and explains 3% of the variance in run times.

$t = -4.83 + (0.42 \times T)$ (Equation 1)

Examination of individual parkrun events shows that five locations have significant relationships between finishing times and temperature (Table 3). Of these, however, Bromley parkrun has a negative relationship with finishing times, suggesting that quicker performances occur under warmer conditions (p=0.05).

Table 3. Individual parkruns and their relationship between finishing times and temperature variations.

Location	Intercept	Temperature Coefficient	F Statistic	R^2 Value	p Value
Bedfont	-3.78	0.24	0.4	-0.002	0.53
Brockwell	1.11	0.01	1.00	3.111e-05	0.32
Bromley	6.57	-0.63	3.98	0.01	0.05
Bushy Park	1564.36	1.2	4.12	0.05	0.05
Crystal Palace	-0.57	0.03	0.01	-0.004	0.93
Finsbury Park	-10.64	0.86	5.73	0.02	0.02
Greenwich	5.84	-0.52	1.34	0.01	0.25
Grovelands	1.34	0.001	0.03	-0.01	0.87
Hackney Marshes	0.64	-0.01	0.001	-0.004	0.98
Kingston	1509.3	-1.41	1.35	0.01	0.25
Lloyd	-5.00	0.4	0.4	-0.002	0.53
Old Deer Park	7.26	-0.87	2.24	0.01	0.14
Richmond	-9.4	0.84	8.21	0.03	<0.01
Roundshaw	-11.03	1.03	4.46	0.01	0.04
Wimbledon	2.06	-0.31	0.79	-0.001	0.38

Gender analyses show that at the events where comparable significant relationships are shown, female run times are more influenced than male. Additionally, when all significant relationships between temperature and finishing times are considered, female coefficients are larger and more significant than male. For example, for the complete female subset, temperature coefficients for correlation, linear regression and multiple linear regression are 0.19, 0.56 and 0.75 respectively with p=<0.01, whilst for the male subset the corresponding values are 0.15, 0.32 and 0.41 with p=<0.02.

Examination of age groups showed some interesting results. Increased temperatures and wind speeds were detrimental to finishing times of the age groups shown in Table 4. Temperature shows significant positive relationships with the middle-aged to older age groups, with no apparent influence on the children, youth and young adult competitors in the 25-29 and younger age groups.

Table 4. Significant linear regression results of age group analysis. Wind speed appears to be the dominant variable regardless of age.

Age Group	Explanatory Variable	Coefficient	P Value
20-24	Wind Speed	2.47	<0.01
25-29	Wind Speed	0.03	<0.01
35-39	Temperature	0.43	0.06
40-44	Wind Speed	1.78	<0.01
	Temperature	0.48	0.02
45-49	Wind Speed	1.34	<0.01
	temperature	0.36	0.06
50-54	Wind Speed	1.2	<0.01
	Temperature	0.52	<0.01
55-59	Wind Speed	1.47	<0.01
65-69	Wind Speed	1.66	0.02
	Temperature	0.74	0.09[JH(G+ESLF1]

[JH(G+ESLF1]Reviewer #2 – Merged the age group cells to make table clearer.

4.1.2. Relative Humidity

Results of the relative humidity analysis suggest that in most cases elevated levels reduce performance. Although not significantly different, the mean finishing time (not decomposed) rises from 1584.41 s under relative humidity levels of 40-55% to 1598.14 s when RH is above 85.1%. Interestingly, female participants are slightly more influenced than male, seeing an increase in finishing time 1.3 s more when RH rises from 40-55% to over 85%. For the age groups this descriptive analysis shows that most see increases in finishing time of 5-30 s, although notably the 70-75 and 80-85 age groups show increases of 131.54 and 77.18 s respectively.

Correlation and linear regression analysis for this explanatory variable shows a number of significant relationships. With the exception of the 25-29 age group and the Richmond event (overall and male subset), these all show that increased RH is associated with slower finishing times (p=<0.08).

4.1.3. Wind Speed

Significant results were only found at seven of the fifteen events as well as the overall and male and female subsets (p=<0.08, Fig 4). R^2 values ranged from 1-12% and a student's T-test revealed a significant difference between the mean run time at high (>6 ms^{-1}) and low (<6 ms^{-1}) wind speeds (p=<0.01) for the overall and male datasets. At a number of events, wind speed increases saw correspondingly higher, thus slower, parkrun finishing times. No particular age group showed a greater influence of wind speed on their finishing times compared to the others (Table 4).

Fig 4. Results of linear regression analysis for the overall (row A), female (row B) and male (row C) parkrun subsets with the three meteorological variables examined.

In most cases, male competitors showed a significant relationship with wind speed that was not matched by the corresponding female analysis. For example, at Wimbledon parkrun male finishing times are slower in association with increased wind speeds through correlation (coefficient - 0.16), regression (coefficient - 2.25) and multiple linear regression (coefficient - 2.75) analysis (p = 0.01).

4.1.4. Combined influences

Multiple linear regression was performed using the influence of temperature, relative humidity and wind speed (Equation 2). These three variables explained 10% of the variance in average parkrun finishing times (p=<0.01), with increased values being associated with slower finishing times. Results of the multiple linear regression are shown in Table 5, with 16% of the variance in finishing times at Bushy Park attributed to the three variables.

Average parkrun time = -23.64 + 0.51 T** + 0.13 RH + 1.07 WS** (Equation 2)

**Significance <0.01

Table 5. Meteorology multiple linear regression results for the fifteen parkrun events.

Location	Intercept	Temperature	RH	Wind Speed	Significance	R^2
Bedfont	-23.69	0.56	0.28	-0.6	0.24	0.004
Brockwell	1.37	0.01	-0.003	No Data	0.52	-0.01
Bromley	-0.26	-0.26	0.69	0.38	<0.01	0.04
Bushy Park	1522.16	1.08	0.42	1.39	<0.01	0.16
Crystal Palace	-5.57	0.06	0.03	0.26	0.96	-0.01
Finsbury Park	-3.15	0.78	-0.09	No Data	0.07	0.02
Greenwich	-31.41	-0.2	0.37	0.67	0.21	0.01
Grovelands	1.26	0.002	0.001	No Data	0.96	-0.02
Hackney Marshes	0.36	-0.04	-0.02	0.22	0.99	-0.01
Kingston	1407.99	-0.75	1.17	0.09	0.17	0.04
Lloyd	10.34	0.18	-0.29	1.2	0.37	0.001
Old Deer Park	-53.91	-0.46	0.52	3.33	0.04	0.02
Richmond	5.75	0.51	-0.24	1.5	<0.01	0.06
Roundshaw	-57.57	1.4	0.41	0.91	0.03	0.02
Wimbledon	-25.59	-0.2	0.2	2.27	0.06	0.02

4.2. Air Quality

Basic descriptive statistics for the data used in this work are shown in Table 6.

Table 6. Descriptive statistics of the air quality conditions encountered by parkrun participants during the study period in comparison to the UK air quality standards.

	Minimum	Maximum (UK standard)	Mean (UK standard - yearly average)
O_3 (ugm^{-3})	1.14	76.91 (120)	33.62 (N/A)
NO_2 (ugm^{-3})	10	95.38 (200)	33.54 (40)
$PM_{2.5}$ (ugm^{-3})	1.4	86 (N/A)	13.33 (25)

4.2.1. Ozone

Examination of the O_3 data showed only two close to significant relationships with finishing times. This was for the male subset with correlation and linear regression suggesting a correlation coefficient of 0.11 and 0.08 respectively (p=0.09). Both the overall and female subsets showed no significant relationships between the variables. However, all analyses despite not being significant, showed O_3 to have positive relationship with finishing times, thus suggesting that run times are getting slower. At individual parkrun events, most showed positive relationships with O_3, with the most notable significant relationships at the Bushy Park, Crystal Palace and Lloyd Park events (p=<0.05). In contrast, however, Greenwich, Kingston and Wimbledon parkruns all showed negative relationships, although these weren't significant. The 55-59 age group also showed a significant (p=<0.09) positive relationships with ozone whilst the 40-44 and 45-49 were close to significant with p=0.07 and 0.09 respectively.

4.2.2. Nitrogen Dioxide

NO_2 for the overall data and two gender subsets shows no significant relationships with performance. However, all results show a negative trend, suggesting a potential for improved performances under elevated NO_2 conditions. Similarly to the larger subsets, most individual parkrun events showed a negative relationship between finishing times and NO_2 levels, with close to significant results shown at Bushy Park, Lloyd and Richmond (p=<0.09). Interestingly, events at Bromley and Finsbury showed positive relationships between the two variables, particularly for the overall and female subsets. Similarly to ozone, age group analysis showed the same demographics, 40-49 and 55-59, had significant (p=<0.05) negative relationships with NO_2.

4.2.3. PM2.$_5$

$PM_{2.5}$ showed no significant relationships with the overall or subset run times. Unlike the O_3 and NO_2 results, which if not consistently significant show clear trends in their relationship with finishing times for both the overall and individual parkrun events, there isn't a clear trend in the $PM_{2.5}$ data (Fig 5.). At individual parkrun events, Bushy, Bromley and Lloyd are the only significant results, which are negative relationships. At the remaining twelve events, three shown positive trends, five are negative and the other four have both positive and negative relationships depending on the subset examined. Only the 45-49 age group had a significant (p=0.01) relationship with $PM_{2.5}$, which was again negative.

Multiple linear regression analysis that included the three pollutants showed only one significant relationship with finishing times (Table 7).

Table[JH(G+ESLF1)] **7.** Air quality multiple linear regression results for the fifteen parkrun events.

Location	Intercept	O_3	NO_2	$PM_{2.5}$	Significance	R^2
Bedfont	-27.83	0.13	7.25	11.7	0.52	0.01
Brockwell	1.18	0.003	-0.04	No data	0.67	-0.02
Bromley	-11.7	0.11	6.66	-2.68	0.8	-0.01
Bushy Park	3.93	0.13	-1.02	-7.16	0.12	0.03
Crystal Palace	-11.15	0.25	-11.15	12.35	0.09	0.02
Finsbury Park	0.96	0.002	0.14	No data	0.84	-0.02
Greenwich	23.17	-0.31	-22.41	14.83	0.12	0.02
Grovelands	1.32	0.003	-0.04	No data	0.36	0.001
Hackney Marshes	16.48	-0.01	-10.83	No data	0.79	-0.01
Kingston	2.12	-0.01	-0.16	-0.3	0.71	-0.04
Lloyd	17.2	0.29	-26.73	1.15	0.01	0.04
Old Deer Park	0.89	0.003	0.25	0.16	0.85	-0.07
Richmond	-13.96	0.08	13.75	-10.13	0.52	-0.01
Roundshaw	-28.33	0.22	5.52	10.00	0.92	-0.03
Wimbledon	3.68	-0.03	-0.54	-3.19	0.99	-0.03

[JH(G+ESLF1)]Reviewer #1 MLR results included as a table as requested.

Discussion

5. Meteorology

5.1.1 Temperature

Running is a weather interference sport where conditions such as the meteorology will influence performance [93]. This is particularly so for higher temperatures that can alter the bodies thermoregulatory systems and increase fatigue and power output [23, 36, 37]. Regression results between parkrun finishing times and temperature predominantly show positive relationships and suggest that temperature is the largest influencer on running times, supporting laboratory tests performed by No and Kwak [94]. Time increases of seconds compared to the larger and more substantial performance reductions shown by Helou *et al*. [25] is to be expected considering the differences in event length and duration. This difference between parkrun and marathon studies is most likely due to the reduced distance and period of time required to complete parkrun events, and therefore the reduced environmental exposure experienced by participants.

Gender analyses suggest that female run times are more susceptible to increased temperatures than male. This contrasts the work of Vihma [33] who showed male athletes to be more susceptible to high temperatures during the Stockholm marathon. This is theorised to be due to males generally have a smaller ratio of surface area to body mass compared to females, making them less efficient at dissipating heat build-up during exercise and prompting earlier decreases in performance due to temperature regulation [34, 35, 95]. However, other studies have shown female participants to be influenced more than male with this being attributed to females having a higher core temperature that is a disadvantage when exercising in warmer conditions [96]. Finally, several events showed no impact of temperature on performance [42-44, 97]. Overall, this research suggests that both genders are, to an extent, impacted by meteorology, as would be expected based upon previous research [25, 32, 34, 35].

Age group analysis suggests that temperature and wind speed is detrimental to several age groups, predominantly those over thirty years of age. This partially contrasts research that suggests that younger demographics are most negatively impacted by temperature through increased heat gain and reduced dissipation [45, 46, 98, 98]. It should be noted, however, that the impact on older competitors does correlate with research that ageing reduces muscle mass, metabolism and thus thermoregulatory adjustments [45, 46, 98, 99]. This would explain the decrease in performance under higher temperatures for older age groups and also agrees with previous research into the influence of urban heat islands and pollution on vulnerable population demographics (i.e. young and old) [76, 100-104].

5.1.2 Relative Humidity

Results suggest that in most cases elevated relative humidity could be associated with slower finishing times. These decreases in performance may be due to a reduced ability to disperse excess body heat generated during exercise, leading to earlier and increased fatigue in participants [34, 35, 47]. Female and the 70-75 and 80-85 age groups showed the largest decreases in performance, the latter particularly so when relative humidity rose from 40-55% to over 85%, suggesting that they are less efficient at dispersing excess heat. Therefore, meteorology could be associated as being the main external control on athletic performance as has previously been theorised [25, 32-35].

5.1.3. Wind Speed

Around half of the events saw significant decreases in performance as wind speed increased and there is a significant difference between finishing times under high (>6 ms^{-1}) and low (<6 ms^{-1}) wind speeds. This corresponds with the work of Davies [48] who showed that headwinds will result in a greater drag force and slower running times. However, the majority of parkrun course are lapped with participants encountering multiple wind directions over the course of the event potentially leading to the insignificant results shown.

The gender analysis showed a number of occasions where female participants were not significantly influenced by wind speed. This could be due to male competitors potentially being larger than their female counterparts and therefore having a larger silhouette to move through the increased wind resistance. A range of age groups showed positive relationships with wind speeds, suggesting that despite previous studies suggesting that the cooling effect from wind can improve performance by up to 4.4% [105, 106], the wind speeds found at parkrun events are too strong to be beneficial. Perhaps more importantly in the UK, wind chill can have a negative impact on performance in cooler conditions, reducing core body temperature and increasing the amount of anaerobic glycolysis in active muscles, leading to increased fatigue [107]. Furthermore, greater fitness levels does not necessarily result in improved cold weather performance, this is more often dictated by body shape, size and sex [108].

5.1.4. Combined Influences

The combined influence of temperature, relative humidity (RH) and wind speed has been noted earlier in this research [25, 32, 33], with the results mostly mirroring those and suggesting that they can significantly result in slower running times. This is supported by the work of Pezzoli *et al*. [109] who believed these three variables to be the greatest influencers on running performance.

5.2. Air Quality

5.2.1. Ozone

Only the male results showed a close to significant relationship (p=<0.09) between ozone and finishing times. Despite a lack of statistically significant results between finishing times and O_3, there are consistent positive relationships shown between finishing times at most parkrun events for the overall, male and female subsets and ozone levels. This may suggest that in some instances the irritant quality of the pollutant on the respiratory system could potentially influence athletic performance and partially supports the work of Helou *et al.* [25] on marathon performances [17]. Furthermore, past research has shown that O_3 can decrease lung function therefore performance in maximal time trial laboratory tests [57-64], although this may not be the case under real-world conditions when the potentially exposure of runners could vary considerably.

5.2.2. Nitrogen Dioxide

There were no significant or close to significant relationships shown between NO_2 and finishing times at the London parkrun events, regardless of event, gender nor age group. However, the majority of results show a negative trend which could suggest that quicker finishing times are recorded under higher NO_2 conditions, which is unlikely due to it also being an irritant [17]. However, due to the processes referenced in section 2.4, it could be suggested that high NO_2 levels are found in cooler temperatures, conditions that are likely to improve running times [25, 40]. A possible explanation for the improved finishing times under elevated NO_2 levels is that nitrate and related species are vasodilators. This can reduce arterial pressure and increase blood flow, although examination of the influence of this on athletic performance has not been performed [110, 111, 112].

5.2.3. PM2.$_5$

With the exception of negative relationships at Bushy, Bromley and Lloyd parkruns, $PM_{2.5}$ has no significant results when compared to finishing times for any analysis groups. The three aforementioned significant negative relationships are result that goes against common thinking of particulate matter being an irritant and highly detrimental to human health [17, 101]. However, Giles et al. [113] found that pre-exercise inhalation of diesel exhaust containing 300 µg/m3 of $PM_{2.5}$ had no significant effect on cycling time trial performance whilst particulate matter impacts are often seen as a long-term health hazard. This could possibly explain the lack of a detrimental impacts on short-term performance, if not the few ‘beneficial’ relationships [101]. The majority of the results suggest that there is no real relationship between short-term athletic performance and $PM_{2.5}$ concentrations.

5.3 Limitations and Future Research

Due to spatial variability in air quality, how representative the air quality data is also needs to be considered. O_3 is generally a regional pollutant with less variation over London and between monitoring locations and parkrun events. Therefore, the significant relationships between O_3 and parkrun finishing times can be considered accurate. However, NO_2 and $PM_{2.5}$ levels are more likely to be influenced by local sources and may result in discrepancies between monitoring and parkrun locations, potentially contributing to insignificant relationships. Although monitoring locations are not ideally located in some instances, they are indicative of air quality levels and this research is not aimed to create a predictive model, more generate insights. To overcome this, in-situ

monitoring at parkrun events could be performed, albeit a potentially costly option. Modelled air quality data could also be used to reduce the likelihood of variability in air quality levels between monitoring sites and parkrun events.

Some further considerations that could be utilised in the future for additional studies include tracking performance changes over time of individual parkrun participants, although this could not be done as parkrun ID numbers were not provided due to data protection. This meant that individual runner's performances could not be followed over the study period to determine whether air quality and meteorology impacted their performance. Consequently, this research provides a useful overall view on the impact of these variables, but not the resolution to determine the impact on individuals. Being able to follow individuals, along with their physiological data such as lean body mass ratio, heat dissipation of tissues and relative maximum oxygen consumptions that are all influential for performance could also provide additional insight in to our results [96]. Furthermore, due to a lack of literature examining the influence of meteorology and air quality on specifically 5 km events, associations between this research and previous work is limited to laboratory tests and long distance running, both of which will to an extent use slightly different energy and physiological systems. However, 5 km events are at least 84% aerobic in the energy systems used, which, although this figure rises as the race distance increases, shows that comparisons between middle and long distance races can to an extent be drawn [114].

Conclusions

The increasing popularity of parkrun events has allowed this research to examine the influence of local air quality and meteorology on short-term athletic performance at a weekly time scale. Previous research has focused on laboratory-based studies or yearly marathon events. Through fifteen Greater London parkrun events, DEFRA AURN and meteorological monitoring analysis has shown a number of relationships between variables and running performance. This includes additional subsets of parkrun data to examine gender differences.

Although the variance in run times explained by these variables are small, the results correlate well with previous laboratory and real-world marathon studies, particularly for temperature, relative humidity and O_3 [25, 32]. This also highlights the importance and impact of body temperature regulation and power output shown by past research [23, 34-37]. Additional analysis in to the impact of wind speed, wind chill, precipitation and radiation has also been performed and has highlighted the impact, or lack thereof, of those variables on performance.

Overall, this research suggests that meteorological changes can be associated with the clearest changes in short-term athletic performance, along with O_3 in some instances, which is potentially linked to increased temperatures. NO_2 and $PM_{2.5}$ do not appear to have any significant impacts, at least in the short-term. Furthermore, this research has started to address the gap surrounding short duration athletic performance in the UK, along with utilising a wider spectrum of participants rather than elite runners.

Despite these potentially hindering associations of UAQ and meteorology on athletic performance, it is important to stress that the health benefits of participating in parkrun events outweighs the short-term exposure to poor UAQ [18]. This is supported by research showing that regular exercise protects against premature deaths attributed to UAQ [22]. Finally, it is important that parkrun and other event organisers, along with policy makers and health care providers are aware of the extent to which air quality and meteorology can impact participants, particularly under future predictions of climate change and urban air quality [112].

Declarations

Ethical Approval and Consent to Participate

The parkrun finishing time data was anonymised prior to research access being given in accordance with the completed and agreed ethics procedures (ERN_17-1583) by the University of Birmingham ethics team.

Consent for publication

Not applicable

Availability of data and materials

The datasets generated and analysed during the study are available in the DANS repository, https://easy.dans.knaw.nl/ui/login;jsessionid=B27725E7352DAA8FC71FC8FBB39CEA90?wicket:bookmarkablePage=:nl.knaw.dans.easy.web.search.pages.PublicSearchResultPage&q=parkrun

Competing Interests

The authors declare that they have no competing interests.

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Authors' contributions

JRH – Conception and design of work. Data acquisition and analysis. Data interpretation. Write up and submission process. Approval of final work.

SE – Conception and design of work. Data acquisition and analysis. Data interpretation. Approval of final work.

LC – Conception and design of work. Data interpretation. Approval of final work.

CH – parkrun data extraction. Approval of final work.

FDP – Conception and design of work. Data interpretation. Approval of final work.

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Abbreviations

O_3 – ozone

NO_2 – nitrogen dioxide

PM/$PM_{2.5}$/PM_{10} – particulate matter/particulate matter of the size fraction 2.5/particulate matter of the size fraction 10.

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Figures

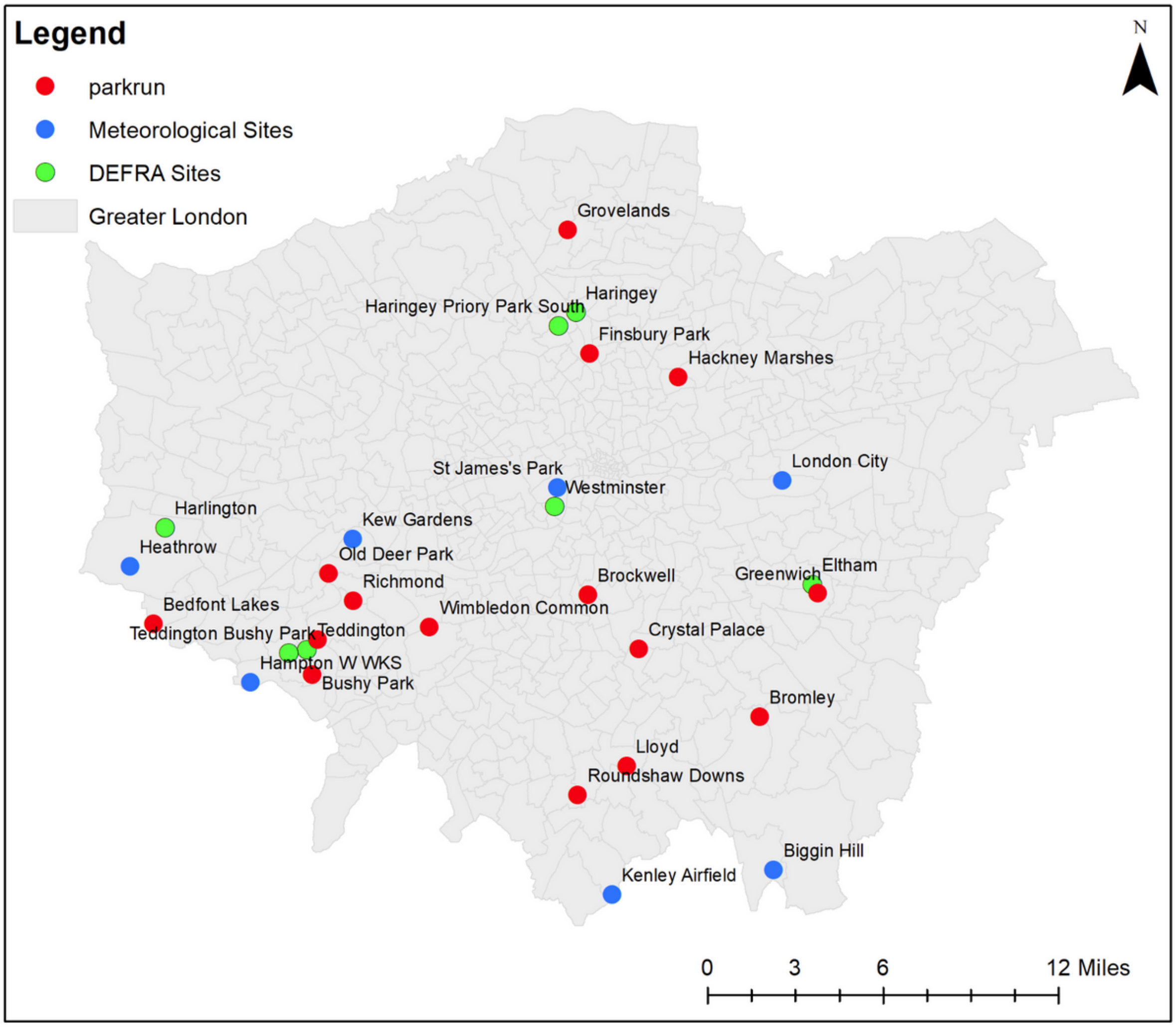

Figure 1

A map showing the locations of the parkrun events, DEFRA AURN stations and meteorological stations within Greater London.

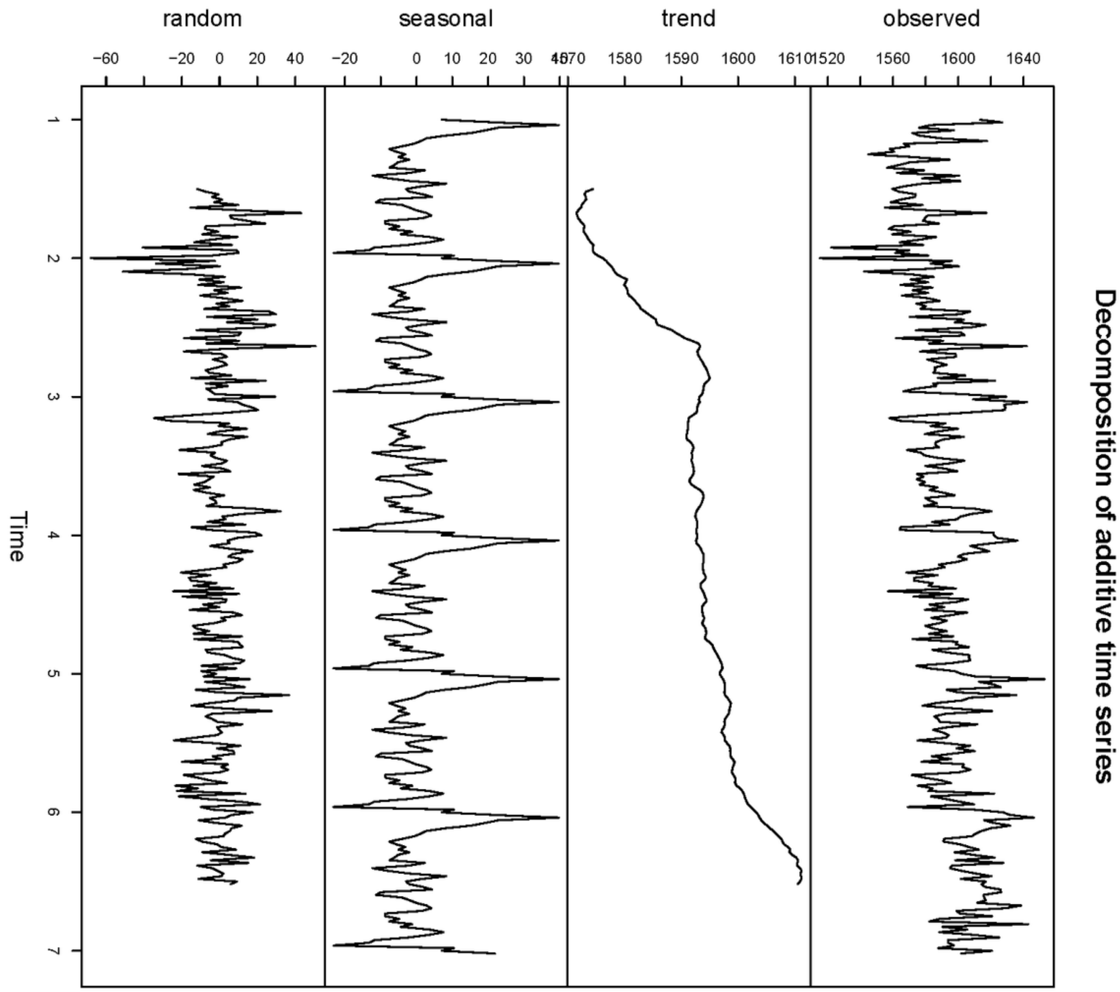

Figure 2

Decomposition of weekly mean parkrun finishing times from 2011 to 2016. The x-axis shows the six yearly periods within the data.

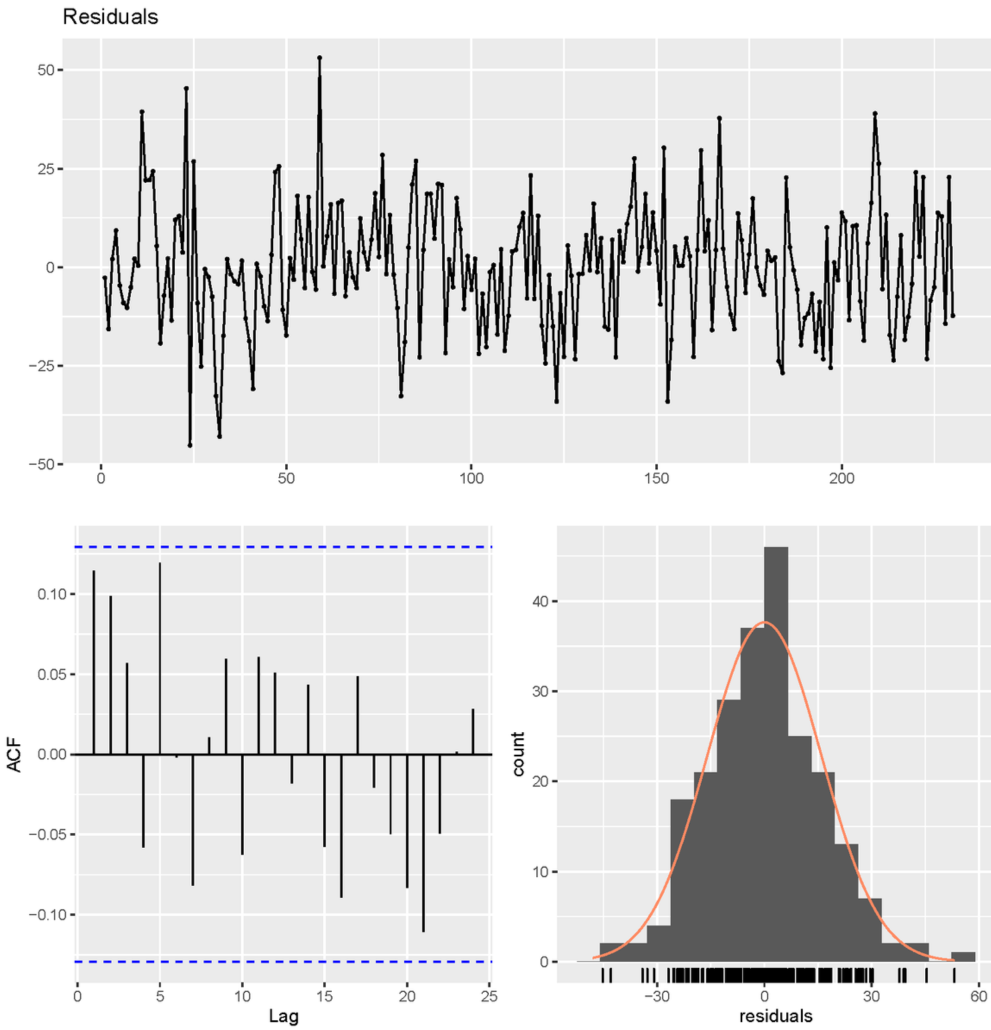

Figure 3

Example post-test analysis of residuals, their distribution and ACF plot for the influence of ozone on finishing times at Bushy parkrun.

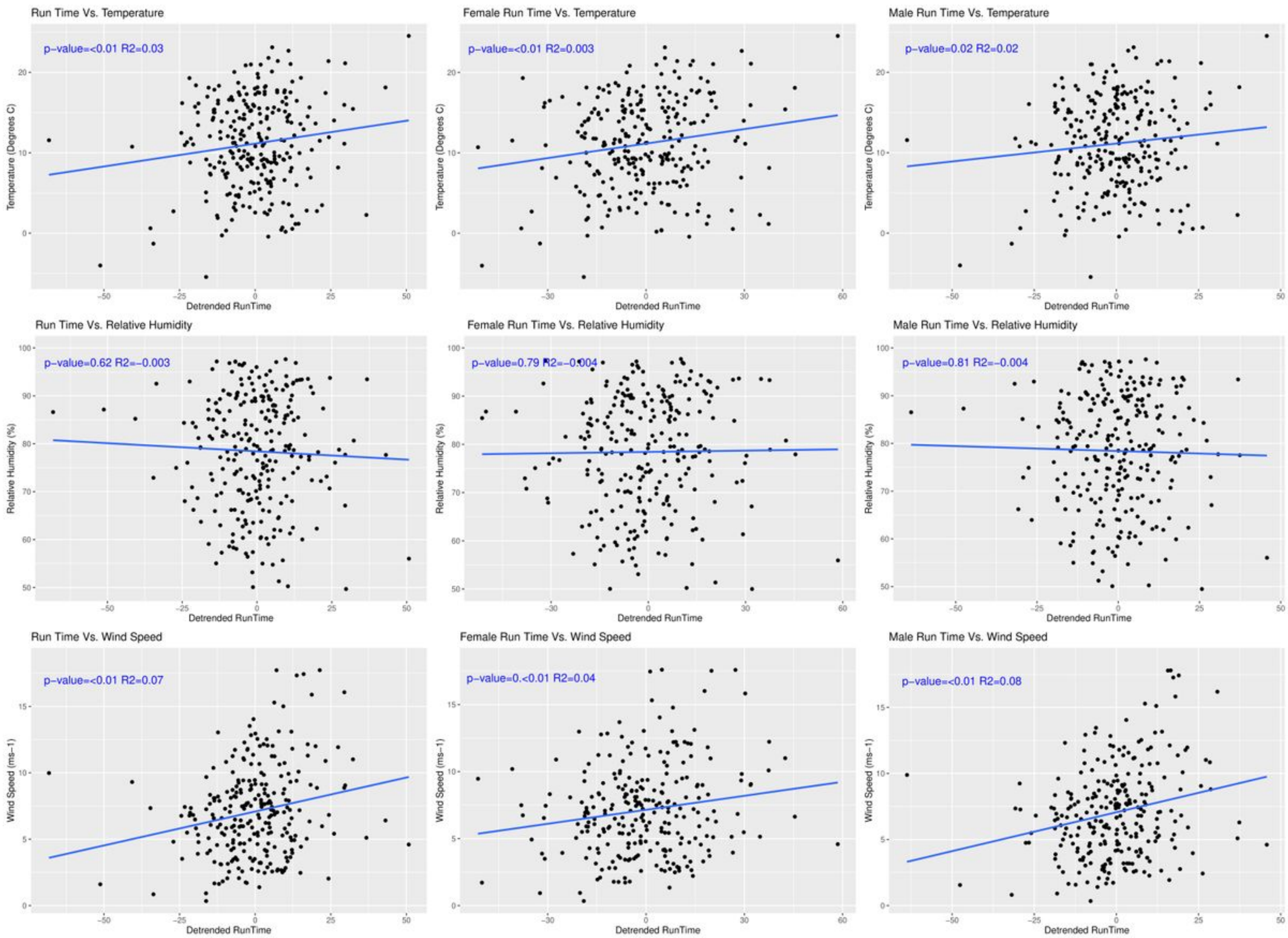

Figure 4

Results of linear regression analysis for the overall (row A), female (row B) and male (row C) parkrun subsets with the three meteorological variables examined.

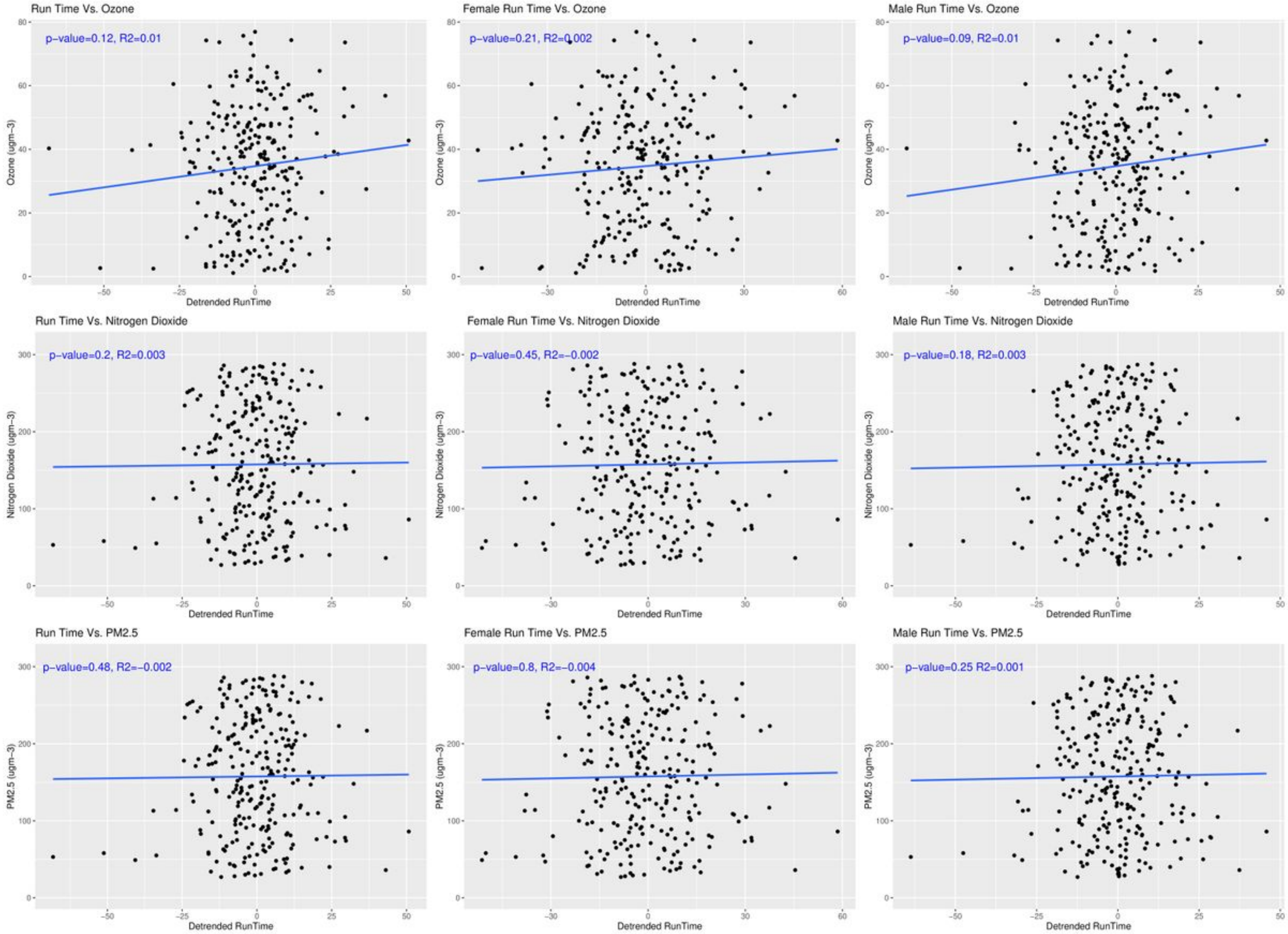

Figure 5

Results of linear regression analysis for the overall (Row A), female (Row B) and male (Row C) parkrun subsets with the three pollutants examined.