THE INFLUENCE OF AIR QUALITY AND METEOROLOGY ON ATHLETIC PERFORMANCE

by

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Abstract

Public perception and knowledge of urban air pollution has increased greatly in recent years, with up to 90% of the world's population living under air quality conditions that exceed some of the World Health Organisations guideline values. It is predicted that this will increase as a greater proportion of the population move to urban areas, with further health risks posed by climate change. Additionally, the world is also facing low activity levels and an increasing obesity crisis, with questions posed as to the best methods to address this. The international phenomena of parkrun has managed to actively engage multiple demographics in weekly 5 km runs, with increased participation in mass running events also occurring over recent years. Sadly however, there have been numerous occurrences of environment-related incidents at athletic events at a range of participant levels. Despite this, there has been little examination of the impact air pollution *and* meteorology, particularly extreme events, has on exercise performance and health benefits associated with outdoor exercise.

Consequently, this thesis examines the influence of air pollution and meteorology on recreational exercisers at parkrun events, elite 5000 m athletes during the Diamond League Athletic Series and the combined elite and recreational athlete fields at The Great North Run (half marathon distance). Utilising fixed-point and modelled data in conjunction with historic race results variation in the impact of pollutants and meteorology on performance is examined. Findings show that temperature is the greatest influencer on both elite and amateur participants. Ozone, albeit linked to temperature, also has a detrimental impact on athletic performance. The influence of other environmental parameters are variable but highlights include increased $PM_{2.5}$ pollution slowing elite female athletes significantly over 5000 m and the slowest finishers at the Great North Run being influenced the most out of all participants due to their prolonged exposure time. Suggestions for further research and implementation of mitigation measures to reduce the effect and likelihood of negative environmental conditions and health-related incidents at all athletic participation levels are also explored with a focus on 'at event' and personal exposure monitoring. This study also highlights the need for further research into the field as well as examination of the variation in effect pollution and meteorology has on different genders and participant abilities.

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Chapter 1 - Introduction

1.1 Background Information

Urban air quality has been recognised as both an international, transboundary issue and a local issue which has numerous detrimental impacts on human health and the wider environment (European Commission, 2017a; 2017b; Du *et al*., 2020; Halkos and Tsilika, 2019; Kampa and Castanas, 2008; Lim *et al.*, 2012; Ryabuhina *et al*., 2019; Walton *et al.,* 2015). Air pollution is likely to continue to worsen if emissions and sources of pollutants are not controlled, with the main pollutants of concern being nitrogen dioxide (NO_2), ozone (O_3) and particulate matter (PM), notably the size fractions less than or equal to 2.5 and 10 microns in diameter ($PM_{2.5}$ and PM_{10}, Devarakonda *et al.*, 2013; United States Environmental Protection Agency, 2016a; Kobayashi *et al.*, 2017; World Health Organisation, 2013). Volatile organic compounds (VOCs), a subset of indoor pollutants, and as a result, indoor air quality are also causes for concern due to people spending 80-90% of their time indoors (Abraham and Li, 2014; Department for Environment, Food and Rural Affairs, 2016a; Tong *et al.*, 2016; Yu *et al.*, 2009).

Over half the world's population currently live in urban areas, the majority of whom are under air quality conditions that exceed the World Health Organisation's guidelines (Hewitt *et al*., 2020; Marmett *et al*., 2020). Consequently, examination of the sources, personal exposure, impacts and solutions to urban air quality are required, especially when by 2025 over 80% of the population will live in urban areas (Hewitt *et al*., 2020; Marmett *et al*., 2020; Trundle *et al*., 2015). This will result in a greater number of people being exposed to harmful pollution levels and urban heat islands, putting greater strain on population health, associated health services and productivity (Kumbhakar *et al*., 2021; Perara *et al*., 2021).

Furthermore, with the world facing high global inactivity levels and an increasing obesity crisis, solutions to improve population health effectively and economically are required (Hallal *et al*., 2012; Marmett *et al*., 2020; Swinburn *et al*., 2011; 2019). As well as hopefully improving the global obesity crisis, increased population activity levels will also lower the likelihood of additional social and economic costs by improving mental health and wellbeing, reducing prevalence of health related diseases and improving productivity (Hallal *et al.*, 2012; Marmett *et al.*, 2020; Swinburn *et al.*, 2011; 2019; Public Health England, 2016; Stevinson and Hickson, 2014; Grunseit *et al.*, 2018; Hindley, 2020; Stevinson *et al.*, 2015).

Prior to the COVID-19 pandemic, participation at parkrun events (weekly, timed 5000m running events) and mass participation runs across a variety of distances were incredibly popular: parkrun reached over six million registered runners in 2019, Helou *et al.* (2012) showed that marathon entries increased over a ten year period and Brocherie *et al.* (2015) also found a 26% increase in the American running population between 2007 and 2012 (Parveen, 2019). There has also been an increase in participation of races of 10 Km or longer: the 2019 London Marathon had a record 42,906 starters with organisers optimistic for over 50,000 taking part in 2021, coronavirus dependent (Scott, 2021; Yankelson *et al.*, 2014). Personal challenges have been cited to be the main reason aside from improving physical fitness for taking part in mass participation events, with events being strongly associated with an improved and healthier lifestyle (Khorram-Manesh *et al.*, 2020; Malchrowicz-Mosko *et al.*, 2018a; 2018b; Malchrowicz-Mosko and Poctza, 2018; Poczta and Malchrowicz-Mosko, 2018a).

During the first United Kingdom coronavirus lockdown, running brand Asics reported a 62% increase in the number of weekly runners with physical and mental health improvements cited as the main reasons for the increase (McGuire, 2020). This has been supported by a number of studies showing that marathon, half marathon and triathlon participation was most associated with entrants wanting to improve self-esteem, mental well-being and to be affiliated with/participate in a group environment (Malchrowicz-Mosko and Poctza, 2018; Malchrowicz-Mosko *et al.*, 2018b; 2020; Poctza and Malchrowicz-Mosko, 2018b). 72% of the UK runners surveyed by Asics reported a desire to continue running post-COVID-19 lockdown(s), and it is hoped that this will lead to a sustained increase in physical activity; benefiting population health and wellbeing, particularly at a time when population activity levels, obesity and related illnesses are of particular concern (McGuire, 2020).

However, the detrimental health effects of urban air quality need to be considered when exercising, especially when in some cases the pollution risks outweigh the benefits of physical activity (Guo *et al.*, 2020 McCreanor *et al.*, 2007; Pasqua *et al.*, 2018; Strak *et al.*, 2010). These risks include short term cardiorespiratory irritation, reduced lung function and increased likelihood of asthma attacks, whilst long term pollution exposure has been shown to contribute to reduced cognition, cardiovascular and respiratory diseases and ultimately a reduction in life expectancy and premature death (Burnett *et al.*, 2014; Calderon-Garciduenas *et al.*, 2016; Lelieveld *et al.*, 2015; Rajagopalan *et al.*, 2018; World Health Organisation, 2020a).

1.1.1. Nitrogen Dioxide

Although NO_2 is one of the main pollutants of concern, it cannot be examined without consideration of nitrogen oxides (NO_x), of which NO_2 is one of. One of the main sources of NO_x are vehicle emissions, primarily in the form of NO, and some NO_2. The former of these react with O_3 to form NO_2 (World Health Organisation, 2005). This is known as the Leighton relationship; NO, NO_2 and O_3 are equilibrated in a photochemical steady state during daylight hours, as shown by equation 1.1 and 1.2 (Clapp and Jenkin, 2001; Leighton, 1961).

$NO+O_3 \rightarrow NO_2+O_2$

Equation 1.1. The closed system of 'Leighton' reactions between NO, NO_2 and O_3. The process results in no net chemistry.

$NO_2+h\nu\ (+O_2) \rightarrow NO+O_3$

Equation 1.2. The closed system of 'Leighton' reactions between NO, NO_2 and O_3. The process results in no net chemistry.

Despite the number of diesel vehicles falling since 1990, they are still prevalent in the public transport and goods sectors as well as making up approximately 50% of the private car fleet in the UK; and therefore contribute to high nitrogen pollution levels in many urban areas (Department for Environment, Food and Rural Affairs, 2004, Department of the Environment and Heritage, 2005; United States Environmental Protection Agency, 2016b; Yang *et al.*, 2016).

NO_2 also contributes to acid rain and nutrient pollution of rivers and coastal waters, damaging ecosystems, buildings and infrastructure (United States Environmental Protection Agency, 2016b). Commonly across Europe annual mean levels of NO_2 are greater than 40µg m^{-3} in urban areas with high levels of vehicular traffic, prompting development in vehicle emission standards (Department for Environment, Food and Rural Affairs, 2016a; Fontaras *et al.*, 2017a; 2017b).

1.1.2. Particulate Matter

Particulate matter is categorised by its diameter, with ultrafine particles having a diameter of less than less than 100nm (<0.1µm), fine particles <2.5µm ($PM_{2.5}$ and thoracic particles <10µm (PM_{10})); the $PM_{2.5-10}$ range is classified as coarse (Environment Protection Authority Victoria, 2013; Hasenfratz *et al.*, 2015; Kim *et al.*, 2015; Kobayashi *et al.*, 2017; Rajagopalan *et al*., 2018; World Health Organisation, 2013). Although ultrafine and coarse particles are increasingly being identified as being detrimental to human health, the majority of research identifies $PM_{2.5}$ as the main concern (Baldauf *et al*., 2016; Delfino *et al*., 2005; Rajagopalan *et al*., 2018). This is due to strong agreement in studies that suggest that even low levels of $PM_{2.5}$, below current national standards, can have adverse effects on health (Baldauf *et al*., 2016; Delfino *et al*., 2005; Papadogeorgou *et al*., 2019; Rajagopalan *et al*., 2018). These fine and ultrafine particles pose a number of health risks, especially so when they can be translocated within the body (Kinney, 2018; Miller *et al*., 2017; Rao *et al*., 2018; Rjagopalan *et al*., 2018). Of the approximately 4.2 million premature deaths globally that are attributed to air pollution, $PM_{2.5}$ is responsible for around half of these (Landrigan *et al*., 2018; Shehab and Pope, 2019; Thurston and Newman, 2018). This makes it the fifth highest cause of premature death (Cohen *et al*., 2017; Shehab and Pope, 2019; Thurston and Newman, 2018).

Due to its size, particulate matter can also be transported significant distances as it can remain in the atmosphere for several weeks, making it a trans-geographic boundary issue (Atkinson *et al.*, 2010; Engel-Cox *et al.*, 2013; Kim *et al.*, 2015; Lin *et al.*, 2015; World Health Organisation, 2013). Particulate matter enters the air through direct emissions or conversion from gaseous precursors (volatile organic compounds, sulphur dioxide and nitrogen oxides), both of which can come from anthropogenic and natural sources (Atkinson *et al.*, 2010; European Environment Agency, 2012; Kim *et al.*, 2015; Pant and Harrison, 2013; Srimuruganandam and Nagendra, 2012). Natural sources of particulate matter include combustion (for example forest fires), sea spray, dust storms and volcanic eruptions (European Environment Agency, 2012; Kim *et al.*, 2015; Pant and Harrison, 2013; Srimuruganandam and Nagendra, 2012; World Health Organisation, 2013). Fuel combustion and road traffic are also the largest anthropogenic particulate matter sources, alongside industrial and agricultural activities (European Environment Agency, 2012; Kim *et al.*, 2015; Pant and Harrison, 2013; Srimuruganandam and Nagendra, 2012; World Health Organisation, 2013). UK levels for $PM_{2.5}$ and PM_{10} are often between 10-30 $\mu g/m^3$ and 10-20 $\mu g/m^3$ respectively, although these can be exceeded during the most congested periods alongside busy roads (Department for Environment, Food and Rural Affairs, 2016).

1.1.3. Ozone

Ozone is the most prevalent secondary pollutant, making up a large proportion of the pollutant mixture in urban areas which is 90% gases or vapour-phase compounds (Brook *et al*., 2010; Rajagopalan *et al*., 2018). It is a photochemical oxidant, and therefore is not directly emitted, rather forming due to the previously demonstrated Leighton chemical reactions between NO_x and VOCs in the presence of sunlight and elevated temperatures (Katsouyanni, 2003; Kinney, 2018; Kobayashi *et al.*, 2017; Leighton 1961; Marc *et al.*, 2015; World Health Organisation, 2000; World Health Organisation, 2005). Consequently, increased levels occur in congested cities due to the numerous NO_x and VOC sources (Bowman, 2013; Marc *et al.*, 2015). Due to this, increased levels of O_3 can occur in heavily congested cities that have numerous vehicular sources of NO_x and volatile organic compounds (Bowman, 2013; Marc *et al.*, 2015).

Additionally, O_3 is a greater pollution problem during summer months and areas with prolonged sunshine (Bell *et al.*, 2007; Department for Environment, Food and Rural Affairs, 2016; Katsouyanni, 2003; Kinney, 2018; Solberg *et al.*, 2008). Due to the reaction between NO and O_3 to form NO_2, UK daily levels of O_3 are between 30-80 $\mu g\ m^{-3}$, with higher levels being found in rural areas (Department for Environment, Food and Rural Affairs, 2016; Sicard et al., 2013; 2020). These higher rural concentrations are known as the 'ozone paradox' and are due to emitted NO from (mainly) vehicles reacting with O_3, as shown in equations 1.1 and 1.2, and thus depleting it locally (Paoletti *et al.*, 2014; Sicard *et al.*, 2013; 2020; Solberg *et al.*, 2005). As there are more sources of NO and thus higher concentrations in urban areas, O_3 concentrations are decreased in urban areas relative to their comparative rural locations (Paoletti *et al.*, 2014; Sicard *et al.*, 2013; 2020; Solberg *et al.*, 2005).In addition to the health effects ozone contributes to and shall be covered shortly, ozone reduces crop yields, with losses in the United States totalling $9 billion per year between 1980 and 2011 (Guerreiro *et al.*, 2014; McGrath *et al.*, 2015).

1.1.4. Volatile Organic Compounds

Volatile organic compounds, although not directly examined in this research, are involved in atmospheric reactions to form O_3 and therefore cannot be overlooked. They are multiple chemical species that contribute to the formation of secondary pollutants such as O_3 and secondary organic aerosol formation, with many species being detrimental to human health (Borbon *et al.*, 2013; Li *et al.*, 2014; Wardencki *et al.*, 2008; Wei *et al.*, 2014; Zhu *et al.*, 2014). Research has also shown the vehicular emissions of VOCs are the most common source of secondary organic aerosol formation (Li *et al.*, 2015; Wardencki *et al.*, 2008). VOCs are also found in cleaning materials and the majority of indoor materials and cleaning products, leading to poor indoor air quality (Borbon *et al.*, 2013; Fauzan *et al.*, 2016; Fenger, 1999; Kim *et al.*, 2010; Langer *et al.*, 2016; Nakaoka *et al.*, 2013; Tsow *et al.*, 2009; United States Environmental Protection Agency, 2017; Zhang *et al.*, 2011).

VOC levels are often highest during rush hour traffic conditions and areas with high levels of vehicular traffic due to the 1-3% of fuel in vehicular combustion engines being unburnt and released from vehicles (United States Environmental Protection Agency, 2017; Fenger, 1999; Kim *et al.*, 2010; Mellouki *et al.*, 2015; Tsow *et al.*, 2009). The specific emissions vary depending on fuel, engine types and operating conditions (Borbon *et al.*, 2013; Li *et al.*, 2014; Wardencki *et al.*, 2008; Wei *et al.*, 2014; Zhu *et al.*, 2014). VOC emissions from anthropogenic and biogenic sources have also been shown to increase as temperature increases (Kinney, 2018; Wardencki *et al.*, 2008).

1.2 Air Quality Impacts

The environmental impacts of poor air quality include the formation of acid rain and nutrient pollution of soils, rivers and coastal waters, consequently damaging ecosystems and reducing crop yields (European Commission, 2017a; Kjellstrom *et al*., 2006; Maipa *et al*., 2001; Manisalidis *et al*., 2020; McGrath *et al*., 2015; Pathak *et al*., 2001; United States Environmental Protection Agency, 2016b; Zuhara and Isaifan, 2018). Buildings and infrastructure can also be damaged as a result of poor air quality (Grontoft, 2020; Lin and Zhu, 2018; United States Environmental Protection Agency, 2016b). Most importantly, poor air quality, or more generally, air pollution, is closely related to climate change (D’Amato *et al*., 2016; Feng *et al*., 2019; Gautam and Bolia, 2020; Manisalidis *et al*., 2020). Increased pollution levels affects the amount of sunlight and ultraviolet radiation that reaches the Earth, as well as trapping heat within the atmosphere; consequently, this leads to a cycle of positive feedback whilst the temperature of the Earth is also increasing (Feng *et al*., 2019; Gautam and Bolia, 2020; Manisalidis *et al*., 2020; World Health Organisation, 2020a).

1.2.1. Air Quality and Health

Poor air quality can be particularly damaging to human health and development. This includes respiratory and cardiovascular distress due to the irritant nature of pollutants (Department for Environment, Food and Rural Affairs, 2016a; Department of the Environment and Heritage, 2005; World Health Organisation, 2005). Irritation of the eyes, nose and throat can also occur and lead to breathing problems both in the short and long term (European Environment Agency, 2013). Inflammation of the respiratory system due to particulate matter is common and also contributes to chronic obstructive pulmonary diseases, lung cancer and impacts the reproductive system (European Environment Agency, 2013; Gautam and Bolia, 2020; Vizcaino *et al*., 2016; World Health Organisation, 2020a). Headaches, often associated with ‘sick building syndrome,’ anxiety and impacts on the central nervous system can also be caused by pollution (European Environment Agency, 2013; Fauzan *et al.*, 2016; Langer *et al.*, 2016; Nakaoka *et al.*, 2013; Zhang *et al.*, 2011).

Finally, neurological, cognitive, immune system and developmental damage can also occur, alongside increased cancer risks and premature death, the latter of which is accountable for 40,000 deaths per year in the UK and over 4.2 million globally (Burnett *et al.*, 2014; European Environment Agency, 2013; Lelieveld *et al.*, 2015; Royal College of Physicians, 2016; World Health Organisation, 2020a; Williams *et al.*, 2014). This makes it the fourth highest cause of deaths globally, as shown in Figure 1.1. Those particularly at risk are the young, elderly and those with pre-existing health conditions, one of the most common of which is asthma with over 12% of the UK population and at least 339 million people globally registered with having some form of the disease (British Lung Foundation, 2020; Fallmann *et al.*, 2013; Lenzuni *et al.*, 2009; Solecki *et al.*, 2005; Trundle *et al.*, 2015; Vos *et al.*, 2017).

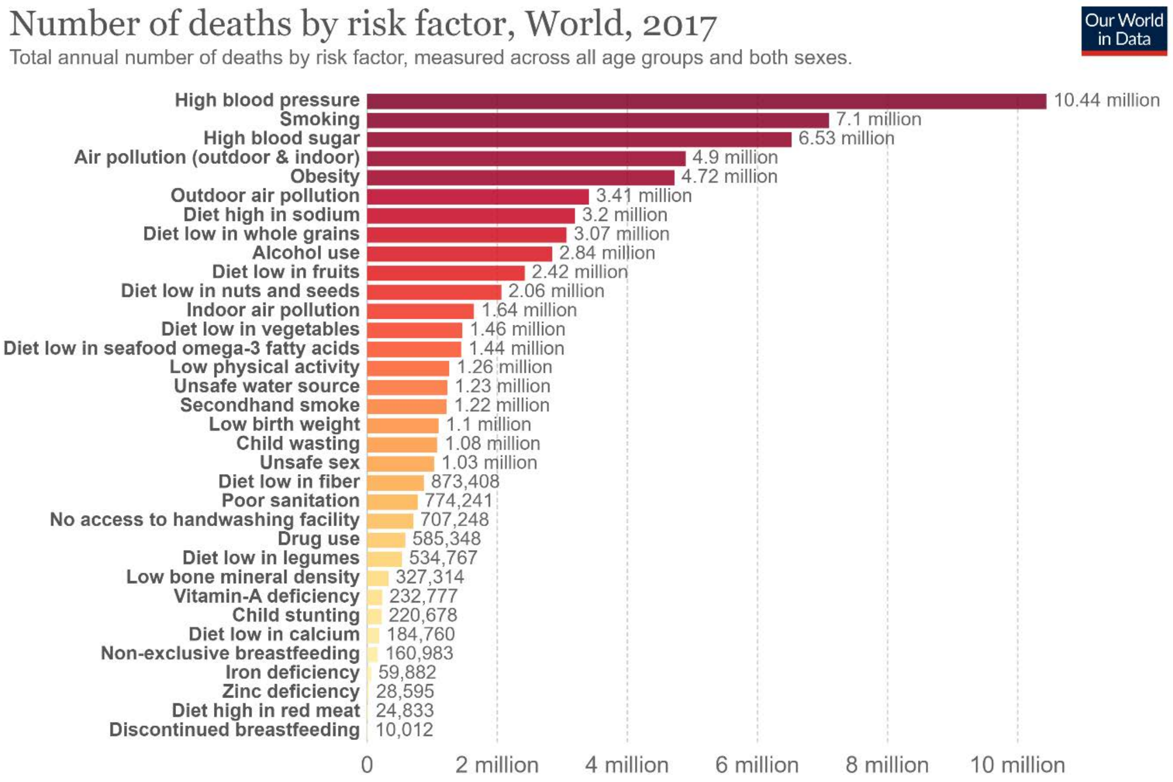


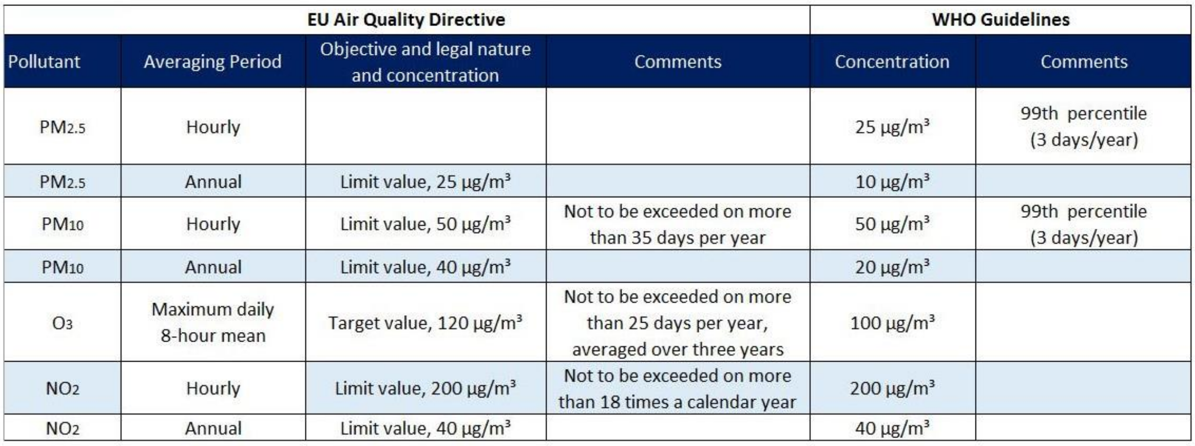
Figure 1.1. The number of global deaths by risk factor. Source: Ritchie, 2019.

In addition to these risks, further industrialisation, vehicle sales, climate change and, in urban areas, urban heat islands have the potential to continue to worsen the global air quality and health outlook (Feng *et al*., 2019; Molina *et al*., 2009; Tomlinson *et al*., 2011 World Health Organisation, 2020a). Urban heat islands in particular can cause a 2.54% increase in deaths occurring in the summer months due to increased temperatures in combination with poor air quality (McMichael *et al*., 2006; Roberts, 2004; Stafoggia *et al.*, 2008). With over half the world's population living in urban areas, the majority of whom are under air quality conditions that exceed the World Health Organisation's guidelines, examination of the sources, causes, impacts and solutions to urban air quality are required, especially when this figure is expected to exceed 80% by 2025 (Hewitt *et al*., 2020; Marmett *et al*., 2020; Trundle *et al*., 2015).

Another issue with regards to urban air quality is the best method(s) to determine and measure a range of regional and localised pollutants (Henne *et al.*, 2010; Janssen *et al.*, 2008; Janssen *et al*., 2012; Martin *et al.*, 2013; Martin *et al*., 2014; Parra *et al.*, 2009; Piersanti *et al.*, 2015; Santiago *et al.*, 2013; Vardoulakis *et al.*, 2005; Venegas and Mazzeo, 2010). This is due to the difficulty to implement a representative monitoring network at any kind of meaningful scale despite advances in low cost monitors (Duyzer *et al.*, 2015; Joly and Peuch, 2012; Karroum *et al*., 2020; Muller *et al.*, 2013a; 2013b; Righini *et al.*, 2014). Consequently, accurate modelling of air quality is still a viable alternative to determine widespread pollution sources and variations (Borge *et al*., 2014). However, uncertainties due to the nature of modelling and how accurate results are compared to in-situ monitoring stations can still be examined (Shorshani *et al*., 2015a).

Due to the aforementioned environmental and physiological damage caused by poor air quality, there are several policies and legislations in place from the World Health Organisation, the European Commission and local governments and authorities in a bid to improve air quality (Table 1.1).

Table 1.1. European Union Air Quality Directive limits and the comparable World Health Organisation air quality guidelines. Source: European Environment Agency, 2019.



EU Air Quality Directive				WHO Guidelines	
Pollutant	Averaging Period	Objective and legal nature and concentration	Comments	Concentration	Comments
$PM_{2.5}$	Hourly			25 µg/m³	99th percentile (3 days/year)
$PM_{2.5}$	Annual	Limit value, 25 µg/m³		10 µg/m³	
PM_{10}	Hourly	Limit value, 50 µg/m³	Not to be exceeded on more than 35 days per year	50 µg/m³	99th percentile (3 days/year)
PM_{10}	Annual	Limit value, 40 µg/m³		20 µg/m³	
O_3	Maximum daily 8-hour mean	Target value, 120 µg/m³	Not to be exceeded on more than 25 days per year, averaged over three years	100 µg/m³	
NO_2	Hourly	Limit value, 200 µg/m³	Not to be exceeded on more than 18 times a calendar year	200 µg/m³	
NO_2	Annual	Limit value, 40 µg/m³		40 µg/m³	

In several instances, improvements have been shown. For example, the United Kingdom and London's air quality has greatly improved over recent decades (Figure 1.2, Andrade *et al.*, 2018; Browne *et al.*, 2007; Gil-Alana *et al.*, 2020). Despite this, however, the city still exceeds the above legislative limits for a number of pollutants, including O_3, NO_2 and PM, and consequently has failed since 2010 to meet European Union air quality standard (Gil-Alana *et al.*, 2020). It has been notable that annual pollution breaches, particularly for NO_2, have occurred in London within a few days of each New Year and is a pattern shown in other European cities (Bessagnet *et al.*, 2005; Gil-Alana *et al.*, 2020; Petit *et al.*, 2017). It has been predicted that at the current rate of NO_2 reduction, legal limits would only be achieved in London in the next twenty years, with some of the worst roads estimated to take up to one hundred and ninety three years (Font *et al.*, 2019; Gil-Alana *et al.*, 2020).

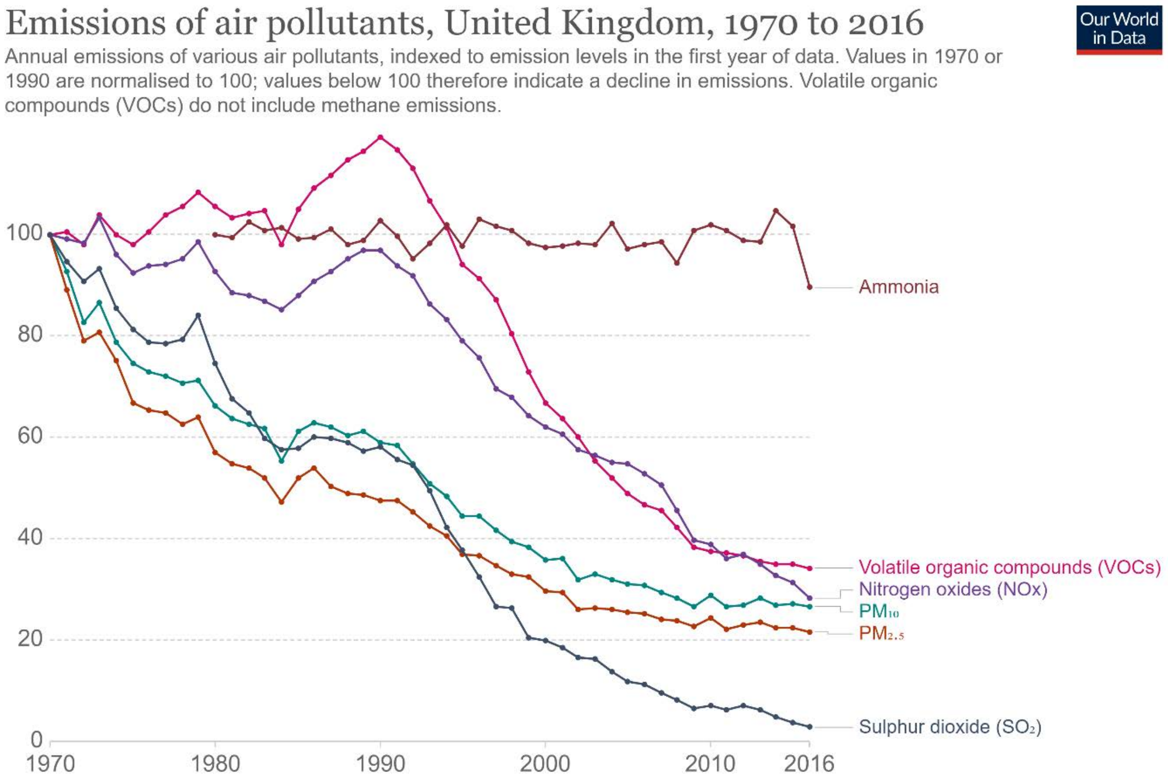


Figure 1.2. Variation in UK air quality emissions from 1970-2016. Source: Ritchie, 2019.

1.3 Air Quality and Exercise Performance

There has been some research into the effect of environmental factors such as air quality on athletic performance; in most cases under laboratory settings (reviewed by Giles and Koehle, 2014). Although findings are mixed, it is believed that the irritant qualities of pollution can reduce athletic performance as well as heightening other respiratory problems such as asthma (Carlisle and Sharp, 2001; Cutrufello *et al*., 2011; Florida-James *et al*., 2011; Folinsbee *et al*., 1994; Kargarfard *et al*., 2015; Lippi *et al*., 2008; McCreanor *et al*., 2007; McKenzie and Boulet, 2008; Rundell and Caviston, 2008; Rundell, 2012; Weinmann *et al*., 1995). It is more commonly agreed, however, that higher intensity exercise increases the potential for increased pollution uptake (Bigazzi, 2016; Giles and Koehle, 2013; Lichter *et al*., 2017; Muns *et al*., 1995; Niinimaa *et al.*, 1980; Ultman *et al*., 2004).

Real world examination of the effects of air quality on athletic performance is limited to elite marathon performances. The work of Marr and Ely (2010) and Helou *et al*., (2012) are the most notable; identifying that O_3 and PM are the most influential on reducing performances under heightened conditions. A long term study of professional football in Germany also highlighted a causal relationship between PM levels and player productivity (Lichter *et al*., 2017).

1.4 Exercise and Meteorology

It has been shown in a number of instances that both can have detrimental impacts on even the most elite of participants. For example, Great Britain's Jonathon Brownlee and Scotland's Callum Hawkins both collapsed whilst leading the 2016 World Triathlon Grand Final and 2018 Commonwealth Games marathon respectively due to the heat (BBC Sport, 2016; BBC Sport, 2018). Additionally, the now postponed 2020 Olympic Games have scheduled a number of events to avoid the warmest of conditions and shows that the majority of studies and event organisation is focused upon the impact of meteorology, rather than air quality and meteorology (BBC Sport, 2019). Sadly these instances are also found in amateur events, most often marathons, and have led to deaths when held under high temperatures (BBC, 2018; The Guardian, 2018).

Even though the aforementioned occurrences under extreme conditions are thankfully rare, additional examination of how meteorology impacts human health during exercise is needed to help determine how best to both mitigate negative effects and how to hold 'safe' sporting events. The work of Kosaka *et al*. (2018) showed that the entire Tokyo 2020 marathon course was classifiable as 'dangerous' or 'extremely dangerous' for athletes due to the expected temperatures and sun exposure; this consequently may have led to scheduling the event and others earlier in the day. Previous research into meteorological impacts on performance have focused on either laboratory tests or marathons (Ely *et al*., 2007; Helou *et al.,* 2012; Vihma*,* 2010; Vugts, 1997).

In general, it has been accepted from previous research that increased temperatures decrease performance due to alterations in the circulatory, endocrine and thermoregulatory systems as a participants internal body temperature rises alongside higher blood lactate levels (Casa, 1999; Ely *et al*., 2007; Helou *et al.,* 2012; Miller-Rushing *et al*., 2012; Nadel, 1990; Nybo *et al*., 2014; Vihma, 2010; Vugts, 1997; Zhao *et al.*, 2013). Increased relative humidity has also been shown to be detrimental to athletic performance as it reduces heat dissipation, leading to increased core body temperatures and decreased performance in the same manner as high temperatures (Casa, 1999; Helou *et al*., 2012; Nadel, 1990).

Wind direction, wind speed and wind chill are the other main and commonly experienced meteorological variables that could influence performance. head- and tail-winds are likely to result in poorer and quicker running performance respectively, although variations in wind direction and courses can negate this (Davies, 1980; Vihma, 2010). Low wind speeds can be beneficial in providing a cooling effect but in colder temperatures wind chill can reduce performance as blood is diverted from contracting muscles to maintain vital functions and the athlete’s core temperature (Maughan *et al*., 2007a; 2007b).

Additionally, with climate change predictions increasing temperatures and heatwaves being the norm by 2040, there are additional concerns regarding health, productivity and well-being (The Committee on Climate Change, 2017). These changes would also impact exercise performance and outdoor activity levels. Estimations suggest that by 2100 marathon times would be noticeably slower due to increased temperatures and heat stress whilst by 2070 outdoor exercise would be impossible for both acclimatised and unacclimatised people (Maloney and Forbes, 2011; Miller-Rushing *et al.*, 2012). Currently, the former would see an increase from a single impossible activity day to between fifteen and twenty-six, whilst the latter would rise from four to five days to thirty-three to forty-five (Maloney and Forbes, 2011).

1.5 Research Gap

Based upon the current work, although a body of work exists in air quality and exercise and exercise and meteorology, there is a clear research gap examining the real-world effect of *both* air quality and meteorology on both amateur and elite athletic performance.

With the world facing high global inactivity levels and an increasing obesity crisis, solutions to improve population health effectively and economically are required (Hallal *et al.*, 2012; Marmett *et al.*, 2020; Swinburn *et al.*, 2011; 2019). One potential option is the UK phenomenon of parkrun, which since its conception and first event in Bushy Park, London, in 2004, has a wide international reach (parkrun, 2020). parkrun, weekly timed 5Km runs that are volunteer organised within local parks is open to all abilities and ages. They have been shown to have greatly increased physical activity levels of local communities as well as providing mental health and community benefits (Grunseit *et al.*, 2018; Hindley, 2020; parkrun 2020; Stevinson and Hickson, 2014; Stevinson *et al.*, 2015).

Although this may appear to be an ideal and cost-effective solution to improve national and international health and activity levels, local air quality and meteorological conditions need to be considered. This is particularly so when research has suggested that in worst case scenarios and with extended exercise and exposure periods, the negative effects of air quality could outweigh the benefits of exercise (Pasqua *et al.*, 2018; Tainio *et al.*, 2016).

However in most cases, shorter duration exercise is beneficial despite the air quality risks, although care should still be taken by those in vulnerable population groups (Andersen *et al*., 2015; Tainio *et al*., 2016).

This is especially so in terms of recreational exercisers given the clear need to increase public health and activity levels (British Heart Foundation, 2017; Pedersen and Saltin, 2006; Public Health England, 2016; Rowley *et al*., 2018). Determining how such conditions could negatively impact participant's needs to be considered, particularly with the use of exercise referral schemes to promote physical exercise and improve health disorders (King and Little, 2017l; National Institute for Clinical Excellence, 2014; Rowley *et al*., 2018). Additionally, as most meteorological impacts on athletic performance have been anecdotal, verification of their potential influence would be beneficial. This is not only for exercisers looking for personal bests but also world record attempts; Eluid Kipchoge became the first person to break the two hour marathon barrier in Vienna 2019 after not only extensive physical preparation, but also meticulous geographic and meteorological investigations beforehand to select the most favourable location and conditions for long distance running (Ineos, 2019). Further examination of how potentially extreme conditions could affect elite athletes is also required given past events presented as well as concern over the environmental conditions at the 2008, 2016 and now 2021 Olympic Games (Donnelly *et al*., 2016; Kosaka *et al*., 2018; Qiao *et al*., 2011; Streets *et al*., 2007; Ventura *et al*., 2019; Wang *et al*., 2009).

Consequently, this thesis looks to examine the associations between air quality and meteorology and how these variables influence the athletic performance of both elite and recreational athletes; utilising both in-situ monitoring and modelled air quality data.

1.5.1. Research Question

As highlighted above, the focus of this thesis is to examine to what extent air quality and meteorology influences the performance of elite and recreational athletes, particularly those competing over 5000m as it is a highly accessible distance and regularly competed over for both groups. Therefore, the research question of ‘To what extent does changing air quality and meteorology influence human athletic performance?’ is presented.

1.5.2. Aim

Based upon the introduction and research question, the aim of this thesis is to determine how air quality and meteorology variations impacts elite and recreational exercisers athletic performance.

1.5.3. Objectives

Data from a number of different events will be used to allow for the generation of insights into both recreational and elite runners. To this end, the research aim will be realised by exploring the following objectives:

Objective 1: Examine associations between local air quality and meteorology and recreational parkrun (5000m) athletic performance.

Objective 2: Examine associations between local air quality and meteorology and elite 5000m athletic performance.

Objective 3: Using a high profile mass participation event, examine associations between local air quality and meteorology on both elite and recreational half marathon performance.

1.6 Thesis Structure

The above research question, aim and objectives will provide the direction that this thesis will take and the analyses that will be performed to allow for associations between air quality and meteorology and athletic performance to be empirically recognised (Sheppard, 2001). To prevent duplication of chapters 3, 4 and 5 which are submitted or soon to be submitted papers, detailed data and methodologies won't be presented here or in a dedicated 'methods' chapter. However, the following chapter outline will provide information as to how the aim and objectives of this thesis shall be met, as well as the focus of each paper.

Chapter 2 shall provide a detailed review of the current literature surrounding air quality, meteorology, measurement techniques and the risks that poor urban air quality poses to human health. The research regarding the effects of pollution and meteorological variables on exercise and athletic performance is also reviewed.

Chapter 3 examines the influence of air quality and meteorology on parkrun performances in conjunction with objective one. This utilises fifteen parkrun events in the Greater London area from 2011 to 2016 inclusive. In addition to parkrun finishing times, air quality data from the Department for Environment, Food and Rural Affairs (DEFRA) Automatic Urban and Rural Network (AURN) monitoring stations are used in conjunction with meteorological data from the British Atmospheric Data Centre (BADC) using the Met Office Integrated Data Archive System (MIDAS). Data from the CMAQ-urban pollution dispersion model developed by King's College London is also examined for data validation purposes. The closest monitoring stations are paired with each of the parkrun locations to allow for analysis between air quality (O_3, NO_2 and $PM_{2.5}$), meteorology (temperature, relative humidity and wind speed) and finishing times through correlation, linear regression and multiple linear regression techniques.

Chapter 4 addresses objective two by examining how air quality and meteorology influences the finishing times of elite 5000 m runners in the Diamond League athletics series at eight international locations from 2010 to 2018 inclusive. Local monitoring authorities have provided nearby air quality and meteorology data for the corresponding time periods that allows for the previously used analysis techniques to determine the explanatory variables effect on elite athletes. Across-event analysis is also performed through one-way analysis of variance tests to further explore the extent to which differing pollution levels influence performances.

Chapter 5 examines the Great North Run held in Newcastle upon Tyne, Great Britain, from 2006 to 2019 inclusive in conjunction with local air quality and meteorology data. Objective three is addressed through this analysis as both elite and recreational runners participate over the same course at the same time. This provides a novel opportunity to examine how both sets of participants respond to the air quality and meteorology they are exposed to over the half marathon (13.1 miles/21.1 km) distance.

Chapter 6 considers the limitations of the presented research and how future studies could be performed to a greater extent. This includes thoughts on the implementation of low cost sensors, wearable sensors and personal exposure determination to provide greater resolution of data and the potential impacts local conditions may be having on athletic performance, exercise and health. Suggestions for safety measures and technological advances to potentially implement at future sporting events are also discussed with the chapter culminating in a proposed future research project at parkrun events.

Chapter 7 concludes this thesis by returning to the research question, aims and objectives and determining the extent to which they have been addressed. The previous chapters are drawn together to determine the broader implications and contributions of the research with recommendations for further research directions and improvements.

Chapter 2 – Literature Review

This chapter will review the current literature surrounding air quality, meteorology, measurement techniques and the combined influence of the former two topics on climate and athletic performance. There are four areas of focus:

1. Air quality impacts on human health and development, namely effects on respiratory, cardiovascular and cognition will be examined.
2. Analyses of the impact air pollution has on meteorology and climate change and the influence these combined variables can have on the urban climate and urban heat islands.
3. An examination of traditional and novel air quality and, to a lesser extent, meteorological measurement techniques, particularly those that are utilised in the subsequent research and are suggested as options to utilise in future research campaigns.
4. The influence of air quality and meteorology on human physiology in a sporting environment, as well as the influence, or lack thereof, the variables have on athletic performances in real-world and laboratory tests. This section also highlights the analytical and methodological choices utilised by previous research and has informed the following chapters.

2.1 Air Quality

Increasing urbanisation and development often coincides with decreasing levels of air quality that has significant detrimental impacts on humans, ecology and the wider environment (European Commission, 2017a; Kumar *et al*. 2015, Lewis and Edwards, 2016; Lim *et al*., 2012a). Negative effects include respiratory and cardiovascular distress, neurological, immune system and developmental damage and increased cancer risk and likelihood of premature death (Burnett *et al*., 2014; Lelieveld *et al*., 2015; Williams *et al*., 2014). These risks affect those in low-, middle- and high-income countries with poor air quality estimated to cause over 4.2 million premature deaths per year (World Health Organisation, 2018).

Consequently, considerable research is being performed to determine how air pollution from various sources behaves spatially and temporally, along with the extent that local populations are exposed to poor air quality (Kaur *et al.*, 2007; Piedrahita *et al.*, 2014). Additionally, the implementation of the European Commission's clean air policy has increased the legislative need for improved air quality and is expected to reduce premature deaths and ecosystem damage from nitrogen pollution and acidification and increase productivity (European Commission, 2017a).

2.1.1. Impacts and Risks of Poor Air Quality

The impacts of air quality are numerous with particular concern regarding the risk posed to human health (Hewitt *et al*., 2020; World Health Organisation, 2018). With the majority of the world's population living in conditions that exceed the World Health Organisation's recommended limits, and the recent determination that air quality can be deemed a legal cause of death, public knowledge and concern with regards to air quality has increased (BBC News, 2020; Hewitt *et al*., 2020). This has included respiratory and cardiovascular health, mental cognition, early life development, disease prevalence and overall life expectancy (Chay and Greenstone, 2003; Chen *et al*., 2013). Particular 'at risk' demographics are the young, elderly or those with pre-existing cardiovascular or respiratory diseases, although research suggests that people of all ages and backgrounds are influenced by poor air quality (Engel-Cox *et al.*, 2013; Lim *et al.*, 2012a; Pope *et al.*, 2009; Sacks *et al.*, 2011; World Health

Organisation, 2013). An overarching theme through all these health risks though, is the number of deaths attributed to air pollution and the calculated reduction in life expectancy. Over 4.2 million deaths per year are thought to be caused by air pollution, with a life expectancy reduction globally of 2.3 to 3.5 years (Lelieveld *et al*., 2015; 2020). This has been supported by Pope *et al*. (2009) who suggested a similar life expectancy *increase* for each 10µg/m^3 reduction in $PM_{2.5}$ in the Unites States of America. Furthermore, although there is not a specific subsection devoted to the impact of air pollution on children and their development, it is important to note that the majority of air quality risks also apply to them and will be highlighted accordingly.

2.1.2. Respiratory impacts

Exposure to high concentrations of pollution has been shown to have detrimental impacts on respiratory development of children along with inflammation and irritation, increased risk of respiratory illnesses and more frequent and severe asthma attacks for those with the condition (Department for Environment, Food and Rural Affairs, 2016a; Department of the Environment and Heritage, 2005; Mudway *et al*., 2019; World Health Organisation, 2005). This is for O_3, NO_2 and $PM_{2.5}$, the latter of which can be deposited within pulmonary tissues deep in the lungs (Block *et al*., 2012; Gilliland *et al*., 2017; Rajagolapan *et al*., 2018). This then contributes to increased prevalence of respiratory diseases (Rajagolapan *et al*., 2018). Research has shown that higher concentrations of particulate matter increases mortality from respiratory disease and lung cancer, particularly in the young, elderly or those with pre-existing cardiovascular or respiratory diseases (Cao *et al*., 2017; Engel-Cox *et al.*, 2013; Lim *et al.*, 2012a; Pope *et al.*, 2009; Sacks *et al.*, 2011; WHO, 2013). Furthermore, of the global lung cancer deaths, 23% were due to air pollution (Landrigan, 2016; Wang *et al.*, 2016).

Similarly, O_3 along with NO_2 and PM has been shown to cause reductions in lung capacity and function, airway inflammation and increased mortality (Caiazzo *et al.*, 2013; Fan *et al.*, 2012; Nyhan *et al.*, 2016; WHO, 2005). With regards to asthma, exposure to pollution during childhood increases the risk of developing the illness, particularly the amount exposed to from birth up to primary school age (4-11) in the UK, with effects still being shown in teenage children (Carlsten *et al.*, 2010; Deng *et al.*, 2016; Khreis *et al.*, 2017; McConnell *et al.*, 2010).

2.1.3. Cardiovascular Impacts

Cardiovascular impacts of air quality are also varied, with $PM_{2.5}$ in particular contributing to cardiovascular mortality and disability (Brook *et al.*, 2010; Miller *et al.*, 2013; Rajagopalan *et al.*, 2018). Increased levels of $PM_{2.5}$ have been shown to increase the risk of acute cardiovascular events by 1-3% with exposure time scales of several years elevating this by up to 10% (Rajagopalan *et al.*, 2018). This latter risk is attributed to cardiometabolic conditions such as hypertension and increased blood pressure, markers of inflammation and decreased heart rate variability are also common health risks associated with air pollution (Delfino *et al.*, 2005; Nyhan *et al.*, 2014; Rajagopalan *et al.*, 2018; Yang *et al.*, 2018). There has also been links shown between increased $PM_{2.5}$ and NO_2 levels and the risk of developing insulin resistance and type 2 diabetes, as well as being related to obesity (Eze *et al.*, 2015; Li *et al.*, 2016; Mehta *et al.*, 2016; Rajagopalan *et al.*, 2018; Wang *et al.*, 2014)

Particulate matter has similarly been found to translocate within the body after inhalation, lasting up to three months after exposure and contributing to cardiovascular disease and increasing the risk of strokes (Miller *et al*., 2017). Diesel emissions and PM are also linked to increased risk of heart attacks and atherosclerosis, again ultimately contributing to increased mortality due to air pollution (Delfino *et al*., 2005; Miller *et al*., 2013).

2.1.4. Cognition Impacts

Air pollution, specifically PM, is also a concern for cognition and childhood development (Calderon-Garciduenas *et al*., 2016). This is because translocation of PM once it is inhaled can occur across the blood-brain barrier: influencing pathways controlling inflammation, blood pressure and metabolism within the body (Block *et al*., 2012; Rjagopalan *et al*., 2018). Furthermore, research has shown that air quality, can also lead to accelerated cognitive decline in adults with pre-markers of Alzheimer's and other illnesses being found more commonly (Carey *et al*., 2018; Chen *et al*., 2017a; Griffiths and Mudway, 2018; Sunyer *et al*., 2015; Zhang *et al*,. 2018).

Potentially one of the most important impacts of long term air pollution exposure is the risk of dementia and Alzheimer's disease, which is the leading cause of death in England and Wales, totalling 12.7% (Carey *et al*., 2018; Office for National Statistics, 2018). Particulate matter and NO_2 concentrations, including those below the annual NO_2 mean 41 µg/m^3 commonly recorded in London and other UK towns and cities, has been shown to increase dementia risk for adults by 40% (Carey *et al*., 2018; Chen *et al*., 2017b; Griffiths and Mudway, 2018). Long term exposure to PM and NO_2 by living close to major roads has also been shown to increase the likelihood of developing dementia (Chen *et al*., 2017b). Research by Crous-Bou *et al*. (2020) also highlighted that both nitrogen oxides and particulate matter contributed to Alzheimer biomarkers increasing and thus increasing the likelihood of developing the disease later in life. A long term study in Taiwan by Jung *et al*.

(2015) also identified $PM_{2.5}$ and O_3 as key contributors to the likelihood of developing Alzheimer's in older populations. Therefore, although a relatively new area of research, there is increasing evidence that air quality can lead to cognitive decline and related illnesses. This is especially highlighted by Bishop *et al*. (2018), who found that just a 1 µg/m^3 increase in $PM_{2.5}$ each decade raises the likelihood dementia diagnosis by 1.68%.

Outside of dementia and Alzheimer's, Kunn *et al*. (2019) found that each 10 µg/m^3 increase in $PM_{2.5}$ saw the probability of an erroneous move by chess players by 26.3% and Shehab and Pope (2019) attributed short term cognitive decline in tests to pre-test exposure to increased particulate matter concentrations via candle burning and roadside emission exposures. Zhang *et al*. (2018) also found that long term exposure to particulate matter contributed to cognitive decline in verbal and math tests, which would in turn could lead to dementia and additional health and economic costs. Similarly to Kunn *et al*. (2019), Zhang *et al*. (2018) suggests that a 10 µg/m^3 change (decrease) in PM_{10} and smaller fractions would reduce the extent of decline. Cognitive development in children can be reduced by pollution exposure (Calderon-Garciduenas *et al*., 2016). High levels of pollution have been linked to poorer test results and increased absence days on numerous occasions (Chen *et al*., 2018; Currie *et al*., 2009; Ebenstein *et al*., 2016; Ham *et al*., 2011; Lui and Salvo, 2017).

2.2 Air Quality, Meteorology and Climate Change

Climate change and air pollution are closely interconnected with many air pollutants being greenhouse gases or climate forcing agents and vice versa (Figure 2.1, De Sario *et al*., 2013; Dennekamp and Carey, 2010; Jacob and Winner, 2009; Noyes *et al*., 2009). Fossil fuel burning has primarily contributed to changes to the global climate system through the increase in greenhouse gases, whilst also adding to global pollution levels (Kinney, 2018;

Maione *et al*., 2016; Melamed *et al*., 2016; Watts *et al*., 2015). Changes in climatic conditions are likely to alter and compound air quality effects on health (De Sario *et al*., 2013; Hassan *et al*., 2015).

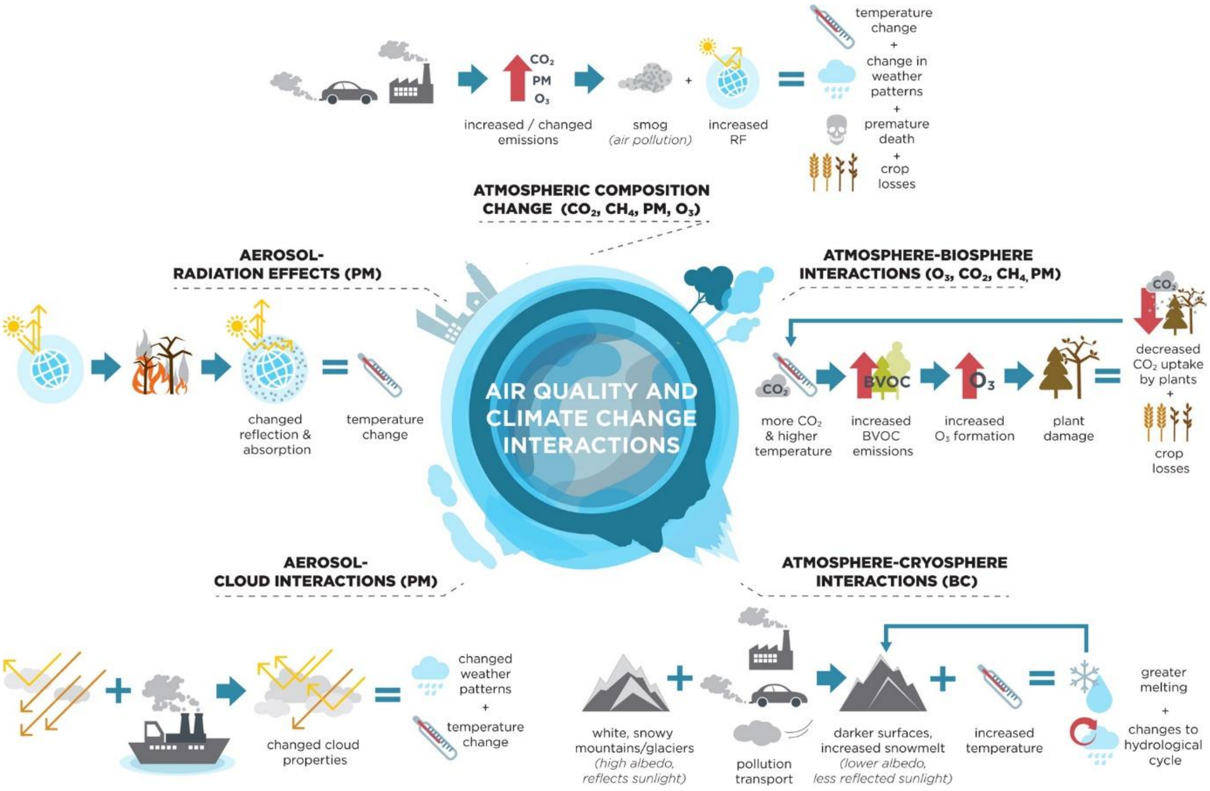


Figure 2.1. An overview of the main, but not all, air quality and climate change interactions. **Source:** von Schneidemesser *et al*., 2015.

Air pollution is strongly influenced by climate and weather: determining the degree to which pollution is spatially and temporally dispersed, transported, chemically transformed and deposited (Fiore *et al*., 2015; Hassan *et al*., 2015; Kinney, 2008; Kinney, 2018; Orru *et al*., 2017; Poole *et al*., 2019). Variations in wind direction and speed alters the dispersion of pollutants both locally and internationally (Cichowicz *et al*., 2020; Kinney, 2018). It is predicted that high pressure weather systems will become more common in the future in the mid-latitudes due to climate change and thus alterations in the jet streams location and strength (Barnes and Screen, 2015; Brunner *et al*., 2018; Stendel *et al*., 2021; Woollings and

Blackburn, 2012). Rapid Artic warming is one climatic factor that influences the temperature gradient and thus location of the jet stream and its strength (Brunner *et al*., 2018; Nakamura and Huang, 2018; Stendel *et al*., 2021). A ‘meandering’ and weakened jet stream will increase the likelihood of atmospheric blocking occurring and high pressue weather systems dominating (Barnes and Screen, 2015; Brunner *et al*., 2018; Nakamura and Huang, 2018; Nabizdeh *et al*., 2019; Stendel *et al*., 2021; Woollings *et al*., 2018). Consequently, this will lead to reduced wind speeds and lower mixing heights that will increase the concentration of pollutants close to their sources (Cichowicz *et al*., 2020; Fiore *et al*., 2015; Kinney, 2018).

Pollution values differ through the year, which is often associated with the climate and atmospheric conditions of the current month (Cichowicz *et al*., 2017). Daily meteorology and anthropogenic activity and emissions are also influential; O_3 concentrations have been shown to increase in the summer months due to longer days, thus increased light, and warmer temperatures (Bell *et al*., 2007; Cichowicz *et al*., 2017; Cooper *et al*., 2014; Monks, 2000; Solberg *et al*., 2008; von Schneidemesser *et al*., 2015). Increased O_3 formation can also occur when wind speeds are reduced and precursor gases are not dispersed (Hassan *et al*., 2015). With increased temperatures, O_3 levels are also predicted to increase, raising health risks associated with them (Bell *et al*., 2007; Intergovernmental Panel on Climate Change, 2014; Solberg *et al*., 2008; Spickett *et al*., 2011).

In winter, PM pollution can increase due to increased use of log burners and other methods within homes (Cichowicz *et al*., 2017; Kelly, 2016; Purcer and Strumbelj, 2018; Saide *et al*., 2016). PM also interacts with cloud formation, influencing the location and amount of precipitation regions receive (Boucher *et al*., 2013; Kim *et al*., 2016; Melamed *et al*., 2016).

NO_2 concentrations have also been reported to increase in winter when there is a corresponding increase in vehicle traffic and a potential reduction in active travel (Marmett *et al*., 2019; Nahal and Mitra, 2018; Uttley and Fotios, 2017). Deposition of nitric acid as acid rain, formed when NO_2 oxidises in the atmosphere, is also influenced by local meteorology: total precipitation, duration and location (influenced by particulate matter) all alter the amount of deposition and influence it has on the environment (Hassan *et al*., 2015; Martin, 1989). Greater rates and levels of oxidisation will also occur under increased temperatures, therefore resulting in greater acid rain potential (Hassan *et al*., 2015).

Increased climate warming (predicted to be 3.7-4.8^{o}C over the next 100 years without mitigation) will also lead to increased heatwave events, wildfires and dust storms (Hassan *et al*., 2015; Intergovernmental Panel on Climate Change, 2014; Spickett *et al*., 2011; Spracklen *et al*., 2009). Wildfires and dust storms will release and lead to increased concentrations of PM, CO_2, VOCs and O_3 among other pollutants and greenhouse gases (De Sario *et al*., 2013; Hodzic *et al*., 2007; Jaffe *et al*., 2008a; 2008b; Pfister *et al*., 2008; Spracklen *et al*., 2009).

It has been argued that due to the long lifetime of pollutants in the atmosphere, immediate efforts may be best focused on reducing air pollution in a bid to improve public and ecosystem health, with an additional benefit of also starting to improve climate change (Kinney, 2018; Rajagolapan *et al*., 2018; Smith *et al*., 2009). However, the two are closely linked which is often overlooked in environmental policies when it should be a joint focus to avoid the likelihood of win/loss or loss/win outcomes with regards to climate change and air pollution (Klausbruckner *et al*., 2016; Maione *et al*., 2016; Melamed *et al*., 2016; Nemet *et al*., 2010; Pettersen and Fleck, 2014; Rao *et al*., 2013; Schmale *et al*., 2014; 2016; von Schneidemesser *et al*., 2015). Targeted policies to reduce greenhouse gas emissions and thus reduce the extent of climate change usually lead to a reduction in pollutant levels (Klausbruckner *et al*., 2016; Rafaj *et al*., 2013; Hassan *et al*., 2015; Kinney, 2018; Melamed *et al*., 2016; Watts *et al*., 2015). For example, rigorous methane reductions will lower O_3 concentrations and reduce climate warming by 0.5^{o}C and prevent 2.4 million premature, air quality related deaths per year (Kinney, 2018; Melamed *et al*., 2016; Schmale *et al*., 2014; Shindell *et al*., 2012; Shindell, 2016).

2.2.1. Impacts and health risks from meteorology

Due to the design of cities and urban areas, there can be a compounding effect on health of poor air quality and meteorology (e.g. urban heat islands: UHIs). As has been previously covered with regards to the connections between air quality, meteorology and climate change, this combination of urban temperatures and air quality can contribute to decreased quality of life and increased mortality risk (Hassan *et al*., 2015; Intergovernmental Panel on Climate Change, 2014).

UHIs were first investigated by Luke Howard in the 1830s before being defined by Oke in 1987 (Howard, 1833; Oke, 1987) as the difference between the urban area and the surrounding rural area, and has been shown to vary from 2.5^{o}C to over 12^{o}C (Akbari *et al*., 2001; Alonso *et al*., 2007; Lai and Cheng, 2009; Oke, 1982; Quattrochi *et al*., 2002; Sailor, 1995; Solecki *et al*., 2005; Yow, 2007). They form through seven contributing causes (Table 2.1) that have been verified through continuing UHI research (Guhathakurta and Gober, 2007; Memon *et al*., 2008; Quattrochi *et al.,* 2002; Sailor, 1995; Senanyake *et al*., 2013; Shahmohadi *et al*., 2013).

Table 2.1. Oke's seven hypothesised contributing causes to UHI formation (Oke, 1982).

Cause Number	Hypothesis
1	Decreased evapotranspiration due to vegetation reductions and increased impermeable surfaces.
2	Increased anthropogenic heat sources (buildings and automobiles).
3	Decreased turbulent heat transport results in less sensible heat loss.
4	Decreased sky view factor from tall buildings and narrow streets reduces long-wave radiation loss to the sky.
5	Increased long-wave radiation due to increased pollution, which absorbs and then re-emits long-wave radiation.
6	Increased short-wave radiation absorption from canyon geometry increasing surface area.
7	Increased sensible heat storage In the daytime due to thermal properties of materials and release at night.

Due to the above factors, UHIs are common in cities and it is predicted that 80% of the urban population will be living in an UHI by 2025 (Giannaros and Melas, 2012; Quattrochi *et al.,* 2002; Trundle *et al.*, 2015; United Nations, 2011). This is of particular concern on its own, let alone when combined with detrimental air quality, as increased urban temperatures have several negative environmental and human health effects (Hattis *et al.,* 2012; Quattrochi *et al*., 2002; Solecki *et al*., 2005; Tomlinson *et al*., 2011; Vardoulakis *et al*., 2013).

These health risks include additional physiological stress, particularly when the body attempts to maintain the correct core temperature, and can lead to severe illnesses or death (Solecki *et al*., 2005). If coinciding with heatwave events, this risk is further increased, as is the likelihood of premature deaths (Dhainaut *et al*., 2004; Klinenberg, 2002; Trundle *et al*., 2015).

UHIs creating thermal discomfort can lead to lost productivity and unfavourable economic impacts (Kjellstrom *et al.* 2009; Lazzarin, 2011, cited by Busato *et al.,* 2014; London Climate Change Project, 2002; Shahmohamadi *et al*., 2013; Yow, 2007). Additionally, as cities grow they will compound the UHI, as will climate change; which will also cause an increase the likelihood of heatwave events (London Climate Change Project, 2002; Sailor, 2014; Trundle *et a*l., 2015; Wilby, 2007). They will also lead to an increased cooling demand, thus increased energy use and production, that will further contribute to pollution and climate change (Kinney, 2018).

Furthermore, projected intensification of heatwave events beyond 2020 may increase deaths by 53% and by 2050 the number of heat-related deaths will double (May *et al*., 2010; Tomlinson *et al*., 2011; Trundle *et al*., 2015). Similarly to poor air quality, the most at risk from these effects are the elderly, young and socio-economically disadvantaged (Fallmann *et al*., 2013; Lenzuni *et al*., 2009; Trundle *et al*., 2015).

2.2.2. Combined risk of urban climatic effects (Urban Heat Islands)

As has been shown, increased urban temperatures can have negative health impacts. These can unfortunately be compounded by air pollution and pose a significant risk to populations. Correlations between air quality, air temperature and mortality have been shown with a 2.54% increased likelihood of death occurring in summer due to a combination of particulate matter and high temperatures (Roberts, 2004; Stafoggia *et al.*, 2008). In the Netherlands, a summer heatwave in association with O_3 and particulates caused an additional 400-600 deaths whilst similar relationships have been shown in China and Australia along with an increased incidence of hospital admissions (Fischer *et al.*, 2004; Li *et al.*, 2011; Qian *et al.*, 2008; Ren and Tong, 2006). Recently, Kalisa *et al*. (2018) also showed a significant relationship between increased temperatures and air pollution (O_3, NO_2 and PM_{10}), particularly during heatwave events.

Furthermore, Aslam *et al.* (2017) has shown relationships between the UHI and increases in $PM_{2.5}$ concentrations in Delhi, suggesting that there a significant correlations between low wind speeds, traffic volume, $PM_{2.5}$ and air temperature. A likely cause for this association is increased population exposure during high temperature conditions through increased ventilation for cooling by either opening doors and windows or air conditioning extractions, as well as increased outdoor pursuits and the likelihood of walking or cycling to work (Georgi and Dimitriou, 2010; Mills, 2017 Roberts, 2004; Trundle *et al.*, 2015; Yu *et al.*, 2009).

Some research has also shown that air pollution has a greater health impact and increased hospital admissions on colder days, showing that the compounding influence of temperature and air quality is not consistent across geographic locations (Cheng and Kan, 2012; Ko *et al.*, 2007; Wang *et al.*, 2013). However, although pollution can at times have a greater impact in winter than summer, research has shown that high atmospheric stability, a tendency of the atmosphere to reduce the vertical motion of air and thus dispersion and dilution of pollution, is needed to increase PM concentrations (Whiteman *et al.*, 2014; Zhang *et al.*, 2014). This is also a meteorological condition that is highly conducive to the formation of urban heat islands (Tomlinson *et al.*, 2012; Whiteman *et al.*, 2014; Zhang *et al.*, 2014). Under cloudless skies and little or no wind UHIs can form more readily, with low winds being emphasised by urban geometry creating street canyons that further reduce air turbulence (Alonso *et al*., 2007; Lai and Cheng, 2009; Oke, 1982; Solecki *et al*., 2005; Trundle *et al*., 2015). Consequently, these conditions will also amplify pollution levels and reduce their dispersion due to reduced turbulent air flow through urban areas (Orru *et al*., 2017). Therefore, despite some locations suggesting that reduced temperatures and pollution are compounding factors and increase health risks, it may actually be a combination of the influence of a local UHI forming due to the atmospheric stability and air pollution.

Additionally, despite the clear detrimental effect UHIs can have on health and mortality during summer months, increased urban temperatures during the winter has been shown to lower the number of cold-related deaths. Winter temperatures can be raised by as much as 9.9^{o}C in the West Midlands, resulting in a 15% reduction in deaths and providing a protective effect (Macintyre *et al*., 2021a; 2021b; Yang and Bou-Zeid, 2018). Consequently, urban air quality and UHI effects throughout the year and potential mitigation measures are needed to be considered to best determine the most effective societal health improvements available.

Overall, air quality and urban climatic conditions can have serious detrimental impacts on not only vulnerable populations, but the population in general – effecting the cardiorespiratory system, cognition and long term health (World Health Organisation, 2018). Climate change will exacerbate these effects unless action is taken and has led to increased international efforts to monitor and reduce global pollution levels and the extent of climate change (Cichowicz *et al.*, 2017; Nagl *et al.*, 2016).

2.3 Air Quality and Meteorological Monitoring

In Europe, there is an ambient air quality Directive, AAQD (2008/50/EC) that is in place to minimise high levels of pollution (European Commission, 2017b; Nagl *et al.*, 2016). Limits on pollution levels are legally binding, and are applied over differing time periods and number of exceedances per year due to the varying health impacts each of the pollutants can have (Table 2., European Commission, 2017c; European Environment Agency, 2017). The introduction of Directive 2008/50/EC introduced new $PM_{2.5}$ limit values whilst Directive 2015/1480/EC determined reference methods, data validation and sampling locations in an attempt to create representative, highly accurate and comparable air quality data across member states (European Commission, 2017c; 2017d). Consequently, EU member states routinely have to make data available to the public and related organisations and are currently working under a Clean Air Programme for Europe since 2013 up to 2030, which has stricter national limits on major pollutants (European Commission, 2017a; 2017d; Guerreiro *et al.*, 2014).

There are equivalent plans and legislation in place globally, often utilising World Health Organisation recommendations for upper limits of pollutants that are lower than that of the EU AAQD (European Commission, 2017a; 2017c; European Environment Agency, 2017; Guerreiro *et al.*, 2014; Nagl *et al.*, 2016; World Health Organisation, 2005). EU limit values are currently higher than World Health Organisation limits, in part due to the lack of success in controlling major pollution sources and that current levels are still being exceeded (European Commission, 2017a; 2017c; European Environment Agency, 2017; Guerreiro *et al.*, 2014; Nagl *et al.*, 2016). With a global drive to reduce air pollution, EU member states are required to provide up-to-date information regarding measured pollutants available to the public along with undertaking the clean air policy that is aimed to avoid 58,000 premature deaths and reduce external costs by 40-140 billion Euros (European Commission, 2017a; 2017e).

Meteorological monitoring is less regionally controlled by directives like air quality, but traditional monitoring stations such as those used by the UK Met Office have a number of desirable and undesirable site characteristics to allow for accurate data capture (Met Office, 2021a; Muller *et al*., 2013a; World Meteorological Organisation, 2006; 2008).

2.3.1. Traditional Air Quality Monitoring Stations and their Representability

Air quality measurements and monitoring can be difficult due to the dynamics of air chemistry and the atmosphere that can result in significant changes and movements in quantities of pollutants (Engel-Cox *et al.*, 2013; Kim *et al.*, 2015; Wardencki *et al.*, 2008). Briefly, there is a difference between analysers and monitors; the former can determine quality, quantity and type of substances in a mixture whilst monitors are often used to alert users when thresholds are met or exceeded (Marc *et al.*, 2012; Wardencki *et al.*, 2008). A key feature required is high sensitivity (the ability to detect low levels of the targeted compound, a quick response time and preferably automatic calibration or lack of sensor drift and the ability to function from an independent power supply without regular maintenance (Lewis and Edwards, 2016; Marc *et al.*, 2015; Wardencki *et al.*, 2008).

The majority of air quality monitoring is performed by government authorities through static networks that are reliable, highly calibrated and measure a range of pollutants (Hasenfratz *et al.*, 2015; Hu *et al.*, 2014; Kumar *et al.*, 2015). However, this comes at a high monetary and maintenance cost, in addition to the need of suitable infrastructure, which limits their spatial distribution (Cocheo *et al.*, 2012; Hasenfratz *et al.*, 2015; Hu *et al.*, 2014; Kumar *et al.*, 2015; Mead *et al.*, 2013; Piedrahita *et al.*, 2014). This is often a negative quality of monitoring networks, the aim of which is to detect as much spatial variability as possible (Duyzer *et al.*, 2015; Ferradas *et al.*, 2010; Kaur *et al.*, 2005; 2007). Often, rural locations in developed countries have intermittent coverage whilst developing countries have little to no coverage (Prud'homme *et al.*, 2013).

With all monitoring networks, the objectives of its development need to be defined to help determine network design and location (Venegas and Mazzeo, 2006). For example, networks can vary in permanence and size from micro-scale designs through to global systems, as demonstrated by Muller *et al.* (2013a). Summarised, the objectives of air quality networks are to: (1) allow for planning and implementation of air pollution reduction strategies; (2) monitor pollution against air quality standards; (3) capturing deterioration in air quality; (4) determining population exposure; (5) detecting emissions from specific sources (Liu, 1977; Liu *et al*., 1986; Modak and Lohani, 1985; Mofarrah and Husain, 2010). It is difficult to design an air quality moniting network that covers all of these objectives, although the majority will cover more than one, resulting in slightly differing network requirements as to placement and number of stations (Piersanti *et al.*, 2015; Rivas *et al*., 2019; Venegas and Mazzeo, 2006; Venegas and Mazzeo, 2010). The location and number of monitoring stations deployed will affect the type of air quality data obtained and how it can be examined in decision making exercises (Baldauf *et al*., 2009). Ultimately, a monitoring network needs to collect as much data over as large of a spatial areas as possible, whilst keeping costs down (Benis *et al*., 2016).

Generally, urban networks utilise monitoring in ‘hot-spot’ locations of high pollution or roadside locations to determine that air quality standards are met – but this can result in difficulties in determing population exposure (Benis *et al*., 2016; Cocheo *et al.*, 2008; Duyzer *et al.*, 2015; Joly and Peuch, 2012; Kanaroglou *et al.*, 2005; Loperfido and Guttorp, 2008). As representative networks may also be required to determine population exposure, compromises may be made between the required number of monitoring stations, their locations and monetary budgets (Cocheo *et al.*, 2008; Duyzer *et al.*, 2015; Joly and Peuch, 2012; Kanaroglou *et al.*, 2005). This is because in addition to roadside ‘hot-spot’ stations, monitors that record background levels of pollution and its spatial variability are required (Benis *et al*., 2016; Muller *et al.*, 2013a; Venegas and Mazzeo, 2006). However, a combination of both monitoring types and locations can be highly resource-intensive and may be substituted for a gridded network that is supplemented by mobile sampling or modelling (Rivas *et al*., 2019; Santiago *et al*., 2013; Santiago and Martin, 2015; Venegas and Mazzeo, 2006). Additionally, care must be taken when considering measurements take at roadside loations in terms of population exposure and health effects as they may not be representative of levels the majority of the population are exposed to consistently (Baldauf *et al*., 2009).

Urban stations are often less spatially representative than those taken at background or rural sites, usually recording high peaks and variability that limits their area of representativeness to a few square kilometres (Joly and Peuch, 2012; Righini *et al.*, 2014). In comparison, rural locations display less variability and can often be deemed representative of areas up to 10 km^2 (Righini *et al.*, 2014). Due to these drawbacks of fixed site stations, a number of alternative methods of measuring air quality that can capture spatio-temporal variations and are more representative can be used (Heard, 2006; Kumar *et al.*, 2015; Mead *et al.*, 2013; Peng *et al.*, 2014).

Finally, although monitoring in developing countries has improved, this does not always result in good data quality (Engel-Cox *et al.*, 2013). Issues with sensor calibration and data management, power supplies, spare parts and regular maintenance which are all required to ensure data standards are met, are often lacking in developing countries, with data sometimes not being shared due to telemetry or political issues (Engel-Cox *et al.*, 2013). Data quality and the ability to cross-reference data can also be questioned due to a lack of metadata and monitoring locations, as guidelines for standardised placements can be difficult to adhere too (Muller *et al.*, 2013a; 2013b). Consequently is has been recommended that standardisation of sensor locations in urban networks refers to installation height and density of stations rather than traditionally being a set distance from roughness elements (Muller *et al.*, 2013b).

In the UK, the Automatic Urban and Rural Network (AURN) controlled by the Department for Environment, Food and Rural Affairs (DEFRA), is the largest monitoring system that measures NO_x, NO_2, SO_2, O_3, CO and $PM_{2.5}$ and PM_{10} (Department for Environment, Food and Rural Affairs, 2017a; Mead *et al.*, 2013). The system reports hourly to an online service accessible by the public to ensure that air quality complies with Ambient Air Quality Directives implemented by the EU (Department for Environment, Food and Rural Affairs, 2017a). Comprised of 147 sites in 2015, the AURN has a series of methodologies in place that maintain instrument performance and calibration alongside EU regulations and utilises the measurement techniques outlined in Table 2.2 (Department for Environment, Food and Rural Affairs, 2016a; 2017a).

Table 2.2. DEFRA AURN air quality measurement techniques (Department for Environment, Food and Rural Affairs, 2016b; 2017a).

Air Quality Measure/Pollutant	**Analysis Method**
NO/NO_2	Chemiluminescence (EN 14211:2012 'Ambient air quality - Standard method for the measurement of the concentration of nitrogen dioxide and nitrogen monoxide by chemiluminescence')
O_3	UV absorption (EN14211:2012 'Ambient air quality – standard method for the measurement of the concentration of ozone by ultraviolet photometry')
SO_2	UV fluorescence (EN 14212:2012 'Ambient air quality – Standard method for the measurement of the concentration of sulphur dioxide by UV fluorescence')
CO	IR absorption (EN 14626:2012 'Ambient air quality - Standard method for the measurement of the concentration of carbon monoxide by non-dispersive infrared spectroscopy')
$PM_{2.5}$ and PM_{10}	Tapered element oscillating microbalance, beta attenuation monitor, gravimetric monitor, filter dynamics systems (FDMS, TS16450:2013 Automatic PM analysers, will be replaced with EN16450:2016)

Data from the AURN undergoes validation and ratification through a manual review of recorded and uploaded data to 'clean up' provisional data and review calibration data of measurement instruments (Department for Environment, Food and Rural Affairs, 2017b).

For other EU member states, air quality monitoring networks are designed to meet EU legislation, however, research has shown that across the continent there are several designs and approaches implemented to measure air quality (ATMO France, 2011; Duyzer *et al.*, 2015).

Monitoring networks globally differ in their methodologies and placement around towns and cities. Consequently, this alters how representative they are with regards to measured pollution levels and population exposure (Duyzer *et al.*, 2015). Furthermore, fixed monitoring stations often cannot capture fine-scale spatial variations in pollutants, despite having a high temporal resolution (Hansard *et al.*, 2011). Despite successful monitoring results, Canada's NAPS network has been noted to be too sparse in areas for modelling studies whilst developing countries often have too few or non-existent monitoring stations and data (Huang *et al.*, 2009; Hystad *et al.*, 2011). Santiago de Chile, Chile, a location highlighted as having a questionable monitoring network, has eight stations that are 80% effective and used in research whilst Malaga, Spain, previously had a monitoring network that was unable to differentiate between traffic-orientated and background pollution (Lozano *et al.*, 2009; Silva and Quiroz, 2003; Toro *et al.*, 2014; 2015). With increased pulic awareness, there has been an increased demand for and development of several other air quality monitoring technologies in a bid to address some of the issues surrounding the cost and representability of traditional in-situ monitoring facilities (Kay *et al*., 2015; Oluwasanya *et al*., 2019).

2.3.2. Traditional Meteorological Monitoring Stations

Traditional meteorological monitoring stations in the UK utilises over 280 automatic weather stations, which measure a combination of hourly synoptic observations and daily climate summaries (Green, 2012; Met Office, 2021b). Stations are around 40 km apart to allow for the recording of weather systems moving across the country, as well as meteorological parameters including temperature, atmospheric pressure, precipitation, wind speed and direction, humidity, cloud height and visibility (Met Office, 2021a). For accurate readings, such monitoring sites need to be placed on level ground with no nearby tall buildings, trees of steep ground that could influence measurements (Met Office, 2021a). This, much like standard air quality monitoring networks, make them difficult and costly to use in urban environments, which can result in low data coverage in highly heterogeneous environments (Muller *et al*., 2013a). Often, traditional monitoring networks are insufficient to evaluate urban models effectively with in some cases data outside of the study area being used (Best, 2006; Best and Grimmond, 2013; Grimmond *et al*., 2010; Muller *et al*., 2013a; Warren *et al*., 2016). This make determination of urban climatic conditions such as urban heat islands (UHIs) difficult without the use of alternative methods (Muller *et al*., 2013a; Tomlinson *et al.,* 2012).

2.3.3. Low Cost Air Quality Sensors

Due to the high costs of standardised monitoring equipment, cheaper alternatives are available that can allow for installation of networks in previously unmonitored locations or higher density networks (Castell *et al.*, 2017; Mead *et al.*, 2013; Schneider *et al.*, 2017). Examples of low-cost sensors include AQMesh that are battery powered devices measuring (NO, NO_2, O_3 and CO) with a total particle count that is used to estimate $PM_{2.5}$ and PM_{10} levels (Castell *et al.*, 2017; Schneider *et al.*, 2017). Low cost-LED and photodiode based sensors have also been produced by several manufacturers, however, they have been shown at times to be unreliable (Budde *et al.*, 2012; Cheng *et al.*, 2014; Tian *et al.*, 2016).

Further examples of low-cost sensors for the pollutants examined in the subsequent studies are highlighted in Table 2.3.

Table 2.3. Potential low cost sensors that could be utilised to provide field measurements of ozone, nitrogen dioxide and $PM_{2.5}$ and PM_{10} levels at selected sports events. Adapted from Idrees and Zheng, 2020.

Pollutant	Sensor Type	Low Cost Sensor
Ozone	Solid-state electrochemical sensor avoiding nitrogen dioxide sensitivity	MiCS2611, MiCS2610, MQ-131
Nitrogen Dioxide	Solid-state electrochemical sensor avoiding ozone sensitivity	Mq-135, GSNT11, MiCS-2714
$PM_{2.5}$, PM_{10}	Light scattering optical analyser	Aerocet 831 Aerosol Mass Measurement Module, OPC-N2 Particle Sensor

There has been increased numbers of commercially available low-cost sensors released in recent years, although their accuracy and reliability in various uses is not clear (Morawska *et al.*, 2018). Consequently, there been calls for such sensors to be tested by academics and official bodies to determine their accuracy and reliability, but this may further increase purchase costs and negate some of the positive impacts that low cost sensors have in raising awareness among the general public of their local air quality (Castell *et al.*, 2017; Lewis and Edwards, 2016). A clear indication of whether a sensor is to be used as a general aid to determining air quality and improving awareness or being as accurate as reference equipment is, at least, required to be investigated (Castell *et al.*, 2017; Lewis and Edwards, 2016). Generally, the reduction in cost of the sensors results in lowered sensitivity or specifity, and potentially both, as well as reduced response times and a lack of calibration options to determine sensor accuracy (Budde *et al.*, 2015; Lewis and Edwards, 2016; Piedrahita *et al.*, 2014).

Issues with regards to low cost sensor accuracy has been classified as internal and external errors (Arfire *et al*., 2016; Idrees and Zhang, 2020). The former are associated to the sensors mechanisms in recording air quality and include signal drift, nonlinear responses and systematic errors (Maag *et al*., 2018; Idrees and Zhang, 2020). External errors refer to local environmental parameters that may influence data recording and is often dependant on the specific sensor and the conditions it is used in (Idrees and Zheng, 2020). Figure 2.2 shows how both errors types influence data collection and the suggested calibration methods to negate this happening for low cost sensors.

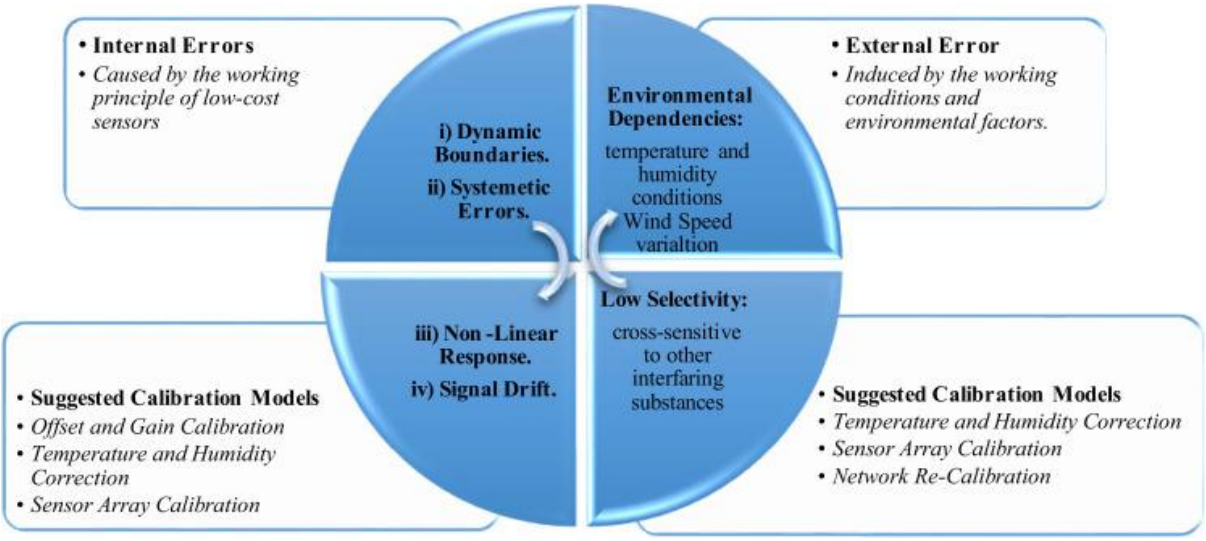


Figure 2.2. Low-cost sensor errors and calibration techniques. **Source:** Idrees and Zheng, 2020.

The number of real-world tests of low-cost sensors has started to increase within academic circles, but those that have been performed have at times highlighted stability and sensitivity issues along with registering interference from other gases and meteorological conditions (Borrego *et al.*, 2016; Castell *et al.*, 2017; Kamionka *et al.*, 2006; Lewis *et al.*, 2016; Lewis and Edwards, 2016; Mead *et al.*, 2013; Schneider *et al.*, 2017). In particular for low cost particulate matter sensors, relative humidity variations have been shown, with values been shown to be as much as 46% higher than standard monitoring equipment (Jayarante *et al*., 2018). Johnson *et al*. (2018) also found that low cost sensors performed poorly in relatively low (<40 µg/m^3) $PM_{2.5}$ locations, suggesting that they would be best suited to highly polluted and roadside environments. However, algorithmic methodologies to correct for relative humidity changes have been proposed and successfully utilised by the Pope group (Crilley *et al*., 2018; 2020).

Furthermore, studies in Kenya utilising low-cost optical particle counters have highlighted that developments in accuracy for both roadside and urban background measurements have improved and such devices can provide a reliable and affordable monitoring network (Pope *et al*., 2018). A low-cost sensor network installation at London Heathrow airport also distinguished airport emissions from long range transport of NO_2, providing sufficient data for the air quality model ADMS-airport to be reliably created and ran (Popoola *et al*., 2018). Cavaliere *et al*. (2018) has developed a low cost air quality station that provides real-time monitoring of CO, CO_2, NO_2, O_3, VOCs, $PM_{2.5}$ and PM_{10}. After laboratory and field calibration, these sensors provided higher accuracy and precision than previous alternatives, with R^2 values of 0.91 and 0.96 for $PM_{2.5}$ and PM_{10} respectively (Cavliere *et al*., 2018). Other low-cost sensors have also returned favourable results, notably the Alphasense UK O_3 sensors, semiconductor-based instruments developed by Williams *et al.* (2013) and low-cost electrochemical CO monitors developed by the University of Cambridge (Heimann *et al.*, 2015; Pang *et al.*, 2017).

Locating monitors for low cost sensors, as well as regular monitoring networks and accessing appropriate locations to perform biomonitoring and other measurement methods, can also prove difficult to ensure that data is representative (Muller *et al.*, 2013a). The same can be said for energy and communication requirements and monitor safety (Muller *et al.*, 2013a). Although these can be partially overcome through the use of citizen science and installation of monitors in secure locations such as schools, over the course of two and a half years and a variety of outreach techniques saw approximately 25% of Birmingham's schools partake in the BUCL monitoring network (Chapman *et al.*, 2015). This provided an extensive, city-wide network that has been applied to UHI studies with inexpensive sensors supported by automatic weather stations and a strong citizen science outreach (Chapman *et al.*, 2015).

Despite some initial shortcomings of low-cost sensors, they can provide coarse, but improving, widespread information on air quality and in conjunction with reference station data and air quality models to provide relatively accurate data (Castell *et al.*, 2017; Pope *et al.*, 2018; Schneider *et al.*, 2017). Furthermore, it has been suggested that low-cost sensors can fulfil their potential with proper pre-instillation calibration and post-processing and data modelling, with numerous studies developing methods to improve accuracy and reliability (Borrego *et al.*, 2016; Gupta *et al.*, 2018; Kim *et al.*, 2018; Spinelle *et al.*, 2015; 2017).

2.3.4. Low Cost Meteorological Sensors

Meteorological low-cost sensors have best been showcased in the aforementioned Birmingham Urban Climate Laboratory (BUCL) as part of the HiTemp project (Ali *et al.*, 2016; Chapman *et al.*, 2015; University of Birmingham, 2021). This has utilised 24 automatic weather stations with approximately 84 low cost air temperature sensors deployed across the city, mostly located at schools (Chapman *et al*., 2015; University of Birmingham, 2021; Warren *et al*., 2016). However, as has been highlighted earlier, BUCL encountered uptake and continued engagement issues (Chapman *et al*., 2015). Similarly, the Urban-Path project in Szeged, Hungary and Novi Sad, Serbia utilised 22 and 25 low cost meteorological stations to monitor urban climate zone fluctuations and identified differences due to the UHI effect present (Skarbi *et al*., 2017; Urban Path). Others, Oklahoma Mesonet, Helsinki testbed and Open Air Laboratories are part of a growing trend of urban meteorological networks, but there is still a shortage of high density networks to support high resolution modelling (Basara *et al*., 2011; Davies *et al*., 2011; Koskinen *et al*., 2011; Warren *et al*., 2016).

2.3.5. Personal Exposure, Novel and Wearable Technologies

There has been an increasing movement of integrated technology and wearables in the consumer and public world, driven by smartwatches and fitness trackers (Kim and Shin, 2015; McIntyre, 2014). However, research into the possibility of utilising wearable technology or body sensors networks for air quality monitoring, among other variables, has been ongoing in a variety of methods (Figure 2.3a, 2.3b, Aliverti, 2017). The benefits of this monitoring angle is the potential for concurrent GPS location data to provide spatial data of pollutant concentrations as many of these devices are ‘smart’ and connected to the Internet of Things and mobile networks (Morawska *et al*., 2018).

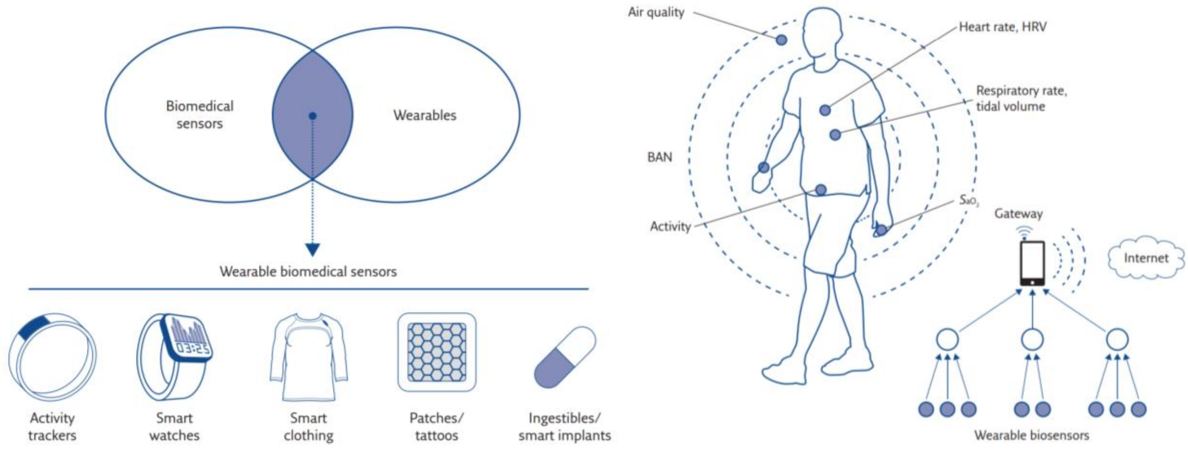


Figure 2.3a (left) and 2.3b (right). Wearable biomedical sensors and the architecture of personal monitoring systems using wearable sensors in conjunction with internet connected devices. HRV: heart rate variability, SaO_2: arterial oxygen saturation. Source: Aliverti, 2017, Gandhi and Wang, 2021.

Devices such as SecondNose, a Bluetooth enabled real-time air quality monitor and AirCloud utilise mobile networks and cloud storage to provide personal air quality data (Cheng *et al.,* 2014; Leonardi *et al.*, 2014). These devices shows the progression of personal, portable air quality monitors with Pre-emptive Media Project's AIR device trialled in New York during 2006 that was considerably larger but operated as a self-contained system, uploading data without the need to pair with a mobile device (Air, 2006). Consequently there has been a proliferation of mobile-paired devices in recent years, with suggestions of creating large-scale sensor networks based on crowdsourcing from personal mobile devices (Hasenfratz *et al.*, 2012; Kanhere, 2011; Stevens and D'Hondt, 2010; Zappi *et al.*, 2012). These have included measuring noise pollution along with traffic conditions and bicycle tracking along with air quality (Hasenfratz *et al.*, 2012; Lai *et al.*, 2011; Mohan *et al.*, 2008; Stevens and D'Hondt, 2010).

Body-worn sensors have been utilised by Nieuwenhuijsen *et al.* (2015) as part of the BREATHE (Brain Air School Investigation) study into black carbon exposure of school children whilst Kao *et al.* (2017) has developed Earth Tones, cosmetic-inspired powders that react, and thus change colour, with polluting chemicals in the atmosphere. Development into more ‘typical’ wearable technology has been demonstrated by MyPart, a personal particle sensor that is wrist-worn and interfaces with a smartphone visualisation and data logging application (Tian *et al.*, 2016). With a cost of less than $50 (US), MyPart is capable of detecting variations in particle sizes and distinguishing between $PM_{2.5}$ and PM_{10}, showing strong correlations against an industrial grade sensor (r^2=0.96 and 0.91, Tian *et al.*, 2016). Sensaris has also developed a wrist-based monitor along with ‘Sensbloks’ that track real-time air quality and used Bluetooth to display data on the users mobile device (Costa, 2015; Indiegogo, 2017; Kim *et al.*, 2015; Sensaris).

Recently, AirPop, who claim to be the world’s first “air wearables company” have released another first: an “air wearable” smart mask (AirPop, 2021; Milsom, 2021). This is a face mask that can be used during physical exercise and connects to the AirPop mobile app, providing details of the pollutants blocked by the mask, filtration replacement reminders and the wearer’s breathing metrics (Milsom, 2021). Previous and similar designs include WearAir, Conscious Clothing and the work of New York University, all of whom have developed t-shirts that either change colour or display flashing lights when local levels of CO, particulate matter and VOCs increase (Fernandez, 2011; Kim *et al.*, 2010; Mark, 2013).

The main questions regarding wearable technology for personal exposure or spatial pollution studies is their accuracy, which has been highlighted by several researchers (Budde *et al.*, 2012; Cheng *et al.*, 2014; Tian *et al.*, 2016). As has also been highlighted in the low cost section of this review, clear distinctions between the level of accuracy (especially at low pollution concentrations) and intended use of wearable or portable air quality monitoring systems needs to be made, especially for those aimed at wide-spread public use (Aliverti, 2017; Lewis and Edwards, 2016; Morawska *et al*., 2018). For example, emerging technology has integrated some air quality measuring capabilities into a functioning smart phone, although they are limited in their use as a personal exposure monitor due to not providing continuous recordings nor data storage capabilities currently (Nyarku *et al*., 2018). Furthermore, there is the question over data ownership, location tracking/identification and third party use of collected data, which can lead to issues with regards to research ethics and utilising collected data in alternative settings such as urban planning (Aliverti, 2017).

Novel methods of data collection for meteorology in urban areas include the suggested use of drones or unmanned aerial vehicles by Li and Sun (2017). This would create a three-dimensional mobile network of sensors, but may have some restrictions with use in all or specific urban locations (Li and Sun, 2017; Parsons, 2019). Similarly, biotelemetric sensors have been developed at the University of Birmingham that can be attached to birds to measure urban temperature changes and have less restrictions compared to drones (Parsons, 2019; Sadler *et al*., 2018; Thomas *et al*., 2018).

Wearable technology has also been trialled in Japan with the development of sensors that track ambient temperature, humidity, wind speed and short/long-wave radiation as well as physiological metrics (Nakayoshi *et al*., 2015). Similar clothing has been developed by Liu *et al.* (2019) whilst Haas and Ellis (2019) have utilised wearable sensors to assess the impact of heat waves on individual’s body temperatures. A wearable anemometer has also been developed by Li *et al*. (2019) which is accurate up to 0.5 m/s as well as providing absolute and relative wind angle and orientation.

2.3.6. Modelling

Models are often considered a monitoring method and their use is encouraged by the 2008 European Air Quality Directive, although they do have higher uncertainty levels than 'real-world' measurements (ATMO France, 2011; Thunis *et al.*, 2016). This is often due to methods of model formation, aggregation and simplification and the quality of data provided (Shorshani *et al.*, 2015a; Silveira *et al*., 2019). Models, at times, can be cheaper than the installation and maintenance of fixed measurements sites, making them a viable alternative if local surroundings are suitable and monitoring sites are unavailable (ATMO France, 2011). Models can help determine spatial variability in pollutants when monitoring networks are insufficient to capture the variability or to determine the influence of air quality plans (Borge *et al.*, 2014; Elbir, 2003). Often, regional and global models are informed by national networks, but higher-resolution, local networks are still required to detect local processes (Miranda *et al.*, 2015; Muller *et al.*, 2013a).

Models have been developed to determine the influence of vehicular and roadway pollution, industrial complexes and biomass burning among others at a range of scales (Cuchiara *et al.*, 2017; Karppinen *et al.*, 2000; Kemball-Cook *et al.*, 2015; Sivacoumar and Thanasekaran, 1999; Sivacoumar *et al.*, 2001; Xing *et al.*, 2015). The use of models can also allow for air improvement schemes to be 'tested' prior to implementation to determine the best potential method (Borge *et al.*, 2014; Elbir, 2003).

Extensive spatial modelling of urban areas has been demonstrated by several researchers (Elbir, 2003; Miranda *et al.*, 2016). Similarly, models have been used to determine temporal and spatial variations of $PM_{2.5}$, its transport, contributing locations and methods of potential pollution control over China whilst transboundary transport of PM and other biomass burning emissions in southeast Asia have been utilised (Aouizerats *et al.*, 2015; Wang *et al.*, 2013).

For urban traffic pollution, there are three main models used: statics models that utilise the population distribution and associated average traffic volumes, dynamic models that predict pollution emissions from vehicle location and time and aggregated dynamic models that represent congestion and evolution of traffic states and pollution (Shorshani *et al.*, 2015a). Dynamic and aggregated dynamic models work at a higher spatial-temporal resolution than static models and are classified as being macroscopic, microscopic or mesoscopic depending on how they represent vehicle movements as either individual or groups of vehicles and their time-space behaviour (Shorshani *et al.*, 2015a).

A variety of emission models utilised in conjunction with traffic models are also required and summarised by Shorshani *et al.* (2015a). Vehicle emission modelling has been demonstrated by a number of researchers, with results showing exposure levels of populations, traffic flow alteration effects and the influence of calm weather conditions on results (Beelen *et al.*, 2013; Beelen *et al.*, 2014; Dons *et al.*, 2013; Osorio and Nanduri, 2015; Shorshani *et al.*, 2015b).

Finally, with tighter restrictions on European Union emission limits, models are required to be more reliable and accurate in complex urban areas that have high numbers of emission sources and population exposure (Borge *et al.*, 2014; Denby, 2011). The spatial representativeness of models and monitoring stations also needs to be considered, with the former potentially indicating high pollution or exposure locations that require further monitoring or action whilst the later can identify model errors (Daly and Zannetti, 2007; Miranda *et al.*, 2015; Janssen *et al.*, 2012).

Meteorological models are developed and used for two main purposes with respect to air quality (Amato *et al.*, 2014; Elbir, 2003; Zannetti, 1990):

1. Understanding and predicting global, regional or local meteorological phenomena or forecasts.
2. Provide meteorological inputs required for air pollution models and studies.

Such models are either numerical or analytical, with the UK Met Office utilising the former for their Unified Model and Numerical Atmospheric-dispersion Modelling Environment (NAME) models for seasonal and climate modelling, weather predictions and atmospheric dispersion modelling (Met Office, 2021c; 2021d; 2021e; 2021f; Zannetti, 1990). Meteorological modelling in the scope of the following research has often been performed with regards to identification of urban heat islands and the influence of urban landscapes on meteorological phenomena (Karlicky *et al*., 2018).

UHIs have traditionally been identified through the use of paired observational sites, one rural and one urban (Heaviside *et al*., 2017). However, this can limit comparisons between cities and with the issues covered previously with regards to urban meteorological stations, accurate measurements, or measurements in general, may not be accurate or available (Heaviside *et al*., 2017; Muller *et al*., 2013a; Tomlinson *et al*., 2012). Furthermore, this method doesn’t highlight UHI variations within the city nor identify areas where health risks will be highest (Heaviside *et al*., 2017). Consequently, modelling the UHI is a widely used alternative option, but does require consideration of the each study cities unique characteristics as well as local meteorological conditions (Heaviside *et al*., 2017; Stewart, 2011).

As highlighted previously, models are only as accurate as their input data and parameters, although most urban models have been shown to be able to accurately reproduce the UHI effect within 2-3°C (Karlicky *et al*., 2018). This is through the coupling of numerical weather prediction or regional climate models to an urban canopy model to capture the influence of urban processes (Chen *et al*., 2011; Karlicky *et al*., 2018; Lee *et al*., 2011; Liao *et al*., 2014). Despite, this some models examined struggled to fully capture the influence of urban geometry on wind speeds and thus heat and pollution dispersion, whilst others fail to capture the influence of urban heterogeneity on UHI formation (Karlicky *et al*., 2018; Sharmin *et al*, 2017). However, modelling of the UHI and urban temperatures allows for identification of 'at risk' populations and areas as well as insight UHI variations and the impact of potential mitigation measures can also be explored (Grimmond and Oke, 1999; Heaviside *et al*., 2017; Martilli *et al*., 2002; Voelkel *et al*., 2016).

2.3.7. Monitoring conclusions

Urban air pollution is a high-profile topic globally with numerous hazardous effects including respiratory, cardiovascular illnesses or distress and is linked to 7 million global deaths annually (World Health Organisation, 2014). Pollutants of concern include NO_x and NO_2, O_3, $PM_{2.5}$ and PM_{10} as the major risks to human health, along with SO_2 and VOCs (Devarakonda *et al.*, 2013; United States Environmental Protection Agency, 2016a; World Health Organisation, 2013). The main sources of these are vehicles, atmospheric chemistry and fuel combustion (Geravandi *et al.*, 2015; Kobayashi *et al.*, 2017; United States Environmental Protection Agency, 2016a). Under EU legislation, countries are bound to monitor pollution using standardise reference methods such as the DEFRA AURN network in the UK whilst around the world there is a mixture of monitoring methods and techniques used (Department for Environment, Food and Rural Affairs, 2017a; European Commission, 2017b; Nagl *et al.*, 2016). Of note is the American EPA's suite of networks using reference methods that are often duplicated by other environment agencies and the lack of monitoring in developing nations (Engel-Cox *et al.*, 2013; United States Environmental Protection Agency, 2016a).

Urban meteorology is also complex to measure, facing similar challenges as air quality monitoring. Due to the cost, maintenance, calibration and several other issues associated with official reference methods utilised by government authorities, alternatives have been sought that can provide high levels of accuracy and reliability at reduced costs (Hasenfratz *et al.*, 2015; Lewis and Edwards, 2016; Mead *et al.*, 2013). It is hoped that viable solutions and methods will result in increased density of monitoring networks to better capture spatial and temporal variability in air quality and population exposure and urban meteorology at reduced costs (Lewis and Edwards, 2016).

2.4 Air Quality and Exercise

Due to the health risks previously covered, research has been performed to determine whether the risks associated with air pollution outweigh the benefits gained from outdoor exercise. With concerns over global activity levels it is hoped that the provision of and encouraged use of green outdoor spaces, cycle to work schemes and parkrun events will make some form on inroad in to inactivity (de Hartog *et al*., 2010; Morici *et al*., 2020; Nieuwenhuijsen and Khreis, 2016; Varo *et al*., 2003; World Health Organisation, 2020b). There has been a global documented increase in the participation of endurance running races and challenges for both fitness and personal challenges, yet the conditions in which exercise performed could be detrimental (Brocherie *et al.*, 2015; Helou *et al.*, 2012; Yankelson *et al.*, 2014). This is due to the increased minute ventilation rate (the volume of air inhaled in one minute) that occurs during exercise (Bigazzi, 2016; de Hartog *et al.*, 2010; Giles and Koehle, 2014; Muns *et al.*, 1995; Niinimaa *et al.*, 1990; Pasqua *et al.*, 2018; Ultman *et al.*, 2004; van Wijnen *et al.*, 1995; Zuurbier *et al.*, 2009). Inhalation and deposition of particulates is predicted to be between 2 and 4.5 times greater during moderate exercise compared to rest (Bigazzi, 2016; Daigle *et al.*, 2003). Research has also shown that up to 42% of exercise and active travel undertaken within the study by Hankey *et al*. (2017) can occur on the highest polluted roads. This could lessen the health benefits associated with physical activity theoretically could be mitigated by travellers being able to plan commuting and exercise routes on less polluted roads if such data was made available. In such cases, exposure could be reduced by 15% if active travel routes are chosen more selectively (Hankey *et al.*, 2017). Consequently, consideration of the conditions exercise is performed in is in need of attention. This is especially so as Bos *et al*. (2014) found, albeit from a small sample population, that the benefits of exercise-improved cognition is reduced by exercising in poor air quality.

Examination of the ten ‘cleanest’ and ‘dirtiest’ cities by Pasqua *et al*. (2018) suggests that the duration of exercise performed should be carefully considered alongside local pollution levels. Using laboratory minute ventilation data, they calculated the pollution uptake at rest and during a hypothetical moderate exercise session across these twenty cities (Pasqua *et al.*, 2018). They found that the inhaled dose of PM_{10} and $PM_{2.5}$ was significantly higher in the dirtiest cities and also during exercise compared to rest (Pasqua *et al.*, 2018). Furthermore, they determined that health benefits would continue to be gained for up to ninety minutes of exercise in the clean cities, whilst this lasted for just fifteen minutes in the dirtiest (Pasqua *et al*., 2018). If exercise continued longer than seventy-five minutes, the detrimental health impacts of air pollution then outweighed the physical exercise benefits (Pasqua *et al*., 2018).

Other research which has suggested similar results to Pasqua *et al*. (2018) has been performed by McCreanor *et al*. (2007) and Strak *et al*. (2010) who examined physiological variables before and after exercise in various polluted conditions. McCreanor *et al*. (2007) found a significant decrease in lung function and increased inflammation when exercising under higher pollution levels whilst Strak *et al*. (2010) found 1-3% decreases in lung function and increased inflammation of the airways post exercise, which lasted up to six hours after exposure. Nyhan *et al*. (2014) also showed that there is increased particulate matter deposition within exercisers lungs compared to those in vehicles on comparable roads, which is linked to decreased heart rate variability: a quantitative health marker of cardiac function. Guo *et al*. (2020) has also shown that $PM_{2.5}$ is associated with larger reduction in lung function for those who exercise the most, despite the increase in physical activity providing other health benefits. This suggests that the increased $PM_{2.5}$ intake for the upper percentiles of exercisers may attenuate the health benefits to an extent, leading to a recommendation that exercisers avoid the most polluted of conditions (Guo *et al*., 2020).

As has been previously examined, air pollution can lead to the development of respiratory conditions and increase the prevalence of asthma in children and adults (Gilliland *et al*., 2017; Jacquemin *et al*., 2015; Ji *et al*., 2016; Morici *et al*., 2020; Orellano *et al*., 2017). Research has also shown that physical exercise under polluted conditions can increase the frequency of asthma being developed in children (McConnell *et al*., 2002), with respiratory symptoms such as shortness of breath and chest tightness being reported during and after exercise more frequently under high pollution levels (Brunekreef *et al*., 1994; Cole-Hunter *et al*., 2015a; Gong Jr *et al*., 1988; Morici *et al*., 2020).

However, this research has mostly suggested that only under the most extreme of air quality levels for extended periods would the health effects of exercise be reduced. The benefits of exercising under lower pollution levels has been shown to be worthwhile, with de Hartog *et al*. (2010) suggesting that a modal shift from car to bicycle for travelling would result in net life years gained. The physical exercise increase would result in three to fourteen months gained with only 0.8-40 and five to nine days lost for increased pollution exposure and traffic accidents respectively (de Hartog *et al*., 2010). Additionally, traffic related air pollution has been shown by Andersen *et al*. (2015) to not have a detrimental impact on exercise benefits in a Danish study whilst Wong *et al*. (2007) suggested that physical exercise in those aged over sixty-five would reduce the risk of premature death attributable to air pollution. This is supported by Sun *et al*. (2020) who found that aerobic exercise in older demographics (≥65 years) reduced the risk of premature death regardless of their long term air quality exposure in Hong Kong.

In a similar study to Pasqua *et al*. (2018), Tainio *et al*. (2016) examined whether air pollution could negate the health benefits of cycling and walking. Determining pollution exposure during exercise in the most polluted city examined, Delhi, India, suggests that cycling for more than thirty minutes would be detrimental to health (Tainio *et al*., 2016). However, for most global regions that were classified as highly polluted (44-153 $\mu g/m^3$) this figure was between 30 and 120 minutes per day for cycling and 90 minutes and 6 hours 15 minutes for walking (Tainio *et al*., 2016). Using the global average urban background $PM_{2.5}$

concentration, it was estimated that it would take over 7 hours of cycling for air pollution impacts to outweigh the physical exercise benefits: a figure likely only to be of concern for those employed in the bike messenger and delivery services (Tainio *et al.*, 2016).

Consequently, although there are health risks associated with exercising in air pollution, in most cases except the most extreme and extended circumstances, research suggests that the benefits of physical exercise are greater and worth pursing to reduce mortality and improve quality of life (Morici *et al.*, 2020; World Health Organisation, 2020b). This is not, however, to suggest that air pollution has no effect on athletic performance, as shown in the following studies, and educating exercisers to the risks associated with poor air quality should be undertaken (Giorgini *et al.*, 2016).

2.4.1. Air Quality and Athletic Performance

Examination of the effect of air quality on athletic performance has mostly focused on either marathon running for 'real-world' analysis or running and cycling laboratory tests to provide additional variable control during testing. Of the former of these there is little research. Most notably Marr and Ely (2010) examined seven United States marathons and found that PM_{10} increases of 10 $\mu g/m^3$ decreased performance by 1.4% for women whilst Helou *et al.* (2012) determined that ozone was detrimental to marathon performances. A study in China examining fifty-six marathons in 2014 and 2015 also suggested that due to the measured air quality index of 320, finishing times were almost five minutes slower in comparison to the average air quality index recorded in China, as well as a likely contributing factor to the large 'did not finish' proportion of entrants (Guo and Fu, 2019).

Other real world studies have included VO_2 max field tests (the maximum amount of oxygen a person can utilise during exercise) to determine performance as well as cardiovascular and haematological variables on football players by Boussetta *et al*. (2017). Tests were performed under conditions classed as polluted and not polluted with results showing that there is a significant decrease in VO_2 max, agility, red blood cell count and haemoglobin levels under polluted conditions compared to the unpolluted conditions (Boussetta *et al*., 2017). Additionally, a long term study of the German professional football league found a causal relationship between particulate matter and player productivity whilst submaximal cycling tests under high particulate matter conditions were lower compared to those performed under low pollution conditions (Cutrufello *et al*., 2011; Lichter *et al*., 2017).

Rundell and Caviston (2008) performed maximal effort cycling tests under low and high PM_1 conditions with nonasthmatic participants. Their results show that under high PM_1 conditions typical of urban environments that exercise performance could be impaired to a significant level (Rundell and Caviston, 2008). Similarly, examination of diesel exhaust emissions and their effect on cycling performance also suggested that fatigue and rate of perceived exertion increased when compared to filtered air, as well as an increased number of respiratory symptoms being shown (Giles *et al*., 2014; 2018; Morici *et al*., 2020).

No significant effects of air pollutants on exercise performance have also been shown though: O_3 exposure during a laboratory 8 km run test showed no detrimental effects, whilst a 20 km cycling time trial on a static bike after being exposed to diesel exhaust also showed no effects other than increased heart rate values (Giles *et al*., 2012; Gomes *et al*., 2010). Similarly, cycling ergometer time trial tests were also unaffected by $PM_{2.5}$ concentrations (Wagner and Clark, 2018). Interestingly, the VO_2 max of primary school children was unaffected by slightly polluted or highly polluted conditions (PM_{10} means of 55.3 $\mu g/m^3$ and 89.57 $\mu g/m^3$ respectively, Ramirez *et al*., 2012). Examination of O_3 and PM_{10}, although below air quality thresholds, also showed no impact on airway inflammation and running performance in a multi-seasonal study by Chimenti *et al*. (2009). Finally, Wagner and Brandley (2020) found no performance differences between 3200 m run time trials under varying $PM_{2.5}$ conditions, although respiratory discomfort was reported to be elevated for participants when $PM_{2.5}$ levels were the highest.

Further consideration also needs to be given to the aforementioned impacts of air quality on physical health such as decreasing lung and cardiovascular function, irritation of the respiratory system, chest tightness and reduced arterial pressure and vasodilation (Carlisle and Sharp, 2001; McKenzie and Boulet, 2008; Rundell and Caviston, 2008; Rundell, 2012). These instances could also lead to decreased athletic performance due to the physiological and energy production systems they would impact, in particular reducing oxygen uptake and VO_2 max and increasing perceived exertion levels (Florida-James *et al*., 2011; Giles *et al*., 2014; 2018; Kargarfard *et al*., 2015). It should also be noted that similarly to everyday life, the influence of air pollution would be heightened for those with cardiorespiratory conditions during exercise as well. Consequently, those with illnesses such as asthma would be more susceptible to decreased performance and at a higher risk of suffering an asthma attack (Cutrufello *et al*., 2011; Rundell *et al*., 2008).

This should be carefully considered for elite level sport, where asthma and exercise induced asthma is widespread within the demographic and could be more noticeably impactful on athlete wellbeing and health (Folinsbee *et al*., 1994; Helenius *et al*., 1997; Langdeau *et al*., 2000; Langdeau and Boulet, 2001; Lippi *et al*., 2008; McCreanor *et al*., 2007; McKenzie and Boulet, 2008; Rundell, 2012; Turcotte *et al*., 2003; Weinmann *et al*., 1995). Attention has been drawn to concerns over air quality at previous Olympic Games held in Athens, Beijing and Rio and the methods used by host nations to improve conditions prior to events, but no research has considered the subsequent impact of environmental conditions on performances (De La Cruz *et al*., 2019; Donnelly *et al*., 2016; Florida-James *et al*., 2011; Wang *et al*., 2009). However, it should be noted that it would not only be those with pre-existing cardiorespiratory conditions who would be influenced by air pollution during exercise: previously reviewed research has included asthmatic and non-asthmatic participants, with pollutants effecting both groups, albeit in separate studies (Cutrufello *et al*., 2011; Rundell *et al*., 2008; Rundell and Caviston, 2008; Rundell, 2012).

Despite the at times contrasting effects of air pollution on athletic performance, this review highlights the need for additional studies similar to those performed by Pasqua *et al*. (2018) and Tainio *et al*. (2016) to identify pollutant and/or time thresholds at which exercise can be safely performed (Morici *et al*., 2020). Also, it needs to be considered that for ethical reasons, the amount of pollution participants can be exposed to in laboratory tests is limited and may not be representative of all outdoor exercise scenarios, thus potentially resulting in some insignificant results (Morici *et al*., 2020, Wagner and Clark, 2018). Additionally, the cognitive impact of air pollution on athletes also needs to be examined to determine how it may alter or impact their decision making. Hu *et al*. (2017) found that when pollution levels increased, outside exercise levels decreased): whilst studies in competitive athletics are also scarce (McKenzie and Boulet, 2008; Morici *et al*., 2020). The timing of real world studies with most athletics events occurring under traffic restricted conditions is also an area for consideration, as is the use of personal exposure monitors during exercise, commuting and everyday life (Chimenti *et al*., 2009; Morici *et al*., 2020).

2.5 Meteorology and Exercise

As covered in chapter 1, meteorology can have a significant impact on the health and athletic performance of amateur and elite athletes, with at times deadly consequences (BBC Sport, 2016; 2018; BBC, 2018; The Guardian, 2018). Anecdotally, weather conditions are cited by both recreational and elite competitors as most often hindering performance, with studies supporting this suggestion (Bigazzi, 2016). The most commonly researched variable is temperature; although relative humidity, wind speed, wind chill, wind direction, precipitation, heat index and other meteorological parameters can be influential. Furthermore, the potential influence of meteorology on athletic performance and human health is likely to increase in the future under predicted climate change that would see increased temperatures and stronger and more common heatwave events (Hassan *et al*., 2015; Maloney and Forbes, 2011). This will lead to an increased in 'non-activity days' (15-26 and 33-45 days per year for acclimatised and acclimatised individuals), resulting in an increased exercise risk both in general and at organised events (Maloney and Forbes, 2011).

These predicted heatwave events and warming conditions are of particular concern as it has been shown that as air temperature increases, there is a corresponding increase in medical incidents and 'did not finish' participants during half marathon and marathon events (Carlstrom *et al*., 2019; William, 2007; 2010). This suggests that meteorological conditions need to be carefully considered by event organisers and exercisers. This is especially so for quicker runners, with analysis of nineteen 10 km road races finding that they were more likely to be treated for heat related illnesses (heat stroke, dehydration and hyperthermia) than other participants, as well as there being a relationship between temperature and relative humidity on the number of heat related medical treatments being performed at events (Breslow *et al*., 2019). DeMartini *et al*. (2014) showed that there were significant correlations between the mean temperature and heat index and the incidence of heat stroke during the Falmouth Road Race (11.26 km run) over an eighteen year period. Yankelson *et al*. (2014) found that heat stroke was a more common incident at Israeli running events than arrhythmic death, arguing that the former, which led to more fatalities between 2007 and 2013, required more scientific, organisational and athlete attention and awareness. The Great North Run in Great Britain has also had a number of reported heat stroke incidents and related deaths (BBC, 2005; Hawes *et al*., 2010).

The consequent reduction in performance due to increased temperatures (as well as associated variables such as relative humidity and heat index) is due to thermoregulation of athlete's internal core temperature in a bid to prevent excessive heat accumulation and thus a rise in core temperature (Altareki *et al*., 2009; Casa, 1999; Miller-Rushing *et al*., 2012; Nadel, 1990; Tucker *et al*., 2006). During exercise, internal body temperatures increase due to the metabolic inefficiency of the human body, but also due to the cardiovascular system prioritising blood flow to vital organs and contracting muscles (Bouscaren *et al*., 2019; Casa, 1999; DeMartini *et al*., 2014; Nadel, 1990). This increased core temperature will cause a redistribution of blood flow from working muscles to the skin to improve heat dissipation (Bergeron, 2014; Bouscaren *et al*., 2019; Cheuvont *et al*., 2010). As a result, there will be a reduction in heart stroke volume and increased heart rate and blood lactate levels; reducing muscle contractive force, increasing perceived exertion and consequently lowering performance (Bergeron, 2014; Bouscaren *et al*., 2019; Cheuvront *et al*., 2010 Miller-Rushing *et al.,* 2012; Nybo *et al*., 2014; Zhao *et al.*, 2013).

Humidity will also influence perceived exertion levels and performance as it can lower evaporative rates and therefore the cooling capacity of exercisers (Cheuvont and Haymes, 2001; DeMartini *et al.*, 2014; Maughan, 2010). Wind speed and direction will also influence convective heat loss (Maughan, 2010). Wind chill can be beneficial or a hindrance to performance depending on the air temperature; it can help maintain an optimum core temperature in warm conditions and prevent thermoregulatory changes, but can lower core temperatures too much in cold and wet conditions, leading to hypothermia and diversion of blood flow to vital organs (Maughan *et al.*, 2007a; 2007b).

Exercising in warmer temperatures can also lead to exercise induced hyperthermia. This can affect the central motor drive and raise the perceived effort of exertion, resulting in decreased running pace or exercise performance (Cheuvront and Haymes, 2001; Ely *et al.*, 2008). Furthermore, warmer conditions increases the evaporative heat loss requirement, which can lead to dehydration and increased fatigue (Bergeron, 2014; Cheuvront and Haymes, 2001; Ely *et al.*, 2008; Gonzales-Alonso *et al.*, 1999). Furthermore, dehydration will effect cardiovascular function: reducing blood flow to working muscles and lowering power output (Bergeron, 2014; Bouscaren *et al.*, 2019; Maughan, 2010). Heat stress has also been shown to reduce VO_2 max and consequently aerobic performance (Arngrimsson *et al.*, 2003; Bassett and Howley, 2000; Cheuvront *et al.*, 2010; di Prampero, 2003).

It has been argued that women are less susceptible to the effects of exercise in heat due to having a generalised lower body mass and larger surface area-to-mass ratio which promotes comparatively lower heat production and increased heat dissipation (Bergeron, 2014; Cheuvront and Haymes, 2001; Kaciuba-Uscilko and Ryszard, 2001; Vihma, 2010). Trubee *et al*. (2014) also found though multiple linear regression analysis that female participants of the Chicago marathon slowed less during the 42.2 km, a difference that was exacerbated in warmer conditions.

Previous research has identified that as temperatures increase, performances correspondingly decreases, with an optimum range for marathon running being 3.8-15°C (Helou *et al*., 2012; Vugts, 1997; William, 2007). However, when temperatures fall below this range, and/or are coupled with windy/wet conditions, there is the risk of hypothermia (a core body temperature falling below 35°C), as well as reduced blood supply and cardiorespiratory capacity (Brocherie *et al*., 2015; Oksa *et al*., 2004; Weller *et al*., 1997; William, 2007). William (2007) also found that during marathons, cold conditions increase the 'did not finish' percentage of entrants during the Twin Cities and Boston Marathons, which was increased if coupled with precipitation.

2.5.1. Meteorology and Athletic Performance

Research is often focused on exercise performance, such as marathon running and cycling time trial performance: and is split between real world, post event analysis, and laboratory based tests. Despite this differentiation, the findings of both research strands are broadly in agreement, with decreases in performance occurring under more stressful or extreme meteorological conditions.

Laboratory cycling tests have shown a significant linear relationship between power output at a controlled rate of perceived exertion under cool, normal and warm conditions (Tucker *et al*., 2006). This also showed significant power output differences between the three temperatures at which tests were performed at (Tucker *et al*., 2006). This is supported by Altareki *et al*. (2009) who showed that 4 km cycling performance was significantly reduced under laboratory conditions of 35°C compared to 13°C. Examination of fifteen minute cycling tests under hot and temperature environments also showed reduced power output, which was mirrored for thirty minute tests with elite cyclists (Ely *et al*., 2009; Tatterson *et* *al*., 2000). For elite cyclists, higher blood lactate levels were also recorded under warmer conditions, suggesting that across experience levels and exercise duration, increased temperatures can significantly reduce athletic performance (Tatterson *et al*., 2000).

Temperature is the most anecdotally cited cause of reduced athletic performance, and research has suggested that increases in temperature would result in slower marathon performances (Miller-Rushing *et al*., 2012). Helou *et al*. (2012) examined results from six European and American marathons between 2001 and 2010, utilising all finisher's results to quantify the effect on the full range of entrants. Significant correlations between temperature and performance were found, as was between humidity and performance (Helou *et al*., 2012). Knechtle *et al*. (2019) performed a long term study on the Boston marathon from 1972-2018 and showed that each 1°C temperature increase would slow times by 01:47 min:sec. Daniels (2014) suggests that a 21°C temperature will cause pace reductions of 1.6%, and each subsequent 5°C increase would see a corresponding 1.6% decrease.

Montain *et al*. (2007) collected finishing results for seven marathons spanning 6-36 years, alongside wet bulb globe temperature which was averaged for three hours to cover the race duration. The top three male and female finishing times were used, as were the 25th, 50th, 100th and 300th place finishers (Montain *et al*., 2007). Results showed that as temperatures increased over 10°C, performances slowed for men and women, and more so for slower finishers (Montain *et al*., 2007). This is supported by Vihma's (2010) Stockholm marathon study and Ely *et al*. (2007) who examined seven American and Canadian marathons. Vihma (2010) showed that temperature and relative humidity were correlated to slower performances, with more of an impact on slower runners, whilst Ely *et al*. (2007) found an overall slowing in performance as temperatures rose from 5 to 25°C, again with a greater impact on slower runners.

In contrast, Ely *et al*. (2008) found that the quicker finishing marathon runners slowed the most when considering the historic results of three Japanese marathons with temperature, relative humidity and wind speed data. The race winner, 25th, 50th and 100th place finishers times were used against the mean meteorological variables for each race and analysed via linear regression and one-way ANOVA (Ely *et al*., 2008). Gasparetto and Nesseler (2020) also determined that faster runners were influenced the most when temperatures increased at the New York City marathon. This is supported by Maughan (2010) who suggests that the optimum temperature for endurance running is lower for quicker runners. Finally, Breslow *et al*. (2019) found that quicker runners were more likely to require heat related medical care post events compared to slower finishers.

The difference in the effect of temperature on running performance for participants classed as ‘fast’ or ‘slow’ is potentially down to self-pacing strategies, with increased temperatures causing the latter group to run slower throughout the event, whilst quicker runners have been shown to decrease in pace towards the end of events (Ely *et al*., 2008; Trubee *et al*., 2014; Tucker *et al*., 2006; Vihma, 2010). It can also be argued that quicker runners will be exercising at a higher intensity relative to other participants, causing greater heat generation and increasing their risk of heat related incidents, which is supported by the previous pacing strategy of runners (Gasparetto and Nesseler, 2020). Daniels (2014), however, argues that pace reductions of 1.6% when temperatures exceed 21°C will occur regardless of ability.

Few studies have directly examined the influence of relative humidity and heat index (the combination of temperature and relative humidity) on athletic performance, with Helou *et al*. (2012) and Vihma (2010) including the former in their marathon studies. Results suggest that relative humidity had a significant slowing influence on participants, with a lesser effect on females suggested by Helou *et al*. (2012, Vihma, 2010). This is potentially due to the difference in heat dissipation between genders (Bergeron, 2014; Cheuvront and Haymes, 2001; Kaciuba-Uscilko and Ryszard, 2001; Vihma, 2010). The effect of relative humidity on performance is coupled with temperature, however, as reduced heat dissipation causes increased core temperatures and consequently reduced performance in a similar fashion (Casa, 1999; Helou *et al*., 2012; Nadel, 1990). Similarly, heat stress can heighten the risk to exercisers health (Maughan *et al*., 2007a; 2007b).

The effect of wind on performance is difficult to quantify due to the large variations in speed and direction across the duration of real world events (Vihma, 2010). However, tail winds at the Boston marathon improved performances, whilst head- or side-winds slowed performances (Knechtle *et al*., 2019). This is supported by Davies (1980) who suggested that head winds will reduce and tail winds improve performances, although the former will be more detrimental than the latter will be beneficial.

Other meteorological variables can influence performances, with Vihma (2010) finding that the occurrence of rainfall improved male finishing times in the Stockholm marathon. Similarly, Knechtle *et al*. (2019) found that precipitation improved the winning time of the Boston Marathon, but also slowed the mean times of the rest of the field.

It should be noted, however, that utilising marathon results and associated data may not be the most representative method to determine meteorological effects on performance. Over the course of the event there is the potential for several environmental changes that a mean value will not represent or show (Cheuvont and Haymes, 2001; Maughan, 2010). Additionally, the influence of meteorological variables on running performance may differ based upon the event duration. This will consequently influence exercise intensity: with higher levels found during shorter events which will contribute to greater metabolic heat production and core temperature increases (Bouscaren *et al*., 2019; DeMartini *et al*., 2014). Therefore, the influence of temperature and heat index in particular are more likely to contribute to decreased performances (DeMartini *et al*., 2014).

Overall, the influence of temperature on athletic performance has been demonstrated on numerous occasions, with marathon and other running events being shown to be influenced the most with regards to heat stress and heat related incidents (Carlstrom *et al*., 2019; Helou *et al*., 2012; Knechtle *et al*., 2019). The influence of other meteorological variables has been examined less, but in some cases has been shown to be detrimental with regards to relative humidity and high wind speeds, and beneficial if tail winds are prevalent (Vihma, 2010). Generally, for meteorological and air quality data, utilisation of a single monitoring location located close to the event location is used for data collection (Helou et al., 2012; Vihma, 2010). Research examining of how air quality and meteorology interact and effect exercise performance is limited to a handful of studies, mainly due to the difficulties in isolating individual variables influence from one another (Gibbons and Adams, 1984; Gomes *et al*., 2010; Gong Jr *et al*., 1985; Helou *et al*., 2012; Morici *et al*., 2020; Zanobetti and Peters, 2015). However, there is a greater need for this area to be examined due to increased public awareness of local air quality and pollution exposure, and the repeated concerns with regards to local air quality at major sporting events (De La Cruz *et al*., 2019; Donnelly *et al*., 2016; Florida-James *et al*., 2011; Wang *et al*., 2009).

2.6. The combination of air quality and meteorology on athletic performance

The influence of biometeorological factors on marathon performances have been examined over an extended period, although not in a great deal of papers in terms of numbers. One of the earliest studies by Trapasso and Cooper (1989) examined meteorological factors on performances at the Boston Marathon. Linear regression and multiple linear regression analysis between performance and one or more explanatory variables showed that lower wet bulb temperatures and light or no precipitation was conducive to quicker performances (Trapasso and Cooper, 1989). The combined influence of air quality and meteorological variables on performance have rarely been examined together, with Helou *et al*. (2012) including O_3, NO_2, $PM_{2.5}$ and SO_2 in their study. Linear regression results suggest that both have a slowing influence on performance, although O_3 was found to increase linearly with temperature, making the influence of O_3 unclear (Helou *et al*., 2012). This issue is a hindrance to real world studies as it is impossible to isolate the effect of a sole pollutant from other variables (Helou *et al*., 2012). Additionally, with most marathon events being held on weekend mornings, urban transport is often reduced and the photochemical production of O_3 is yet to peak, meaning that exposure levels are generally lower (Chimenti *et al*., 2009; Helou *et al*., 2012; Morici *et al*., 2020).

Laboratory examination of the influence of meteorological variables and pollution is also limited. Gomes *et al*. (2010) found that 8 km running performance slowed under increased temperatures and increased temperatures combined with O_3 pollution compared to the control conditions. However, performance under the control conditions with additional O_3 pollution (0.10 ppm) was not statistically slower, suggesting that temperature is the more influential variable (Gomes *et al*., 2010). More historical research suggests that O_3 does compound the effect of increased temperatures during exercise, albeit at higher concentrations. Exercise duration ceased prematurely with increased participant discomfort during hot and polluted tests (O_3 at 0.30 ppm) performed by Gibbons and Adams (1984) in comparison to tests without O_3 pollution. Gong Jr *et al*. (1985) also performed maximal exercise tests under increased temperatures with filtered air and O_3 concentrations of 0.12 ppm and 0.20 ppm. The lower concentration, like Gomes *et al*., 2010, showed no significant impacts on performance, whereas 0.20ppm reduced exercise time and workload by 30% and 8% respectively (Gong Jr *et al*., 1985). Both Gibbons and Adam (1984) and Gong Jr *et al*. (1985) also showed reductions in lung function and fitness after tests containing O_3 pollution were performed, with greater ozone-related symptoms being shown by participants under higher concentrations. This suggests to an extent that there is a tipping point at which pollution, or at a least O_3 pollution, does compound the effect of temperature on athletic performance.

2.7. Exercise Performance Summary

The majority of research into the effect of environmental variables on athletic performance have utilised correlation and linear regression analysis (Billat *et al*., 2001; Casado *et al*., 2019; Conley and Krahenbuhl, 1980; Helou *et al*., 2012; Marr and Ely. 2010; Trapasso and Cooper, 1989; Vihma, 2010). T-tests and ANOVA has also been used to examine if differences occur between groups of finishers, most often to determine if faster or slower finishers or genders are influenced the most (Ely *et al*., 2008; Gibbons and Adam, 1984; Gomes, 2010). Results that have not been laboratory based have utilised event results with data from local monitoring stations (Helou *et al*., 2012, Knechtle *et al*., 2019; Vihma, 2010). Findings suggest that temperature, relative humidity and wind speed are all detrimental to athletic performances, with O_3 and PM being detrimental in some circumstances (Helou *et al*., 2012; Ely *et al*., 2008). There is debate over the influence of these variables with regards to gender and pace of athlete's effected the most, with no clear results being shown (Daniels, 2014; Gasparetto and Nesseler, 2020). Consequently, further real-world examination of how environmental variables influence various athletic populations is required to improve the health and safety of elite athletes and recreational exercisers. This is due to the numerous health impacts poor urban air quality and climatic conditions (UHIs) can have, particularly so when it is predicted that 80% of the population will live in cities by 2025 (Trundle *et al.*, 2015). Although in most instances it is thought that the benefits of exercise outweigh the detrimental effects of air pollution, this is not unanimous and if conditions worsen in the future, may change (Giorgini *et al*., 2016; Morici *et al*., 2020; Pasqua *et al*., 2018; Tainio *et al*., 2016).

2.8. Overall Conclusions

Urban air quality has several negative impacts on human health, including cardiovascular illnesses, cognition, early life development and reduced life expectancy (Hewitt *et al*., 2020; World Health Organisation, 2018). Air quality and climate are closely interlinked, with predicted climate change likely to contribute to further degradation of air quality (De Sario *et al*., 2013; Hassan *et al*., 2015). In addition, the compounding effects of air pollution and urban heat islands can heighten the risk of detrimental health impacts (Stafoggia *et al.*, 2008).

Air quality and meteorological monitoring methods are standardised with regards to location and regional directives, although traditional monitoring methods generally have shortcomings with regards to cost and spatial coverage, particularly in less developed countries (Engel-Cox *et al.*, 2013). Alternatives include the development of low cost monitors and personal exposure sensors and modelling. All have advantages and disadvantages, but cohesively can provide an accessible and clearer insight into urban air quality and meteorology than standalone methods can (Lewis and Edwards, 2016).

With concerns regarding the health effects of air quality and adverse weather conditions, research suggests that in most, but not all, cases the benefits of exercise outweigh the health risks (Tainio *et al*., 2016). Despite this, the impact of environmental conditions on exercisers cannot be discounted and have been shown several times at elite and amateur sporting events (BBC Sport, 2016; 2018; BBC, 2018). There has been some real world examination of the impact environmental variables have on sporting events, often running (Helou *et al*., 2012; Marr and Ely, 2010). This has been coupled with a number of laboratory studies with neither giving a clear indication of the impact air quality has on performance (Giles *et al*., 2012; Gomes *et al*., 2010). Meteorological impacts have been more clear, particularly temperature, but questions still remain over which demographics of exercisers are impacted the most (Ely *et al*., 2008; Montain *et al*., 2007; Trubee *et al*., 2014). This is becoming increasingly required given the predicted climate change and increased proportion of the population living in urban areas (Miller-Rushing *et al*., 2012; Trundle *et al*., 2015). Consequently, the following research will utilise finishing results from several mass participation amateur and elite events and a mixture of monitoring station and modelled environmental data. This will be analysed following methodologies previously utilised by other researchers to examine the effect environmental conditions have on athletic performance, with suggestions regarding the use of additional monitoring methods and mitigation strategies that could be utilised in future studies and events.

Chapter 3 - The influence of meteorology and air quality on parkrun athletic performance

This chapter addresses objective one of this thesis – examining how local air quality and meteorology variations may influence the performance of recreational athletes and exercisers at parkrun events in London, United Kingdom. For plagiarism clarity - extensive parts of this chapter have been submitted to the journal *Sports Medicine – Open* and has been published online as a preprint. A full copy of the submitted article is included in Appendix A.

3.1 Introduction

Large-scale, mass participation events, particularly for running, have become increasingly popular, with a large number of distances ranging from 5 km to marathon events (Allison, 2010; Cleland *et al.*, 2019; Ridinger *et al.*, 2012; Whitehead *et al.*, 2020). The former distance of these, 5 km, has become the main distance completed in the United States whilst the popularity of parkrun has further strengthened this globally (Bell and Stepenson, 2014; Whitehead *et al.*, 2020). Due to their increased number and popularity, such events are a facilitator to increased physical activity levels, although motives differ between participants (Buning and Walker, 2016; Funk *et al.*, 2011; Whitehead *et al.*, 2020). However, with the exception of parkrun, there are barriers to participation and continued activity levels after events; the cost and annual nature of events has been highlighted by research, as has the 'elite' nature of such events that can deter hard to engage demographics and less experienced and non-runners from participating (Cleland *et al.*, 2019).

Consequently, this work investigates the role of urban air quality and meteorology on amateur athletic performance using parkrun as a natural experiment. parkrun events provide free, timed 5 km 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 (parkrun, 2018; Stevinson and Hickson, 2014). 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 (elliotline.com, 2019; Grunseit *et al*., 2018; Hindley, 2020; Stevinson *et al*., 2015). The participation numbers at the fifteen events examined in this study alongside the mean finishing times is shown in Figure 3.1. 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.

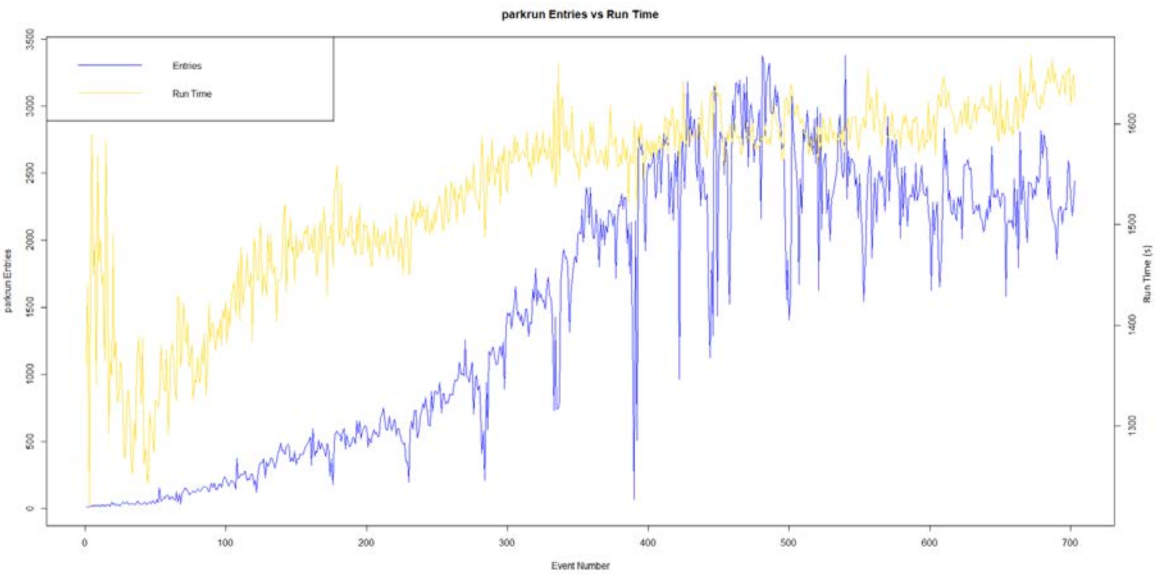


Figure 3.1. Changes in the number of parkrun participants and mean finishing time for fifteen Greater London events from 2004-2017.

3.1.1 Why is parkrun popular: An ideal environment to examine population activity levels and exposure?

A lack of physical activity can be as dangerous in terms of chronic disease and premature death as smoking and obesity (Cleland *et al.*, 2019; Lee *et al.*, 2012). Inactivity globally costs $13.7 billion in lost productivity and $53.8 billion in healthcare costs (Cleland *et al.*, 2019; Ding *et al.* 2016). It is estimated that 23-44% of the global population fails to meet the physical activity guideline of 150 minutes of moderate exercise per week, with high-income countries at the higher end of the range (Cleland *et al.*, 2019; Hallal *et al.*, 2012; World Health Organisation, 2010). With such widespread and detrimental impacts of low exercise levels, methods to facilitate and increase are required (Cleland *et al.*, 2019).

To counter this, increased levels of green space and provision public bike access have been shown to positively increase population activity levels and consequently public health (Cole-Hunter *et al.*, 2015b; Hankey and Marshall, 2017). Green space combined with physical activity has been identified as providing acute psychological wellbeing, which can be at a greater level than just exercise alone (Bullas *et al.*, 2020; Pretty *et al.*, 2005; Pretty *et al.*, 2007; O'Sullivan *et al.*, 2016). parkrun by its nature creates this 'green exercise' environment explored by Pretty *et al.* (2005) and therefore has a greater potential to improve population health and wellbeing. Increased activity levels help reduce the prevalence of cardio-metabolic conditions including high blood pressure, diabetes and obesity, and reduce the economic health strain on societies (Cole-Hunter *et al.*, 2015b; Furie and Desai, 2012). This also has the potential to improve mental health and wellbeing and to reduce air pollution exposure and the effect of the urban heat island (Hankey and Marshall, 2017; Hartig *et al.*, 2003; Hewitt *et al.*, 2020; Honold *et al.*, 2012).

The UK phenomenon of parkrun is a potential option both within the country and abroad to examine the influence of urban meteorology and air quality on performances and public health with events held in twenty-two countries (parkrun, 2020). The 5 km mass participation events are highly accessible and have been shown to greatly increase the physical activity levels of local communities as well as providing mental health and community benefits (Grunseit *et al.*, 2018; Hindley, 2020; parkrun 2020; Stevinson and Hickson, 2014; Stevinson *et al.*, 2015). With parkrun events being volunteer-run in public spaces, they are also a cost-effective solution to help improve health and activity levels.

The rise of parkrun and its impacts on local society are multiple. Research has shown that parkrun's location in pleasant environments creates informal social interaction opportunities and engages priority groups – positively improving participant's mental health and wellbeing (Grunseit *et al.*, 2020; Morris and Scott, 2019; Quirk and Haake, 2019; Rogerson *et al.*, 2016; Stevinson and Hickson, 2019). parkrun is effective at engaging often underrepresented societal groups (women, the under active and over thirty-fives) and has a dose-response effect on improving activity levels, body mass index and other fitness metrics for a sustained period (Bowness *et al.*, 2020a; Cleland *et al.*, 2019; Grunseit *et al.*, 2020; Peterman *et al.*, 2020; Sharman et al, 2019; Stevinson and Hickson, 2014; Stevinson and Hickson, 2019).

parkrun's reach has been unmatched by other public health interventions aimed at improving physical activity levels in terms of sustainability, accessibility and scale (Grunseit *et al.*, 2020; Reis *et al.*, 2016; Schell *et al.*, 2013; Wiltshire and Stevinson, 2018). This is due to parkrun providing free, low-demand participation along with variation in ability of runner's which encourages initial and sustained participation at events (Grunseit *et al.*, 2020). As well as a sense of achievement fostered by the parkrun ethos, the environment helps develop social ties and a community environment with the volunteering aspect of events adding to a feeling of giving back to the local area (Grunseit *et al.*, 2020; Sharman *et al.*, 2019; Stevinson *et al.*, 2015). This sense of achievement and volunteering aspect is strengthened not only by the times ran, but also the milestone t-shirts gained through regular attendance and parkrun events being viewed as a key social interaction space (Grunseit *et al.*, 2020; Hindley, 2020). This helps ground parkrun as an event that rewards participation rather than performance (Grunseit *et al.*, 2020; Sharman *et al.*, 2019; Stevinson *et al.*, 2015).

The low-competitive nature of parkrun, coupled with its inclusive, family-friendly nature, also helps frame 'personal body projects' for improved health and fitness as a collective aim rather than an individual's responsibility (Bowness *et al.*, 2020a; Cleland *et al.*, 2019; Grunseit *et al.*, 2020; Stride *et al.*, 2020; Peterman *et al.*, 2020; Whitehead *et al.*, 2020). The establishment of parkrun events is grounded in community demand and results in higher levels of engagement and long term participation than other physical activity options (Grunseit *et al.*, 2020; Sperandei *et al.*, 2016). Indeed, research has shown that parkrun participation of self-identified ‘non-runners’ results in them engaging in running outside of parkrun events (Bowness *et al.*, 2020b; Haake *et al.*, 2020). Alongside the positive mental aspects of outdoor exercise, this parkrun community has been shown to promote mental health improvement in both short and long term studies of parkrun participation (Grunseit *et al.*, 2020; Rogerson *et al.*, 2016; Stevinson and Hickson, 2019).

parkrun has also been shown to facilitate the movement of social and cultural capital from ‘high’ to ‘low’ groups, reducing social inequalities through physical activity and community (Grunseit *et al.*, 2020; Wiltshire and Stevinson, 2018; Wiltshire *et al.*, 2018). Similarly, the aforementioned volunteering aspect of parkrun, along with its low commitment, short time frame model removes traditional gender barriers in sport (Grunseit *et al.*, 2020; Stride *et al.*, 2020). The importance of a tail runner at parkrun is of high importance whilst the parkrun model makes volunteering and exercise more easily available for those, in particular women, whose family responsibilities may prevent it in other sports and leisure contexts (Grunseit *et al.*, 2020; Stride *et al.*, 2020). Sharman *et al.* (2019) also suggests that there are potentially community economic effects of parkrun (Grunseit *et al.*, 2020).

To conclude, parkrun is a rare mass participation physical activity initiative suitable for those of all ages and abilities, both physically and mentally (Grunseit *et al.*, 2020). It has been able to engage those who are typically under-represented in most organised sports and physical activity settings; the elderly, women, girls, ethnic minorities, low income demographics and those with physical and mental disabilities and illness (Cleland *et al.*, 2019; Grunseit *et al.*, 2020; Guthold *et al.*, 2018; Hanlon *et al.*, 2019; Quirk and Haake, 2019). Furthermore, parkrun can make a significant contribution to individuals meeting the recommended weekly exercise amount, with evidence suggesting that those who meet the prescribed 150 minutes have 30-40% less risk of all-cause and cardiovascular disease mortality (Cleland *et al.*, 2019; O'Donovan *et al.*, 2017). Finally, the parkrun *prima facie* lends itself to scientific research due to its consistent worldwide model; events must be an accurately measured 5 km in distance, are free, timed and volunteer organised and run (Grunseit *et al.*, 2020; parkrun 2021). These factors do not change regardless of international location and therefore make translation of this and other research highly practical and valuable (Grunseit *et al.*, 2020).

3.2 Data and Methodology

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 (Carrington, 2017; Carrington, 2018; London Council, 2017; Taylor, 2019).

Between 2011 and 2016 there were 47 parkrun events held across Greater London, with a focus to the central and south areas. Of these, the first fifteen events established within the region (Figure 3.2) were selected as they were the only events being held throughout the 2011-2016 period (some of the 47 started in 2015 for example) and were located across the Greater London area with the exception of the north east region. Their relative proximity to background air quality Department for Environment, Food and Rural Affairs (DEFRA) monitoring stations (<15 km) to utilise as accurate ‘at event’ readings as possible was also a factor, as was a lack of extensive grey infrastructure other than paths located within the parks that was verified through Google Maps satellite imagery (Duyzer *et al*., 2015; Ferradas *et al*., 2010; Kaur *et al*., 2005; Kaur *et al*., 2007). Finishing times for participants of the fifteen parkrun events from 2011-2016 were provided by the parkrun research board. 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).

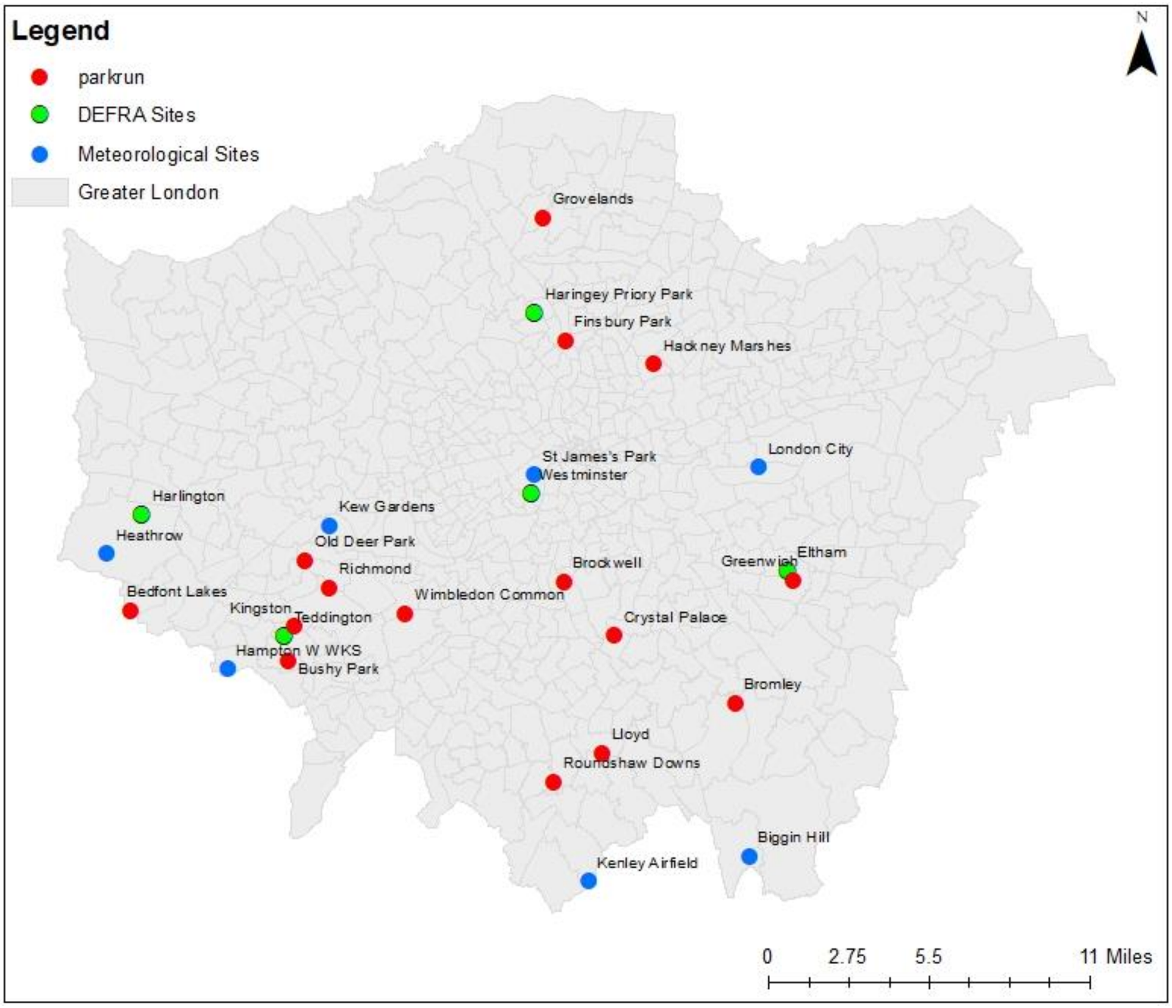


Figure 3.2. A map showing the locations of the parkrun events, DEFRA AURN stations and meteorological stations within Greater London.

Prior to analysis, parkrun finishing times over ninety minutes were discarded, as these were technical issues indicated by parkrun as well as being outliers to the dataset (parkrun, 2017). For each parkrun event, the weekly mean finishing time was then calculated and used for further analyses as performed by Knetchtle *et al*. (2019). 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 and the average athletic performance decreasing. Therefore, decomposition of the run times was performed to extract the seasonal, trend and random components of the time series. 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. Therefore, the influence of increased participation and increased finishing times will have less effect on subsequent analyses. 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; whilst the random value of this decomposition was used for analysis against the explanatory variables of temperature, relative humidity, wind speed, O_3, NO_2 and $PM_{2.5}$ (Figure 3.3).

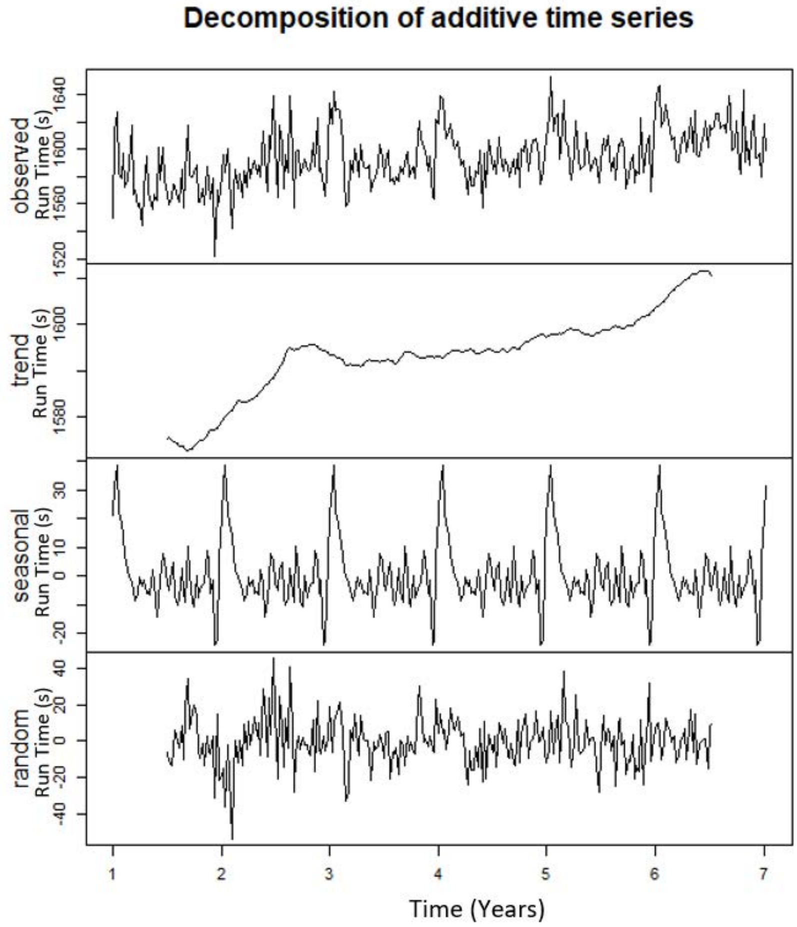


Figure 3.3. Decomposition of weekly mean parkrun finishing times from 2011 to 2016. The x-axis shows the six yearly periods within the data.

Meteorological data was obtained from the British Atmospheric Data Centre (BADC) using the Met Office Integrated Data Archive System (MIDAS). Seven stations (Figure 1) were used due to their proximity to the parkrun events being examined. Hourly mean 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 (Carslaw, 2020). 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 (Lott, 2004).

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 mean 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 (Rajagopalan *et al*., 2018). Locations of the monitoring sites can be seen in Figure 3.2 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 measurement locations (Table 3.1). Although some are not optimally placed in close proximity to parkrun locations to provide 'at event' pollution levels, they are indicative of the local air quality- which was validated through the use of modelled air quality from King's College London. The Community Multi-scale Air Quality Model (CMAQ-urban) is an air quality dispersion model, combined with the Atmospheric Dispersion Modelling Systems (ADMS) roads (Beevers *et al*., 2012; Beevers *et al*., 2013). CMAQ-urban predicts gridded, hourly air quality data for London and has been shown to be in reasonable agreement with observed data (Beevers *et al*., 2013; Carslaw, 2011). As well as establishing spatio-temporal variability in NO_x-NO_2, $PM_{2.5}$ and PM_{10}, the model also shows good performance of NO-NO_2-O_3 concentrations around road sources (Beevers *et al*., 2012; Beevers *et al*., 2013).

Table 3.1. 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 Priory Park	2.2	St James Park	7.3
Greenwich	Eltham	0.6	London City Airport	4.3
Grovelands	Haringey Priory Park	5.3	St James Park	14.4
Hackney	Haringey Priory Park	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

Modelled air quality data from CMAQ-urban at AURN locations was extracted on parkrun dates at 09:00 as well as at parkrun locations across the study area. Although only the first three years of data were available, January 2011 to December 2013, the equivalent data from the DEFRA monitoring sites was comparatively examined through correlation analysis. These results, as have been shown through CMAQ-urban's validation processes, showed moderate but significant correlations (<0.01) between the measured DEFRA air quality data and the model predictions at AURN sites and parkrun locations for all pollutants (Table 3.2, Beevers *et al*., 2012; Beevers *et al*., 2013; Carslaw, 2011). Correlations between AURN data and modelled parkrun values are moderate and significant (0.3-0.6, p=<0.01), with a similar range being shown between AURN data and modelled AURN values (0.36-0.6, p=<0.01). Due to the longer time series available with the AURN data and it's moderate, significant correlations with modelled air quality data at parkrun events, monitored data was used for all statistical analyses performed in this study.

Table 3.2. Correlation results between AURN monitored air quality and CMAQ-urban modelled air quality data at parkrun and AURN locations.

parkrun/AURN	**Pollutant**	**Correlation**	**p-value**	**parkrun/AURN**	**Pollutant**	**Correlation**	**p-value**
Bedfont	NO_2	0.35	<0.01	**Lloyd**	NO_2	0.31	<0.01
	O_3	0.39	<0.01		O_3	0.37	<0.01
	$PM_{2.5}$	0.47	<0.01		$PM_{2.5}$	0.58	<0.01
Brockwell	NO_2	0.35	<0.01	**Old Deer**	NO_2	0.35	<0.01
	O_3	0.42	<0.01		O_3	0.38	<0.01
	$PM_{2.5}$	No AURN data	No AURN data		$PM_{2.5}$	0.57	<0.01
Bromley	NO_2	0.3	<0.01	**Richmond**	NO_2	0.33	<0.01
	O_3	0.38	<0.01		O_3	0.36	<0.01
	$PM_{2.5}$	0.6	<0.01		$PM_{2.5}$	0.57	<0.01
Bushy	NO_2	0.37	<0.01	**Roundshaw**	NO_2	0.28	<0.01
	O_3	0.38	<0.01		O_3	0.31	<0.01
	$PM_{2.5}$	0.56	<0.01		$PM_{2.5}$	0.55	<0.01
Crystal Palace	NO_2	0.32	<0.01	**Wimbledon**	NO_2	0.33	<0.01
	O_3	0.39	<0.01		O_3	0.36	<0.01
	$PM_{2.5}$	0.57	<0.01		$PM_{2.5}$	0.55	<0.01
Finsbury	NO_2	0.35	<0.01	**Harlington AURN**	NO_2	0.4	<0.01
	O_3	0.6	<0.01		O_3	0.57	<0.01
	$PM_{2.5}$	No AURN data	No AURN data		$PM_{2.5}$	0.46	<0.01
Greenwich	NO_2	0.33	<0.01	**Westminster AURN**	NO_2	0.47	<0.01
	O_3	0.4	<0.01		O_3	0.47	<0.01
	$PM_{2.5}$	0.59	<0.01		$PM_{2.5}$	No AURN data	No AURN data
Grovelands	NO_2	0.43	<0.01	**Eltham AURN**	NO_2	0.34	<0.01
	O_3	0.39	<0.01		O_3	0.42	<0.01
	$PM_{2.5}$	No AURN data	No AURN data		$PM_{2.5}$	0.59	<0.01
Hackney	NO_2	0.45	<0.01	**Teddington AURN**	NO_2	0.38	<0.01
	O_3	0.41	<0.01		O_3	0.39	<0.01
	$PM_{2.5}$	No AURN data	No AURN data		$PM_{2.5}$	0.56	<0.01
Kingston	NO_2	0.35	<0.01	**Haringey Priory Park AURN**	NO_2	0.41	<0.01
	O_3	0.37	<0.01		O_3	0.6	<0.01
	$PM_{2.5}$	0.56	<0.01		$PM_{2.5}$	No AURN data	No AURN data

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. 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 ($p>0.11$).

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 (Helou *et al.,* 2012; Marr and Ely, 2010; Trapasso and Cooper, 1989; Vihma, 2010). 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 marathon studies, was used to compute the R^2 value, showing the total percentage of variance in finishing times explained by the control variables (Ely *et al*., 2008; Maffetone *et al*., 2017; Trubee *et al*., 2014). Prior to these tests being performed, checks for normality were performed through skewness and kurtosis tests and data was logged where necessary to improve the distribution of data.

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, Fitted vs Residuals, Cooks-Distance and ACF plots and histograms of residuals (Figure 3.4).

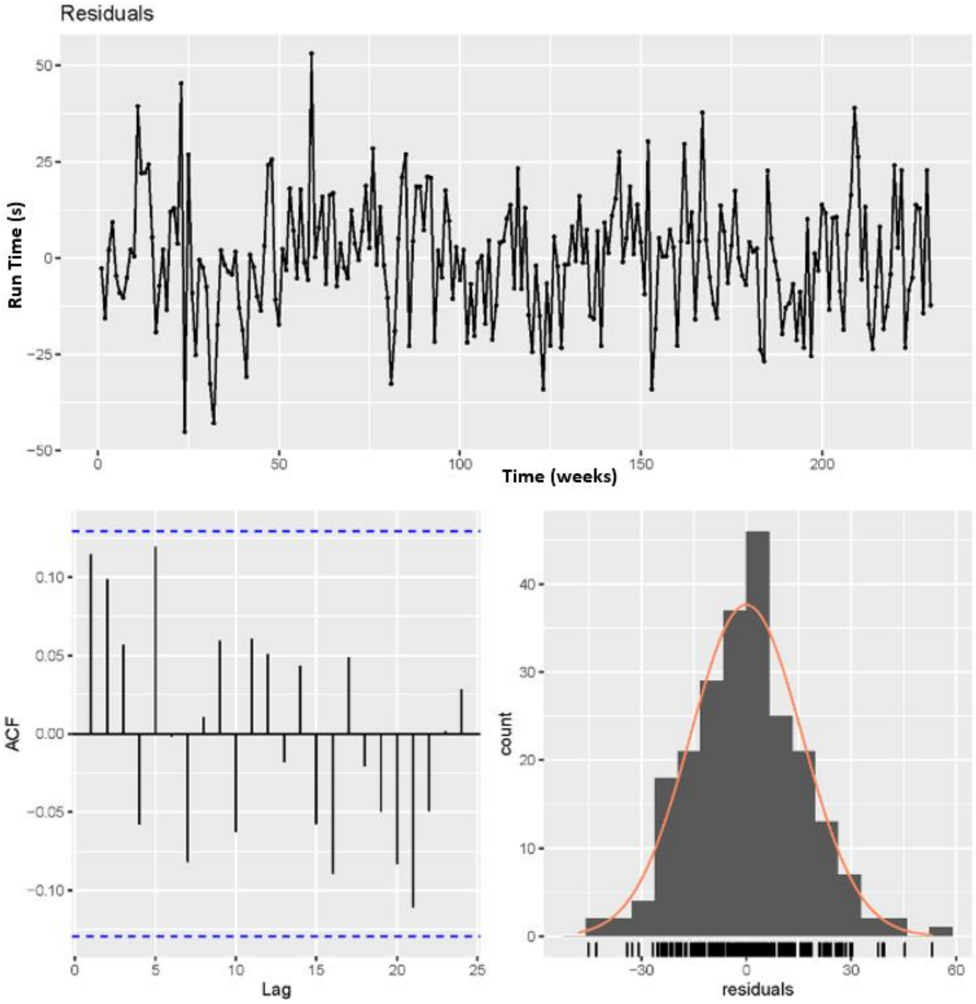


Figure 3.4. Example post-test analysis of residuals, their distribution and ACF plot for the influence of ozone on finishing times at Bushy parkrun.

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 (e.g. how much of the routes are grass, trail, tarmac), elevation profiles (especially vertical gain) and elevation above sea level that could lead to false conclusions. However, controlling these factors over a spatial analysis would prove challenging and probably be 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.

3.3 Results

3.3.1. Meteorology

Basic descriptive statistics for the data used in this work are shown in Table 3.3. Figures 3.5 and 3.6 show the relationship between detrended run times and temperature and run times and temperature respectively on scatter plots. Although there is a lot of spread in run times, a more linear relationship between detrended run time and temperature can be seen. Linear analysis was also performed due to the methodologies and results shown by previous research examining athletic performance and environmental variables, incuding temperature (Ely *et al*., 2008; Maffetone *et al*., 2017; Marr and Ely, 2010; Trapasso and Cooper (1989); Trubee *et al*., 2014; Tucker *et al*., 2006; Vihma, 2010).

Table 3.3. 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 (°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

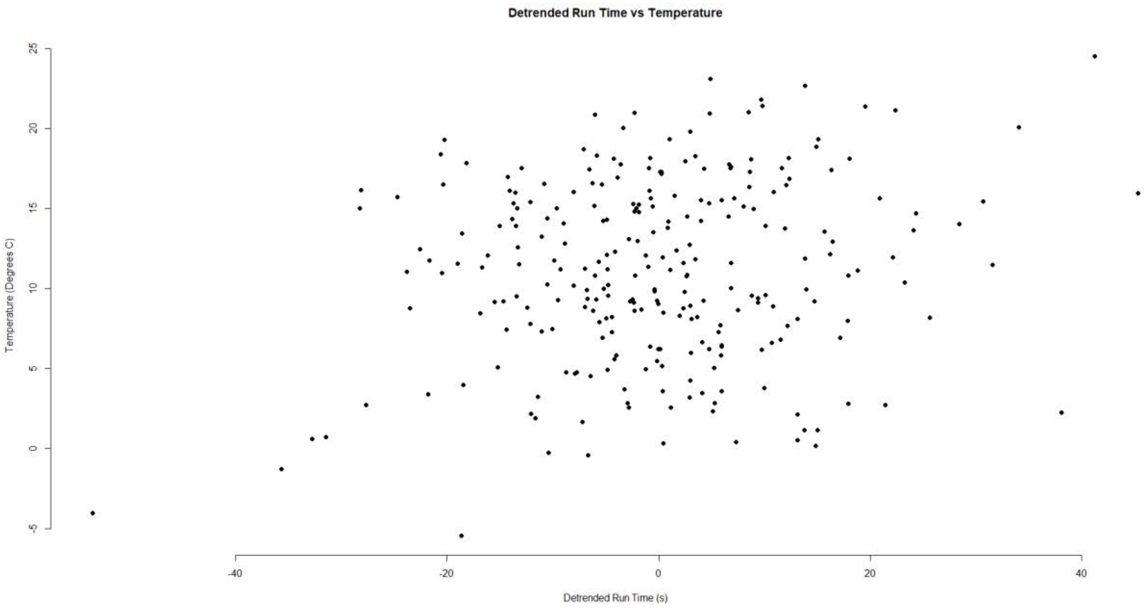


Figure 3.5. Scatterplot of detrended run times at parkrun events against temperature.

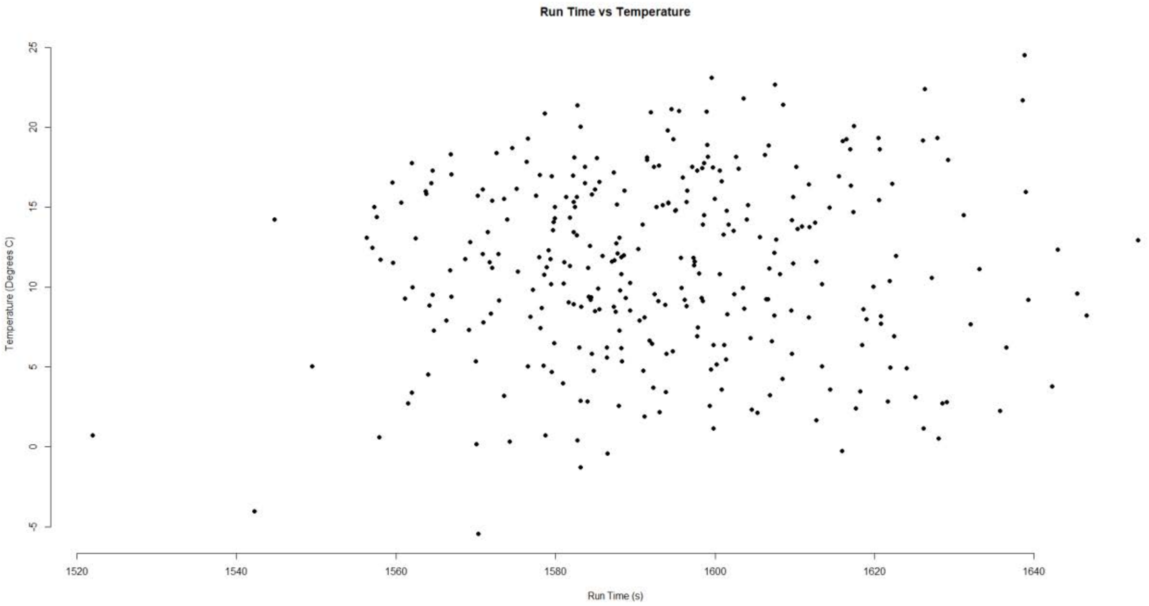


Figure 3.6. Scatterplot of run times at parkrun events against temperature.

3.3.2. Temperature

Initial analysis shows that the distribution of run times are predominantly between 20 and 30 minutes, with temperatures between 8-15°C. Linear regression analysis across all parkrun events resulted in the regression equation (Equation 3.1) below, where *t* is the change in run time in s, and *T* is temperature in °C. Consequently, a temperature of 11.5°C is determined to not hinder nor aid performance with the equation being significant at the 99% confidence interval and explaining 3% of the variance in run times.

$t = -4.83 + (0.42 \times T)$ (standard error = 0.14) (Equation 3.1)

Examination of individual parkrun events shows that five locations have significant relationships between finishing times and temperature (Table 3.4). Of these, however, Bromley parkrun has a negative relationship with finishing times, suggesting that quicker performances occur under warmer conditions (p=0.05).

Table 3.4. Individual parkruns and their relationship between finishing times and temperature variations.

Location	Intercept	Coefficient	Standard Error	R^2 Value	p Value
Bedfont	**-3.78**	**0.24**	**0.37**	**-0.002**	**0.53**
Brockwell	**1.11**	**0.02**	**0.009**	**3.111e-05**	**0.32**
Bromley	**6.57**	**-0.63**	**0.15**	**0.01**	**0.05**
Bushy Park	**-5.63**	**0.51**	**0.19**	**0.03**	**<0.01**
Crystal Palace	**-0.57**	**0.03**	**0.38**	**-0.004**	**0.93**
Finsbury Park	**-10.64**	**0.86**	**0.37**	**0.02**	**0.02**
Greenwich	**5.84**	**-0.52**	**0.45**	**0.01**	**0.25**
Grovelands	**1.34**	**0.001**	**0.008**	**-0.01**	**0.87**
Hackney Marshes	**0.64**	**-0.01**	**0.6**	**-0.004**	**0.98**
Kingston	**4.98**	**-0.48**	**0.21**	**0.01**	**0.27**
Lloyd	**-5.00**	**0.4**	**0.64**	**-0.002**	**0.53**
Old Deer Park	**7.26**	**-0.87**	**0.58**	**0.01**	**0.14**
Richmond	**-9.4**	**0.84**	**0.29**	**0.03**	**<0.01**
Roundshaw	**-11.03**	**1.03**	**0.49**	**0.01**	**0.04**
Wimbledon	**2.06**	**-0.31**	**0.35**	**-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 were detrimental to finishing times of the age groups shown in Table 3.5. 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 3.5. Significant linear regression results of age group analysis. Wind speed appears to be the dominant variable regardless of age.

Age Group	Explanatory Variable	Intercept	Coefficient	Standard Error	R^2	P Value
20-24	Wind Speed	-13.52	2.05	0.79	0.02	<0.01
25-29	Wind Speed	0.99	0.02	0.01	0.01	<0.01
35-39	Temperature	-2.99	0.43	0.22	0.01	0.06
40-44	Wind Speed	-10.56	1.78	0.3	0.08	<0.01
	Temperature	-4.35	0.48	0.19	0.02	0.02
45-49	Wind Speed	-7.73	1.34	0.29	0.05	<0.01
	Temperature	-3.3	0.36	0.17	0.01	0.06
50-54	Wind Speed	-6.97	1.2	0.32	0.03	<0.01
	Temperature	-4.63	0.52	0.19	0.02	<0.01
55-59	Wind Speed	-9.12	1.47	0.39	0.04	<0.01
65-69	Wind Speed	-10.64	1.66	0.73	0.01	0.02
	Temperature	-7.41	0.74	0.44	0.01	0.09

3.3.3. 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 ($p=<0.08$).

3.3.4. Wind Speed

Significant results were only found at seven of the fifteen events as well as the overall and male and female subsets ($p=<0.08$, Figure 3.7). 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 3.5).

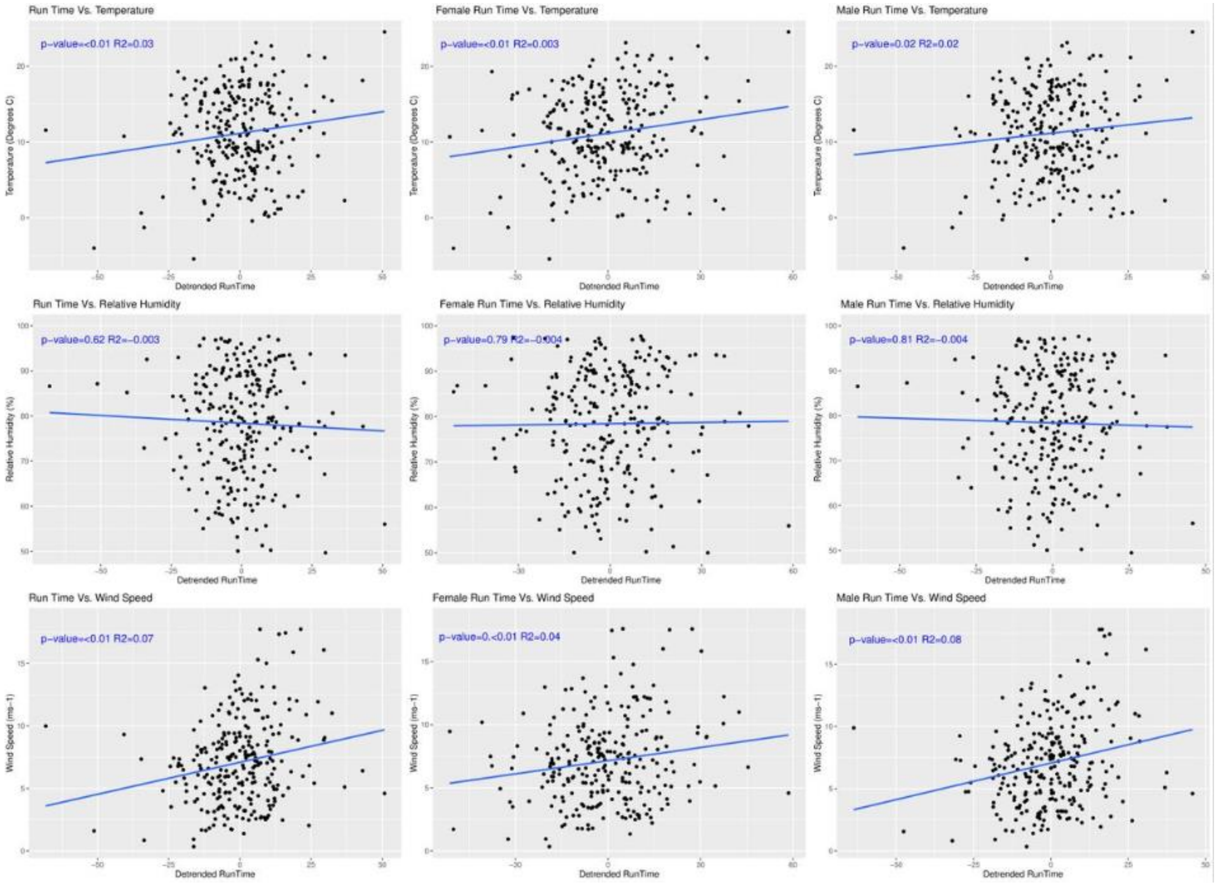


Figure 3.7. Results of linear regression analysis for the overall (row A), female (row B) and male (row C) parkrun subsets with the three meteorological variables examined.

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).

3.3.5. Combined influences

Multiple linear regression was performed using the influence of temperature, relative humidity and wind speed (Equation 3.2 – change in parkrun time in s, temperature in ^{o}C, RH in % and wind speed in ms^{-1}). 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 3.6, with 16% of the variance in finishing times at Bushy Park attributed to the three variables.

Change in parkrun time = -23.64 + 0.51 T** + 0.13 RH + 1.07 WS** (0.08 standard error)

(Equation 3.2)

**Significance <0.01

Table 3.6. Meteorology multiple linear regression results for the fifteen parkrun events.

Location	Intercept	Temperature	RH	Wind Speed	Standard Error	R^2	p-value
Bedfont	-28.41	0.68	0.29	-0.35	0.19	0.004	0.27
Brockwell	1.33	0.02	-0.003	No Data	0.01	0.02	0.11
Bromley	-39.79	-0.11	0.72	0.43	0.16	0.04	<0.01
Bushy Park	1.96	0.43	-0.09	1.39	0.16	0.26	0.02
Crystal Palace	-5.57	0.06	0.03	0.26	0.19	-0.01	0.96
Finsbury Park	-3.15	0.78	-0.09	No Data	0.19	0.02	0.07
Greenwich	-31.41	-0.2	0.37	0.67	0.24	0.01	0.21
Grovelands	1.26	0.002	0.001	No Data	0.004	-0.02	0.96
Hackney Marshes	0.36	-0.04	-0.02	0.22	0.31	-0.01	0.99
Kingston	-21.58	-0.2	0.3	0.09	0.12	0.04	0.23
Lloyd	10.34	0.18	-0.29	1.2	0.33	0.001	0.37
Old Deer Park	-53.91	-0.46	0.52	3.33	0.33	0.02	0.04
Richmond	5.75	0.51	-0.24	1.5	0.16	0.06	<0.01
Roundshaw	-57.57	1.4	0.41	0.91	0.24	0.02	0.03
Wimbledon	-25.59	-0.2	0.2	2.27	0.22	0.02	0.06

3.4. Air Quality

Basic descriptive statistics for the data used in this work are shown in Table 3.7.

Table 3.7. 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)

3.4.1. 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.

3.4.2. 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.

3.4.3. $PM_{2.5}$

$PM_{2.5}$ 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 (Figure 3.8). 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.

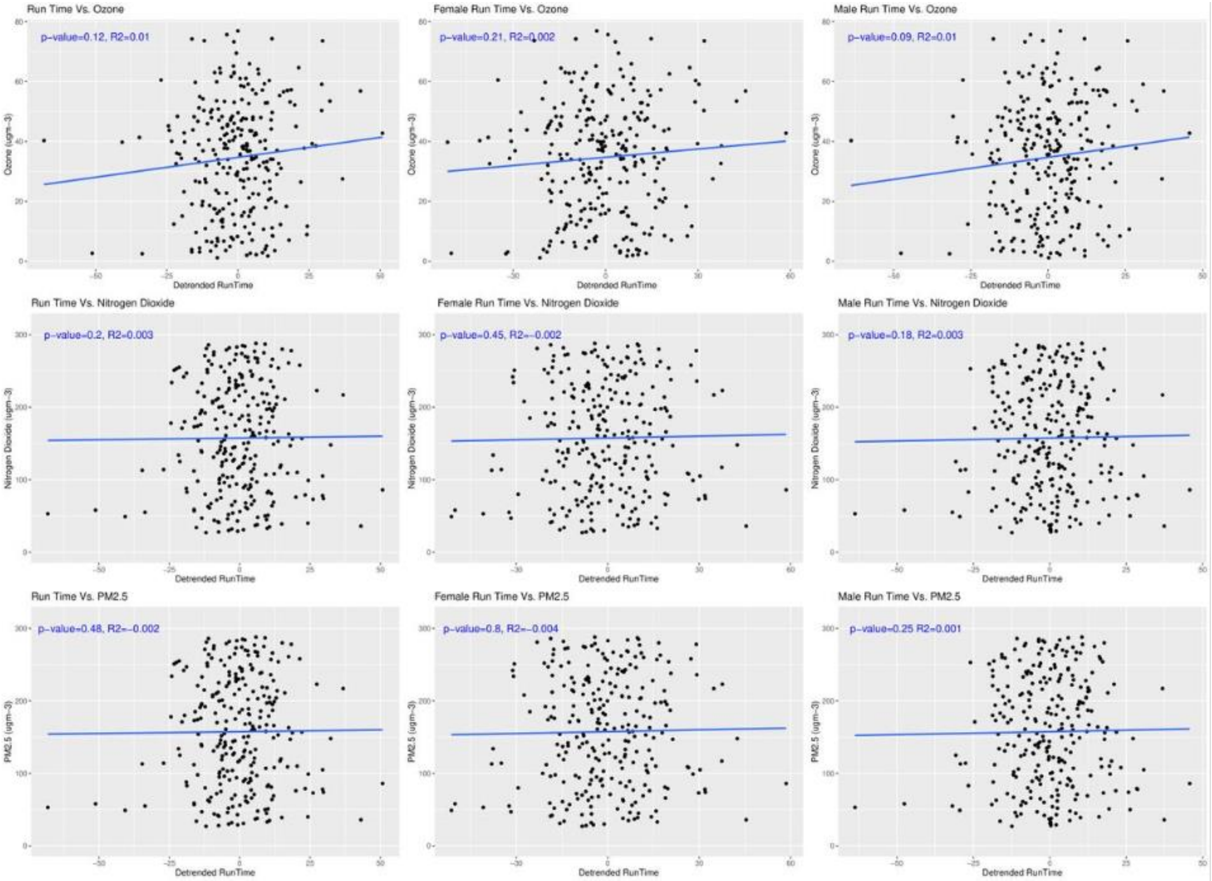


Figure 3.8. Results of linear regression analysis for the overall (Row A), female (Row B) and male (Row C) parkrun subsets with the three pollutants examined.

Multiple linear regression analysis that included the three pollutants showed only one significant relationship with finishing times (Table 3.8).

Table 3.8. Air quality multiple linear regression results for the fifteen parkrun events.

Location	Intercept	O_3	NO_2	$PM_{2.5}$	Standard Error	R^2	p-value
Bedfont	-27.83	0.13	7.25	11.7	0.18	0.01	0.52
Brockwell	1.18	0.003	-0.04	No data	0.004	-0.02	0.67
Bromley	-11.7	0.11	6.66	-2.68	0.13	-0.01	0.8
Bushy Park	3.93	0.13	-1.02	-7.16	0.14	0.03	0.12
Crystal Palace	-11.15	0.25	-11.15	12.35	0.18	0.02	0.09
Finsbury Park	0.96	0.002	0.14	No data	0.003	-0.02	0.84
Greenwich	23.17	-0.31	-22.41	14.83	0.19	0.02	0.12
Grovelands	1.32	0.003	-0.04	No data	0.003	0.001	0.36
Hackney Marshes	16.48	-0.01	-10.83	No data	0.28	-0.01	0.79
Kingston	2.12	-0.01	-0.16	-0.3	0.01	-0.04	0.71
Lloyd	17.2	0.29	-26.73	1.15	0.27	0.04	0.01
Old Deer Park	0.89	0.003	0.25	0.16	0.008	-0.07	0.85
Richmond	-13.96	0.08	13.75	-10.13	0.23	-0.01	0.52
Roundshaw	-28.33	0.22	5.52	10.00	0.38	-0.03	0.92
Wimbledon	3.68	-0.03	-0.54	-3.19	0.22	-0.03	0.99

3.5. Discussion

3.5.1. Temperature

Running is a weather interference sport where conditions such as the meteorology will influence performance (Thornes, 1977). This is particularly so for higher temperatures that can alter the bodies thermoregulatory systems and increase fatigue and power output (Miller-Rushing *et al.*, 2012; Nybo *et al.*, 2014; Zhao *et al.*, 2013). 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 (2016). Time increases of seconds compared to the larger and more substantial performance reductions shown by Helou *et al*. (2012) 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 (2010) 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 (Casa, 1999; Kaciuba-Uscilko and Grucza, 2001; Nadel, 1990). 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 (Gagnon *et al*., 2009). Finally, several events showed no impact of temperature on performance (Havenith *et al*., 2008; Sandsund *et al*., 2012; Renberg *et al*., 2014; Maffetone *et al*., 2017). Overall, this research suggests that both genders are, to an extent, impacted by meteorology, as would be expected based upon previous research (Casa, 1999; Ely et al., 2007; Helou et al., 2012; Nadel, 1990).

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 (Committee on Sports Medicine and Fitness, 2000; Kenny and Hodgson, 1987; Navaratnarajah and Jackson, 2013; Rowland, 2008). 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 (Committee on Sports Medicine and Fitness, 2000; Kenny and Hodgson, 1987; Navaratnarajah and Jackson, 2013; Rowland, 2008). 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 (Donnelly *et al*., 2016; Fallmann *et al*., 2013; Gauderman *et al*., 2004; Gouveia and Fletcher, 2000; Lenzuni *et al*., 2009; Solecki *et al*., 2005).

3.5.2. 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 (Casa, 1999; Maughan *et al*., 2007a; 2007b; Nadel, 1990). 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 (Ely et al., 2007; Casa, 1999; Helou et al., 2012; Nadel, 1990; Vihma, 2010).

3.5.3. 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 (1980) who showed that headwinds will result in a greater drag force and slower running times. However, the majority of parkrun courses are lapped with participants encountering multiple wind directions during 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% (Bongers *et al*., 2017; Teunissen *et al*., 2013), 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 (Doubt, 1991). Furthermore, greater fitness levels does not necessarily result in improved cold weather performance, this is more often dictated by body shape, size and sex (Castellani and Young, 2012).

3.5.4. Combined Influences

The combined influence of temperature, relative humidity and wind speed has been noted earlier in this research (Ely *et al*., 2007; Helou *et al*., 2012; Vihma, 2010), 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*. (2013) who believed these three variables to be the greatest influencers on running performance.

3.5.5. Ozone

Only the male results showed a close to significant relationship ($p=<0.09$) between O_3 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 O_3 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.* (2012) on marathon performances (European Environment Agency, 2013). Furthermore, past research has shown that O_3 can decrease lung function and therefore performance in maximal time trial laboratory tests (Carlisle and Sharp, 2001; Folinsbee *et al*., 1994; Lippi *et al*., 2008; McCreanor *et al*., 2007; McKenzie and Boulet, 2008; Rundell and Caviston, 2008; Rundell, 2012; Weinmann *et al*., 1995), although this may not be the case under real-world conditions when the potential exposure of runners could vary considerably.

3.5.6. 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 (European Environment Agency, 2013). However, due to Leighton reactions, it could be suggested that high NO_2 levels are found in cooler temperatures, conditions that are likely to improve running times (Helou *et al*., 2012; Vugts, 1997). 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 (Cosby *et al*., 2003; Lim *et al*., 2005).

3.5.7. $PM_{2.5}$

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 results that go against common thinking of particulate matter being an irritant and highly detrimental to human health (European Environment Agency, 2013; Gauderman *et al*., 2004). However, Giles *et al*. (2012) 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 also often seen as a long-term health hazard. Furthermore, Marr and Ely (2010) and Helou *et al*. (2012) both showed that $PM_{2.5}$ had no influence on marathon performances. This could possibly explain the lack of a detrimental impacts on short-term performance, if not the few 'beneficial' relationships (Gauderman *et al*., 2004). The majority of the results suggest that there is no real relationship between short-term athletic performance and $PM_{2.5}$ concentrations.

3.6. 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. 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.

However, the use of the CMAQ-urban model which has been shown to provide accurate figures for our studied pollutants, shows good agreements between AURN measurements and predicted parkrun concentrations (Beevers *et al*., 2011; Beevers *et al*., 2012; Carslaw, 2011). Therefore, although monitoring locations are not ideally located in some instances, they are indicative of air quality levels, and as this research is not aimed to create a predictive model, more generate insights it can be concluded that the use of AURN data at the current time is valid. To provide potentially more detailed data for analysis, in-situ monitoring at parkrun events could be performed, albeit a potentially costly option. Additional modelled air quality data from either CMAQ-urban or another source could also be used to reduce the likelihood of some variability in air quality levels occurring between monitoring sites and parkrun events. Furthermore, assessing the impact of pollution, especially a single pollutant, is difficult due to the natural combination of pollutants and influencing factors parkrun participants would be exposed to (Helou *et al*., 2012).

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 (Gagnon *et al*., 2009). 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 (Gastin, 2001).

3.7. 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 (Ely *et al.*, 2007; Helou *et al.*, 2012). This also highlights the importance and impact of body temperature regulation and power output shown by past research (Casa, 1999; Miller-Rushing *et al.*, 2012; Nadel, 1990; Nybo *et al.*, 2014; Zhao *et al.*, 2013).

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 (Helou *et al.*, 2012). 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 (Giles and Koehle, 2014). This is supported by research showing that regular exercise protects against premature deaths attributed to UAQ (Wong *et al*., 2007). 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 (Chan and Ryan, 2009).

Chapter 4 - The Diamond League Athletic Series:

Does the Air Quality Sparkle?

This chapter addresses objective two of this thesis – examining how local air quality and meteorology variations may influence the performance of elite athletes at Diamond League athletics events. For plagiarism clarity - extensive parts of this chapter have been published within the *Journal of International Biometeorology* and the full article can be found in Appendix B.

4.1. Introduction and Background

In extreme cases, the negative impacts of urban air quality (UAQ) could outweigh the positive impacts of exercise (Guo *et al*., 2020; Strak *et al*., 2010; Tainio *et al*., 2016. Consequently, with encouragement for greater levels of exercise and active transport to combat a global obesity crisis and pollution: there is a likelihood of a greater proportion of society being exposed to poor, albeit improving, UAQ (COMEAP, 2009; 2010; Devarakonda *et al.*, 2013; Kobayashi *et al.*, 2017; Sallis, 2008; Shugart, 2016).

In contrast to recreational exercisers who are largely free to choose when they exercise, elite athletes and professional sport-people are constrained to set competition times, potentially resulting in them performing in less than ideal environmental conditions. Although at some landmark events, such as the now rearranged 2021 Tokyo Olympic Games, start times of some events are scheduled to avoid the most detrimental meteorological conditions (BBC Sport, 2019).

The International Association of Athletics Federations has held a season-long track and field athletics series known as Diamond League since 2010, with plans to continue developing the series in the future (IAAF, 2019). With events taking place in multiple European locations and additional international locations, Diamond League provides a global case study of the impact of local meteorological and air quality conditions on elite athletes, something that has rarely been studies outside of laboratory conditions (Giles and Koehle, 2013). In this chapter the impacts of meteorological variables (temperature, relative humidity, heat stress and wind speed) and air quality (O_3, NO_2 and particulate matter in the $PM_{2.5}$ and PM_{10} size fractions) upon athletic performance are assessed using a statistical approach.

4.2. Data and Methodology

This research follows a similar approach to the previous investigation into the influence of local meteorology and air quality on the performance of the general public at parkrun events in Greater London (Chapter 3). Here, the focus is on elite 5 km running events, which requires maximal oxygen uptake (VO_2 max, or the maximum amount of oxygen a person can utilise during exercise), to determine whether elite athletes are influenced by variations in local air quality and meteorological conditions. Furthermore, this allows for a direct comparison to our previous work examining the influence of meteorology and air quality on recreational runners over the same distance.

Diamond League events are relatively consistent in their held locations over the season, travelling to various major cities, although there is a strong European presence. Finishing times for eight events/locations that have multiple years' worth of data have been collected from the IAAF Diamond League results archive, as well as a solitary event from Doha in 2010 (Figure 4.1). Events in Rome, Eugene, Rabat and Monaco, although hosting 5 km events, have not been included in this analysis due to a lack of readily available meteorological or air quality data. As well as finishing times of all 5 km participants, official start times of events and notation of whether it was a male or female event were also recorded to allow for accurate pairing of race times to local meteorological and air quality measurements, along with examination of male and female data subsets, as performed by Marr and Ely (2010). It is noted that Diamond League events do not necessarily have the same races for males and females on the same day, or even same year, for individual locations.

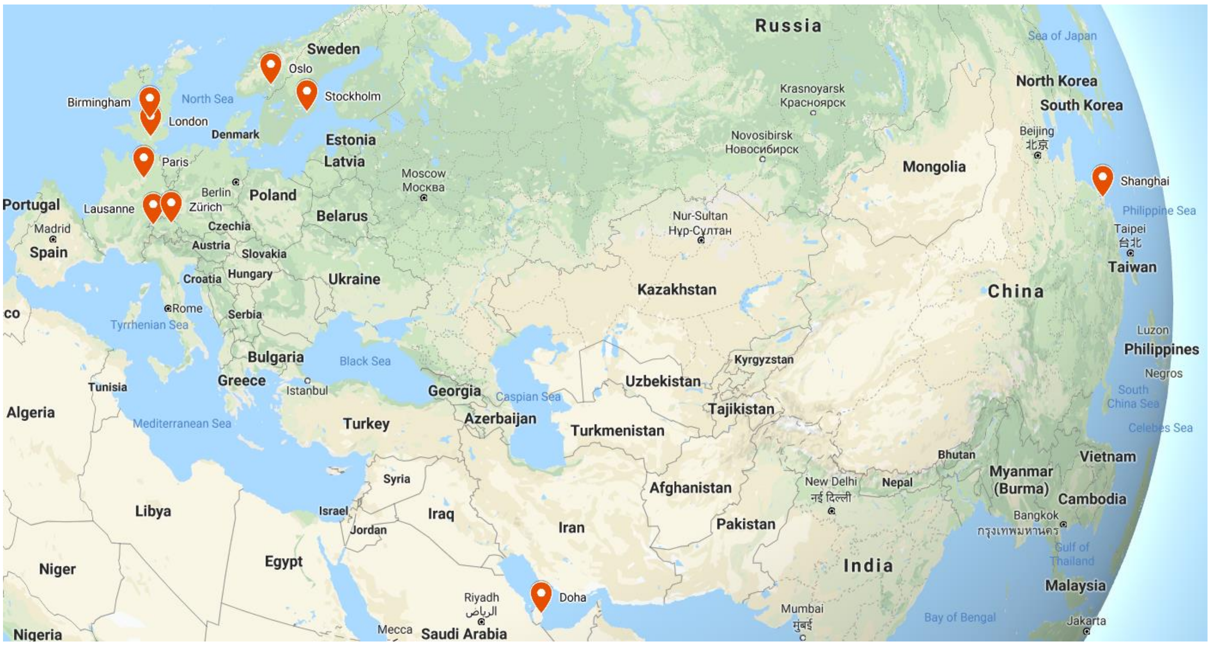


Figure 4.1. Map of Diamond League locations used in the analysis.

The meteorological data used for analysis has either been retrieved through the worldmet package in R (Carslaw, 2018), or (where available) official data used by national monitoring bodies. Air quality and meteorological data was acquired from the following local authorities, MeteoSwiss (Switzerland), Oslo Kommune (Norway), AirParif (France), The Department for Environment, Food and Rural Affairs (UK) and The Swedish Meteorological and Hydrological Institute (Sweden) for data provision. To ensure data was as representative as possible, the closest available and suitable (i.e. urban background, not roadside) stations that provided hourly readings were used. In most instances this meant that there was only one station that could be utilised.

Data representativeness also needs to be considered. O_3 is generally a regional pollutant with less variability compared to NO_2 and $PM_{2.5}$, which are more likely to be influenced by local sources and may have greater potential for discrepancies between monitoring and event locations. The selection of background monitoring sites which are typically away from major pollution sources such as roads and are broadly representative of wider pollution concentrations should minimise the chance of local pollution sources influencing the data obtained as well as the likelihood of spatial variation influencing analysis. The distances between monitoring sites and Diamond League venues is shown in Table 4.1.

Table 4.1. Distances between Diamond League venues and their monitoring locations.

Event	Distance to Meteorology Station (km)	Distance to Air Quality Station (km)
London	8.16	7.83
Birmingham	14.0	1.27
Paris	1.0	0.63
Zurich	7.85	2.09
Oslo	2.63	1.57 ($PM_{2.5/10}$) / 2.1 (O_3/NO_2)
Doha	8.99	No Data
Shanghai	26.83	No Data
Stockholm	0.85	1.19
Lausanne	1.48	0.22

With the exception of London, all of the urban background air quality monitoring stations are in close (<2.1 km) proximity to the Diamond League athletics stadiums studied. This provides confidence that the air quality measured on event dates and times is representative of conditions at the venues and subsequent findings are robust. Meterological stations in some cases are less ideally located, particularly in the case of Shanghai. However, as meteorological conditions are less spatially variable than air quality this is less of a concern, although potential relationships (or a lack thereof) will be examined with any excessive distances between locations in mind. A full summary of the acquired data for Diamond League events, meteorology and air quality can be seen in Table 4.2. Similarly to the parkrun study in Chapter 3, not all Diamond League locations had all pollutants or meterology variables recorded and thus some events have been analysed against a reduced time series as event dates containing missing data were been removed from analysis.

Table 4.2. IAAF Diamond League events examined, along with the corresponding availability in local air quality and meteorology data. It is important to note that there is only a single (male or female) 5K race held at each event, e.g. London 2011 only has a female race, whilst 2012 is a male race.

Event	Years	O_3	NO_2	PM_{10}	$PM_{2.5}$	Wind Speed	Temperature	RH
London	2011, 2012, 2014-2016, 2018	All years	All but 2012	All but 2015	All years	All years	All years	All years
Birmingham	2011, 2013, 2015, 2016	All years	All years	2015, 2016	2015, 2016	All years	All years	All years
Paris	2010-2015	All years	All years	No data	No data	2010-2014	2010-2014	2010-2014
Zurich	2010-2014, 2016-2018	2018	2018	2018	2018	All years	All years	All years
Oslo	2010-2016	All years	No data	All years	All but 2014	All years	All years	All years
Doha	2010	No data	No data	No data	No data	All years	All years	All years
Shanghai	2010-2018	No data	No data	No data	No data	All but 2015 and 2017	All years	All years
Stockholm	2010, 2011, 2014, 2016, 2018	All but 2018	All but 2018	No data	2010, 2011, 2016	All years	All years	All years
Lausanne	2011, 2013, 2015, 2017, 2018	2018	2018	2018	No data	All years	All years	All years

Each Diamond League event was paired with the closest meteorological and air quality monitoring station and the closest average hourly reading to the event time was used. All data was checked for normality and homogeneity prior to analysis through skewness, kurtosis and Shaprio-Wilks and Levene's tests and was logged where necessary to improve data distributions. As per Helou *et al.* (2012), Marr and Ely (2010), Trapasso and Cooper

(1989) and Vihma (2010), a correlation analysis between finishing times and control variables was performed for the whole data set as well as individual events. This followed a preliminary analysis to investigate the role of gender due to the large differences between male and female finishing times. Next, linear regression was used to determine the extent to which the control variables influenced finishing times, as per previous marathon studies whilst multiple linear regression analysis examined the combined influence of meteorological and air quality variables on performance (Maffetone *et al*., 2017). For multiple linear regression analysis, PM_{10} has been removed from analyses due to its high correlation to $PM_{2.5}$ and the higher association of the latter pollutant with deleterious health effects. Finally, post-test analyses were also performed using the following diagnostic tests; Quantile-Quantile, Scale-Location, Fitted vs Residuals and Cooks-Distance plots. Variable inflation factors (VIFs) were also checked post-test for the multiple linear regression models to ensure that they were below the threshold of 3.

To determine whether there were any significant differences between male and female events finishing times and the explanatory variables at the respective event times, a one-way ANOVA with suitable post-hoc tests was performed. This was also used to determine whether there were differences between the nine events response and explanatory variables, and was again looked at as a complete dataset and male/female subsets. The mean finishing times of successfully completed races and explanatory variable figures were also determined to aid descriptive statistics and one-way ANOVA comparisons and analysis.

4.3. Results and Discussion

4.3.1. Overall Performance Analysis

Analysis showed that at both male and female events, higher wind speeds and temperatures resulted in slower finishing times whilst higher relative humidity saw correspondingly quicker events (p=<0.01) (Table 4.3 and Figures 4.2-4.4). The subsequent multiple regression analysis also indicated that higher temperatures slowed performances (p=<0.01 and p=0.06 for male and female events respectively). As noted already, the influence of wind and temperature on performance is to be expected, whilst higher relative humidity is thought to reduce heat dissipation and consequently lead to slower finishing times (Casa, 1999; Nadel, 1990). Despite this, at both the male and female events, temperature and relative humidity are negatively correlated, which explains the relationship shown between relative humidity and finishing times. Temperature is therefore the more influential parameter on performance and athletes are able to run faster in cooler but more humid conditions (Bigazzi, 2017). This has been previously shown by Daniels (2014), Helou *et al*. (2012) and Knechtle *et al*. (2019) examining marathon events, where each 5^{o}C increase in temperature will decrease performance by up to 1.6%. This is likely due to changes in athlete's circulatory and thermoregulatory systems to maintain a stable core body temperature (Casa, 1999; Ely *et al.*, 2007; Helou *et al.,* 2012; Miller-Rushing *et al.*, 2012; Nadel, 1990; Nybo *et al.*, 2014; Vihma, 2010; Vugts, 1997; Zhao *et al.*, 2013). Athlete's core body temperature is likely to increase at a quicker rate than the aforementioned marathon studies because of the higher intensity exercise being performed, and thus metabolic heat produced during shorter duration events (Cheuvront and Haymes, 2001; Gasparetto and Nesseler, 2020).

Table 4.3. Linear regression results between female and male finishing times and associated explanatory variables.

Event	**Temperature**					**Relative Humidity**				
	Intercept	**Coefficient**	**Standard Error**	**R^2**	**p-value**	**Intercept**	**Coefficient**	**Standard Error**	**R^2**	**p-value**
Female	870.4	1.86	0.51	0.05	<0.01	925.72	-0.32	0.09	0.04	<0.01
Male	2.89	0.01	0.005	0.01	<0.01	2.91	-0.001	0.00002	0.04	<0.01
	Heat Index					**Wind Speed**				
	Intercept	**Coefficient**	**Standard Error**	**R^2**	**p-value**	**Intercept**	**Coefficient**	**Standard Error**	**R^2**	**p-value**
Female	876.28	1.55	0.49	0.04	<0.01	886.462	5.35	1.14	0.09	<0.01
Male	2.89	0.01	0.04	0.01	0.02	2.9	0.001	0.0002	0.02	<0.01
	Ozone					**Nitrogen Dioxide**				
	Intercept	**Coefficient**	**Standard Error**	**R^2**	**p-value**	**Intercept**	**Coefficient**	**Standard Error**	**R^2**	**p-value**
Female	892.26	0.2	0.08	0.04	0.01	911.61	-0.28	0.15	0.02	0.07
Male	2.9	0.0001	0.00002	-0.02	0.49	2.91	-0.003	0.002	0.01	0.11
	PM_{10}					**$PM_{2.5}$**				
	Intercept	**Coefficient**	**Standard Error**	**R^2**	**p-value**	**Intercept**	**Coefficient**	**Standard Error**	**R^2**	**p-value**
Female	886.93	1.24	0.31	0.2	<0.01	897.64	1.14	0.42	0.06	<0.01
Male	2.9	-0.001	0.0001	-0.004	0.54	2.9	-0.00002	0.0002	-0.006	0.89

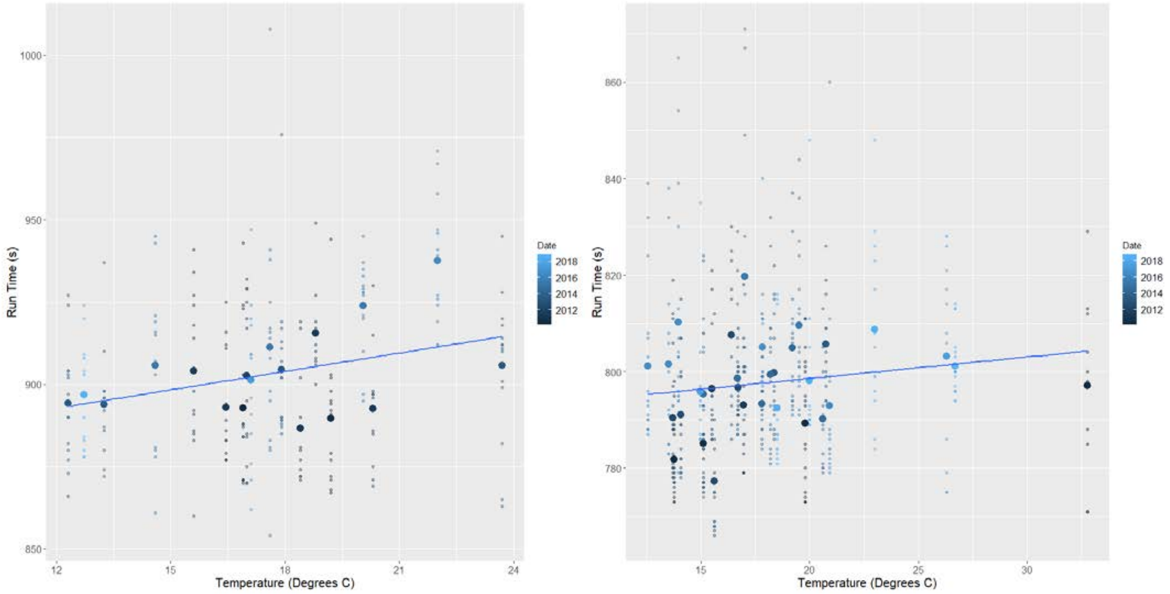


Figure 4.2. The effect of increasing temperatures on (left) female and (right) male races across the study period. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

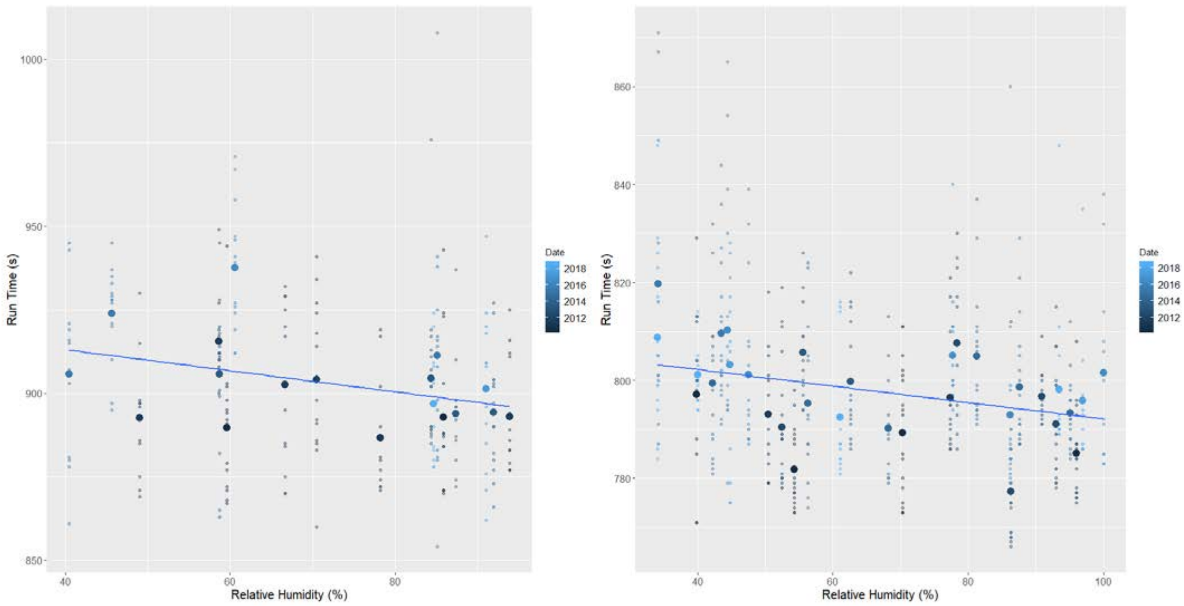


Figure 4.3. The effect of increasing relative humidity on (left) female and (right) male races across the study period. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

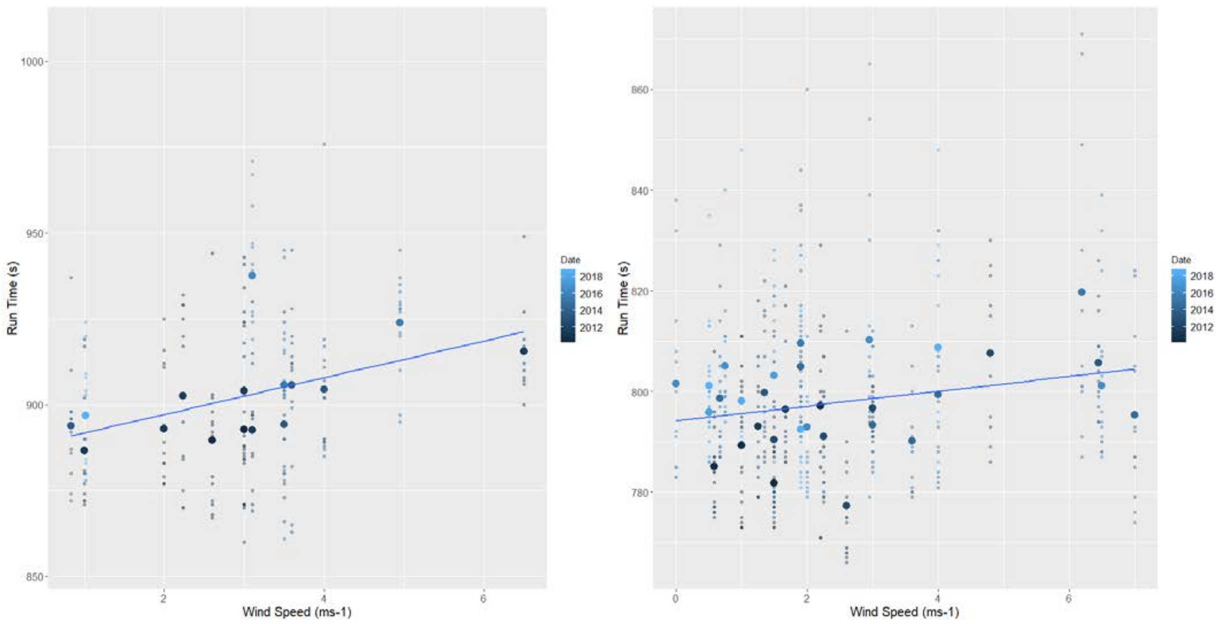


Figure 4.4. The effect of increasing wind speeds on (left) female and (right) male races across the study period. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

The combined influence of temperature and relative humidity was also calculated as a heat index using the weathermetrics package in R Studio (Anderson *et al*., 2013). For male athletes, heat index was detrimental to performance ($p=<0.02$). For female athletes, heat index also contributed to slower running times ($p=<0.01$) and when combined with increased wind speeds was also detrimental ($p=0.06$). Consequently, the combined influence of variables is likely to increase core body temperatures of athlete's and limit heat dissipation, with heat stress being cited as a concern for health during exercise, particularly under future climate change scenarios (Miller-Rushing *et al.*, 2012; Morici *et al.*, 2020). These results also support those of Vihma (2010) and Knetchle *et al*. (2019) who suggested that despite difficulties in quantifying the effect of wind on performance due to its variable nature; head- and cross-winds will reduced running speeds. This is likely to be found at Diamond League events held on a standard 400m athletics track with potentially less of the distance covered per lap being assisted with a tailwind. Furthermore, any potential tailwind is unlikely to benefit athlete’s in this circumstance overall as research has shown that head- and cross-winds are more detrimental than tailwinds are beneficial (Davies, 1980). The slightly reduced effect of heat index and wind speed on female athletes compared to male may be due to gender differences in heat dissipation. Core temperature control is greater for females due to a generally larger surface area to mass ratio and higher subcutaneous fat content (Gagnon *et al.*, 2009; Kaciuba-Uscilko and Ryszard, 2001). Female body mass is also likely to be lower due to physiological differences in stature, musculature and body fat percentages: which has been shown to be advantageous for running under increased temperatures (Cheuvront *et al*., 2002; Cheuvront *et al*., 2005; Marino *et al.*, 2000; Zouhal *et al.*, 2011). Females also have a higher running economy than males, which would lead to reduced heat production and less performance decreases over time (Billat *et al.,* 2001). Consequently, it can be hypothesised that under elevated heat index conditions, female athletes are producing less metabolic heat and also being cooled sufficiently by the wind to maintain a stable core temperature and suffer less of a performance decrease compared to their male counterparts (Maughan *et al*., 2007a; 2007b; Maughan, 2010).

In addition to significant relationships with temperature, relative humidity and wind, female races also returned several other significant results (Figures 4.5 and 4.6). In terms of air quality, O_3 and both $PM_{2.5}$ and PM_{10} caused female athletes to also produce slower finishing times ($p=<0.01$, Table 4.2). The known impacts of air quality on physical health-decreasing lung and cardiovascular function, irritation of the respiratory system, chest tightness and reduced arterial pressure and vasodilation-are likely to have contributed to these results in female performances (Carlisle and Sharp, 2001; McKenzie and Boulet, 2008; Rundell and Caviston, 2008; Rundell, 2012). This is through a reduction in oxygen uptake and VO_2 max and increased perceived exertion levels (Florida-James *et al*., 2011; Giles *et al*., 2014; Giles *et al.,* 2018; Kargarfard *et al*., 2015). It should also be noted that the above air quality impacts would be heightened for those with cardiorespiratory conditions such as asthma (Cutrufello *et al*., 2011; Rundell *et al*., 2008). As asthma and exercise induced asthma is widespread within the elite athlete demographic, this may be a contributor to the results presented and should be carefully considered for elite sports events in the future (Folinsbee *et al*., 1994; Helenius *et al*., 1997; Langdeau *et al*., 2000; Langdeau and Boulet, 2001; Lippi *et al*., 2008; McCreanor *et al*., 2007; McKenzie and Boulet, 2008; Rundell, 2012; Turcotte *et al*., 2003; Weinmann *et al*., 1995).

Overall, these findings add additional insight into the potential role of air quality in previous research that has shown temperature to be the biggest environmental influencer on athletic performance (Ely *et al*., 2007; Helou *et al*., 2012; Marr and Ely, 2010). Similar results for the male races were not observed. The reason as to why female athletes are more influenced by air quality than male athletes is currently unclear but was also shown by Marr and Ely (2010) with PM_{10} increases of 10 $\mu g/m^3$ reducing performance by 1.4%.

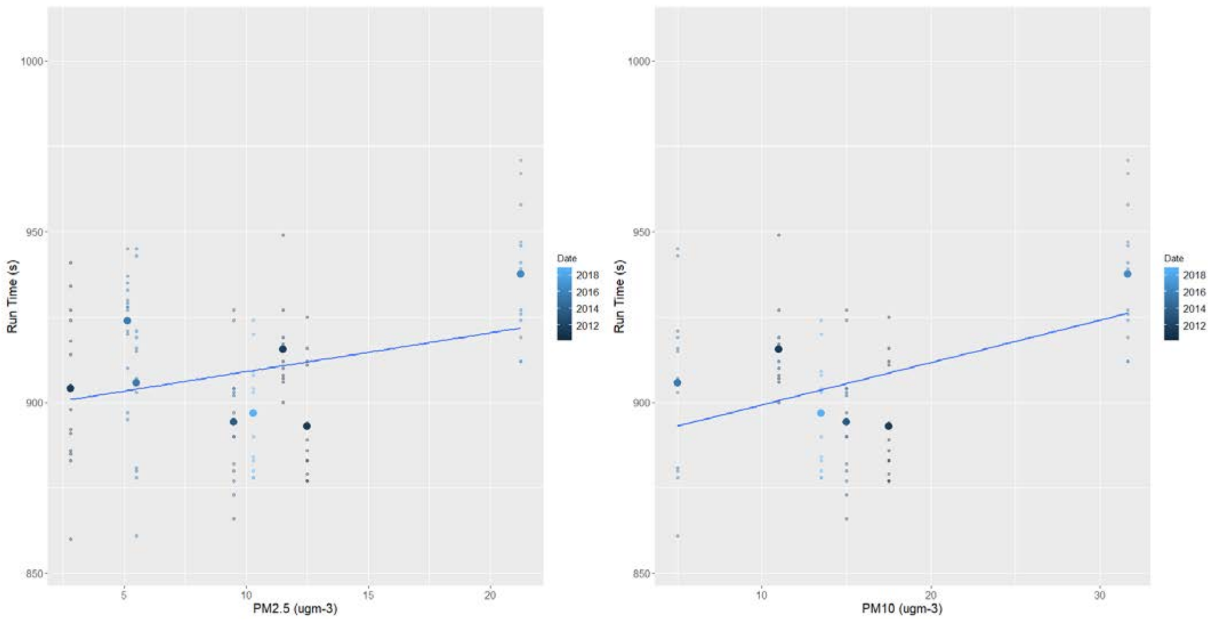


Figure 4.5. The effect of increasing $PM_{2.5}$ (left) and PM_{10} (right) male races across the study period. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

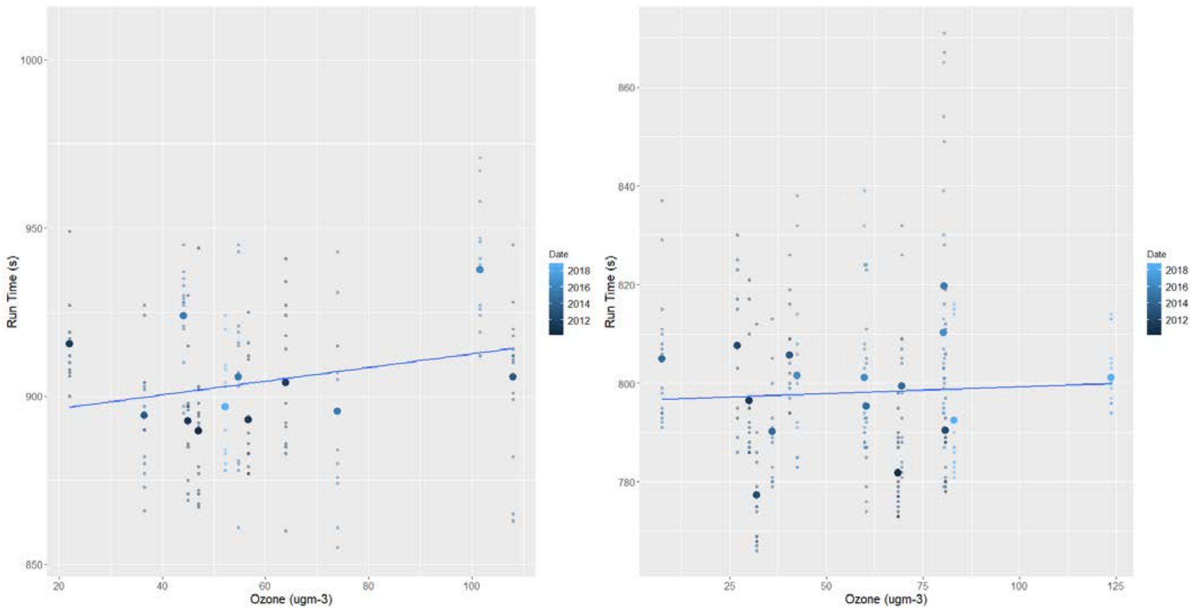


Figure 4.6. The effect of increasing ozone on female (left) and male (right) races across the study period. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

4.3.2. Individual Events

Events at the nine individual locations were also analysed to determine whether individual locations showed relationships between finishing times and the explanatory variables. A one-way ANOVA was subsequently performed to determine whether differences in finishing times across the nine events could be explained by variations in the explanatory variables.

The mean finishing times of the male and female events are shown in Table 4.4. The fastest two events for both genders were Paris and Oslo respectively. Zurich is the third quickest female event and fourth for the male subset, with Shanghai being fourth and third quickest. With the exception of Doha's solitary race, the other four locations are slower than the mean finishing times. Interestingly, London and Birmingham are the second slowest and slowest events of the Diamond League series, the latter being over 35 s slower than the mean female time and nine seconds for male events. For the female events, the ANOVA further shows that London is significantly slower than the four quickest events (p=<0.01) and Birmingham is slower than the top four events as well as Stockholm that is also slower than the mean finishing time (p=<0.04). ANOVA analysis of the men's events also shows a number of significant differences. Again, Birmingham and London are significantly slower than the quickest two events (p=<0.01) and Paris is also significantly quicker than Stockholm and Lausanne (p=<0.01).

Table 4.4. Mean finishing times of the nine Diamond League events.

Event	Female Mean Finishing Time (s)	Male Mean Finishing Time (s)
Paris	895.92	783.23
Oslo	897.36	792.97
Zurich	897.84	795.41
Shanghai	899.88	795.18
Doha	N/A	797.09
All Events	902.55	797.7
Stockholm	904.14	797.89
Lausanne	N/A	800.09
London	920.42	805.69
Birmingham	937.62	806.74

Table 4.5 below shows the linear regression results for the gender analysis of all the Diamond League events, followed by additional discussion of each location.

Table 4.5. Linear regression intercepts (Int), coefficients (coef), standard error (SE), R^2, and p-values (p) between finishing times and explanatory variables.

Location	Temperature	Relative Humidity	Heat Index	Wind Speed	Ozone	Nitrogen Dioxide	PM$_{10}$	PM$_{2.5}$
Paris Female	Int=819.27, Coef=3.64, SE=1.62, R^2=0.09, p=0.03	Int=877.53, Coef=0.33, SE=0.75, R^2=-0.02, p=0.66	Int=827.85, Coef=3.24, SE=1.44, R^2=0.1, p=0.03	Int=846.38, Coef=16.09, SE=7.54, R^2=0.08, p=0.04	Int=879.6, Coef=0.24, SE=0.12, R^2=0.06, p=0.05	Int=911.93, Coef=-0.57, SE=0.56, R^2=0.001, p=0.31	N/A	N/A
Paris Male	Int=737.1, Coef=2.57, SE=0.93, R^2=0.21, p=0.01	Int=838.67, Coef=-0.71, SE=0.26, R^2=0.21, p=0.01	Int=738.64, Coef=2.58, SE=0.93, R^2=0.21, p=0.01	Int=743.8, Coef=12.88, SE=4.66, R^2=0.21, p=0.01	Int=674.24, Coef=3.22, SE=1.17, R^2=0.21, p=0.01	Int=805.81, Coef=-0.92, SE=0.33, R^2=0.21, p=0.01	N/A	N/A
Oslo Female	Int=897.8, Coef=-0.03, SE=1.95, R^2=-0.03, p=0.99	Int=915.14, Coef=-0.23, SE=0.13, R^2=0.05 p=0.09	Int=911.16, Coef=-0.99, SE=1.5, R^2=-0.02, p=0.55	Int=884.28, Coef=4.36, SE=4.73, R^2=-0.004, p=0.36	Int=887.27, Coef=0.21, SE=0.36, R^2=-0.02, p=0.57	Int=904.54, Coef=-0.26, SE=0.25, R^2=0.004, p=0.29	Int=910.86, Coef=-1.06, SE=0.62, R^2=0.05, p=0.09	Int=914.66, Coef=-1.87, SE=1.17, R^2=0.04, p=0.12
Oslo Male	Int=2.88, Coef=0.02, SE=0.01, R^2=-0.003, p=0.37	Int=2.94, Coef=-0.001, SE=0.0002, R^2=0.17, p=<0.01	Int=786.1, Coef=0.52, SE=0.86, R^2=-0.01, p=0.53	Int=2.89, Coef=0.002, SE=0.0005, R^2=0.0003, p=<0.01	Int=2.92, Coef=-0.002, SE=0.0001, R^2=0.03, p=0.09	Int=2.91, Coef=-0.001, SE=0.0001, R^2=0.2, p=<0.01	Int=2.91, Coef=-0.001, SE=0.0001, R^2=0.00003, p=<0.01	Int=2.9, Coef=-0.0002, SE=0.0003, R^2=-0.01, p=0.49
Zurich Female	Int=873.31, Coef=1.71, SE=1.62, R^2=0.003, p=0.3	Int=928.51, Coef=-0.39, SE=0.34, R^2=0.01, p=0.26	Int=873.44, Coef=1.78, SE=1.82, R^2=-0.001, p=0.33	Int=889.99, Coef=5.71, SE=5.00, R^2=0.01, p=0.26	N/A	N/A	N/A	N/A

Table 4.5 continued. Linear regression intercepts (Int), coefficients (coef), standard error (SE), R^2, and p-values (p) between finishing times and explanatory variables.

Location	**Temperature**	**Relative Humidity**	**Heat Index**	**Wind Speed**	**Ozone**	**Nitrogen Dioxide**	**PM_{10}**	**$PM_{2.5}$**
Zurich Male	Int=728.37, Coef=4.23, SE=0.99, R^2=0.18, p=<0.01	Int=873.07, Coef=-0.87, SE=0.19, R^2=0.2p=<0.01	Int=732.46, Coef=3.95, SE=0.9, R^2=0.19, p=<0.01	Int=795.01, Int=-4.74, SE=6.7, R^2=-0.001, p=0.48	N/A	N/A	N/A	N/A
Shanghai Female	Int=2.98, Coef=-0.001, SE=0.003, R^2=-0.01, p =0.67	Int=2.91, Coef=0.001, SE=0.0004, R^2=0.01, p=0.21	Int=818.76, Coef=4.6, SE=6.62, R^2=-0.01, p=0.49	Int=2.94, Coef=0.003, SE=0.001, R^2=0.08, p=0.04	N/A	N/A	N/A	N/A
Shanghai Male	Int=2.9 Coef=-0.0002, SE=0.0006, R^2=-0.02, p=0.77	Int=2.89, Coef=-0.0001, SE=0.0003, R^2=-0.02, p=0.71	Int=800.98, Coef=-0.31, SE=1.19, R^2=-0.02, p=0.8	Int=2.9, Coef=-0.001, SE=0.001, R^2=-0.01, p=0.65	N/A	N/A	N/A	N/A
Stockholm Female	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Stockholm Male	Int=790.42, Coef=0.41, SE=0.65, R^2=-0.01, p=0.53	Int=805.12, Coef=-0.11, SE=0.1, R^2=0.002, p=0.29	Int=792.76, Coef=0.29, SE=0.68, R^2=-0.01, p=0.67	Int=796.64, Coef=0.45, SE=0.89, R^2=-0.01, p=0.62	Int=815.78, Coef=-0.34, SE=0.38, R^2=-0.01, p=0.38	Int-786.6, Coef=0.92, SE=0.57, R^2=0.04, p=0.11	N/A	Int=993.96, Coef=-24.37, SE=11.37, R^2=0.1, p=0.04
Lausanne Female	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lausanne Male	Int=736.35, Coef=49.42, SE=31.49, R^2=0.02, p=0.12	Int=828.65, Coef=-0.55, SE=0.23, R^2=0.06, p=0.02	Int=785.15, Coef=0.77, SE=0.55, R^2=0.01, p=0.16	Int=785.4, Coef=9.19, SE=6.89, R^2=0.01, p=0.19	N/A	N/A	N/A	N/A

Table 4.5 continued. Linear regression intercepts (Int), coefficients (coef), standard error (SE), R^2, and p-values (p) between finishing times and explanatory variables.

Location	Temperature	Relative Humidity	Heat Index	Wind Speed	Ozone	Nitrogen Dioxide	PM_{10}	$PM_{2.5}$
London Female	Int=788.73, Coef=6.74, SE=4.72, R^2=0.04, p=0.17	Int=953.66, Coef=-0.65, SE=0.46, R^2=0.04, p=0.17	Int-763.79, Coef=8.43, SE=5.91, R^2=0.04, p=0.17	Int=950.846, Coef=-5.43, SE=3.81, R^2=0.04, p=0.17	Int=907.13, Coef=0.38, SE=0.27, R^2=0.04, p=0.17	Int=865.04, Coef=1.4, SE=0.98, R^2=0.04, p=0.17	N/A	Int=930.76, Coef=-1.33, SE=0.93, R^2=0.04, p=0.17
London Male	Int=2.91, Coef=-0.0004, SE=0.0002, R^2=0.03, p=0.09	Int-2.91, Coef=0.00001, SE=0.00006, R^2=-0.02, p=0.8	Int=817.87, Coef=-0.63, SE=0.36, R^2=0.03, p=0.08	Int=2.9, Coef-0.001, SE=0.0007, R^2=0.01, p=0.17	Int=2.91, Coef=-0.00001, SE=0.00002, R^2=-0.01, p=0.53	Int=2.91, Coef=-0.00002, SE=0.00005, R^2=-0.02, p=0.73	Int=2.91, Coef=-0.004, SE=0.0003, R^2=0.01, p=0.29	Int=2.91, Coef=0.004, SE=0.0004, R^2=0.002, p=0.29
Birmingham Female	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Birmingham Male	Int=2.9, Coef=-0.001, SE=0.0007, R^2=-0.02, p=0.52	Int=2.92, Int=-0.0003, SE=0.00008, R^2=0.2, p=<0.01	Int=797.6, Coef=0.55, SE=1.55, R^2=-0.02, p=0.73	Int=2.9, Coef=0.002, SE=0.0007, R^2=0.12, p=0.02	Int=2.9, Coef=0.0002, SE=0.00007, R^2=0.2, p=<0.01	Int=2.91, Coef=-0.0003, SE=0.001, R^2=0.17, p=<0.01	N/A	N/A

4.3.3. Birmingham

Birmingham is the slowest event of the Diamond League calendar and the male subset showed a number of significant results. More O_3 and windier conditions produced slower results (Figure 4.7), whilst higher levels of NO_2 and relative humidity were often conducive to quicker results ($p=<0.02$). This suggests that, in the case of Birmingham, the irritant qualities of O_3 can play a detrimental role during the 5 km event. In contrast, but similar to results of Hodgson *et al*. (preprint), NO_2 slightly improved finishing times, potentially linked to the reaction between O_3, VOCs, NO_2 and sunlight, with higher NO_2 levels occurring under lower temperatures.

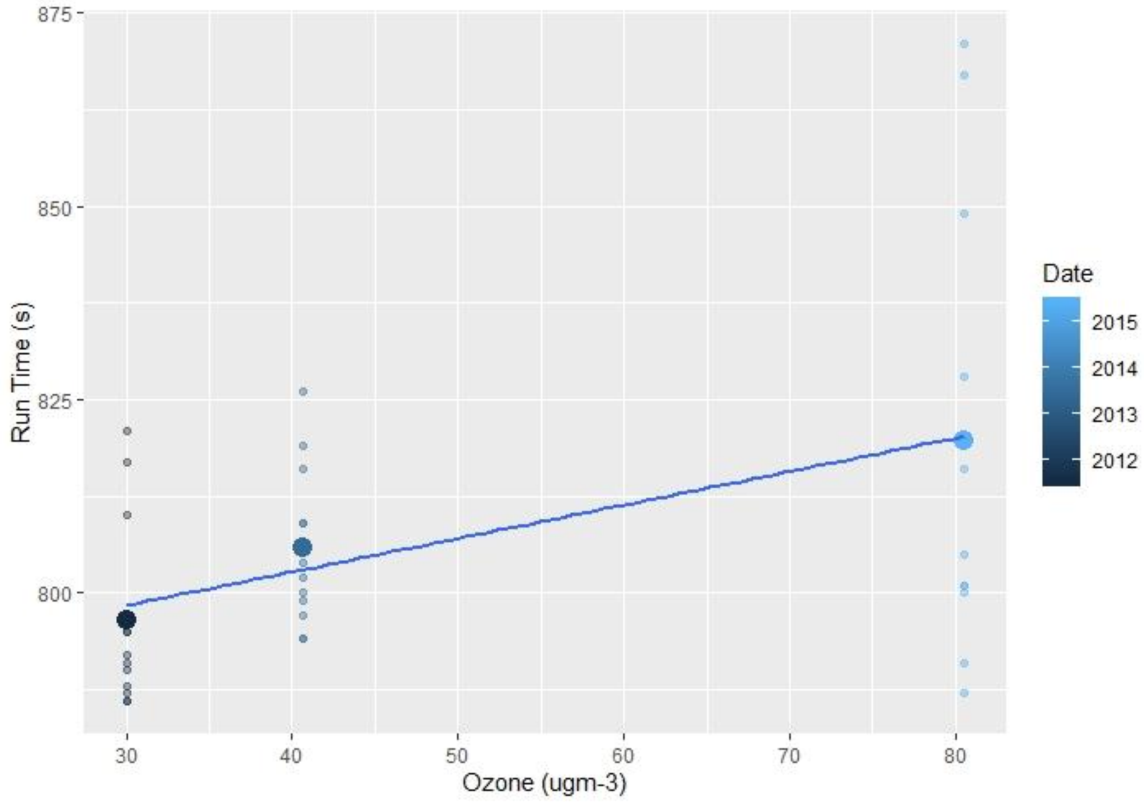


Figure 4.7. The effect of increasing O_3 levels on male races held in Birmingham. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

Birmingham showed significant and detrimental relationships with O_3, PM_{10} and $PM_{2.5}$ and temperature slowing finishing times ($p=<0.01$). Conversely, higher levels of NO_2 saw improved finishing times, likely due to the lower temperatures found under those conditions and highlighted previously ($p=<0.01$). Additionally, the highest mean levels of O_3 are found at these events, along with the second lowest NO_2 levels. Based upon previous research, these high O_3 and low NO_2 levels could be contributing to slower finishing times (Ely *et al*., 2007; Helou *et al*., 2012; Marr and Ely, 2010). Furthermore, the city registers the second highest PM levels on race times and is also the windiest event, significantly more so than several calmer locations ($p=<0.02$). Based upon these ANOVA and regression results, it appears that high O_3 and PM levels, coupled with low NO_2 and high wind speeds, is contributing to the slower finishing times at the Birmingham races.

4.3.4. Doha

Doha only had one event and was therefore not analysed independently.

4.3.5. Lausanne

No air quality data was available for the study period in Lausanne which also only had male events to analyse. There were no significant relationships between finishing times and temperature, relative humidity, wind speed or heat index. Generally, Lausanne has low wind speeds and relative humidity, but is the warmest event once Doha is discounted. Consequently, it is suggested that the high temperatures and low cooling wind speeds are potentially contributing to Lausanne's mean finishing time being the third slowest – although this cannot currently be statistically proven and only provides a guideline to the impact of local meteorology on athletic performance.

4.3.6. London

For the gender subsets of events held in London, there were no significant relationships shown. Despite this, London, along with Birmingham, was the slowest event for male and female athletes, significantly so compared to the other six locations ($p=<0.08$). The conditions athletes were competing in also included the highest O_3, NO_2, PM_{10} and $PM_{2.5}$ levels. For PM, London's levels were significantly the highest ($p=<0.01$). These combined pollutants and their irritant qualities are likely to have slowed performances to an extent in the London events (Cutrufello *et al*., 2011; EEA, 2013; Rundell and Caviston, 2008; Rundell *et al*., 2008; Rundell, 2012).

For female races, London is the second slowest event, but has significantly low O_3 levels ($p=<0.02$) and higher NO_2 ($p=<0.01$). Along with Stockholm, London has the lowest levels of PM ($p=<0.09$) and is the windiest event. From this, there isn't necessarily a clear picture as to why London's female races are on the slower end of the spectrum, due to the low O_3 and PM levels. The main explanation could be the high wind speeds of 5.6 ms^{-1}. Although this isn't significantly higher than other locations, it may be enough to contribute to the decreased running speeds as shown by Davies (1980).

4.3.7. Oslo

The male subset in Oslo only showed three significant results, generally, finishers are quicker under elevated NO_2 (Figure 4.8), relative humidity and PM_{10} concentrations ($p=<0.01$). For female events, higher relative humidity and PM_{10} produced quicker results ($p=0.09$). Oslo is the second quickest event for male and female races, and often has cooler and more humid conditions, which would promote fast times and correlates well with previous research (Hodgson *et al.*, preprint). Furthermore, NO_2 concentrations peak at below 25 ugm^3, which is lower than WHO guideance limits and thus, coupled with lower temperatures, is not detrimentally effecting performance. This is likely due to temperature being a more influential environmental variable and therefore athletes are able to perform better under cooler, albeit slightly more polluted, conditions (Bigazzi, 2017). The PM results are not to be expected due to the irritant nature of the pollutant, however (EEA, 2013). On both counts, however, the reduced sample size at Oslo of four races may also have contributed to the unexpected results.

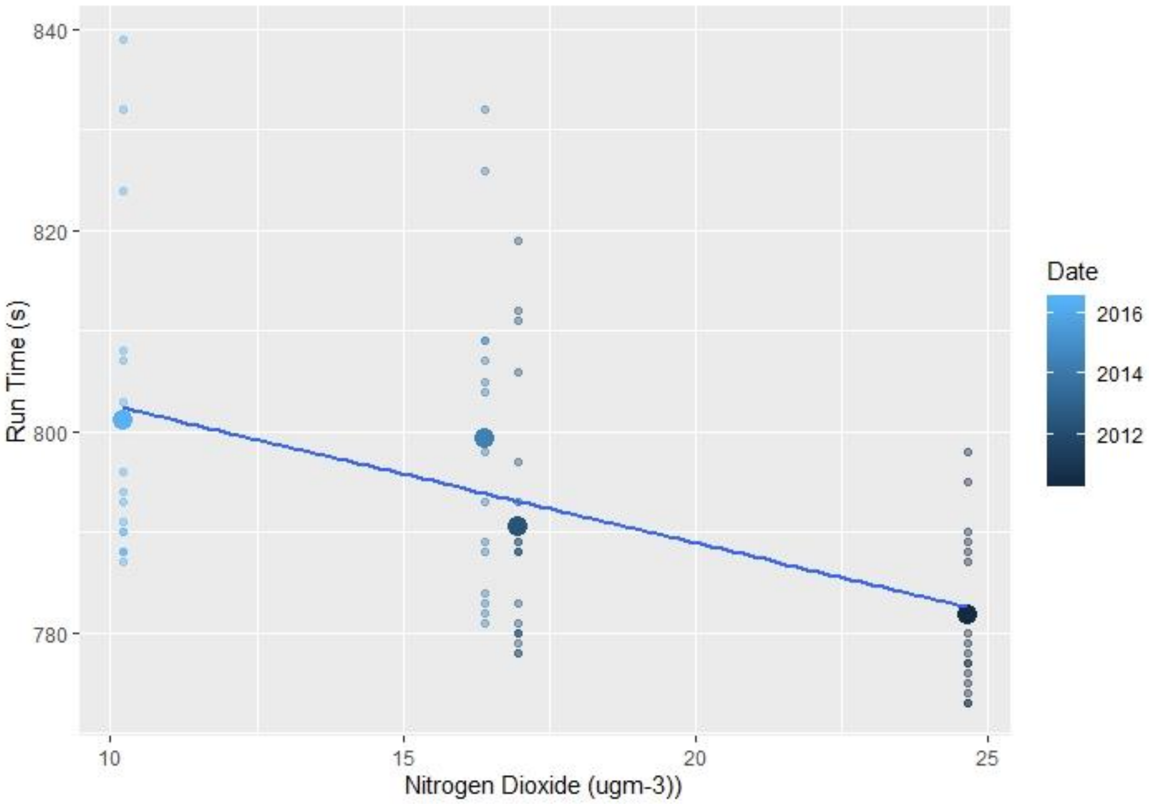


Figure 4.8. The effect of increasing NO_2 levels on male races held in Oslo. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

4.3.8. Paris

The male subset at Paris also showed a number of significant results. Higher O_3, temperatures and windy conditions produced slower results, whilst increased levels of NO_2 and relative humidity improved performances ($p=<0.02$). Heat index results also suggest that under combined high temperatures and relative humidity performances are slower ($p=0.01$). The female subs*et* also showed the same impacts of those three variables ($p=<0.05$) and mirrors previous research findings (Casa, 1999; Ely *et al*., 2007; Helou *et al.,* 2012; Chapter 3).

From ANOVA analysis, Paris is the quickest event for male and female mean times when compared to a number of the slower locations. Paris has the lowest O_3 and highest NO_2 levels, significantly so when compared to the highest and lowest locations respectively ($p=<0.01$). Consequently, this may explain why the male event at Paris is the quickest of the nine. However, for female events, pollutant and meteorological conditions don’t show any significantly high or low values for Paris.

4.3.9. Shanghai

Shanghai only has meteorological data available and the male subset showed no significant relationships whilst female events are slower under windier conditions ($p=0.04$, Figure 4.9). This reduction in running speed under higher wind speeds is to be expected (Davies 1980). The lack of significant relationships is likely due to the distance between the monitoring station and event location (>25 km – Table 4.1) being greater than that of other locations. Additionally, a lack of relationships between run times and temperature or relative humidity could also be attributed to Shanghai not having particularly high or low temperatures, instead having the highest relative humidity of around 90%. Shanghai is also around the mean run time of all events, suggesting that the meteorological conditions are not extreme enough, in a detrimental capacity, to have a clear impact on the overall finishing times compared to other locations.

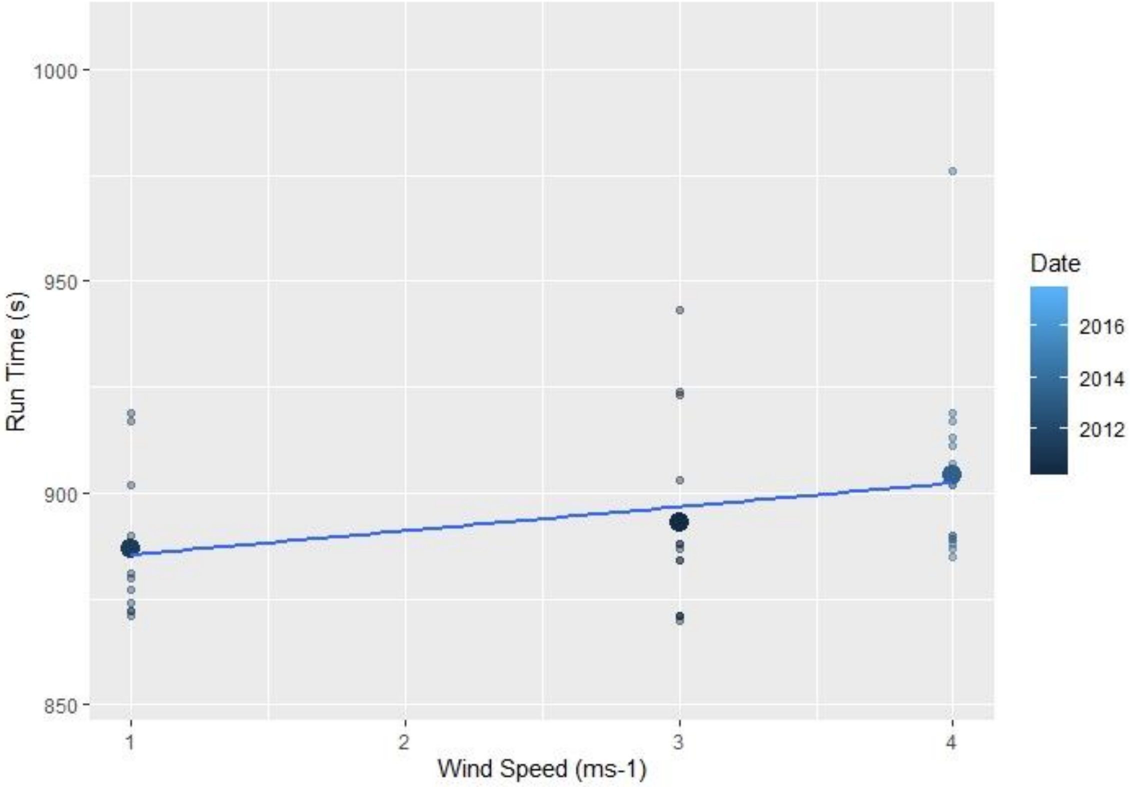


Figure 4.9. The effect of increasing wind speeds on female races held in Shanghai. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

4.3.10. Stockholm

For the male subset at Stockholm, only $PM_{2.5}$ had a significant relationship with finishing times, improving them under elevated levels ($p=0.04$). There were no female events to analyse. Despite this unusual relationship with $PM_{2.5}$, Stockholm generally has the lowest readings at its events ($p=<0.03$) as well as significantly low NO_2 levels ($p=<0.05$). O_3 concentrations are also low. Temperature, relative humidity and wind speeds are not particularly extreme in either direction, suggesting that other factors may be influencing performance or that in this instance, the meteorological and air quality conditions are not great enough to impact elite athletic performance.

4.3.11. Zurich

Zurich's male subset conformed to previous research with higher temperatures slowing performances, whilst relative humidity was beneficial (p=<0.01, Figure 4.10). Heat index was also detrimental to performance (p=<0.01). The female subset showed no significant results. Generally, Zurich is one of the colder and more humid events, as well as having the lowest wind speeds (p=<0.01). This could suggest that under 'normal' conditions Zurich is below an optimum race temperature for sufficient muscular performance as well air density being higher and thus providing increased resistance. Also, without air quality data, full conclusions as to the influence of variables on performance cannot be drawn.

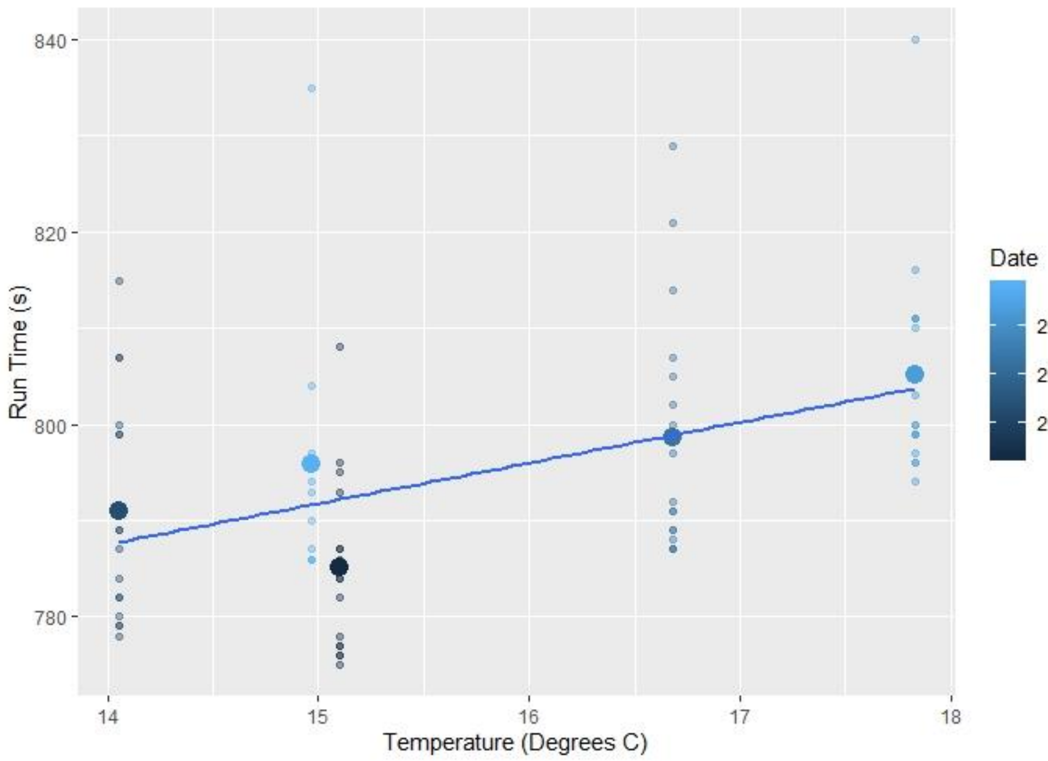


Figure 4.10. The effect of increasing temperatures on male races held in Zurich. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

4.4. Summary and Practical Applications

Overall, there is a lot a variability in results when examining different locations that host Diamond League events. This is to be expected with distances between events and monitoring locations and the highly spatial variability of pollutants, particularly PM and NO_2 (Duyzer *et al.*, 2015; Ferradas *et al.*, 2010; Kaur *et al.*, 2005; 2007). Furthermore, potential confounding factors that are hard to account for are individual athlete's acclimatisation to environmental conditions as well as reduced sample sizes at some individual events. With respect to meteorology results, windier conditions and higher temperatures are most detrimental to performance, with the latter inversely correlated with relative humidity and quicker finishing times coming from events with low temperatures and high relative humidity. With regards to track surfaces, Diamond League venues have to meet and maintain IAAF standards, so although there might be some small difference between track age and composition there is unlikely to contribute to vastly different running performances.

Paris and Birmingham show the most promising results. Paris has the quickest finishing times, whilst also having the lowest O_3 conditions and second highest NO_2 levels. Additionally, events are held under lower than average temperatures and regression results suggest that low O_3, temperatures and higher NO_2 levels will result in the quickest times. For Birmingham, the slowest event, high O_3, PMs and temperatures result in slower performances, and events are generally held under high levels of the first two variables. This potentially suggests that despite elite athletes training for high temperatures, they are not as well conditioned to high pollution levels, particularly PM, which will generally be low at high altitude training locations.

Although attention has previously been drawn to concerns regarding air quality at the previous Olympic Games held in Athens, Beijing and Rio, along with the methods used by host nations to improve conditions prior to events, there has to date been no consideration of the impact of environmental conditions on performances (De La Cruz *et al*., 2019; Donnelly *et al*., 2016; Florida-James *et al*., 2011; Wang *et al*., 2009). It is hoped that this research will prompt further investigation into the influence of air quality and meteorology variables on elite athletic performance and health, as well as scheduling events at times when pollution is lowest not only for athletes, but also spectators who will also be influenced by air pollution. This has previously occurred with regards to temperature with the (now) 2021 Tokyo Olympics endurance events being scheduled to avoid the warmest of temperatures, but additional mitigation measures could also be implemented (BBC Sport, 2019). For instance, road closures along and around events as well as the provision of public, active or ‘green’ transport options for spectators and officials may help reduce pollution levels at the event whilst Kosaka *et al*. (2018) suggested that increased shading along the Tokyo marathon route may reduce the likelihood of heat stress related medical incidents (Morici *et al.*, 2020). This is especially so when research has highlighted the positive relationship between increased temperatures, associated medical incidents and the total number of ‘did not finish’ participations (Carlstrom *et al.*, 2019; Khorram-Manesh *et al.*, 2020; Schwabe *et al.,* 2014). Given the research evidence, there is a real opportunity for organisers to consider making changes, not only from a health perspective, but also for PR as optimising environmental conditions will inevitably lead to an improved chance of new records adding to the legacy of the event.

Finally, with over half the world’s population currently live in urban areas, the majority of whom are under air quality conditions that exceed the World Health Organisation’s guidelines, consideration of not only elite athletic event locations and timings but also recreational exercisers should be considered (Hewitt *et al*., 2020; Marmett *et al*., 2020). Prior to the COVID-19 pandemic, participation at parkrun events (weekly, timed 5000m running events) and mass participation runs across a variety of distances were incredibly popular (Scott, 2021; Yankelson *et al*., 2014): parkrun reached over six million registered runners in 2019, Helou *et al*. (2012) showed that marathon entries increased over a ten year period and Brocherie *et al*. (2015) also found a 26% increase in the American running population between 2007 and 2012 (Parveen, 2019). This has the potential for a greater number of people being exposed to harmful pollution levels, putting greater strain on population health, associated health services and productivity (Kumbhakar et al., 2021). This highlights the need for additional research into the effect of air pollution and meteorology on athletic performance and health, as well as the best methods to mitigate detrimental outcomes at local and international sporting events and during recreational exercise.

4.5. Conclusions

Following on from previous research into marathon studies and examination of parkrun events, this research has looked to examine the influence of meteorology and air quality on elite 5 km running performance at Diamond League events. Although analysis results vary across event locations, the influence of meteorological parameters correlates well with previous research and suggests that they are the most influential on elite athletic performance. Of pollutants, O_3 and particulate matter appear to be the greatest influencers on performance, with NO_2 seeing improved finishing times. This correlates with previous research and is likely linked to the relationship between these two pollutants, sunlight (temperature) and VOCs. Although specifically aimed at elite athletes, this study helps support research in the air quality and physical activity field, as well as providing insights into the timing of events for both elite and recreational athletes to best minimise potentially detrimental impacts on athletic performance as well health related effects of air pollution.

Chapter 5 - Great Expectations: Does local meteorology and air quality influence half marathon performance at the Great North Run?

5.1. Introduction and Background

As has been shown in chapters three and four, the influence of air quality and meteorology on athletic performance during 5000 m events can be significant, especially with regards to meteorological variables. At parkrun, increased temperatures and wind speeds are most likely to influence running performances with O_3 occasionally also being detrimental. Similarly, elite athletes at the Diamond League series are detrimentally influenced by temperature, wind speed, O_3 and PM pollution. These results are also supported by the analysis which includes multiple event locations that have varied meteorological and atmospheric conditions.

To further explore the influence of the environmental variables on athletic performance, this chapter examines the Great North Run: a yearly half marathon (13.1 miles/21.1 kilometres) event held in Newcastle Upon Tyne, England, during September. Since its inception in 1981, the Great North Run has become a highly popular event for both recreational and elite male and female athletes, earning the title of the 'largest half marathon' in the world in 2014 (Guinness World Records, 2021). The often warm weather experienced in September (even in Newcastle!) is known to affect athletes. Previous studies of the Great North Run have also shown that heat stroke has been commonly reported at the event, with four participants having the condition listed as their suspected cause of death in 2005 (BBC, 2005; Hawes *et al.*, 2010; Yankelson *et al.*, 2014). Adverse meteorological conditions have also been shown to seriously affect elite athletes; Jonathon Brownlee and Callum Hawkins both collapsed at the World Triathlon Grand Final and

Commonwealth Games marathon respectively whilst a third of the 2019 Marathon World Championships field failed to finish in Doha due to the extremely high (>40^{o}C), albeit expected, temperatures (BBC Sport, 2016; 2018).

Despite previous research that has generally focussed on marathon events, Schwabe *et al.* (2014) found that the risk of serious medical incidents were as common in half marathon events as full- and ultra-marathon events. Examination of the Gothenburg half marathon in Sweden has also shown that as temperatures increase, particularly from 15^{o}C and above, the number of medical emergencies and 'did not finish' participants increased (Carlstrom *et al.*, 2019; Khorram-Manesh *et al.*, 2020; Luning *et al*., 2019). This is corroborated by Hostler *et al*. (2014) who found 39 cases of heat-related incidents at the 2011-2013 Pittsburgh combined half and full marathon event. Hostler *et al*. (2014) noted that more incidents occurred after the half marathon route was changed and resulted in increased sun exposure. D'ulisse (2019) also reported 24 incidents of heat-related illness during the 2017 Montreal half marathon held under heatwave conditions. Half marathon running pace under hot and humid conditions have also been shown to decrease when core body temperatures reach 39^{o}C between the 6 and 9 km mark of events (Rodrigues Junior *et al*., 2020). These factors, coupled with increasing temperatures and concerns regarding the potentially detrimental effects of air quality and meteorology on health and performance mean that further examination of participants responses to such variables is required (Miller-Rushing *et al.*, 2012; Morici *et al.*, 2020). Most previous research has either focused separately on either elite or recreational runners over either 5000 m or marathon distances (Helou *et al.*, 2012). Therefore, this examination of the Great North Run provides a novel environment to examine how both elite and recreational athletes respond to variations in air quality and meteorology at the same event.

5.2. Data and Methodology

Finishing times for the Great North Run were extracted for 2006-2019 inclusively from the events data archive. This included the entire male and female elite fields and the quickest and slowest amateur participants. The fastest and slowest amateur participants were estimated by taking the first 150 and last 150 male and female amateur finisher's times taken from the Great North Run website. This gave three specific groups of finishers to examine and unlike previous studies which have utilised the first or top three finishers only, provides a wider-ranging view as to the potential effects meteorology and air quality may have on participants.

Utilising the quickest finishers in the amateur field will provide a good comparison between elite and amateur athletes and whether there are any differences between their respective finishing times in response to meteorology or air quality. There is also an increased likelihood that these amateurs will have higher volume training regimes as part of athletics clubs. Increased exercise levels have been shown to increase the minute ventilation rate and pollution exposure compared to more sedentary activities (Giles and Koehle, 2014; Pasqua *et al.*, 2018). Therefore, these 'first' finishers are potentially more likely to be working at a higher percentage of their VO_2 max and consequently have a higher uptake of air and thus pollution which may influence their performance. The slowest finisher's times were also examined to explore the argument that meteorology and air quality influences slower participants more. This is most likely due to reduced training and physiological capacity and conditioning, and increased exposure to external variables (Ely *et al.*, 2007; Vihma, 2010).

Consequently, the following hypotheses for this study were formulated:

1. All athletic groups show performance decreases under more adverse meteorological and air quality conditions.
2. Elite athletes show a greater performance decrease than amateur athletes.
3. Meteorological variables will have a greater influence on performance compared to air quality variables.

Air quality data was extracted from the only Department for Environment, Food and Rural Affairs (DEFRA) Automatic Urban and Rural Network (AURN) urban background monitoring station located in Newcastle centre (Figure 5.1). This provided hourly readings for O_3, NO_2 and $PM_{2.5}$. Hourly meteorology data for temperature, relative humidity and wind speed was obtained through the worldmet package in R (Carslaw, 2018) from the site located North West of the city at Newcastle International Airport (Figure 5.1). Like the air quality monitoring station, this was the only available monitoring station to access local meteorology data from. Additionally, heat index, the combined influence of temperature and relative humidity, was calculated using the weathermetrics package in R Studio (Anderson *et al.*, 2013). This uses equations created by the National Weather Service (Equation 5.1 – where T = temperature in °F and rh is relative humidity in %). This method of calculation has been shown to provide the most accurate values in a study of 21 algorithms by Anderson *et al.* (2013).

$$
\begin{aligned}
\text{Heat Index} = {} & -42.379 + (2.04901523 \times T) + (10.14333127 \times rh) \\
& - (0.22475541 \times T \times rh) - (6.83783 \times 10^{-3} \times T^{2}) \\
& - (5.481717 \times 10^{-2} \times rh^{2}) + (1.22874 \text{ x } 10^{-3} \text{ x } T^{2} \text{ x } rh) \\
& + (8.5282 \times 10^{-4} \text{ x } T \text{ x } rh^{2}) - (1.99 \text{ x } 10^{-6} \text{ x } T^{2} \text{ x } rh^{2})
\end{aligned}
\qquad \text{(Equation 5.1)}
$$

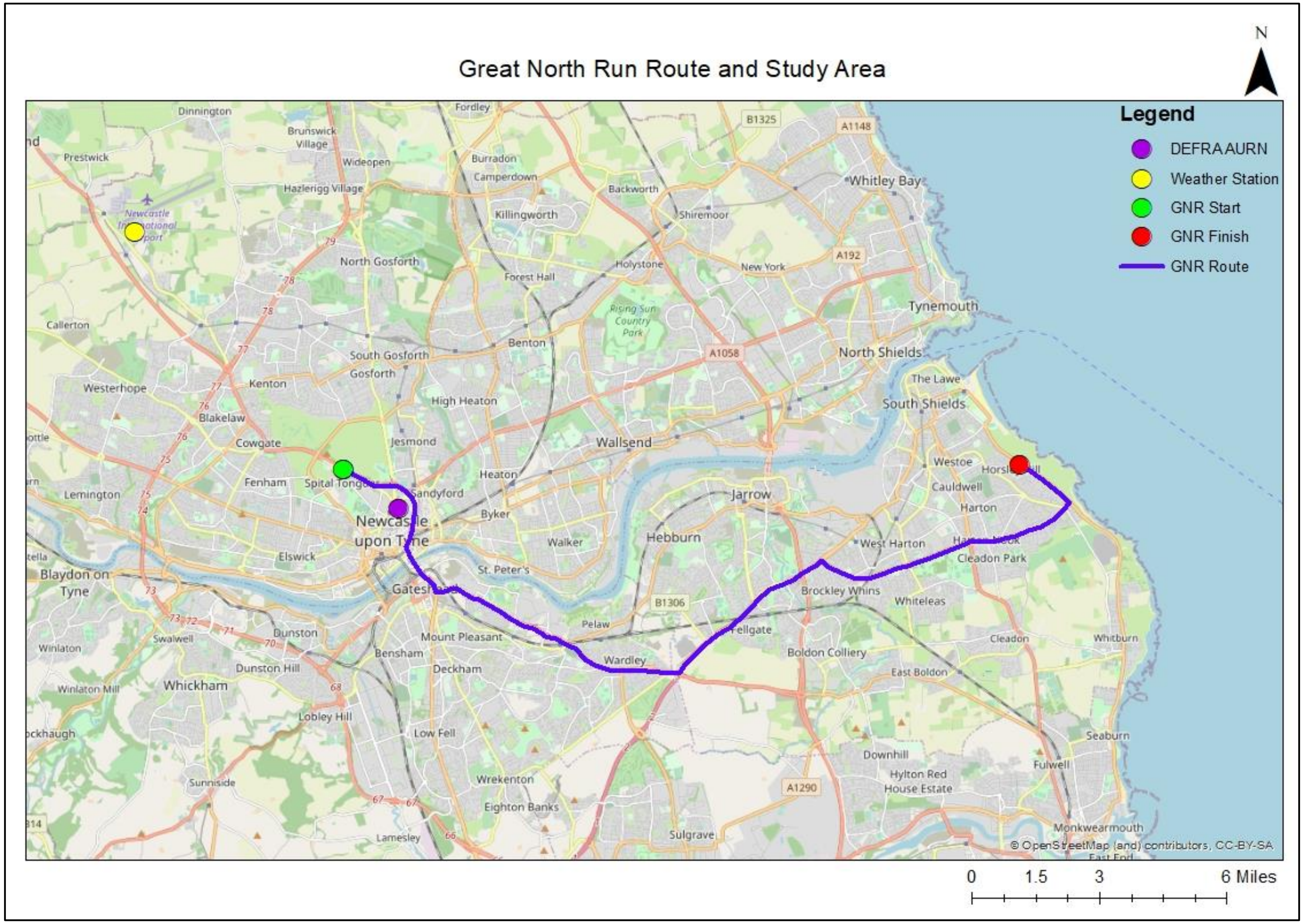


Figure 5.1. The Great North Run Route from central Newcastle to the eastern coast. The DEFRA AURN monitoring site is located in the city centre whilst the meteorology monitoring station is in the North West at Newcastle International Airport.

The air quality and meteorology monitoring stations used in this study both provide point sources of data, whilst the Great North Run route in Figure 5.1 covers a wider spatial area, with sections of the route coastal in nature and potentially exposed to different meteorological conditions. For example, studies have shown that the land-sea breeze can influence air quality and meteorology of coastal areas (Bagtasa and Yuan, 2020; Park and Chae, 2018). Thermal contrasts between the land and water temperatures can induce a stronger land-sea breeze that will disperse pollution, particularly $PM_{2.5}$ and PM_{10}, whilst weaker land-sea breezes can result in pollutant accumulation in coastal areas (Bagtasa and Yuan, 2020; Igel *et al*., 2017; Papanastasiou and Melas, 2008; Rafiq *et al*., 2020; Tsai *et al*., 2011). Furthermore, Li *et al*. (2020), Papanastasiou and Melas (2008) and Zhang *et al*. (2020) also showed that O_3 concentrations can be greatly increased along coastal areas by sea breezes. In addition to these pollution effects, land-sea breezes can lower land surface temperatures and increase the recorded wind speeds on land (Baur, 2020; Park and Chae, 2018; Yamamoto and Ishikawa, 2020).

The ‘ozone paradox’ discussed in chapter one may also have an influence as the route moves from the city centre through more rural locations to the east coast. Previously, however, similar research has also adopted this single measurement site for data acquisition; and although air pollution and meteorology can be spatially variable, the measurements utilised will be indicative of local values and conditions faced by participants (Helou *et al.*, 2012; Marr and Ely, 2010; Vihma, 2010). Furthermore, it is the most representative and best data available for the area on the race days. This is enhanced by the fact that the monitoring locations and Great North Run route is consistent across the study period.

Other confounding factors that are hard to account for are similar to those mentioned in the previous chapters: individual athlete's training state and acclimitisation to environmental conditions may influence performances, as would damp underfoot conditions and shoewear choices as carbon-plated shoes become more prevalent outside of elite fields.

The mean finishing time for male and female participants combined, as well as both for individual gender subsets, was calculated for the elite and amateur fields respectively. The mean air quality and meteorological variables between 10:00 and 12:00 hours inclusive and 10:00-15:00 hours inclusive was also calculated. These time periods used cover the designated Great North Run start time for the elite and amateur fields as well as the length of time participants whose results are used in this study would be running for. This was to provide as much explanatory variability as possible during the participant's time on course, something that has been highlighted previously as a limitation in studies which only use a single mean value (Cheuvront and Haymes, 2001; Maughan, 2010).

Prior to analysis, all data was checked for normality and homogeneity through skewness, kurtosis and Shaprio-Wilks and Levene's tests and was logged where necessary due to data not being normally distributed. Outliers detected by the boxplot '$out" function in r for the elite finishers were also removed. Similarly to Helou *et al*. (2012), Marr and Ely (2010), Trapasso and Cooper (1989) and Vihma (2010), analysis was performed through correlation, linear regression and two multiple linear regression models, one for the meteorology variables and one for the air quality variables. Meteorology and air quality variables were not included in the same multiple linear regression model due to the risk of multicollinearity, in particular between temperature, NO_2 and O_3. Post-test analysis was performed using diagnostic tests; Quantile-Quantile, Scale-Location, Fitted vs Residuals and Cooks-Distance plots. Variable inflation factors (VIFs) were also checked post-test for the multiple linear regression models to ensure that they were below the threshold of 3.

Further correlation and linear regression analysis was also performed between the temperature, heat index, O_3 and NO_2 variables to further determine the relationships between them during the Great North Run and the potential influence they may have on performances. This is because it is inherently difficult to fully extract the influence of one of these variables on participants due to their interactions (Helou *et al.*, 2012). As O_3, temperature and nitrogen oxides (nitric oxide (NO) and NO_2) are related through the Leighton reactions (chapter 1), analysis was performed between the variables (temperature, heat index, O_3 and NO_2) showing a significant effect on performance (Clapp and Jenkin, 2001; Leighton, 1961).

To determine whether there was a difference between elite, fastest amateur and slowest amateur finishing times and the associated meteorological and air quality variables the athletes were exposed to, descriptive statistics and a one-way ANOVA with suitable post-hoc tests were performed. This was designed to better account for the increased time the slowest participants took to complete the half marathon in comparison to the elite and quickest amateur participants. Correspondingly, the explanatory variable period used for analysis was increased. This allows for the examination of the debate surrounding whether air pollution and/or meteorology influences the quickest or slowest athletes the most.

Finally, the influence of wind direction needs to be taken into account due to the start and finish points of the event being located in different places. The dominant wind directions are between south-southwest and west-northwest (Table 5.1). Due to the shallow ‘v’ shape of the course these winds would be slight tail or cross-tail wind. There are no dominant easterly winds that would be a headwind and potentially slow events. Consequently, as all wind directions during the study period would show some form of benefit and no real hindrance like an easterly wind, analysing them together and not in smaller groups is appropriate.

Table 5.1. Wind direction during Great North Run events. Direction is in degrees.

Event Year	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Time														
10:00	190	No data	280	280	190	290	225	205	295	170	215	199	246	265
11:00	227	180	306	285	180	306	220	215	315	177	220	190	260	280
12:00	178	200	360	270	330	331	225	210	330	180	190	210	260	260
13:00	174	No data	5	275	275	4	220	195	313	175	200	205	255	248
14:00	176	293	20	275	270	350	220	233	340	184	210	200	245	300
15:00	140	280	40	275	260	345	260	270	5	170	205	205	260	274
Main Wind Directions	SSW	S-WNW	W-NNE	W	S-NNW	WNW-N	SW	SW	NW	S	SSW	SSW	WSW	W

5.3. Results

Descriptive data is found in table 5.2, consistent age data was not available across the study period so was not included in analyses. Noticeably there is less variation in running times for the elite athletes compared to the amateur participants, with the quickest amateurs also showing less variation than the slowest entrants.

Table 5.2. The minimum, mean, maximum and standard deviation of variables examined at the Great North Run event between 2006 and 2019.

Variable	Minimum	Mean	Maximum	Standard Deviation
Elite male (s)	3536	4033	4704	253.1
Elite female (s)	3868	4670	5894	433.3
Fast amateur (male - s)	3611	4701	5061	498.89
Fast amateur (female - s)	4585	5580	6019	502.01
Slow amateur (male - s)	12512	14158	53974	1362.4
Slow amateur (female - s)	13420	14932	54789	2049.94
Temperature (elite and fast amateur – °C)	9.7	14.3	17.8	2.0
Temperature (slow amateur – °C)	10.8	15.1	17.8	1.7
Relative Humidity (elite and fast amateur- %)	60.0	73.6	97.9	10.3
Relative Humidity (slow amateur – %)	55.2	70.3	97.9	10.4
Wind Speed (elite and fast amateur – ms^{-1})	0.4	3.8	8.3	2.2
Wind Speed (slow amateur – ms^{-1})	0.4	4.2	8.8	2.2
Heat Index (elite and fast amateur – °C)	8.0	14.0	18.0	2.4
Heat Index (slow amateur – °C)	10.0	14.6	17.0	1.8
O_3 (elite and fast amateur – ugm^{-3})	20.7	40.3	87.0	11.5
O_3 (slow amateur – ugm^{-3})	17.0	39.4	87.0	9.9
NO_2 (elite and fast amateur – ugm^{-3})	15.9	22.4	29.0	3.5
NO_2 (slow amateur – ugm^{-3})	17.1	27.3	56.2	11.3
$PM_{2.5}$ (elite and fast amateur – ugm^{-3})	3.5	7.2	11.7	3.3
$PM_{2.5}$ (slow amateur – ugm^{-3})	2.7	7.8	14.4	4.1

5.3.1. Elite Athletes

For elite athletes, male finishing times ranged from 0:59:07 to 1:18:24 h:m:s across the study period, with female times between 1:04:28 and 1:38:14 h:m:s. This was after outliers were removed as explained in section 5.2. Data and Methodology. Correlation and linear regression analysis between the mean combined male and female finishing times each year and the corresponding explanatory variables showed that O_3 had a slowing effect (coefficient=269.5, R^2=0.28, p=0.04). This was also repeated for the female elite subset (coefficient=470.4, R^2=0.47, p=<0.01). Interestingly for the male subset, multiple linear regression suggests that O_3 and $PM_{2.5}$ slightly improved performances (p=<0.04).

5.3.2. Fastest Amateurs

For the quickest finishing amateur participants, male finishing times ranged from 1:00:11 to 1:24:21 h:m:s, and female times from 1:16:23 to 1:40:25 h:m:s (thus showing some overlap with the elite athletes). However, the median and mean finishing times of elite athletes as one would expect is considerably quicker, and was shown to be significantly so through the use of a Kruskal-Wallace and subsequent Dunn test (p=<0.01). This same test also confirmed that statistically the slowest amateur finishing times were significantly different to the quickest amateurs and the elite athletes (p=<0.01).

Similarly to the results for the elite athletes, analysis for the combined male and female data showed no significant nor close to significant results for the quickest amateurs to the air quality variables. Interestingly, for the male subset close to significant relationships were highlighted by the multiple linear regression for O_3 (coefficient=-0.06, p=<0.01) and $PM_{2.5}$ (-0.001, p=0.05, R^2=0.87). However, upon closer inspection with post-hoc tests, the variable inflation factors (VIFs) were not within the accepted boundaries of 3 and subsequent multiple linear regression tests with O_3 and NO_2, O_3 and $PM_{2.5}$ and NO_2 and $PM_{2.5}$ that did satisfy the VIFs conditions showed no significant relationships. The female subset analysis did not show any significant nor close to significant results, including those for the effect of O_3 and $PM_{2.5}$.

5.3.3. Slowest Amateurs

The slowest finishers, unlike their quicker counterparts, showed a number of significant relationships between finishing times and the local meteorology and air quality variables. For the combined male and female results, correlation analysis showed that increased temperatures and O_3 concentrations contributed to slower performances ($p=<0.01$), whilst increased levels of NO_2 improved results ($p=0.02$). Correlation analysis showed tht heat index was close to being significantly detrimental ($p=0.11$). These results were all supported via linear regression with heat index also being significant with this analysis ($p=<0.04$). To determine the relationships between temperature, heat index, O_3 and NO_2, analysis was also performed for those three variables. Both temperature and heat index were significantly related to O_3 levels ($p=<0.05$), which was also shown for temperature and O_3 in relation to NO_2 ($p=<0.07$). Details of all the significant results are shown in Table 5.3 and provides an insight into how run times can be expected to increase or decrease with a corresponding change in the explanatory variable. The multiple linear regression model for meteorology also showed that increased temperatures slowed performances (coefficient=201.61, $R^2=0.37$, $p=0.01$), whilst no significant results were found for the air quality model.

Table 5.3. Significant linear regression analysis results for the combined slowest male and female finishing times and corresponding explanatory variables.

Variable (vs run time unless stated)	**Intercept**	**Coefficient**	**Standard Error**	**R^2 value**	**p value**
Temperature	11377.75	209.43	65.82	0.41	<0.01
Heat Index	11813.39	187.47	59.59	0.42	<0.01
O_3	13042.93	37.27	11.58	0.44	0.01
NO_2	17596.5	-2185.5	932.2	0.3	0.04
Temperature vs O_3	-15.215	3.62	1.36	0.34	0.02
Heat Index vs O_3	10.09	0.11	0.04	0.27	0.03
Temperature vs NO_2	23.81	-6.23	3.11	0.22	0.07
O_3 vs NO_2	127.66	-62.54	8.58	0.83	<0.01

Analysis of the male subset mirrored the overall results, with temperature, heat index and O_3 showing detrimental relationships and quicker times being recorded under higher NO_2 levels for correlation ($p=<0.04$). The same results were shown for the linear regression analysis ($p=<0.01$, NO_2 $p=0.06$). Temperature and heat index was also significantly related to O_3 levels ($p=<0.04$) with all significant results shown in Table 5.4. Multiple linear regression only had one significant result, with temperature being positively related to finishing times (coefficient=180.55, $R^2=0.4$, $p=0.02$).

Table 5.4. Significant linear regression analysis results for the slowest male finishing times and corresponding explanatory variables.

Variable (vs run time unless stated)	**Intercept**	**Coefficient**	**Standard Error**	**R^2 value**	**p value**
Temperature	11225.43	191.77	63.82	0.4	0.01
Heat Index	11706.02	167.14	59.04	0.37	0.01
O_3	12747.55	34.63	10.9	0.43	<0.01
Temperature vs O_3	-15.22	3.62	1.36	0.34	0.02
Heat Index vs O_3	-4.98	3.05	1.27	0.29	0.03
Temperature vs NO_2	24.17	-6.23	2.88	0.27	0.05
O_3 vs NO_2	125.27	-62.54	8.13	0.83	<0.01

Finally, female analysis of the slowest finishers also mirrored that of the male and overall subsets. Temperature, heat index and O_3 all showed positive correlations and linear relationships with finishing times (p=<0.03) whilst NO_2 again showed a negative relationship for correlation and linear regression (p=<0.05, Table 5.5). Multiple linear regression also showed temperature to be detrimental to performance (coefficient=222.67, R^2=0.26, p=0.03) whilst temperature and heat index were also positively related to O_3 levels (p=<0.05).

Table 5.5. Significant linear regression analysis results for the slowest female finishing times and corresponding explanatory variables.

Variable (vs run time unless stated)	**Intercept**	**Coefficient**	**Standard Error**	**R^2 value**	**p value**
Temperature	11557.2	227.09	80.01	0.36	0.01
Heat Index	11932.96	207.80	70.94	0.38	0.01
O_3	13346.1	40.44	14.2	0.37	0.02
NO_2	18285	-2399	1006	0.29	0.04
Temperature vs O_3	-15.22	3.61	1.36	0.32	0.03
Heat Index vs O_3	-4.98	3.04	1.27	0.32	0.03
Temperature vs NO_2	24.17	-6.46	2.88	0.25	0.05
O_3 vs NO_2	125.27	-62.54	8.13	0.83	<0.01

Interestingly, it appears that the slowest female participants may be slightly less influenced by detrimental variables, with temperature and O_3 explaining slightly less of the variance in their finishing times compared to their male counterparts. Figures 5.2 and 5.3 below show the relationships between these variables, heat index and NO_2 for the male and female subsets.

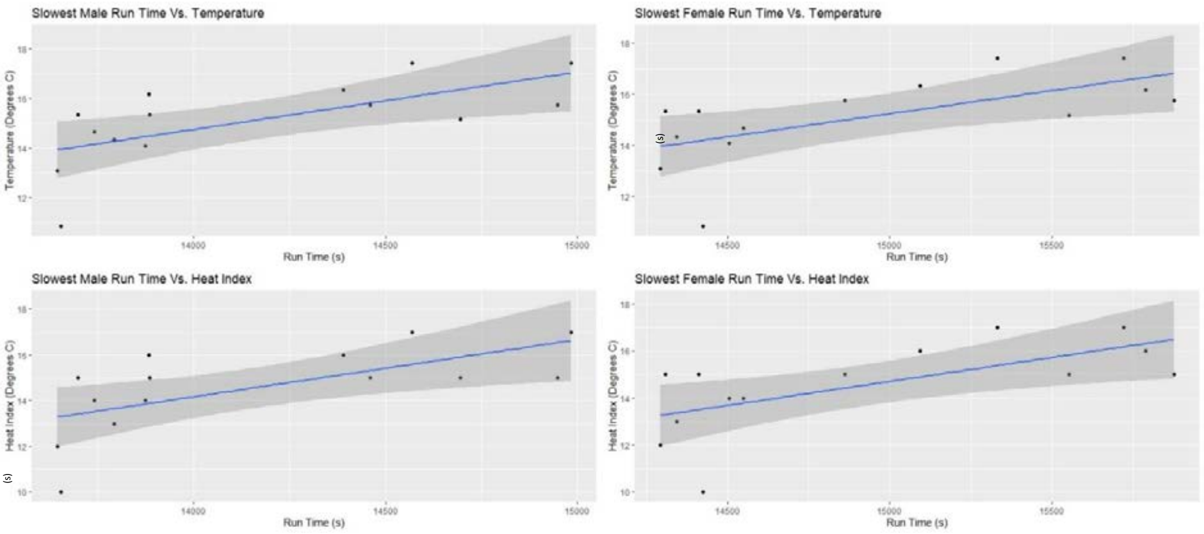


Figure 5.2. The influence of temperature (top) and heat index (bottom) on male and female subsets (left and right respectively) at the Great North Run.

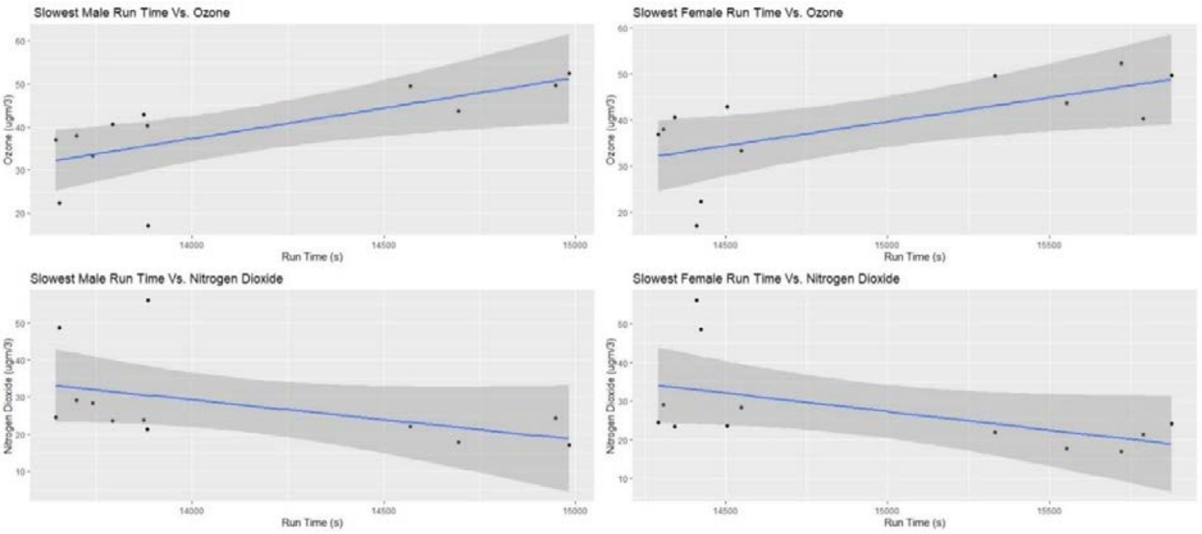


Figure 5.3. The influence of O_3 (top) and NO_2 (bottom) on male and female subsets (left and right respectively) at the Great North Run.

5.3.4. Finishing ‘Group’ Differences

To determine whether the significant results shown by the slowest amateur participants was due to differences in the air quality and meteorological conditions they experienced over a long time period on the half marathon route, analysis between the 10:00-12:00 and 10:00-15:00 data was performed. Despite descriptive statistics showing, on average, slightly warmer, windier and more polluted conditions for the 10:00-15:00 data period, results showed that there were no significant differences between the conditions experienced by the fastest and slowest finishers of the Great North Run (p=>0.05). As has been previously highlighted, there were significant differences between the finishing times of all three groups (p=<0.01). This, and the slightly more ‘adverse’ conditions faced by the slowest amateurs are shown in Figure 5.4.

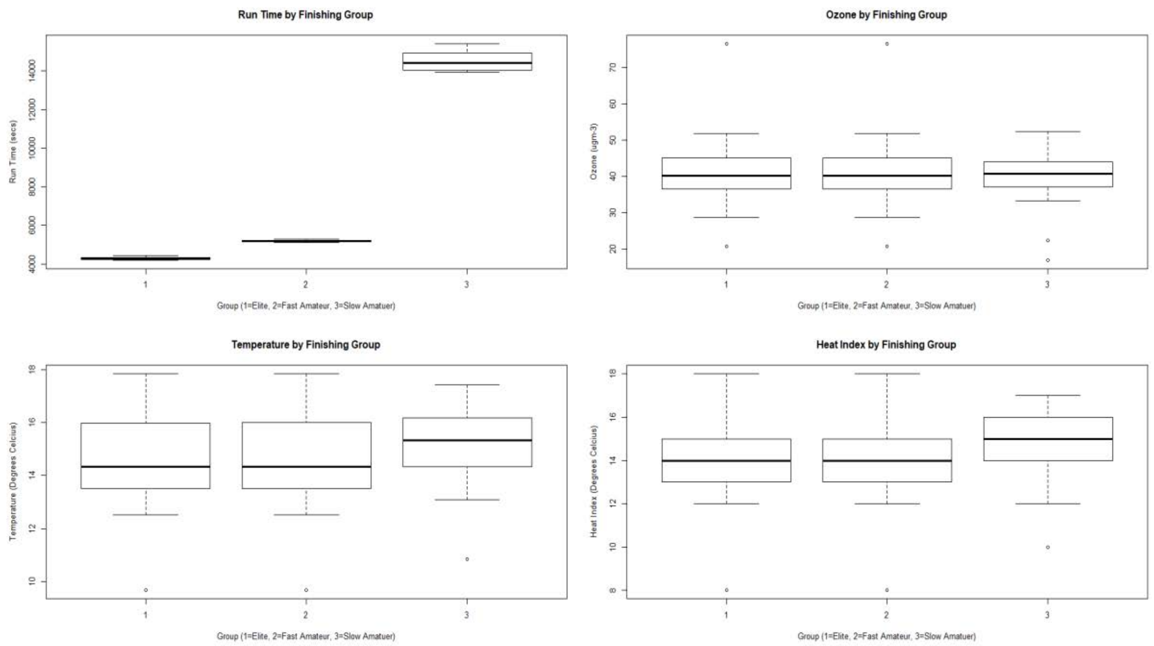


Figure 5.4. From left to right, top to bottom: Variations in the mean finishing time, O_3, temperature and heat index measurements experience by the elite, quickest amateur and slowest amateur participants at the Great North Run across the study period of 2006-2019. The elite and fastest amateur ozone, temperature and heat index measurements are the same as highlighted in the methods section.

5.4. Discussion

This study has provided a novel opportunity to examine the influence of meteorology and air quality on both amateur and elite participants at the Great North Run, following the same course at the same time. Results suggest that the elite female athletes are detrimentally impacted by increased O_3 levels, whilst male elites are not. This reflects the results of the Diamond League athletics series examined in Chapter 4 which showed female athletes to be more susceptible to the effects of air pollution, temperature and wind speeds. The cause of this influence on specifically female athletes is currently unknown and has also been previously been highlighted by Helou *et al*. (2012). In contrast, however, the elite male and the quickest amateur participants are not significantly influenced in terms of their finishing time by the meteorological or air quality conditions found on the event day. Despite this, anecdotally and from laboratory tests, the local conditions may have caused an increase in perceived exertion and an irritant response of the eyes and respiratory system, but not to an extent that would be shown in the finishing times (Florida-James *et al.*, 2011; Giles *et al.*, 2014; 2018; Kargarfard *et al.*, 2015). Furthermore, the work of Helou *et al.* (2012) and Marr and Ely (2010) showed no effects of $PM_{2.5}$ on marathon performances, as has been demonstrated in this study.

Particularly for the elite participants, a lack of significant relationships other than the female elites slowing under elevated O_3 concentrations may also be due to them having a higher running economy, which results in reduced energy demands and heat production and enables them to run faster for longer in adverse conditions (Conley and Krahenbuhl, 1980; Maughan, 2010; Noakes, *et al.*, 1990). This counters the theory by Gasparetto and Nesseler (2020) that although quicker runners run for the shortest period of time, they are doing so more intensely and closer to their maximal capacity, making them more likely to suffer from overheating and other performance decreases. However, the work of Ely *et al.* (2007), Montain *et al.* (2007) and Vihma (2010) all suggested that quicker runners would be influenced less. Whilst Renberg *et al.* (2014) showed that temperature ultimately had no influence on running performance despite increased heart rate and blood lactate levels being recorded. However, Gasparetto and Nesseler’s (2020) argument can be used to suggest why that, despite having physiological, psychological and genetic advantages over amateur runners, elite female athletes saw performance decreases under higher O_3

concentrations whilst the fastest amateurs did not. This may be due to elite athletes performing closer to their maximal capacity and thus more likely to be influenced by pollution and other environmental factors (Gasparetto and Nesseler, 2020). As is noted previously, why this has only been shown for female athletes is still unknown and requires further study (Chapter 4, Helou *et al*., 2012).

The influence of improved running economy can also be considered for the quickest amateur finishers, many of whom finished in a similar time to or even quicker than some of the elite field, suggesting that they too have a suitably high enough running economy to perform well in unfavourable conditions. It is also likely that the quickest and elite runners will have put in the highest amount of training prior to the event (often 150-260 km per week) which has been shown to significantly influence overall race performances (Billat *et al.*, 2001; Casado *et al.*, 2019; Enoksen *et al.*, 2011; Ferreira and Rolim, 2006; Klemm, 1989; Noakes, 1986; Tjelta *et al.*, 2014; Tjelta, 2016). This results in athlete's being more physiologically and psychologically adapted to perform well, including in warmer conditions (Hargreaves, 2008; Helou *et al.*, 2012; Kenefick *et al.*, 2007; Maughan *et al.*, 2007a; 2007b; Zouhal *et al.*, 2009). Elite athletes will also be well acclimatised to potentially warm conditions with either access to overseas training camps or originating from and training in the running 'hotbed' of Africa: East African athletes in particular are the dominant force in distance running (Baker and Horton, 2003; Hamilton, 2000; Larsen, 2003) and made up 89.5% of male and 54.5% of female marathon winners in the study by Helou *et al.* (2012). This is supported by the close bunching of the elite finishing times compared to the fastest amateurs and then in turn the slowest amateurs. There is less variation between the minimum and maximum finishing times as well as less standard deviation for the quickest groups (Figure 5.4, Table 5.1). This supports research that has shown elite and the quickest amateur runners often pace distance running races better than amateur and the slowest amateur runners respectively (Ely *et al*., 2008; Santos-Lozano *et al*., 2014; Trubee *et al*., 2014).

These reasons may, in reverse, also be contributing to the significant results shown for the slowest finishers at the Great North Run: where relationships between finishing times and temperature, heat index and O_3 levels where p=<0.02. Fitness differences relative to physiological potential will contribute to finishing time variation and the effect of external variables such as temperature on performance (Helou *et al.*, 2012; Ely *et al.*, 2007; Alvarez-Ramirez and Rodriguez, 2006; Alvrez-Ramirez *et al.*, 2007; Montain *et al.*, 2007). Slower runners are likely to be further away from their physiological potential, thus resulting in a greater influence of temperature and heat index on their performance. Sandsund *et al.* (2012) also showed that running economy decreases under increased temperatures: consequently, slower runners with reduced running economy will be further influenced as the temperature increases when compared to elite and quicker runners. Additionally, Ely *et al.* (2007; 2008), Montain *et al.* (2007) and Vihma (2010) all argued that slower runners are more vulnerable to environmental influences and will have the greatest reduction in performance, especially under high temperatures and heat indexes as they are running for longer periods and therefore are exposed more. This is supported by these findings that show temperature and heat index to be significantly related to decreased performances (p=<0.02).

Furthermore, the same can also be said as to why O_3 has a significant slowing influence on the slowest of participants. Increased exposure time would result in increased perceived exertion and cardiorespiratory irritation, especially when exercise causes increased pollution uptake (Bigazzi, 2016; Daigle *et al.*, 2003; Gibbons and Adams, 1984, Giles and Koehle, 2014; Gong Jr *et al.*, 1985). Rundell (2012) suggested that chronic exposure to pollutants would reduce lung function and increase vascular dysfunction, contributing to reduced performance. Helou *et al.* (2012) showed that O_3 was detrimental to marathon performances and both Gibbons and Adams (1984) and Gong Jr *et al.* (1985) determined that O_3 pollution would reduce workload and time to fatigue by 30% and 8% respectively. Additionally, due to events, including the Great North Run, starting in the morning, the photochemical production of O_3 will not have peaked for the elite and quickest finishers but will be increasing for slower finishers (Chimenti *et al.*, 2009; Helou *et al.*, 2012; Morici *et al.*, 2020).

The relationship between O_3, NO_2 and temperature as outlined in the methodology could suggest that the effect of O_3 on performance may be related to temperature increases (Chimenti *et al.*, 2009; Helou *et al.*, 2012; Lippi *et al.*, 2008; Shephard, 1984). However, O_3 has been shown to have a detrimental effect on general lung function and athletic performance, even when combined with high temperatures (Gibbons and Adams, 1984, Gong Jr *et al.*, 1985; Rundell, 2012). Additionally, linear regression results suggest that O_3 concentrations explain a similar or even larger proportion of the variance in finishing times than temperature and heat index, indicating that the effect of the pollutant on performances cannot be overlooked and in this case, is most likely to be detrimental to slowest of participants who are exposed for longer periods of time.

Similarly, the 'beneficial' impact of increased NO_2 levels on the slowest finisher's performances is unexpected but is also shown in chapters three and four examining amateur and elite 5000 m performances. Due to the Leighton reactions in equation 1.1 and 1.2, it could be hypothesised that higher NO_2 levels are found in cooler temperatures and these have been shown to improve performance (Helou *et al.*, 2012; Vugts, 1997). Therefore, the lower temperature is more beneficial than the subsequent increase in NO_2 is detrimental to performance (Helou *et al.*, 2012; Vugts, 1997). Furthermore, correlation and linear regression analysis between temperature and NO_2 found that there was a negative relationship between the two variables ($p=<0.07$) which would suggest that to some extent the improve times under higher NO_2 could be attributed to lower temperatures. Finally, as well as reduced temperatures contributing to quicker times under increased NO_2 levels, the effect of nitrate and related species as vasodilators, thus increasing blood flow through reduced arterial pressure, could be beneficial, although thorough laboratory examination of this theory has not been performed (Cosby *et al.*, 2003; Lim *et al.*, 2005).

Another consideration for the greater influence of temperature and heat index on the slowest finisher's performance is a propensity for slower runner's to run together in larger groups than quicker runner's, who may also be solo running (Alvarez-Ramirez and Rodriguez, 2006; Alvrez-Ramirez *et al.*, 2007; De Freitas *et al.*, 1985). In these large group dynamics, convective heat loss is more than halved compared to a solo runner, leading to increased core temperatures, perceived exertion and overall heat stress up to three times higher than a solo runner would experience under the same conditions (De Freitas *et al.*, 1985; Montain *et al.*, 2007).

Due to physiological difference between male and female participants, male finishing times across the three groups analysed were significantly quicker, as was also found by Helou *et al.* (2012). Although slight, results for the slowest finishers suggest that male participants are influenced more than female. This is especially so for temperature and O_3, the former of which is supported by Kaciuba-Uscilko and Ryszard (2001). It has been shown that thermal responses to heat and heat loss, including during exercise, differ between the genders, with core temperature control being greater for women due to a larger surface area to mass ratio, higher subcutaneous fat content and potentially lower exercise capacity (Gagnon *et al.*, 2009; Kaciuba-Uscilko and Ryszard, 2001). Furthermore, body mass is generally lower for females compared to males due to physiological differences in stature, musculature and body fat percentages: with lower mass being shown to be advantageous for running under increased temperatures (Marino *et al.*, 2000; Zouhal *et al.*, 2011). Billat *et al.* (2001) also found that male marathon runners had a lower running economy than their female counterparts, which would lead to increased heat production and more pronounced performance decreases over time.

Variation in wind speeds in this study did not show any significant relationships. Although some research has suggested that increased wind speeds can slow performance in terms of a head wind and improve performance as a tail wind, its influence is difficult to quantify due to multiple variations in speed and direction during real world events (Davies, 1980; Knechtle *et al.*, 2019; Vihma, 2010). This is especially so for an event such as the Great North Run which over the course of 21.1 km has multiple changes in direction and variability in building density alongside the route. Consequently, there would be variation in wind parameters over the event duration that would not be represented in neither the results nor the data captured for analysis (Cheuvront and Haymes, 2001; Maughan, 2010). Data has shown that across study years, the majority of wind directions encountered has been a cross-tail wind and to capture more detail on this and variations could be overcome through the use of additional monitoring sites at strategic locations alongside the route.

Although identified by Bigazzi (2016) as the second most influential variable that could influence athletic performance due to limited heat dissipation, relationships between relative humidity and finishing times of the Great North Run were not found. This may be due to the amateur group's exercise intensity and/or relative humidity levels not being consistently high enough to elicit excess heat production and also limit heat dissipation. In contrast, for the overall elite field and female subsets, positive relationships were found at close to significant p-values (p=0.1 and p=0.07 respectively). This slightly more detrimental impact on elite female finishing times may be due to their increased exercise intensity and thus higher heat production compared to amateur participants which cannot be dissipated as easily under the higher relative humidity (Casa, 1999; Cheuvront and Haymes, 2001; Gasparetto and Nesseler, 2020; Helou *et al.*, 2012; Nadel, 1990). This result has also been demonstrated in chapter 3 which showed that female parkrun participants displayed greater decreases in performance compared to male. As the influence is statistically more noticeable for elite women, this is likely because of reduced sweat rates compared to their male counterparts as detailed by Kaciuba-Uscilko and Ryszard (2001).

As a result of these findings, the following hypothesis deductions can be made; hypothesis 1 is rejected as not all athletic groups showed performance decreases under more adverse environmental conditions; hypothesis 2 is also rejected as the slowest amateur participants showed larger and more significant relationships with air quality and meteorology changes; and finally hypothesis 3 is accepted as, particularly for the slowest amateurs, meteorology has a greater influence that air quality on their finishing times.

5.5. Conclusions

The effect of urban air quality on human health is a major concern, and with the need to increase global activity levels, the effect of pollution on the growing number of athletic event entrants needs to be examined. This is also required for elite athletes with concerns over their safety being raised at previous and future Olympic venues, and several notable medical incidents in recent years being attributed to adverse meteorological conditions (BBC Sport, 2016; 2018; 2019; Bloom, 2019; De La Cruz *et al.*, 2019; Donnelly *et al.*, 2016; Florida-James *et al.*, 2011; Kosaka *et al.*, 2018; Wang *et al.*, 2009). With climate change predictions suggesting that mean and extreme temperatures will increase, this will have a knock-on effect on physical activity in general, event performances and increase the risk of heat stress related medical incidents (Hawes *et al.*, 2010; Maloney and Forbes, 2011; Miller-Rushing *et al.*, 2012; Yankelson *et al.*, 2014).

This study has built on previous research examining the effect of meteorology and air quality on marathon and 5000 m athletic performances, highlighting the difference in effect the two variable groups have on elite, first amateur finishers and the last amateur finishers. Most notably, increased temperatures and heat index slow the performance of the slowest finishers, which is not corroborated by the elite and first amateur groups. Increased O_3 levels are detrimental to the slowest participant group and the elite female athletes, although ozone concentrations are correlated with temperature. However, results and previous research suggest that O_3 cannot be discounted as an influencing variable on Great North Run performances (Gibbons and Adams, 1984, Gong Jr *et al.*, 1985; Rundell, 2012). NO_2 has been linked to improved performances, although again this is likely in relation to lower air temperatures. Finally, no significant relationships were found between finishing times, relative humidity, wind speed and $PM_{2.5}$ for any of the participant groups.

This research has also provided additional insight into half marathon studies, which have included the Great North Run, and other endurance events which have reported increased heat stress incidents for participants by detailing the effect of increased temperatures and heat index on the slowest participants in particular due to increased exposure times (Ely *et al.*, 2007; Ely *et al.*, 2008; Montain *et al.*, 2007; Vihma, 2010). This will prove highly beneficial to future event organisers when planning event start times, as has been seen with the Rio and Tokyo Olympics, as well as 'do not start' temperatures and highlighting which participants may be more likely to require medical aid (Kosaka *et al.*, 2018; William, 2007; William, 2010). It also highlights the need for additional meteorological and air quality monitoring in urban and rural areas: where events move between urban, rural and coastal locations extra monitoring sites will be needed to capture variation between these areas.

Chapter 6 – Critique, Limitations, Future Work and Recommendations

This chapter examines the results shown in the previous chapters between athletic performance and local meteorological and air quality conditions, examining how future research could develop the findings shown through field research and sensor development potential.

6.1. Introduction

As has been shown in the previous chapters covering parkrun, the Diamond League athletics series and the Great North Run, the influence of meteorological extremes has generally been shown to be detrimental to performance, especially temperature. Air quality, due to in part to its spatial variability and the difficulty in solely isolating the effect of one airborne pollutant out of a selection, is harder to decisively determine. However, results have shown that O_3 in particular is broadly detrimental to performances, whilst PMs influence is variable and NO_2 has been associated with quicker performances. The former and latter results are potentially associated with temperature variations and require further validation with regards to their concentration levels at athletic events. This also holds true with PM variations along with the influence meteorology and air quality has on spectators, who, albeit likely breathing at a slower rate than athletes, are still exposed to the same pollution, in addition to participants/athletes.

6.2. Data Difficulties at parkrun and public exercise events

Although parkrun and increased provision of green space and public bike access could be an effective solution to improve activity levels, the influence air quality and meteorology on health needs to be considered: especially when climate change predictions show increased numbers of non-activity days and the cost:benefit ratio of exercising in poor air quality is variable (Miller-Rushing *et al.*, 2012; Pasqua *et al.*, 2018, Tainio *et al.*, 2016). The negative effects of air quality could outweigh the benefits of exercise in worst case scenarios, especially for those in vulnerable groups (Andersen *et al.*, 2015; Pasqua *et al.*, 2018; Tainio *et al.*, 2016). Research into the level of pollution exercisers are exposed to whilst taking part in popular, global activities such as parkrun would be highly beneficial to accurately determine potential health benefits and/or life years gained. Additionally, with increased awareness of air quality and its health effects, this is a high impact topic with a wide dissemination potential. Additionally, knowledge of how air quality could affect both recreational and elite exercisers would be beneficial given past concerns over the environmental conditions at the 2008, 2016 and now 2021 Olympic Games (Donnelly *et al.*, 2016; Kosaka *et al.*, 2018; Ventura *et al.*, 2019; Wang *et al.*, 2009).

Despite the previously discussed benefits of parkrun and other mass participation events, the influence of air quality and meteorology can at times be variable both when considering field and laboratory based research shown in chapters 3-5 (Giles and Koehle, 2014). This is likely due to spatial variation in explanatory variables, coupled with the use of single point monitoring stations for data acquisition and the difficulty in isolating the effect of a single variable on performance (Cheuvront and Haymes, 2001; Helou *et al.*, 2012; Maughan, 2010). In laboratory contexts, a lack of significant results at times could be associated with the limited pollutant concentration range permitted for ethical reasons, with some studies showing that detrimental athletic impacts are shown when concentrations are increased as part of the same study (Gibbons and Adam, 1984; Gong Jr *et al.*, 1985; Morici et al 2020). Consequently, the main limitation of this research has been data availability directly at study locations. For example, the Great North Run moves through urban, rural and coastal locations, but has limited monitoring stations to capture fine-scale variations. In some regards, the results presented may be exaggerated or unexaggerated depending on the distance between study site and monitoring station, although they have provided a representative indication of the effects environmental parameters have on various athletic performances.

To overcome this limitation and to take this research to the next level, new and innovative approaches to measuring personal exposure should be considered. This would build upon the work performed in chapters 3-5, examining the relationships between air quality and athletic performances and exercise, with closer attention paid to on location monitoring and personal exposure. This would utilise traditional in-situ monitoring stations and modelled data, but also implement low cost sensors and personal exposure/wearable sensors to improve the level of detail with regards to environmental conditions directly experienced by event participants.

6.3. Monitoring and Research Options

Locating traditional monitoring stations close to sporting events/exercise locations would be a long term and costly option to try and implement: especially when some locations may not be suitable in some regard for a monitor installation (Duyzer *et al.*, 2015; Idrees and Zheng, 2020). The sheer number required would also be prohibitive. The installation of specific stations and the use of modelling from their data could be implemented in a similar vein to the CMAQ-urban model covered and used in chapter 3, but this still raises issues with regards to the monitoring data's representability and model accuracy (Amato *et al.*, 2014;

Joly and Peuch, 2012; Righini *et al.*, 2014). Currently, as has been shown in this previously documented research, monitoring stations are often less than ideally located for sports venues or exercise locations (Figure 6.1).This has also been demonstrated in chapters 3-5 with monitoring sites not being located along event routes and thus only providing local approximations of conditions rather than actual 'at event' measurements. To date, the athletics stadium in Monaco is the first venue with a monitoring station located within its grounds or close enough specifically for athlete and spectator pollution exposure (International Association of Athletics Federations, 2018). This is likely to be the best practice in the future to monitor the conditions experienced by athletes and spectators with regards to their health and safety as well as increasing the likelihood of improved athletic performances and world record attempts occurring. However, due to the cost of implementing such systems this is unlikely to be repeated on wide scale outside of elite venues and therefore provides a strong case for the use of low cost monitoring devices.

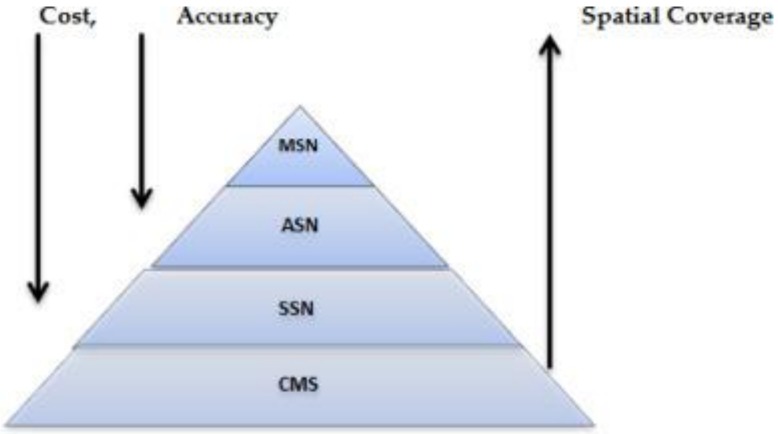


Figure 6.1. The trade-offs between the cost, data accuracy and spatial coverage of air quality monitoring stations. Key: CMS – conventional monitoring station. SSN – static sensor network. ASN – Automobile sensor network (mobile sensors). MSN – municipal sensor network (low cost sensors). Source: Idrees and Zheng, 2020.

6.3.1. Low Cost Monitoring

In terms of regularly held events that are spatially dispersed such as parkrun, the use of low cost air sensors is the most viable option to improve monitoring coverage, and thus providing a clearer indication of the pollution people are exposed to, both within the context of the proposed future research but also in general for higher resolution background air quality monitoring at a reduced cost. Furthermore, although air quality levels have generally been below guidance thresholds within the previous studies, there may be occasions and locations where higher levels are reached and not necessarily detected by traditional monitoring stations currently installed. Therefore, determination of these, if located at or close to study sites, through low cost monitors would be of benefit in terms of exposure for exercisers and the wider public. Finally, the new World Health Organisation Guidelines for Air Quality (released 22nd September 2021) have lowered NO_2 and $PM_{2.5}$ levels to 10 and 5 ugm^{-3} respecitvely – values which are now exceeded much more regularly both within the previous studies and future ones.

Over the last decade low-cost sensor technology has improved considerably, making them highly portable, low maintenance and able to provide near real-time continuous monitoring (Chojer *et al.*, 2020, Morawska *et al.*, 2018). This would make them ideal for gathering 'at event' data for analysis: either along the entire route at events such as parkrun or centrally located. As parkrun events generally take place on public land and are community organised and led, the implementation of such monitors would merge well with the organisations values and not be prohibitive to their implementation and upkeep. Finally, for larger and less regular events such as the Great North Run, a mixture of already installed traditional monitoring stations and specifically located low cost monitors would be of benefit. Traditional stations would allow for accurate data collection at key parts of the event that would be supported by the low cost sensors in hard to access locations as well as providing validation of concentration interpolations or modelling that may be performed after the event.

The use of low cost electrochemical gas sensors with appropriate calibration and data processing would allow for detection of O_3 and NO_2 levels (Castell *et al.*, 2017; Idrees and Zheng, 2020; Lewis and Edwards, 2016; Tian *et al.*, 2016). These have been shown to provide accurate monitoring data across a useable range of concentrations, but are obviously not as reliable as traditional monitoring stations (Idrees and Zheng, 2020; Morawska *et al.*, 2018). This is due to their need of pre-installation calibration and recalibration after a period of time to prevent drift in recorded data (Borrego *et al.*, 2016; Castell *et al.*, 2017; Idrees and Zheng, 2020; Lewis and Edwards, 2016; Mead *et al.*, 2013; Schneider *et al.*, 2017).

For PM, optical particle sensors would be used to measure $PM_{2.5}$ and PM_{10} concentrations as such devices are small and provide quick sampling of a variety of particle sizes (Crilley *et al*., 2018; Idrees and Zheng, 2020; Popoola *et al.*, 2018). Care would need to be taken though to ensure that the monitors did not have cross sensitivity to other pollutants that may artificially inflate or decrease measurements (Borrego *et al.*, 2016; Castell *et al.*, 2017; Lewis and Edwards, 2016; Mead *et al.*, 2013). This is particularly so for O_3 and NO_2 levels whilst local environmental conditions can influence the readings of low cost PM monitors (Borrego *et al.*, 2016; Castell *et al.*, 2017; Idrees and Zheng, 2020; Jayarante *et al.*, 2018; Lewis and Edwards, 2016; Mead *et al.*, 2013; Schneider *et al.*, 2017). However, the monitors detailed in Table 6.1 have shown good levels of power consumption, sensitivity and life expectancy and would provide a dependable reading of local air quality levels (Idrees and Zheng, 2020). Data acquired from these sensors as well as local Department for Environment, Food and Rural Affairs Automatic Urban and Rural monitoring sites would be used alongside parkrun and other event finishing times to determine pollution exposure, health benefits and the relationship between local air quality and athletic performance.

Table 6.1. Potential low cost sensors that could be utilised to provide field measurements of ozone, nitrogen dioxide and $PM_{2.5}$ and PM_{10} levels at selected sports events. Adapted from Idrees and Zheng, 2020.

Pollutant	**Sensor Type**	**Low Cost Sensor**
Ozone	Solid-state electrochemical sensor avoiding nitrogen dioxide sensitivity	MiCS2611, MiCS2610, MQ-131
Nitrogen Dioxide	Solid-state electrochemical sensor avoiding ozone sensitivity	Mq-135, GSNT11, MiCS-2714
$PM_{2.5}$, PM_{10}	Light scattering optical analyser	Aerocet 831 Aerosol Mass Measurement Module, OPC-N2 Particle Sensor

To overcome some of the difficulties regarding low cost sensor measurements, calibration before and after sensor placement should be performed (Arfire *et al.*, 2016; Idrees and Zheng, 2020). Therefore, alongside DEFRA AURN stations and modelled data, low cost sensors would provide a highly accurate picture of the air quality at parkrun events. Additionally, they could also provide an insight into the potential benefit of green infrastructure improving local air quality. For example, the studied parks natural 'greenery' could be determined by normalised difference vegetation index to provide an indication of how 'green' each park is and allow for comparisons between study sites in such instances as well as pollution levels. This would also require monitoring directly outside the park(s), taking into account the influence of roadside emissions if required, in addition to the monitoring performed inside the park. Comparisons of 'outside' and 'inside' park air quality alongside levels of park 'greenery' would provide a beneficial insight into alterations in air quality from potentially roadside locations into green spaces and help inform future air quality mitigation schemes and the general public's exercise habits.

6.3.2. Personal Exposure Monitors

Studies under real-life conditions are now simpler because of the availability of wearable sensors that are able to reliably measure exposure at the individual level (Dons *et al.*, 2017; Morici *et al.,* 2020). The use of mobile monitoring systems on people, public transport and dedicated vehicles has increased in recent years with the development of low cost and wearable monitors, especially when combined with other wearable technology (Aberer *et al.*, 2010; Andres, 2016; Idrees and Zheng, 2020; Jiao *et al.*, 2016; Shehab *et al*., 2021; Yokoyama *et al.*, 2017). This wearable technology has also become widespread in recent years, with tracking of steps, sleep, stress levels and more being provided by a number of apps and devices (Kim and Shin, 2015; McIntyre, 2014). Consequently, this, along with increased use of at home air quality monitoring sensors, would provide an opportunity to directly determine personal exposure of parkrun or other event participants by tracking the air quality they are exposed to along the event route, with corresponding GPS data.

As has been mentioned, the use of personal fitness trackers and other wearables has also been growing, increasing public awareness of personal physical activity levels and lifestyle factors (Hattingh, 2020). However, their use as a means to increase physical activity long term is unsustainable, with use declining within weeks (Haake *et al.*, 2020). However, it has been shown that the integration of wearables and other technology with events such as parkrun informs and encourages participants to continue physical exercise both at and outside of events in the long term (Haake *et al.*, 2020; Shih *et al.*, 2015). Therefore, the use of technology should enhance physical exercise interventions rather than be central to them (Haake *et al.*, 2020).

Personal exposure monitors would also be provided to a number of participants. These latter monitors would ensure that personal exposure to air quality can be determined as well as verified by the low cost sensors around the course. This would also allow for development of the work by Wachowicz *et al*. (2019) who combined fitness tracker data with meteorological monitors to allow for greater insight into sports performance and activity levels. However, care would have to be taken with the placement of sensors around courses with regards to ethics and data safety. This could be potentially ensured by placing them within the closed road areas of the course rather than just outside with public access.

The use of wearable devices that track location, speed and heart rate (or have the capability for heart rate capturing devices to be added) would also allow for accurate calibration of personal exposure monitors carried by study participants as well as providing the ability to determine minute ventilation rates through the use of population-derived formulas, the latter of which have been improved in recent research (Cozza *et al.*, 2015; Dons *et al.*, 2017; Guo *et al.*, 2021; Nyhan et al,. 2014; Zuurbier *et al.*, 2009). Such clothing has already been developed by Liu *et al*. (2019) and Nakayoshi *et al*. (2015). Heart rate data and ventilation rate calculations would allow for a second estimation of pollution uptake of participants when coupled with the personal exposure and/or low cost sensors. Examination of the reliability and accuracy of low cost sensors and personal exposure monitors would also be performed to determine the best methods for their use in future studies. Similarly to the 2018 Commonwealth Games monitoring campaign by Kuhn *et al*. (2021) and guidelines for low-cost monitoring generated by Zimmerman (2021); this would require pre-calibration of sensors against reference instruments in both laboratory and ambient outdoor conditions prior to use as well as at least one monitor being co-located alongside a Defra monitoring station.

6.4. Event Mitigation Measures

As has been shown in Chapters 3-5, the influence of air quality and meteorology on athletic performance can be highly detrimental and lead to increased numbers of medical incidents (Hostler *et al*., 2014). This is particularly so with predicted climate change that will see temperatures increase by up to 4.8^{o}C and has already sparked a report surrounding the 2021 Tokyo Olympics risk to athlete and spectator health and the BBC examining how sport could change in 2050 (BBC Sport, 2021a; British Association for Sustainable Sport, 2021a; Intergovernmental Panel on Climate Change, 2014). The former, ‘Rings of Fire – How heat could impact the 2021 Tokyo Olympics’ focuses on how Tokyo’s climate will impact a range of sports with suggested mitigation measures whilst the BBC examines the influence climate change may have on cricket, golf, football and winter sports (BBC Sport, 2021b; British Association for Sustainable Sport, 2021a). Changes for Olympic Games include increased athlete heat acclimatisation and duty of care protection to reduce the likelihood of athletes becoming ill under hot conditions and subsequently competing; implementing cooling techniques pre- and during events, altering scheduling of events and utilising advanced technologies to monitor heat and body temperatures (British Association for Sustainable Sport, 2021a). Ultimately, it is suggested that the Olympics are carefully located geographically and seasonally to reduce the risk of environmental variables detrimentally effecting athlete’s and their performances (British Association for Sustainable Sport, 2021a).

Meanwhile, the BBC’s Sport 2050 articles are written and informed by various researchers and climate change meteorologists to provide insight into how changes may occur in the future (BBC Sport, 2021a). They are also supported by two additional British Association for Sustainable Sport Reports: ‘Hit for six – The impact of climate change on cricket’ and ‘Game Changer – How climate change is impacting sports in the UK’ (British Association for Sustainable Sport, 2021b; British Association for Sustainable Sport, 2021c). This has included night time or inside only events, restrictions on overseas fans, a loss of current snow sport venues due to receding and unreliable snowfall, fewer golf venues due to coastal erosion and monitoring of athlete physiological data in real time via their clothing (BBC Sport, 2021c; 2021d; 2021e; 2021f). To an extent, monitoring of internal core temperatures is already being trialled in preparation for the Tokyo Olympics by the Norwegian elite triathlon team to determine their body’s response under increased temperatures and relative humidity levels (Super League Triathlon, 2021a). Monitoring clothing has also been developed by Nakayoshi *et al*. (2015) and Liu *et al*. (2019) whilst wearable sensors have been used to monitor body temperature responses in heatwave events (Hass and Ellis, 2019). Additionally, live monitoring of blood glucose levels has started being used by elite and amateur endurance athletes thanks to body sensors that could be further utilised to determine risks posed under extreme conditions (Supersapiens, 2021).

Furthermore, transmission of live data is already being utilised by the indoor cycling and running events hosted by Zwift, notably Super League Triathlon’s Arena Games, indoor cycling championships and a host of indoor elite events hosted during the 2020 lockdowns (Super League Triathlon, 2021b). This has generally provided heart rate, power and speed data to viewers as well as ensuring that competitors are not cheating to gain an advantage from the computer algorithm. However, further utilisation of other physiological metrics such as sweat rate and body temperature would be relatively easy to implement. It was already noted by Super League triathlon after events that certain athletes were able to recover quicker and thus perform more consistently between rounds due to the live data provided during the event (Super League Triathlon, 2021c). Live and post-event cycling data has also been made available for some events and once again could be expanded to other metrics to provide details as to whether athletes are approaching a danger zone with regards to their body temperature.

With 90% of people's daily lives being spent indoors, there is the potential for people to be exposed to very different levels of air pollution, in particular, and meteorological extremes when they exercise outside (Lowther *et al*., 2019). This could make selection of when and where to exercise (if possible) highly important with regards to exposure. To minimise this risk, there are a number of actions and emerging technologies that organisers at elite, mass participation and community-led events could implement to reduce the impact of environmental variables and medical incidents occurring. However, the most easily implemented are detailed below.

6.4.1. Green-Blue Infrastructure and Shading

It is believed that parkun's with enhanced vegetation levels and courses further away from surrounding roads will have lower pollution levels than those that are not. This would examined in future (field) work to determine whether research suggesting that vegetation can be an effective barrier to pollution is corroborated at study locations (Abhijith *et al.* 2017; Abhijith and Kumar, 2020; Hewitt *et al.*, 2020; Tomson *et al.*, 2021). The implementation of green infrastructure between sources and pedestrians (i.e. parkrunners) could help reduce pollution exposure. Hedges and other vegetation acts to increase the distance between pollution sources and receptors, reducing overall exposure, as well as pollution being deposited on the vegetation (Abhijith and Kumar, 2020; Hewitt *et al.*, 2020; Tong *et al.*, 2016).

Consequently, it can be hypothesised that participants at events held under higher pollution levels will see increased exposure and reduced health benefits or life years gained. If this is shown via the proposed future research, the aim would be not to reduce activity numbers in general nor in the most polluted locations, rather to inform exercisers of their local conditions and prompt the implementation of action plans to improve air quality through local authorities and action groups. There are instances when green infrastructure can negatively impact urban air quality. For example, tree canopies can trap ground-level pollution sources and increase ground-level concentrations (Abhijith *et al.* 2017; Hewitt *et al.*, 2020; Vos *et al.*, 2013). However, in most parkrun instances, it is unlikely that there will be numerous pollutant sources within parks and a dense vegetation canopy will be beneficial by increasing pollution deposition onto vegetation as air percolates down through the canopy (Hewitt *et al.*, 2020; Tomson *et al.*, 2021).

In addition to potentially reduced pollution, parkrun events and measurements in event areas would provide an insight into the potential cooling effect of vegetation and green infrastructure on the urban heat island effect. This is particularly important given results in chapters 3 to 5 suggest that temperature has the greatest effect on performance. Research has shown that parks can provide significant cooling effects that can extend beyond the boundaries of the park (Cao, 2010; Chang *et al.,* 2007; McPherson *et al.,* 1997; Senanayake *et al.*, 2013; Sproken-Smith and Oke, 1998; Yu and Hien, 2006; Zhang *et al.,* 2010). This can be up to 12°C over an area 0.5km^2 larger than the green space (Balany *et al.*, 2020; Georgi and Dimitriou, 2010; Hwang *et al.*, 2015; Jonsson, 2004; Shashua-Bar and Hoffmann, 2000; Yu and Hien, 2006). Vegetation can also significantly reduce the risk of heat exposure, keeping surface temperatures 7°C cooler than exposed urban materials whilst also providing up to 8-12°C of cooling during the day (Bartesaghi-Koc *et al.*, 2020; Hwang *et al.*, 2015; Venter *et al.*, 2020). Consequently, green infrastructure and shading has been recommended for use along the 2021 Tokyo Marathon route to reduce the risk of heat related incidents (Kosaka *et al.*, 2018; Venter *et al.*, 2020). Utilisation of NDVI could be analysed to determine which parkrun events have the highest levels of shading and vegetation in place, and thus have the greatest cooling potential.

Although green spaces are widely recognised as the main nature-based thermal mitigation method in urban areas, urban blue spaces can provide benefits: but have been examined to a lesser extent (Lin *et al*., 2020). Therefore, the potential influence of blue infrastructure on parkruns would have to be taken into account in the future as research has shown that urban water bodies can have a cooling effect (Gunawardena *et al*., 2017; Shi *et al*., 2020; Yu *et al*., 2020). Large waterbodies have been shown to have a greater influence compared to several smaller bodies, with water fountains, spray fountains and misting systems also being shown to have negligible thermal effects (Lehnert *et al*., 2021; Theeuwes *et al*., 2013; Yu *et al*., 2020; Wang and Ouyang, 2021). Furthermore, the cooling effect of urban rivers is spatially smaller in high-latitude cities compared to lower-latitude cities (Hathway and Sharples, 2012; Murakawa *et al*., 1991; Yu *et al*., 2020). Based on this aforementioned research, the would be a focus on examining whether larger bodies of water within parkrun provide a cooling effect and how far this may extend away from the 'source' area.

10 out of the 15 parkruns examined in chapter 3 have some form a lake (boating or otherwise), pond, fishery or river within the park area. This would be done by field measurements which could be interpolated across parks and supported by land surface temperature data from thermal infrared satellite sensing, as utilised by Lehnert *et al*. (2021), Lin *et al*. (2020), Shi *et al*. (2020) and Wang and Ouyang (2021). It is expected that larger water bodies would have a greater effect than smaller bodies and rivers on thermal cooling (Du *et al*., 2016; Theeuwes *et al*., 2013; Yu *et al*., 2020). However, green infrastructure is still expected to have a greater cooling effect and thus benefit to parkrun performances compared to blue infrastructure based upon previous research (Gunawardena *et al*., 2017; Lehnert *et al*., 2021; Lin *et al*., 2020).

Overall, parkrun events that are more highly vegetated and located further away from pollution sources could in theory be cooler and less polluted, and therefore conducive to quicker performances (Hewitt *et al.*, 2020). The inclusion of larger water bodies close to race routes may also provide a thermal benefit. As has been previously covered, the locating of events in green spaces would also provide additional psychological wellbeing improvements, which may also lend itself to greater participant retention and thus improved population health (Bullas *et al.*, 2020; Pretty *et al.*, 2005; Pretty *et al.*, 2007; O'Sullivan *et al.*, 2016).

However, for events such as the Great North Run and Diamond League athletic series, which are held in urban areas or athletic stadiums with variable or no natural shading, alternative measures would have to be implemented to reduce environmental risks to athletes. This would include ensuring that runners could utilise the shade of buildings along the route, expanding tree canopies by reducing pre-event pruning or the implementation of artificial and temporary shading. This could be implemented at the highest risk locations where the duration of sun exposure is the longest or most intense: potentially towards the end of events as the time moves closer to midday and beyond. Such canopies could be implemented at athletic stadiums to provide some level of additional shade if required whilst green infrastructure around the outside of the stadium would also help lower pollution levels. This could be enhanced by reducing the amount of parking directly at athletic venues and encouraging green transport options and park and ride schemes.

6.4.2. Start Times

With regards to parkrun, UK-events start at 09:00 on Saturday's, which is unlikely to be changed due to the long-standing and accessible nature of such a start time. This is also, generally, an acceptable time to hold events with regards to meteorology and pollution, with peak daytime temperatures likely not reached and the equivalent rise in O_3 concentrations also not occurred fully. However, mass participation events such as the Great North Run, London Marathon and others which require large-scale pre-event planning and road closures (to be discussed shortly) could be scheduled at preferential times to avoid the most adverse environmental conditions. This is particularly so for the Diamond League Athletics series which in Chapter 4 has shown that the conditions athletes have competed in may not be preferentially timed. Incidentally, many mass participation triathlon events held pre-COVID had start times between 06:00-08:00 and such precautions have already been taken at the Rio and Tokyo Olympic Games. Furthermore, Kosaka *et al*. (2018) showed that starting the

Tokyo marathon one hour earlier than originally planned would significantly reduce the heat risk to athlete’s health. These earlier start times would also help contribute to reduced ozone concentrations and thus lessen the detrimental impact this pollutant has on performance alongside elevated temperatures as has been previously shown.

6.4.3. Road closures

As parkrun events are often held in parks and advocate green transport methods to attend the events or car-sharing when safe, it would be hoped that the events are in some respects removed from roads and other pollution sources. Furthermore, due to their location, frequency of occurrence and spatial coverage, closures of the surrounding roads for a volunteer-organised event is not feasible. For mass participation events, however, road closures are required for athlete and spectator safety as they are held on open roads through often urban centres. Implementation of road closures earlier prior to the event and extending these to a wider number of surrounding roads would help contribute to reduced pollution levels on and alongside event routes. This could be further improved by ensuring that roads in the direction of the prevailing wind are closed to a greater extent to reduce the likelihood of dispersion over the route. The aforementioned implementation of distanced parking for competitors and spectators would also reduce congestion in and around the race venue prior to starting.

6.4.4. Proposed Project

Based upon the research presented in chapters 3-5 and suggestions for future research already in this chapter, a propsed project utilising field research to examine the influence of air quality and meteorlogy on selected parkrun events will now be presented with suggested time lines, locations, participant numbers and recruitment.

Identification of a suitable parkrun(s) for use within the the study would be selected based upon course surface, elevation gain/loss of the course, level of greenery and blue and grey infrastructure within the park. Preferentially, parkruns performed on tarmac or concrete paths rather than grass, trail or other permeable surfaces that are likely to alter in their firmness and grip the most based upon rainfall will be selected. This is to help reduce the potential confounding effect of surface characteristics on finishing times. Additionally, parks without excessive grey infrastructure but a good level of green-blue infrastructure (similar percentages if possible) would also reduce the potential of confounding factors.

Once identified, individual parkrun organisers would be contacted to outline the project and participant requirements. Due to the aforementioned close-knit nature of the parkrun community and their organised and easily accessible social media groups for individual events – communication with and recruitment of regular parkrunners is hoped to be relatively straightforward. Recruitment of regular parkrunners (>3 out of 4 parkruns per month) spanning both genders would be required to see if environmental conditions differently affected each group, as shown in chapter 4. Participants at a range of ‘performance’ levels will be required: regular finishers in the top 25%, middle 50% and last 25% groups from historic parkrun performances will be recruited. It is hoped that a minimum of five participants from each of the three groups are recruited to provide ‘during event’ feedback, data from a GPS and heart rate enabled device and carry exposure monitors. They would also provide a representative population of all runners taking part in the parkrun and allow for a more detailed analysis of how pollution and meteorology may impact performances.

Participants will be supplied with a pre-testing questionnaire covering their running background, current training volume, personal best times, any current or past injuries and physiological metrics such as height, weight and if possible, body fat percentage. Similarly, post event questionnaires would also be used to gather information on the event and participants feelings. Questions including details of the course surface, shoe choice (i.e. carbon plated or not), current training state/injuries and rate of perceived exertion would be included. This would also allow for determination of participaints shoewear, training state and course conditions (dry or wet, influence of wet grass and mud accumulation), all of which in the previous research present in chapter 3-5 is difficult or impossible to ascertain.

In addition to the pre-study and post-parkrun questionnaires, data from the participant’s fitness tracking and heart rate devices to provide GPS location and associated running speed and heart rate information to be analysed in more detail alongside the personal exposure monitor readings and AURN values. This pace and heart rate data would also allow for the calculation of minute ventilation rates through the use of population-derived formulas which have been improved in recent research, and allow for a second estimation of pollution uptake of participants when coupled with the personal exposure and/or low cost sensors (Cozza *et al.*, 2015; Dons *et al.*, 2017; Guo *et al.*, 2021; Nyhan et al,. 2014; Zuurbier *et al.*, 2009).

In addition to the provision of low cost personal exposure sensors to the selected runners, low cost sensors for pollution and meteorology would be placed at the start/finish locations and other parts of the route. This would be dependent on individual route configurations and suitable mounting points but sampling at around every 1km mark of the route would be beneficial, as would any points where the route passes close to roads outside the park (if relevant). Utilisation of local Defra AURN and meteorology monitoring sites would be used validate the low cost sensor readings and provide additional data to analyse alongside the official parkrun results for all runners. Through a combination of personal exposure sensors and low cost monitors, the potential pollution uptake of the parkrun field and the effect pollution may have on participants, as well as meteorological conditions, would be able to be considered in greater detail than just with secondary data.

It is proposed that once ethics and equipment and resources are acquired, the advertisement and recruitment process for the pre-selected parkrun event(s) would commence, approximately for a month but potentially more or less time depending on uptake from parkrunners. This would also include assessment questionnaires being filled in and participants being informed of the nature of the research and how they will be involved. Over the following short period, estimated to be less than a couple of weeks, installation of the low-cost monitors and provision of personal exposure sensors would be performed, allowing for monitoring to take place almost immediately after the recruitment stage. Monitoring would aim to last from 6-12 months and longer if possible, to provide as much detail as possible given parkrun events are a only a weekly occurrence. However, with low cost monitors recording constantly, determination of general air quality and meteorological conditions within the studied parks could also be determined and be used to inform potential public exposure to pollution and to see if the parks are recording lower pollution and lower temperatures compared to monitoring sites not within their boundaries. Data cleaning and analysis could be continuously performed on a weekly basis to ensure that the low cost sensors, personal exposure monitors and participants GPS and heart rate data is functioning accurately, which ultimately would reduce the overall time taken to perform a full analysis of the complete dataset.

A similar methodology could be implemented for larger, ‘one-off’ events such as the Great North Run and other mass-participation events, from 10 Km through to marathon distances. Recruitment of a larger and wider range of participants would be required, as would placement of more monitoring sites along the route. However, this would hopefully provide a more representative picture of how envirohmental conditions changed along the route and during the event duration, as well as highlighting the ‘ozone paradox’ and its potential effect if present.

6.5. Conclusions

Inherently, data availability directly at study locations has been the main limiting factor of this research and may to some extent under- or over-exaggerated the influence of air pollution and meteorology on athletic performances. However, they provided a representative indication of the effects these parameters have on athletic performance. To overcome this limitation, future research would draw upon personal exposure monitors and low cost sensors at community events and the implementation of monitoring stations at elite events and sports stadiums. This research into personal air quality exposure during parkrun events would provide a novel and new insight into the health benefits of exercising in urban areas under potentially poor air quality conditions. Furthermore, it would allow for the potential differences in ambient air quality and pollution exposure to be seen due to the different periods of time participants would be running for. The effectiveness of air quality improvement measures, urban heat island mitigation and the accuracy of low cost and personal exposure monitors would also be examined, providing detailed information into how to best utilise a rapidly increasing field of monitoring options. Ultimately, with the upcoming 2022 Commonwealth Games being held in Birmingham and a likely increase in physical activities, alongside increased outdoor exercise during the COVID-19 pandemic, determining the impact of air quality on health and athletic performance is a research area that readily needs examining. It would also provide insight into the conditions required for optimal athletics performance and provide suggestions to help reduce environmental stress on participants and spectators through the effective implementation of green infrastructure, shading, road closures and scheduling of events.

Chapter 7 – Conclusions

The aim of this thesis was to *examine the extent to which air quality and meteorology influence athletic performance for both recreational exercisers and elite athletes in real world events.* The following objectives were also outlined to help shape the direction of the research performed:

Objective 1: Examine associations between local air quality and meteorology and recreational parkrun (5000 m) athletic performance.

Objective 2: Examine associations between local air quality and meteorology and elite 5000 m athletic performance.

Objective 3: Using a high profile mass participation event, examine associations between local air quality and meteorology on both elite and recreational half marathon performance.

7.1. Objective 1: parkrun

Examination of amateur athletic performance was assessed by utilising highly popular and socially inclusive parkrun events in the Greater London area between 2011 and 2016. Paired with local air quality and meteorology monitoring stations, results across fifteen parkrun events suggest that temperature and wind speed are the biggest influencers on amateur athletic performance over 5 km distances. Linear regression results show significant positive relationships between these variables and finishing times ($p=0.01$), with a greater impact on male participants for wind speed analysis. High wind speed events ($>6\ ms^{-1}$) also resulted in statistically slower finishing times. Although not statistically significant, relative humidity showed numerous slowing effects on performance: an increase from 40-55% relative humidity to over 85.1% resulted in mean times being over 14 s slower. Furthermore, the participants from older age groups (70 years and older) attending parkrun showed the largest decreases in performance when relative humidity increased.

The influence of air pollution was variable. At some events, air pollution was shown to be significantly detrimental as in the case of O_3, notably at Bushy Park, Crystal Palace and Lloyd parkruns. However, the other examined events all had a positive relationship between O_3 and temperature, suggesting that the pollutant is detrimental to some extent to performance. Similarly, NO_2 had no significant results. Although not significant, the data did suggest a bias towards a potentially beneficial association with its negative relationship with finishing times. However, it was concluded that this is unlikely to be due to a benefit provided by NO_2 because of its irritant effect on the respiratory system. Instead, the influence of temperature and Leighton chemical reactions are likely contributing to these air quality results with higher and lower temperatures respectively occurring alongside increased O_3 and NO_2 levels. Finally, PM analyses showed no significant results nor suggestive trends. Consequently, meteorological parameters (i.e. temperature and wind speed) are deemed to be the more influential variable on parkrun performances.

7.2. Objective 2: Diamond League

The annual, elite track and field Diamond League athletics competition includes male and female 5000 m events at a range of international locations, of which nine were examined between 2010 and 2018. Events were again paired with local authority air quality and meteorology monitoring stations close to the event stadiums to provide as representative as possible data at the time the 5000 m events were held. Due to significant and clear differences between elite male and female finishing times over the race distance, analysis was kept to gender-specific groups and performed for all combined events as well as individual locations.

For combined locations, female elite athletes demonstrated the greatest susceptibly to both meteorological and air quality conditions. Higher temperatures, wind speeds and heat index all slowed finishing times of female athletes the most, although they did perform better under higher relative humidity levels compared to their male counterparts. However, this result is likely due to the inverse relationship between temperature and relative humidity that saw low temperatures being recorded when relative humidity was high, thus leading to quicker performances as temperature is generally deemed to be the more influential environmental variable (Bigazzi, 2016). Interestingly, male athletes showed no effect of air quality on their performances, whilst female's times slowed as O_3 and $PM_{2.5}$ and PM_{10} concentrations increased. NO_2 showed no effect for either gender. The cause of female athletes being influenced the most by air quality variations is currently unknown, and further examination of this in other real-world and laboratory tests is required and recommended as part of future research studies.

Individual analysis within and between Diamond League locations also showed that variations in local environmental variables influenced finishing times. For example, Birmingham was the slowest of the nine locations, it also had the highest O_3 and PM concentrations as well as higher than average temperatures, which further suggests that such conditions are not preferential for fast race performances and was again backed up by significant statistical relationships. Contrastingly, Paris was the quickest event of the examined locations and was generally held under lower than average temperatures and some of the lowest pollution levels, thereby reinforcing these findings.

7.3. Objective 3: Great North Run

The response of a combined field of elite and recreational athletes to environmental changes was analysed at the half marathon distance Great North Run in Newcastle-Upon-Tyne. The longstanding mass participation event includes a high-quality elite athlete field starting at the same time along the same route as the amateur runners, allowing for direct comparison between both groups of runners. Finishing times of the elite field and the first and last 150 amateur runners from 2006 to 2019 were analysed alongside the cities air quality and meteorology readings for the duration of the elite race and the slowest amateur finishers.

For the elite field, both overall and for the female elite subset, only O_3 was shown to be detrimental to performance. However, this result was not replicated for the quickest amateur entrants, who were statistically slower than the elite field but statistically quicker than the slowest amateurs ($p=<0.01$). Instead an analysis of the slowest 150 finishers showed the most interesting results with temperature, heat index and O_3 all resulting in slower performances, whilst NO_2 saw quicker times. However, there was a significant relationship between lower temperatures and higher NO_2 concentrations, suggesting that these quicker times under high NO_2 levels are more due to the favourable air temperatures than the pollutant having a physiological performance benefit.

These findings were mirrored for the male and female subsets, although male participants in the slowest amateur group were influenced more than their female counterparts for temperature and heat index analyses. This is in contrast to the elite athletes studied at the Diamond League events, albeit with an additional pollution focus. However, previous studies suggest that male runners are more likely to decrease performance under elevated temperatures (Billat *et al.,* 2001; Marino *et al.*, 2000; Kaciuba-Uscilko and Ryszard, 2001; Zouhal *et al.*, 2011). Greater performance decreases for the slowest amateurs is likely due to their increased exposure time and slightly elevated mean exposures over the course of the event in comparison to elite athletes and the quickest amateurs. These latter two groups will also be conditioned to performing to a greater physiological ability under environmental stress (Hargreaves, 2008).

7.4. Implications and Further Research Avenues

As a result of the studies outlined above, the aim and objectives of this thesis have been examined at a selection of distances, event locations and time periods. With the effect of a changing climate and air pollution a major concern for public health and activity levels, these three studies have shown to varying extents that careful consideration of exercise and/or event location and ambient conditions are required. The effect of a warming climate and predicted increased frequency extreme weather events, including heat waves means that understanding humans physiological responses during exercise at various distances is key to ensure improved public health and safety.

These results show that the influence of meteorology and air quality on recreational and elite exercisers can be statistically significant over both 5000 m and half marathon distances, supporting previous work mostly at marathon distances (Helou *et al*., 2012; Knechtle *et al.*, 2019; Vihma, 2010). Variation in gender responses to environmental variables has been discussed by several researchers but not been conclusive as to which are influenced the most (Kaciuba-Uscilko and Ryszard, 2001). The same is also true with regards to the pace of runners in events (Gasparetto and Nesseler, 2020). Unfortunately, this research does not conclusively show that one gender or group of runners are influenced the most, albeit elite athletes and the slowest of entrants may be more vulnerable for different reasons. Notably, elite athletes are likely to be performing close to their VO_2 max and more prone to suffering overheating and cardiorespiratory distress under elevated temperatures and pollution levels whilst the slowest of participants will be exposed the most to environmental variables and the cumulative effect of this shall contribute to decreased performances.

This research must be caveated with the fact that there are potentially confounding factors that are incredibly difficult or impossible to account for without additional studies specifically targeting them. As has been highlighted in chapter 3, the influence of changes in parkrun terrains and elevation profiles is hard to account for; shoe choice for athletes with increased availability of carbon-plated shoes could also effect times in parkrun and Great North Run instances; the effect of the ‘ozone paradox’ may have an influence during the Great North Run too. For all events, the training state and preparation of athletes and their acclimitisation to environmental conditions is impossible to ascertain without personal surveys and laboratory testing. Finally, the reduced sample sizes at individual Diamond League events is also problematic but presents an excellent opportunity to have an ongoing yearly dataset to be built upon yearly as the series continues.

Despite these issues, as has been highlighted in chapter 6, some of these difficulties could be come and findings enhanced through the use of low-cost, at-event field monitoring of environmental variables and personal exposure monitors. Furthermore, additional research questions can also be considered with regards to the results shown already. Namely; determining whether differences between the effect of environmental parameters on elite athletes and recreational exercisers/event participants holds true for other events, distances and sports; and the effect of gender on performance under various potentially detrimental environmental parameters. There is also the potential to further examine the results at combined field events (such as the Great North Run) to examine the effect of variables on elites and subsets of recreational athletes to better determine specific cut off or thresholds at which all or certain groups are influenced during exercise.

Additional research questions related to this work, and previously published findings, could also be considered. Firstly, investigation into whether elite athletes are better conditioned to meteorological variables but not pollution due to their training being geared towards ‘heat training’ and acclimatisation in locations with low pollution concentrations relative to the often city-centre venues they compete in. In contrast, recreational exercises could be better ‘acclimatised’ to such pollution levels given they would most likely be continuously exposed to similar levels and thus show reduced performance decreases under pollution compared to elite athletes.

There is also a great opportunity to factor air quality and meteorology into the planning and organisation of upcoming megaevents – especially the forthcoming 2022 Commonwealth Games held in Birmingham (particularly so given the Diamond League results shown for

Birmingham). Indeed, the Olympic Games have regularly been noted as an area of concern since the 1984 Los Angeles Games due to smog but has only been actively studied or reduced at Beijing 2008. There have been several high-profile and serious medical incidents occurring at elite sporting events in recent years due to environmental conditions. Consequently, athlete health and safety with regards to meteorology and air quality levels needs to be considered carefully. This should be taken into consideration for both amateur and mass participation events, as it is not only elite athletes who are at risk of medical incidents. The Great North Run and London Marathon have both seen a number of deaths and heat-related incidents whilst research at other events have also shown increased medical tent admissions occurring under adverse environmental conditions (Luning *et al*. 2019). Simple mitigation actions can be effective such as the alteration of routes to provide more shade, additional aid stations and/or changes to start times and these should be taken into consideration based upon the forecast and pre-event weather conditions. This would not only reduce the risk of medical incidents occurring, but also improve participant thermal comfort and enjoyment, and make them more likely to return to the event (or others) as well as sustain a hopefully healthier lifestyle and recreational activity than be put off by the conditions they experience. This is especially so for an event such as parkrun which aims to foster an inclusive and sociable running community within the local area.

Finally, these findings, particularly for elite athletes, provide useful additional insights into planning and attempting potential World or Olympic records. Previously, conditions have been considered for Eliud Kipchoge's sub-2 hours marathon success but such consideration can be further utilised by this research to inform not only standalone world record attempts but also to hold organised events such as the Olympic and Commonwealth Games at times and locations that would be conducive to improved athlete performances, potential record-breaking times and thus greater spectator viewing enjoyment and favourable media coverage.

7.5. Final Remarks

Overall, this thesis has highlighted the importance of considering local meteorology and air quality conditions for recreational exercise, mass participation events and elite athletic performance. Furthermore, this can be expanded to outdoor sport and recreation and amateur and elite level more broadly than just running, as well as highlighting the need for additional laboratory and field testing as suggested in chapter 6 which could limit the influence of hard to ascertain confounding factors. Conclusive determination of the main influencing variables for both men and women and various levels of experience is required, but it has been shown that increased temperatures and wind speeds are the most detrimental to performance over 5000 m and half marathon distances, with influence from other environmental variables depending on the analysis performed. It has however supported previous research looking at marathon events and environmental influences and provides strong avenues for further research into the field.

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Appendix

The Appendix contains full submitted versions of the parkrun and Diamond League articles which have been presented in parts in chapters 3 and 4.

Appendix A

Extensive parts of chapter 3 have been submitted to the journal *Sports Medicine – Open* and has been published online as a preprint.

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: 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 ($p=0.01$). 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. 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.

Key Words
parkrun, athletics, meteorology, air quality, London, physical health

1. 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.

2. 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^{o}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.

3. 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).

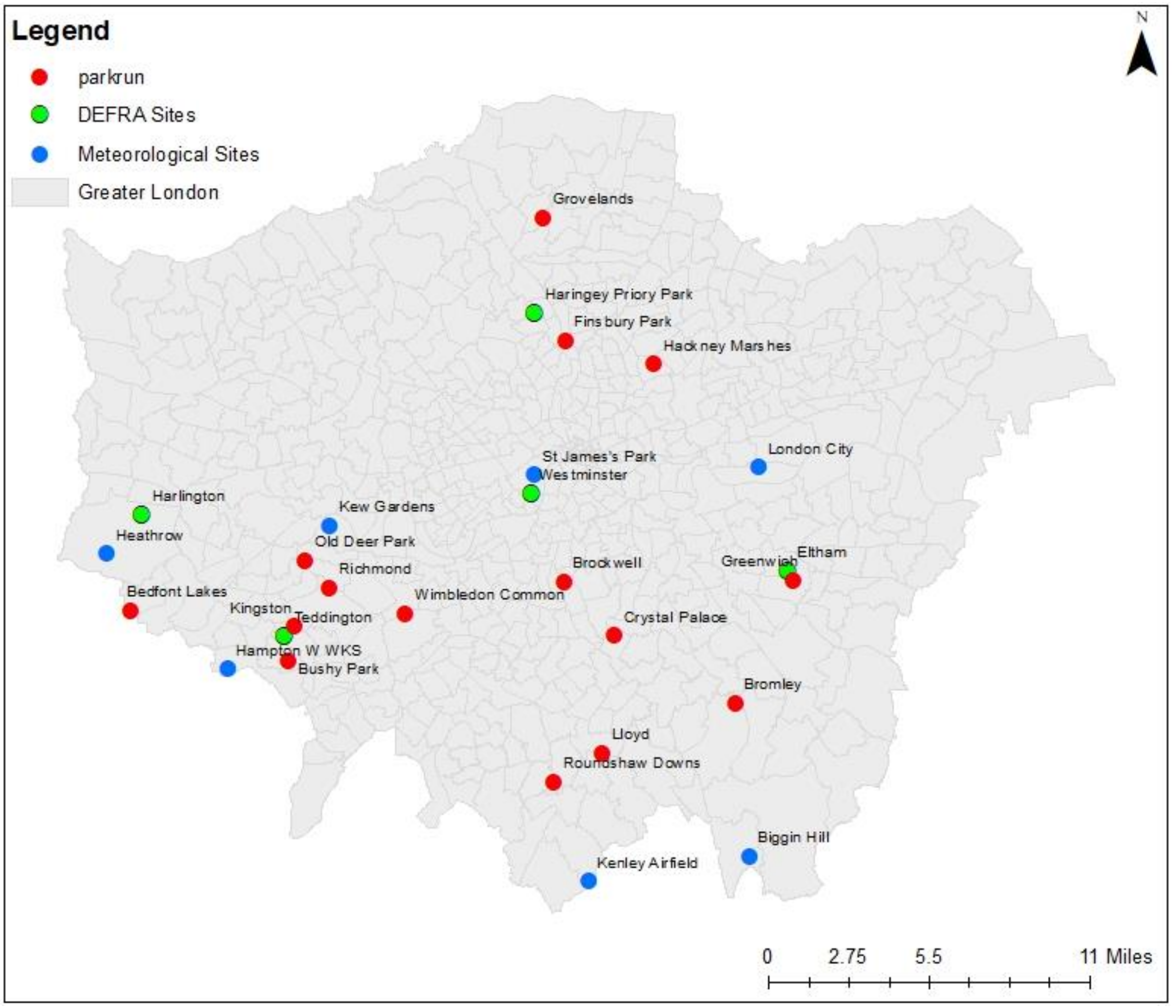

Fig 1. A map showing the locations of the parkrun events, DEFRA AURN stations and meteorological stations within Greater London.

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).

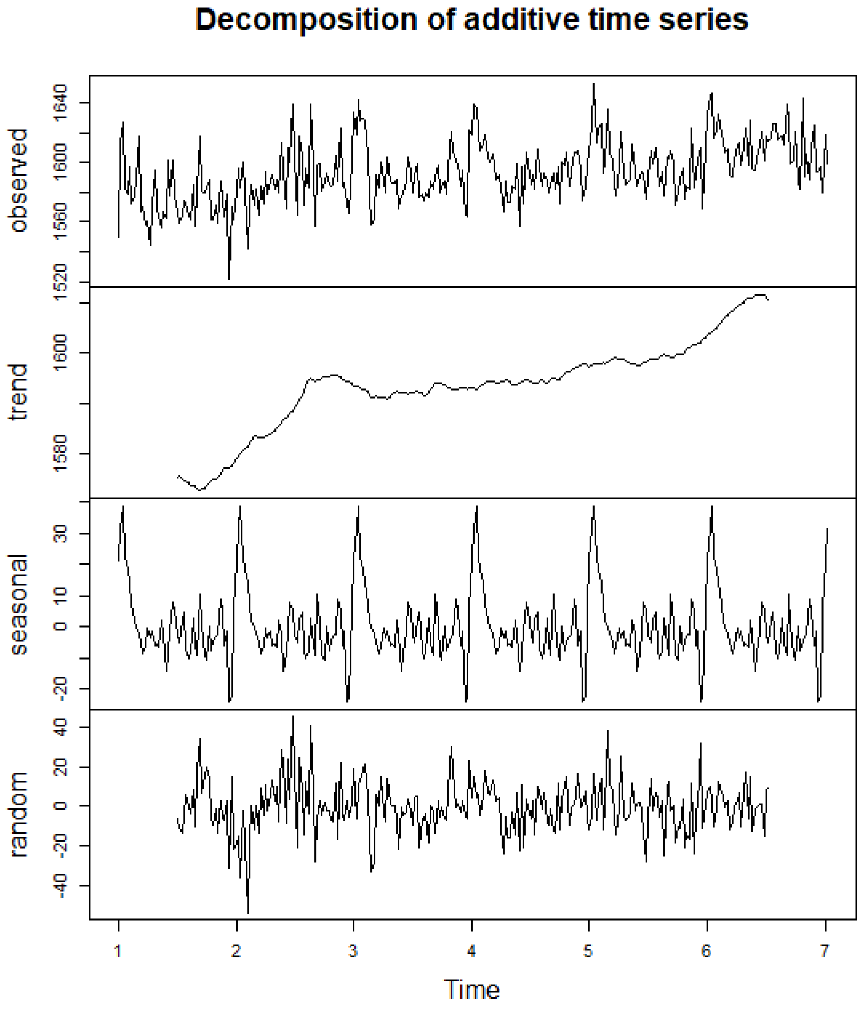

Fig 2. Decomposition of weekly mean parkrun finishing times from 2011 to 2016. The x-axis shows the six yearly periods within the data.

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).

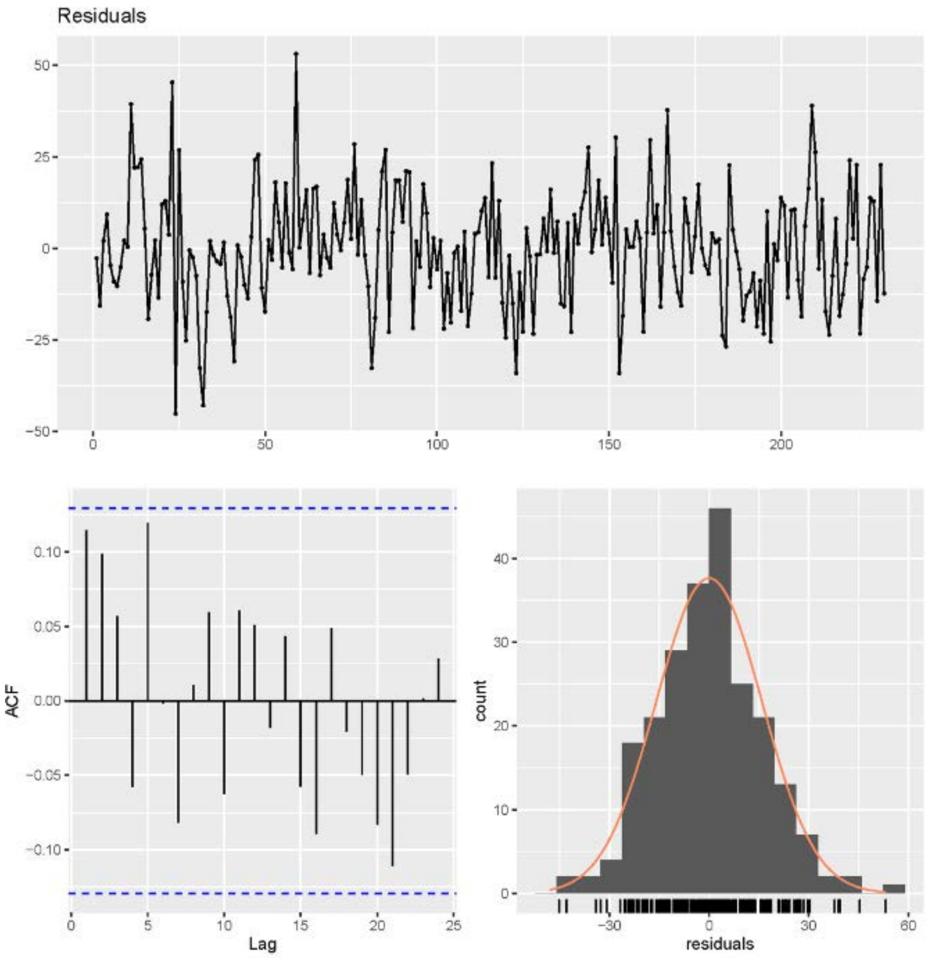

Fig 3. Example post-test analysis of residuals, their distribution and ACF plot for the influence of ozone on finishing times at Bushy parkrun.

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. Other confounding factors include the level of individual athlete’s acclimatisation to environmental conditions, their training state and the increased prevalence of carbon plated running shoes. Similarly to event surface differences, these factors are incredibly difficult to account for without extensive ‘at event’ and in person studies to determine participant fitness levels and acclimisation and shoe choices.

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.

4. 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

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).

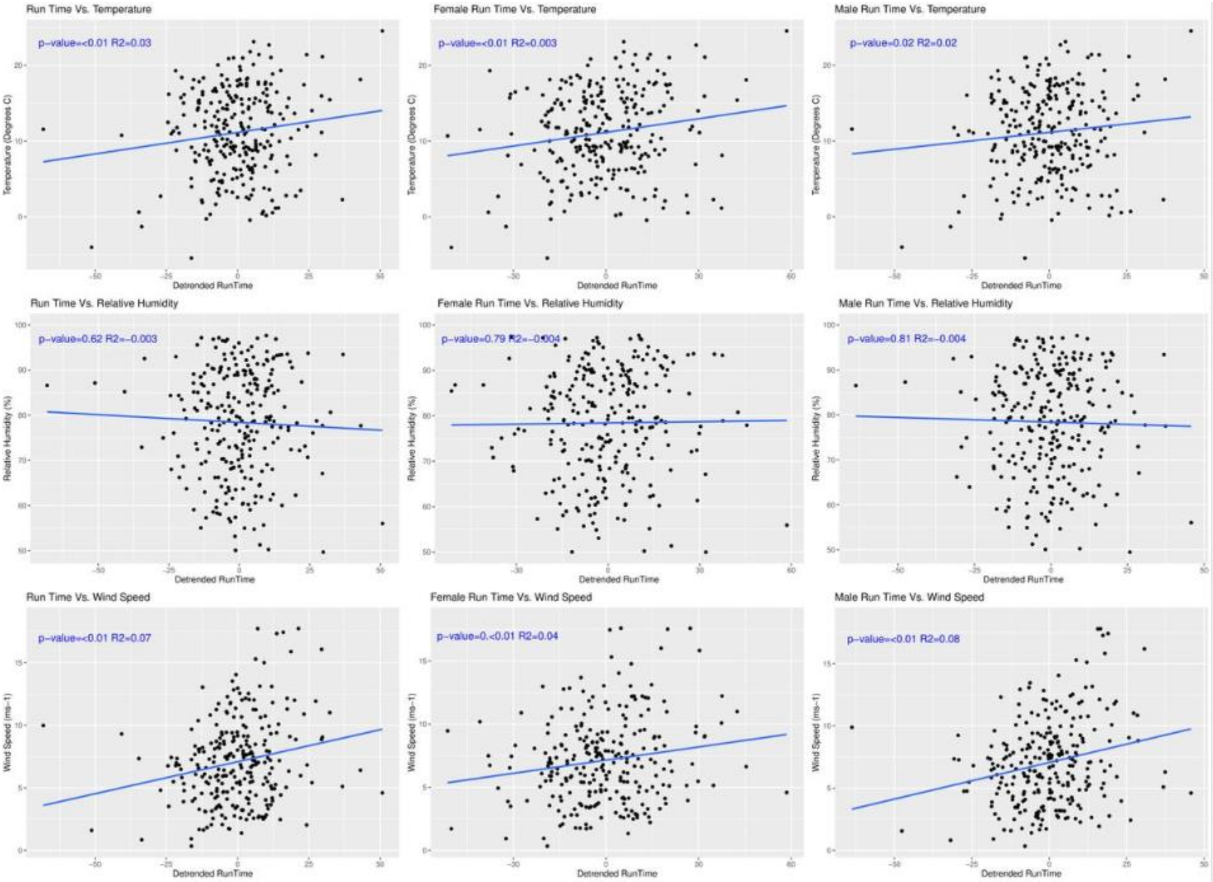

Fig 4. Results of linear regression analysis for the overall (row A), female (row B) and male (row C) parkrun subsets with the three meteorological variables examined.

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**$_{\text{(Equation 2)}}$

**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. $PM_{2.5}$

$PM_{2.5}$ 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.

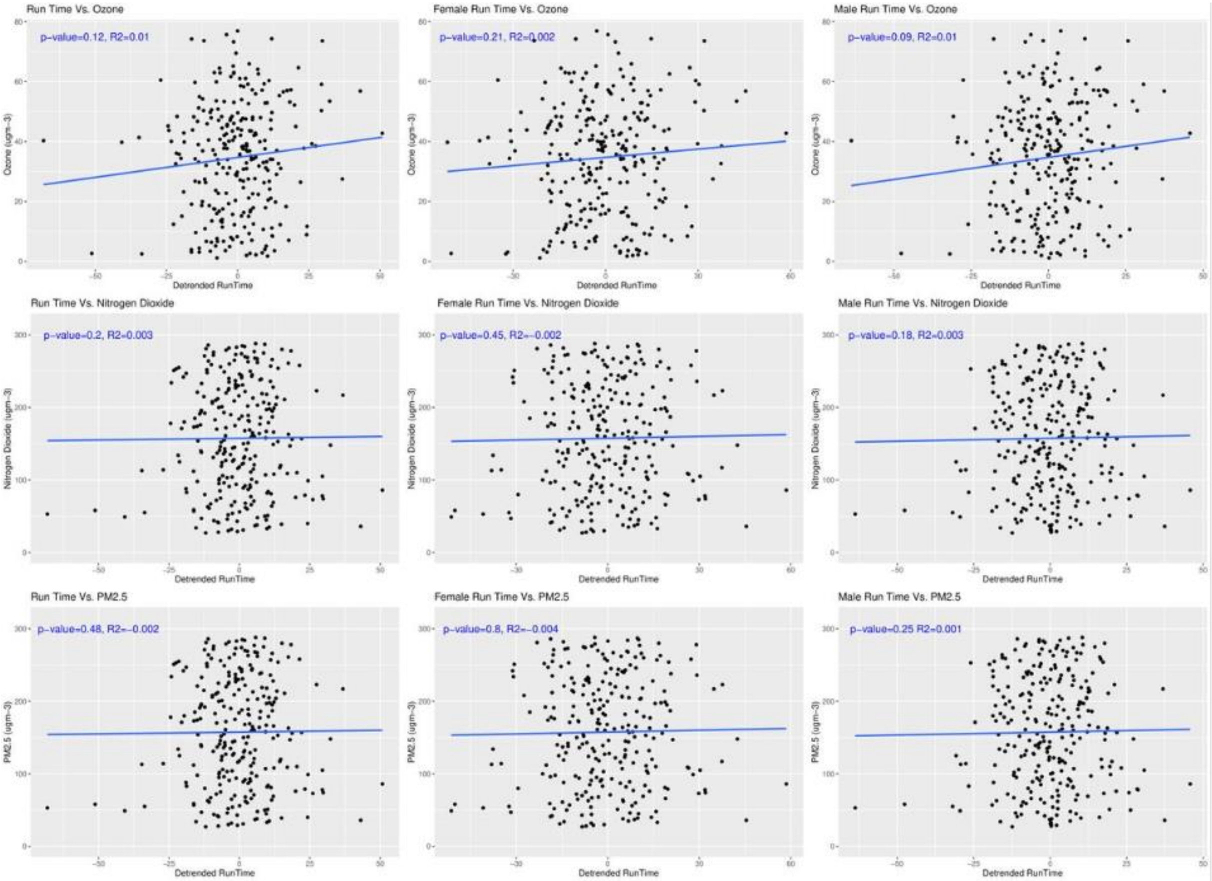

Fig 5. Results of linear regression analysis for the overall (Row A), female (Row B) and male (Row C) parkrun subsets with the three pollutants examined.

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

Table 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

5. Discussion

5.1. 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. $PM_{2.5}$

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].

6. 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].

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.

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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Appendix B

Appendix B below shows the full transcript of the accepted article from *The International Journal of Biometeorology* which chapter 4 is based on.

The Diamond League Athletic Series: Does the Air Quality Sparkle?

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Abstract

Urban air pollution can have negative short- and long-term impacts on health, including cardiovascular, neurological, immune system and developmental damage. The irritant qualities of pollutants such as ozone (O_3), nitrogen dioxide (NO_2) and particulate matter (PM) can cause respiratory and cardiovascular distress, which can be heightened during physical activity and particularly so for those with respiratory conditions such as asthma. Previously, research has only examined marathon run outcomes or running under laboratory settings. This study focuses on elite 5-kilometre (5 km) athletes performing in international events at nine locations. Local meteorological and air quality data are used in conjunction with race performance metrics from the Diamond League Athletics series to determine the extent to which elite competitors are influenced during maximal sustained efforts in real-world conditions. The findings from this study suggest that local meteorological variables (temperature, wind speed and relative humidity) and air quality (ozone and particulate matter) have an impact on athletic performance. Variation between finishing times at

different race locations can also be explained by the local meteorology and air quality conditions seen during races.

Key Words

Diamond League, athletics, meteorology, air quality, physical health, exercise performance

Declarations

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Conflicts of Interest/Competing Interests

The authors declare that they have no competing interests.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

Datasets generated and used during the study are available in the DANS repository, https://doi.org/10.17026/dans-xmr-tnx5

Code availability

Code is available in the DANS repository, https://doi.org/10.17026/dans-xmr-tnx5

Authors' Contributions

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

LC – Conception and design of work. Data interpretation. Write up editing and approval of final work.

FDP – Conception and design of work. Data interpretation. Write up editing and approval of final work.

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1. Introduction and Background

Poor urban air quality (UAQ) is a serious worldwide environmental issue with detrimental impacts on human health and the wider environment (European Commission, 2017a; 2017b; Kampa and Castanas, 2008; Lim *et al.*, 2012; Walton *et al.,* 2015). Along with premature deaths, shorter-term effects including cardiovascular and respiratory distress and irritation are common in the wider populations, and heightened for those with pre-existing conditions (Burnett *et al.*, 2014; Lelieveld *et al.*, 2015). The main pollutants concerning human health are nitrogen dioxide (NO_2), ozone (O_3) and particulate matter (PM: Particles with a diameter of 10 micrometers (PM_{10}) and 2.5 micrometers ($PM_{2.5}$) or less, Rajagopalan *et al*., 2018; Sun and Zhu, 2019). As well as short-term irritation of the nose, mouth, throat and cardio-respiratory systems, these pollutants, along with others, can lead to cardiovascular and respiratory diseases, reduced lung function and asthma (Burnett *et al.*, 2014; EEA, 2013; Lelieveld *et al.*, 2015). Recent work has also highlighted negative impacts of UAQ upon cognitive level (Calderon-Garciduenas *et al.,* 2016; Clifford *et al.,* 2016; Shehab and Pope, 2019; Sunyer *et al.,* 2015).

In extreme cases, the negative impacts of UAQ could outweigh the positive impacts of exercise (Guo *et al*., 2020; Strak *et al*., 2010; Tainio *et al*., 2016. Consequently, with encouragement for greater levels of exercise and active transport to combat a global obesity crisis and pollution: there is a likelihood of a greater proportion of society being exposed to poor, albeit improving, UAQ (COMEAP, 2009; 2010; Devarakonda *et al.*, 2013; Kobayashi *et al.*, 2017; Sallis, 2008; Shugart, 2016).

In contrast to recreational exercisers who are largely free to choose when they exercise, elite athletes and professional sport-people are constrained to set competition times, potentially resulting in them performing in non-ideal environmental conditions. Although at some landmark events, such as the now rearranged 2021 Tokyo Olympic Games, start times of some events are scheduled to avoid the most detrimental meteorological conditions (BBC Sport, 2019).

The International Association of Athletics Federations has held a season-long track and field athletics series known as Diamond League since 2010, with plans to continue developing the series in the future (IAAF, 2019). With events taking place in multiple European locations and additional international locations, Diamond League provides a global case study of the impact of local meteorological and air quality conditions on elite athletes, something that has rarely been studies outside of laboratory conditions (Giles and Koehle, 2013). In this paper we assess the impacts of meteorological variables (temperature, relative humidity, heat stress and wind speed) and air quality (O_3, NO_2 and particulate matter in the $PM_{2.5}$ and PM_{10} size fractions) upon athletic performance using a statistical approach.

1.1. Meteorological Impacts on Performance

Meteorological impacts on performance are often anecdotal, but a number of laboratory and marathon studies have shown that elevated temperatures over 9.9°C decrease performance (Ely *et al.*, 2007; Helou *et al.,* 2012; Vihma*,* 2010; Vugts, 1997). This is due to alteration in circulatory, endocrine and thermoregulatory systems during exercise to reduce the likelihood of negative effects caused by increased internal body temperatures (Casa, 1999; Miller-Rushing *et al*., 2012; Nadel, 1990). Internal body temperature increases and can result in dehydration, hyperthermia and heat stress and occur due to the cardiovascular system giving precedence to maintaining blood flow to vital organs during exercise (Casa, 1999; Nadel, 1990). Consequently, the rise in internal body temperatures results in higher blood lactate levels within contracting muscles and reduced maximal oxygen uptake, contributing to fatigue and reduced power output of functioning muscles (Nybo *et al*., 2014; Zhao *et al.*, 2013; Miller-Rushing *et al.,* 2012). Reduced temperatures can limit internal core temperatures and improve performances to an extent, although extreme cold results in reduced blood supply and cardiorespiratory capacity (Oksa *et al*., 2004; Weller *et al*., 1997). Marathon performances have often been examined in relation to the impact of temperature on competitors, with several studies confirming that increased temperatures result in slower finishing times and determining that temperatures in the range of 3.8-9.9°C are ideal (Helou *et al*., 2012; Vugts, 1997).

After temperature, relative humidity has been identified to be the next most influential meteorological variable on performance (Bigazzi, 2017). Reduced heat dissipation under high humidity levels results in difficulty in maintaining optimum core body temperatures as previously examined, with the negative impacts of which being identical (Casa, 1999; Helou *et al*., 2012; Nadel, 1990). The combined influence of increased temperatures and relative humidity, otherwise termed heat stress, can also heighten the risk to health as well as athletic performance due to the combined stress this puts on the body (Maughan *et al*., 2007a).

Wind direction, speed and chill can influence performance. Head- and tail-winds are likely to reduce and improve performance, respectively, due to increased resistance or additional propulsion (Davies, 1980). However, this has not always been shown in previous research due to variability in wind directions experienced during the race and the lapped nature of many events, particularly those held on athletics tracks (Vihma, 2010). In events which have both head- and tail-winds, it is likely that the former will be more detrimental than the latter is beneficial (Davies, 1980). Similarly, the cooling effect of wind can help maintain optimal core temperatures in elevated temperatures but can lead to reduced performance in colder conditions as blood flow is diverted from contracting muscles to help maintain core temperatures and vital functions (Maughan *et al*., 2007*a*). Finally, Hodgson *et al*. (preprint), determined that local meteorology, particularly a combined influence of increased temperature, relative humidity and wind speeds, could be detrimental to the performance of the general public's performance in timed 5 km events (parkrun).

1.2. Air Quality Impacts on Performance

The majority of research on air quality and athletic performance has been conducted in highly controlled laboratory settings to allow for greater control of variables (synthesised in Giles and Koehle, 2013). Although findings are mixed, there is agreement that higher intensity exercise sees an increased potential for pollution uptake due to a switch from nasal to oral breathing and reduced respiratory defences (Giles and Koehle, 2013; Muns *et al*., 1995; Niinimaa *et al*., 1980; Ultman *et al*., 2004). Also, research has shown that increases from an average walking speed of 2-6 km/h to jogging and running and cycling 10 km/h quicker can more than double the inhalation dose of pollutants due to increased inhalation and exposure to pollution (Bigazzi, 2017; Lichter *et al*., 2017).

Several studies have highlighted that O_3 can reduce performance, likely due to reduced lung function and irritant qualities (Carlisle and Sharp, 2001; McKenzie and Boulet, 2008; Rundell and Caviston, 2008; Rundell, 2012). This irritant quality of O_3 and other pollutants can trigger asthma attacks, a common respiratory condition in both the general public and elite athletes, with exercise also enhancing the negative impacts of pollution (Folinsbee *et al*., 1994; Lippi *et al*., 2008; McCreanor *et al*., 2007; McKenzie and Boulet, 2008; Rundell, 2012; Weinmann *et al*., 1995). The same has been shown with PM exposure impacting on lung function (Cutrufello *et al*., 2011; Rundell and Caviston, 2008; Rundell *et al*., 2008; Rundell, 2012). Furthermore, research has shown that pre-exposure to pollution, as well as exercise performance in polluted conditions, can reduce VO_2 max (Florida-James *et al*., 2011; Kargarfard *et al*., 2015).

As with real-world examination of meteorological effects, little work on the actual impact of air quality on athletic performance has been conducted. Of this, the most notable is that of Marr and Ely (2010) and Helou *et al*. (2012) who both examined yearly marathon finishing times. Results suggest that PM_{10} is detrimental to female performance whilst O_3 is the most common inhibitor to quick finishing times. This latter result corresponds well with the findings of Hodgson *et al*. (preprint) and the examination of parkrun finishing times over a six year period. However, both studies noted that the reduction in performance under elevated O_3 levels is likely tied to the commonly associated temperature increases as well as the pollutants irritant qualities. Additionally, Hodgson *et al*. (preprint) showed in a number of instances that higher NO_2 concentrations saw improved performances, again likely tied to the O_3-VOC-light-NO_x chemical reaction and reduced temperatures. The influence of PM was often unclear or insignificant, although this is thought to be due to the highly spatially variable nature of the pollutant and distances between monitoring sites and parkrun events.

To support this, a long-term study of the German professional football league has shown a causal relationship between local PM levels and player productivity (Lichter *et al*., 2017).

In summary, there has been limited real-world examination of the impacts of meteorology and/or air quality on athletic performance, and what has been performed has largely been focused on elite marathon competitors (Helou *et al*., 2012; Marr and Ely, 2010; Vihma, 2010). However, our recent study examined the impact of both on the general public over 5-kilometer events, highlighted the need to recognise that meteorology and air quality and not separate parameters for investigation (Hodgson *et al*., preprint). For example, the aforementioned variations in O_3 and NO_2 levels in response to elevated temperatures and sunlight and the impact of relative humidity and wind speed on PM. Consequently, meteorology, and by further extension, climate, and air quality are intrinsically linked, with the combined effect of elevated temperatures and pollution contributing to an approximate 423-769 additional deaths during the 2003 UK heatwave (Donnelly *et al*., 2016; Stedman, 2004). There have also been recent deaths during athletic events held in extreme temperatures, for example, the Belfast and London marathons (mostly competed by the general public) and also serious medical incidents concerning elite athletes, such as the infamous case of Jonathon Brownlee collapsing in Cozumel, Mexico in 2016 during the triathlon Grand Final and Scottish marathon runner Callum Hawkins during the 2018 Commonwealth Games held on the Gold Coast, Australia (BBC Sport, 2016; 2018; BBC, 2018; The Guardian, 2018). As a result, and with predicted increases in global temperatures, the relevance of this research for both the health and safety of elite athletes and recreational exercisers is increased (Trundle *et al*., 2015). This study therefore addresses the need to examine how local meteorology and air quality can affect elite athletes to better inform event scheduling and safeguard both elite and recreational exercisers.

2. Data and Methodology

This research follows a similar approach to our previous investigation into the influence of local meteorology and air quality on the performance of the general public at parkrun events in Greater London (Hodgson *et al*., preprint). In this paper, the focus is on the 5 km running event, which requires maximal oxygen uptake (VO_2 max, or the maximum amount of oxygen a person can utilise during exercise), to determine whether elite athletes are influenced by variations in local air quality and meteorological conditions. Furthermore, this allows for a direct comparison to our previous work examining the influence of meteorology and air quality on recreational runners over the same distance.

Diamond League events are relatively consistent in their held locations over the season, travelling to various major cities, although there is a strong European presence. Finishing times for eight events/locations that have multiple years' worth of data have been collected from the IAAF Diamond League results archive, as well as a solitary event from Doha in 2010

(Figure 1). Events in Rome, Eugene, Rabat and Monaco, although hosting 5 km events, have not been included in this analysis due to a lack of readily available meteorological or air quality data. As well as finishing times of all 5 km participants, official start times of events and notation of whether it was a male or female event were also recorded to allow for accurate pairing of race times to local meteorological and air quality measurements, along with examination of male and female data subsets, as performed by Marr and Ely (2010). It is noted, that Diamond League events do not necessarily have the same races for males and females on the same day, or even same year, for individual locations.

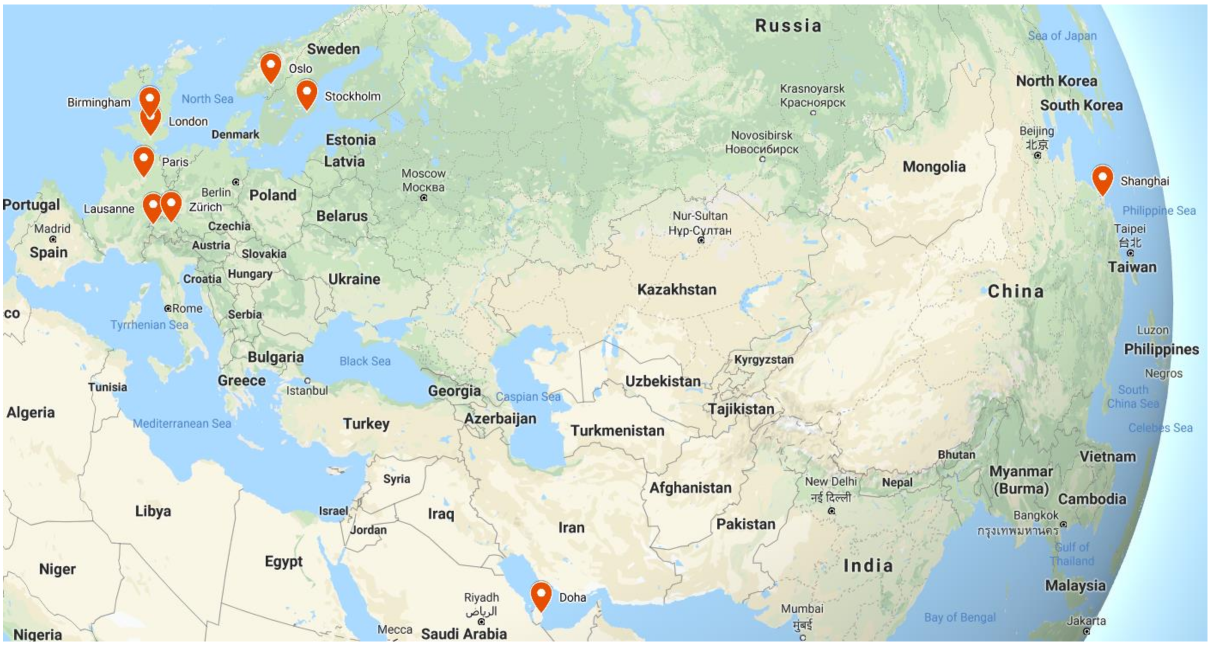

Fig 1 Map of Diamond League locations used in the analysis.

The meteorological data used for analysis has either been retrieved through the worldmet package in R (Carslaw, 2018), or (where available) official data used by national monitoring bodies. Monitoring locations were selected due to their proximity to event locations and ability to provide hourly readings of temperature, relative humidity and wind speed. Air quality and meteorological data was acquired from the following local authorities, MeteoSwiss (Switzerland), Oslo Kommune (Norway), AirParif (Frane), The Department for Environment, Food and Rural Affairs (UK) and The Swedish Meteorological and Hydrological Institute (Sweden) for data provision. Again, air quality monitoring sites are chosen for their proximity to Diamond League events to minimise the chance of spatial variation in pollutants influencing analysis and, where possible, includes hourly measurements of O_3, NO_2, PM_{10} and $PM_{2.5}$. How representative the air quality data for the Diamond League event needs to be considered. O_3 is generally a regional pollutant with less variability compared to NO_2 and $PM_{2.5}$, which are more likely to be influenced by local sources and may have greater potential for discrepancies between monitoring and event locations. For multiple linear regression analysis, PM_{10} has been removed from analyses due to its high correlation to

$PM_{2.5}$ and the higher association of the latter pollutant with deleterious health effects. A summary of the acquired data for Diamond League events, meteorology and air quality can be seen in Table 1.

Table 1. IAAF Diamond League events examined, along with the corresponding availability in local air quality and meteorology data. It is important to note that there is only a single (male or female) 5K race held at each event, e.g. London 2011 only has a female race, whilst 2013 is a male race.

Event	Years	O_3	NO_2	PM_{10}	$PM_{2.5}$	Wind Speed	Temp	RH
London	2011, 2012, 2014-2016, 2018	All years	All but 2012	All but 2015	All years	All years	All years	All years
Birmingham	2011, 2013, 2015, 2016	All years	All years	2015, 2016	2015, 2016	All years	All years	All years
Paris	2010-2015	All years	All years	No data	No data	2010-2014	2010-2014	2010-2014
Zurich	2010-2014, 2016-2018	2018	2018	2018	2018	All years	All years	All years
Oslo	2010-2016	All years	No data	All years	All but 2014	All years	All years	All years
Doha	2010	No data	No data	No data	No data	All years	All years	All years
Shanghai	2010-2018	No data	No data	No data	No data	All but 2015 and 2017	All years	All years
Stockholm	2010, 2011, 2014, 2016, 2018	All but 2018	All but 2018	No data	2010, 2011, 2016	All years	All years	All years
Lausanne	2011, 2013, 2015, 2017, 2018	2018	2018	2018	No data	All years	All years	All years

Each Diamond League event was paired with the closest meteorological and air quality monitoring station and the closest average hourly reading to the event time was used. All data was checked for normality, homogeneity and kurtosis prior to analysis and was logged where necessary. As per Helou *et al.* (2012) and Hodgson *et al*. (preprint), a correlation analysis between finishing times and control variables was performed for the whole data set as well as individual events. This followed a preliminary analysis to investigate the role of gender due to the large differences between male and female finishing times. Next, linear regression was used to determine the extent to which the control variables influenced finishing times, as per previous marathon studies whilst multiple linear regression analysis examined the combined influence of meteorological and air quality variables on performance (Maffetone *et al*., 2017). Finally, post-test analyses were also performed using the following diagnostic tests; Quantile-Quantile, Scale-Location, Fitted vs Residuals and Cooks-Distance plots. To determine whether there were any significant differences between male and female events finishing times and the explanatory variables at the respective event times, a one-way ANOVA with suitable post-hoc tests was performed. This was also used to determine whether there were differences between the nine events response and explanatory variables, and was again looked at as a complete dataset and male/female subsets. The mean finishing times of successfully completed races and explanatory variable figures were also determined to aid descriptive statistics and one way ANOVA comparisons and analysis.

3. Results and Discussion

Overall Performance Analysis

Analysis showed that at both male and female events, higher wind speeds and temperatures resulted in slower finishing times whilst higher relative humidity saw correspondingly quicker events ($p=<0.01$) (Table 2 and Figures 2-4). The subsequent multiple regression analysis also indicated that higher temperatures slowed performances ($p=<0.01$ and $p=0.06$ for male and female events respectively). As noted already, the influence of wind and temperature on performance is to be expected, whilst higher relative humidity is thought to reduce heat dissipation and consequently lead to slower finishing times (Casa, 1999; Nadel, 1990). Despite this, at both the male and female events, temperature and relative humidity are negatively correlated, which explains the relationship shown between relative humidity and finishing times. Temperature is therefore the more influential parameter on performance and athletes are able to run faster in cooler but more humid conditions (Bigazzi, 2017). This has been previously shown by Daniels (2014), Helou *et al*. (2012) and Knechtle *et al*. (2019) examining marathon events, where each 5^{o}C increase in temperature will decrease performance by up to 1.6%. This is likely due to changes in athlete's circulatory and thermoregulatory systems to maintain a stable core body temperature (Casa, 1999; Ely *et al.*, 2007; Helou *et al.,* 2012; Miller-Rushing *et al.*, 2012; Nadel, 1990; Nybo *et al.*, 2014;

Vihma, 2010; Vugts, 1997; Zhao *et al.*, 2013). Athlete's core body temperature is likely to increase at a quicker rate than the aforementioned marathon studies because of the higher intensity exercise being performed, and thus metabolic heat produced during shorter duration events (Cheuvront and Haymes, 2001; Gasparetto and Nesseler, 2020).

Table 2. Linear regression coefficients and associated p-values between female and male finishing times and associated explanatory variables.

	Temperature	**Relative Humidity**	**Heat Index**	**Wind Speed**	**Ozone**	**Nitrogen Dioxide**	**PM$_{10}$**	**PM$_{2.5}$**
Female	1.86, p=<0.01	-0.32, p=<0.01	1.55, p=<0.01	5.35, p=<0.01	0.2, p=0.01	-0.28, p=0.07	1.24, p=<0.01	1.14, p=<0.01
Male	0.01, p=<0.01	-0.001, p=<0.01	17.6, p=0.02	0.001, p=<0.01	0.0001, p=0.49	-0.003, p=0.11	-0.001, p=0.54	-0.00002, p =0.89

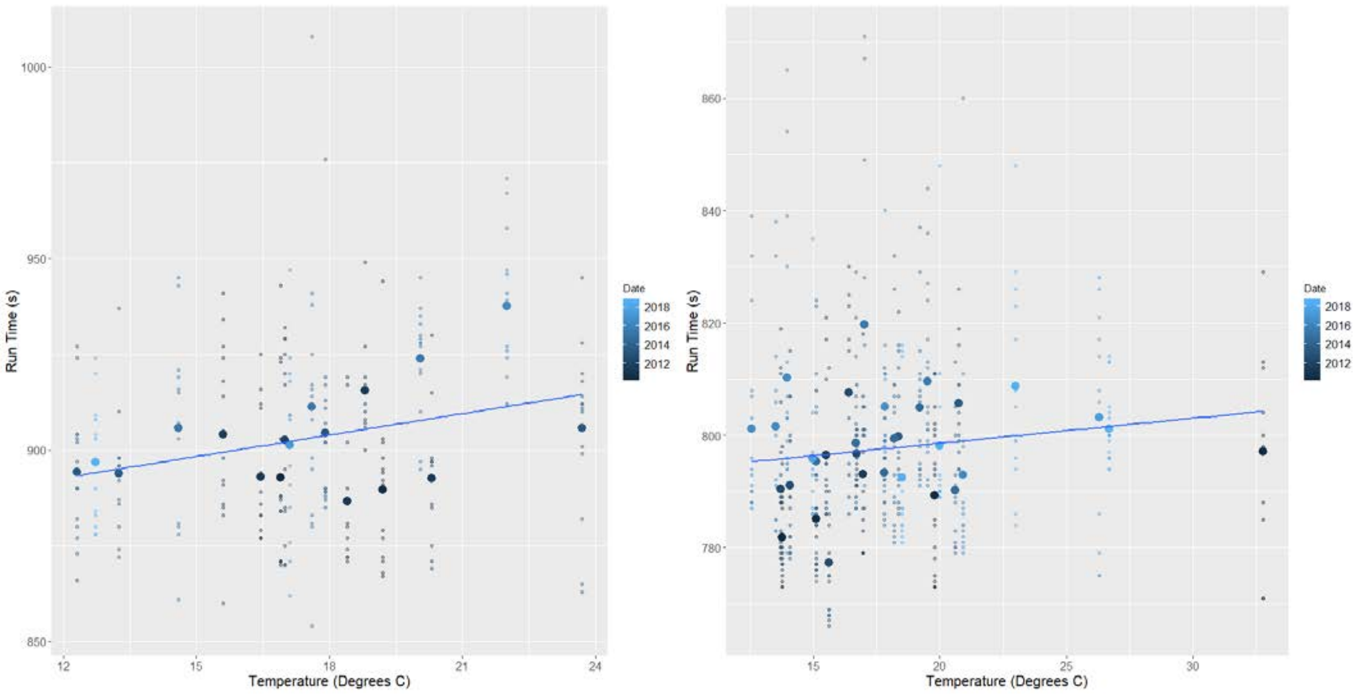

Fig 2 The effect of increasing temperatures on (left) female and (right) male races across the study period. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

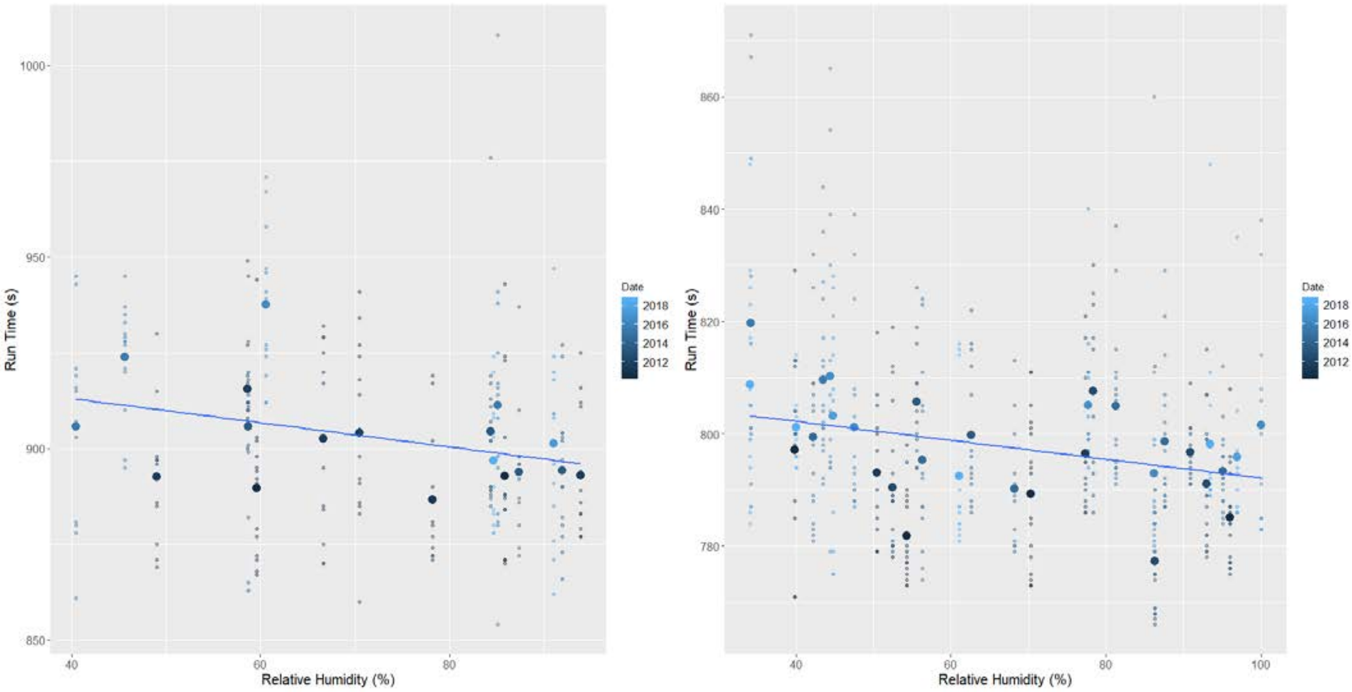

Fig 3 The effect of increasing relative humidity on (left) female and (right) male races across the study period. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

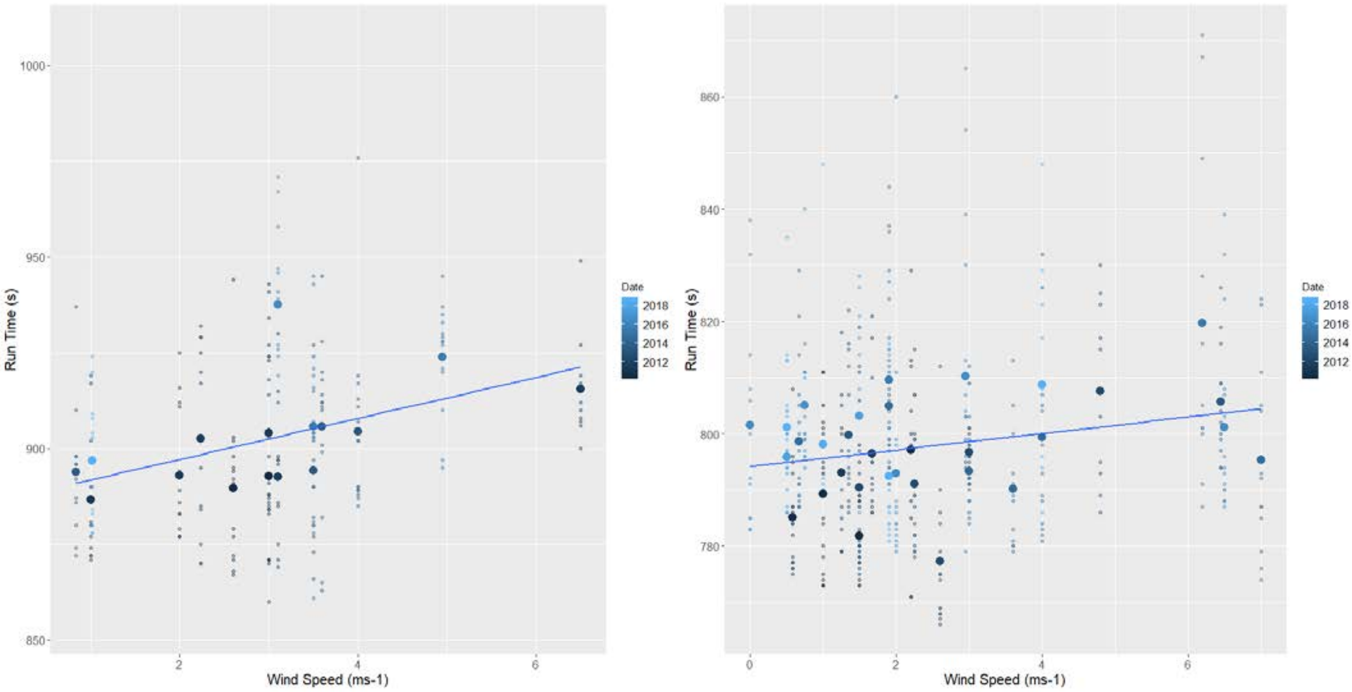

Fig 4 The effect of increasing wind speeds on (left) female and (right) male races across the study period. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

The combined influence of temperature and relative humidity was also calculated as a heat index using the weathermetrics package in R Studio (Anderson *et al*., 2013). For the male analysis, correlation, regression and multiple linear regression (heat index + wind speed) was detrimental to performance ($p=<0.02$). For female athletes, heat index also contributed to slower running times for correlation and regression ($p=<0.01$) and when combined with increased wind speeds was also detrimental ($p=0.06$). Consequently, the combined influence of variables is likely to increase core body temperatures of athlete's and limit heat dissipation, with heat stress being cited as a concern for health during exercise, particularly under future climate change scenarios (Miller-Rushing *et al.*, 2012; Morici *et al.*, 2020). These results also support those of Vihma (2010) and Knetchle *et al*. (2019) who suggested that despite difficulties in quantifying the effect of wind on performance due to its variable nature; head- and cross-winds will reduced running speeds. This is likely to be found at Diamond League events held on a standard 400m athletics track with potentially less of the distance covered per lap being assisted with a tailwind. Furthermore, any potential tailwind is unlikely to benefit athlete's in this circumstance overall as research has shown that head- and cross-winds are more detrimental than tailwinds are beneficial (Davies, 1980). The slightly reduced effect of heat index and wind speed on female athletes compared to male may be due to gender differences in heat dissipation. Core temperature control is greater for females due to a generally larger surface area to mass ratio and higher subcutaneous fat content (Gagnon *et al.*, 2009; Kaciuba-Uscilko and Ryszard, 2001). Female body mass is also likely to be lower due to physiological differences in stature, musculature and body fat percentages: which has been shown to be advantageous for running under increased temperatures (Cheuvront et al., 2002; Cheuvront et al., 2005; Marino *et al.*, 2000; Zouhal *et al.*, 2011). Females also have a higher running economy than males, which would lead to reduced heat production and less performance decreases over time (Billat *et al.,* 2001). Consequently, it can be hypothesised that under elevated heat index conditions, female athletes are producing less metabolic heat and also being cooled sufficiently by the wind to maintain a stable core temperature and suffer less of a performance decrease compared to their male counterparts (Maughan *et al*., 2007a; Maughan *et al*., 2007b; Maughan, 2010).

In addition to significant relationships with temperature, relative humidity and wind, female races also returned several other significant results (Figures 5 and 6). In terms of air quality, O_3 and both $PM_{2.5}$ and PM_{10} caused female athletes to also produce slower finishing times ($p=<0.01$, Table 2). The known impacts of air quality on physical health-decreasing lung and cardiovascular function, irritation of the respiratory system, chest tightness and reduced arterial pressure and vasodilation-are likely to have contributed to these results in female performances (Carlisle and Sharp, 2001; McKenzie and Boulet, 2008; Rundell and Caviston, 2008; Rundell, 2012). This is through a reduction in oxygen uptake and VO_2 max and increased perceived exertion levels (Florida-James *et al*., 2011; Giles *et al*., 2014; Giles *et al.,* 2018; Kargarfard *et al*., 2015). It should also be noted that the above air quality impacts would be heightened for those with cardiorespiratory conditions such as asthma (Cutrufello *et al*., 2011; Rundell *et al*., 2008). As asthma and exercise induced asthma is widespread within the elite athlete demographic, this may be a contributor to the results presented and should be carefully considered for elite sports events in the future (Folinsbee *et al*., 1994; Helenius *et al*., 1997; Langdeau *et al*., 2000; Langdeau and Boulet, 2001; Lippi *et al*., 2008; McCreanor *et al*., 2007; McKenzie and Boulet, 2008; Rundell, 2012; Turcotte *et al*., 2003; Weinmann *et al*., 1995).

Overall, these findings add additional insight into the potential role of air quality in previous research that has shown temperature to be the biggest environmental influencer on athletic performance (Ely *et al*., 2007; Helou *et al*., 2012; Marr and Ely, 2010). Similar results for the male races were not observed. The reason as to why female athletes are more influenced by air quality than male athletes is currently unclear but was also shown by Marr and Ely (2010) with PM_{10} increases of $10 \mu g/m^3$ reducing performance by 1.4%.

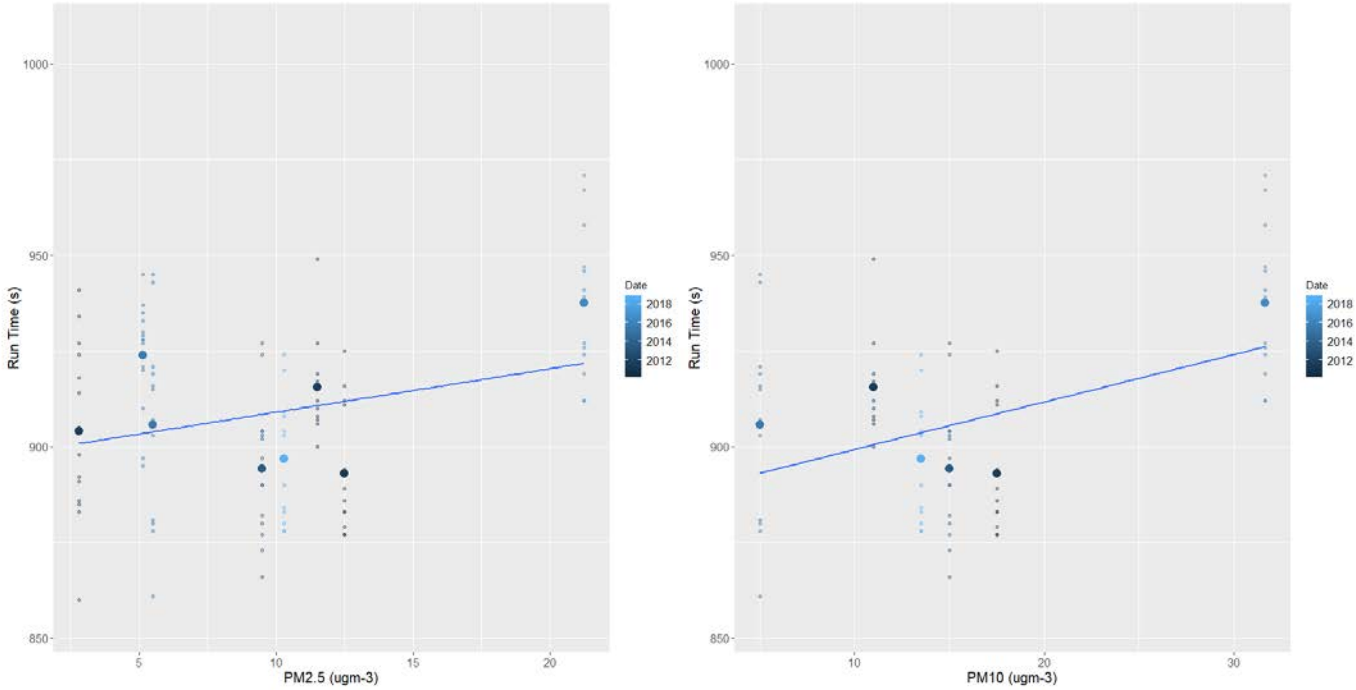

Fig 5 The effect of increasing $PM_{2.5}$ (left) and PM_{10} (right) male races across the study period. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

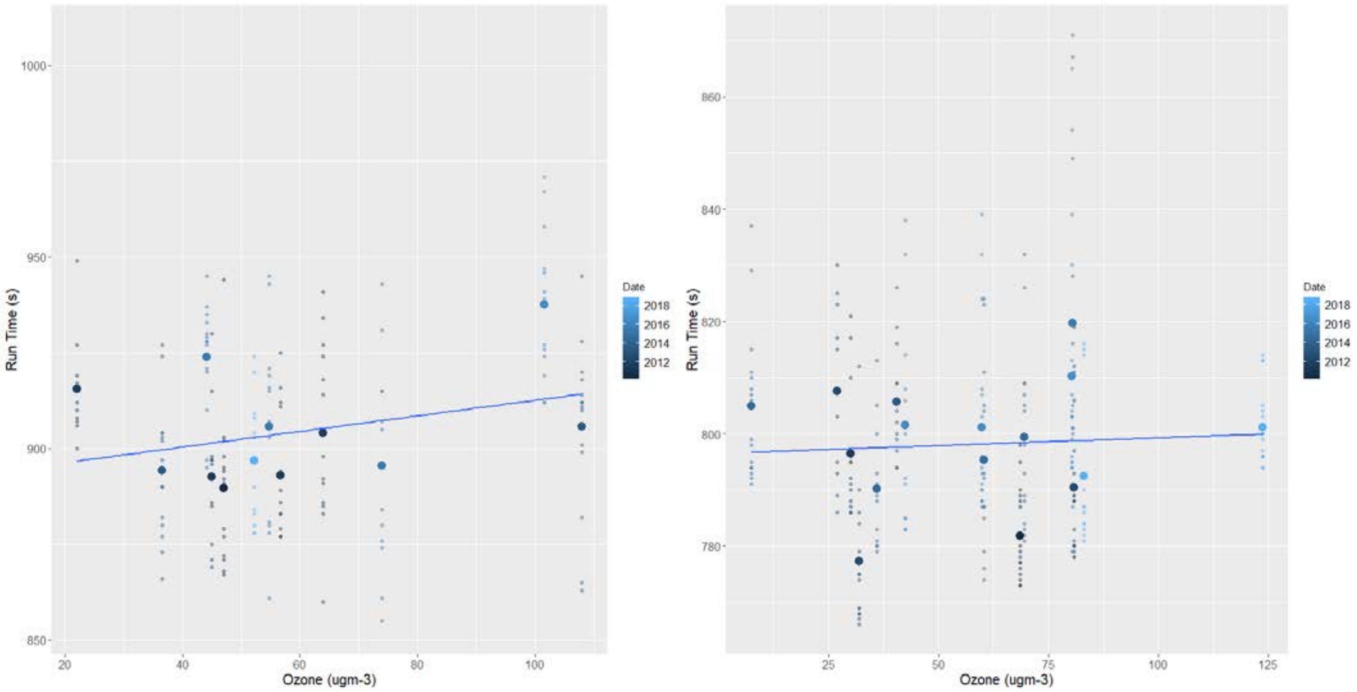

Fig 6 The effect of increasing ozone on female (left) and male (right) races across the study period. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

3.1. Individual Events

Events at the nine individual locations were also analysed to determine whether individual locations showed relationships between finishing times and the explanatory variables. A one-way ANOVA was subsequently performed to determine whether differences in finishing times across the nine events could be explained by variations in the explanatory variables.

The mean finishing times of the male and female events are shown in Table 3. The fastest two events for both genders were Paris and Oslo respectively. Zurich is the third quickest female event and fourth for the male subset, with Shanghai being fourth and third quickest. With the exception of Doha’s solitary race, the other four locations are slower than the mean finishing times. Interestingly, London and Birmingham are the second slowest and slowest events of the Diamond League series, the latter being over 35 s slower than the mean female time and nine seconds for male events. For the female events, the ANOVA further shows that London is significantly slower than the four quickest events (p=<0.01) and Birmingham is slower than the top four events as well as Stockholm that is also slower than the mean finishing time (p=<0.04). ANOVA analysis of the men’s events also shows a number of significant differences. Again, Birmingham and London are significantly slower than the quickest two events (p=<0.01) and Paris is also significantly quicker than Stockholm and Lausanne (p=<0.01).

Table 3. Mean finishing times of the nine Diamond League events.

Event	**Female Mean Finishing Time (s)**	**Male Mean Finishing Time (s)**
Paris	895.92	783.23
Oslo	897.36	792.97
Zurich	897.84	795.41
Shanghai	899.88	795.18
Doha	N/A	797.09
All Events	902.55	797.7
Stockholm	904.14	797.89
Lausanne	N/A	800.09
London	920.42	805.69
Birmingham	937.62	806.74

Table 4 below shows the linear regression results for the gender analysis of all the Diamond League events, followed by additional discussion of each location.

Table 4. Linear regression coefficients and p-values between finishing times and explanatory variables.

Location	Temperature	Relative Humidity	Heat Index	Wind Speed	Ozone	Nitrogen Dioxide	PM$_{10}$	PM$_{2.5}$
Paris Female	3.64, p=0.03	0.33, p=0.66	3.24, p=0.03	16.09, p=0.04	0.24, p=0.05	-0.57, p=0.31	N/A	N/A
Paris Male	2.57, p=0.01	-0.71, p=0.01	2.58, p=0.01	12.88, p=0.01	3.22, p=0.01	-0.92, p=0.01	N/A	N/A
Oslo Female	-0.03, p=0.99	-0.23, p=0.09	0.52, p=0.55	4.36, p=0.36	0.21, p=0.57	-0.26, p=0.29	-10.06, p=0.09	-1.87, p=0.12
Oslo Male	0.02, p=0.37	-0.001, p=<0.01	-0.99, p=0.53	0.002, p=<0.01	-0.002, p=0.09	-0.001, p=<0.01	-0.001, p=<0.01	-0.0002, p=0.49
Zurich Female	1.71, p=0.3	-0.39, p=0.26	1.78, p=0.33	5.71, p=0.26	N/A	N/A	N/A	N/A
Zurich Male	4.23, P=<0.01	-0.87, P=<0.01	3.95, p=<0.01	-2.52, P=0.28	N/A	N/A	N/A	N/A
Shanghai Female	-0.001, p=0.67	0.001, p=0.21	4.6, p=0.49	0.003, p=0.04	N/A	N/A	N/A	N/A
Shanghai Male	-0.0002, p=0.77	-0.0001, p=0.71	-0.31, p=0.8	-0.001, =0.65	N/A	N/A	N/A	N/A
Stockholm Female	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Stockholm Male	0.41, p=0.53	-0.11, p=0.29	0.29, p=0.67	0.45, p=0.62	-0.34, p=0.38	0.92, p=0.11	N/A	-24.37, p=0.04
Lausanne Female	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lausanne Male	49.42, p=0.12	-0.55, p=0.02	42.07, p=0.12	9.19, p=0.19	N/A	N/A	N/A	N/A
London Female	6.74, p=0.17	-0.65, p=0.17	8.43, p=0.17	-5.43, p=0.17	0.38, p=0.17	1.4, p=0.17	N/A	-1.33, p=0.17
London Male	-0.0004, p=0.09	0.00001, p=0.8	-0.63, p=0.08	0.001, p = 0.17	-0.00001. p=0.53	-0.00002, p=0.73	-0.004, p=0.29	0.004, p=0.29
Birmingham Female	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Birmingham Male	0.001, p=0.52	-0.0003, p=<0.01	0.55, p=0.73	0.002, p=0.02	0.0002, p=<0.01	-0.0003, p=<0.01	N/A	N/A

3.1.2. Birmingham

Birmingham is the slowest event of the Diamond League calendar and the male subset showed a number of significant results. More O_3 and windier conditions produced slower results (Figure 7), whilst higher levels of NO_2 and relative humidity were often conducive to quicker results ($p=<0.02$). This suggests that, in the case of Birmingham, the irritant qualities of O_3 can play a detrimental role during the 5 km event. In contrast, but similar to results of Hodgson *et al*. (preprint), NO_2 slightly improved finishing times, potentially linked to the reaction between O_3, VOCs, NO_2 and sunlight, with higher NO_2 levels occurring under lower temperatures.

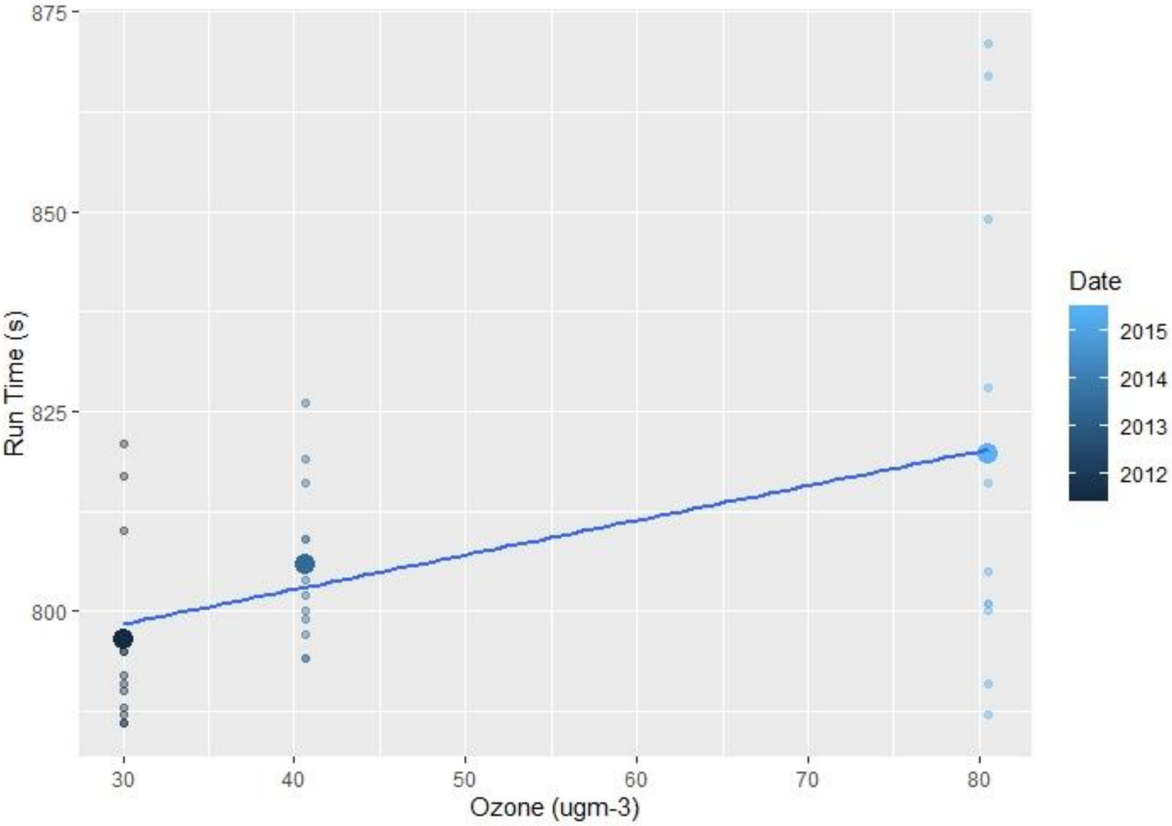

Fig 7 The effect of increasing Ozone levels on male races held in Birmingham. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

Birmingham showed significant and detrimental relationships with O_3, PM_{10} and $PM_{2.5}$ and temperature slowing finishing times ($p=<0.01$). Conversely, higher levels of NO_2 saw improved finishing times, likely due to the lower temperatures found under those conditions and highlighted previously ($p=<0.01$). Additionally, the highest mean levels of O_3 are found at these events, along with the second lowest NO_2 levels. Based upon previous research, these high O_3 and low NO_2 levels could be contributing to slower finishing times (Ely *et al.*, 2007; Helou *et al.*, 2012; Marr and Ely, 2010). Furthermore, the city registers the second highest PM levels on race times and is also the windiest event, significantly more so than several calmer locations ($p=<0.02$). Based upon these ANOVA and regression results, it appears that high O_3 and PM levels, coupled with low NO_2 and high wind speeds, is contributing to the slower finishing times at the Birmingham races.

3.1.3. Doha

Doha only had one event and was therefore not analysed independently.

3.1.4. Lausanne

No air quality data was available for the study period in Lausanne which also only had male events to analyse. There were no significant relationships between finishing times and temperature, relative humidity, wind speed or heat index. Generally, Lausanne has low wind speeds and relative humidity, but is the warmest event once Doha is discounted. Consequently, it is suggested that the high temperatures and low cooling wind speeds are potentially contributing to Lausanne's mean finishing time being the third slowest – although this cannot currently be statistically proven and only provides a guideline to the impact of local meteorology on athletic performance.

3.1.5. London

For the gender subsets of events held in London, there were no significant relationships shown. Despite this, London, along with Birmingham, was the slowest event for male and female athletes, significantly so compared to the other six locations ($p=<0.08$). The conditions athletes were competing in also included the highest O_3, NO_2, PM_{10} and $PM_{2.5}$ levels. For PM, London's levels were significantly the highest ($p=<0.01$). These combined pollutants and their irritant qualities are likely to have slowed performances to an extent in the London events (Cutrufello *et al.*, 2011; EEA, 2013; Rundell and Caviston, 2008; Rundell *et al.*, 2008; Rundell, 2012).

For female races, London is the second slowest event, but has significantly low O_3 levels ($p=<0.02$) and higher NO_2 ($p=<0.01$). Along with Stockholm, London has the lowest levels of PM ($p=<0.09$) and is the windiest event. From this, there isn't necessarily a clear picture as to why London's female races are on the slower end of the spectrum, due to the low O_3 and PM levels. The main explanation could be the high wind speeds of 5.6 ms^{-1}. Although this isn't significantly higher than other locations, it may be enough to contribute to the decreased running speeds as shown by Davies (1980).

3.1.6. Oslo

The male subset in Oslo only showed three significant results, generally, finishers are quicker under elevated NO_2 (Figure 8), relative humidity and PM_{10} concentrations ($p=<0.01$). For female events, higher relative humidity and PM_{10} produced quicker results ($p=0.09$). Oslo is the second quickest event for male and female races, and often has cooler and more humid conditions, which would promote fast times and correlates well with previous research (Hodgson *et al*., preprint). The PM results are not to be expected due to the irritant nature of the pollutant, however (EEA, 2013).

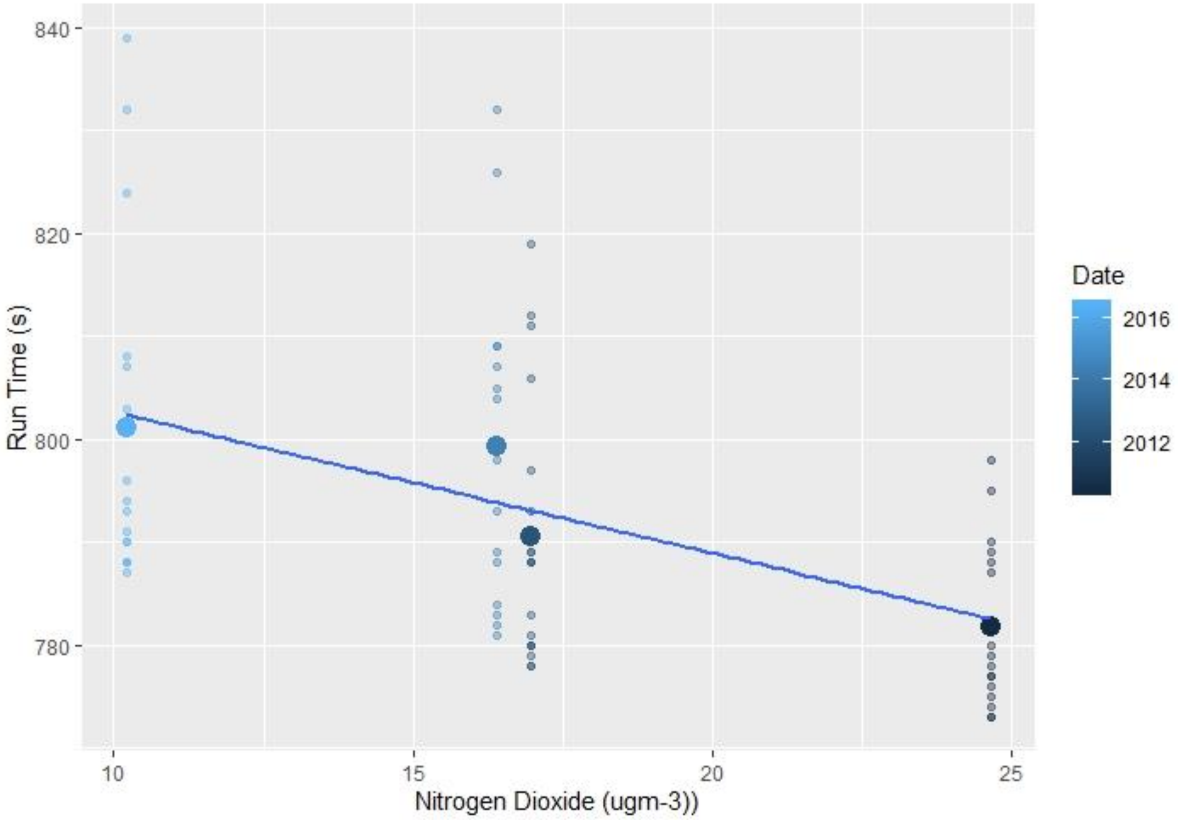

Fig 8 The effect of increasing NO_2 levels on male races held in Oslo. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

3.1.7. Paris

The male subset at Paris also showed a number of significant results. Higher O_3, temperatures and windy conditions produced slower results, whilst increased levels of NO_2 and relative humidity improved performances ($p=<0.02$). Heat index results also suggest that under combined high temperatures and relative humidity performances are slower ($p=0.01$). The female subs*et al*so showed the same impacts of those three variables ($p=<0.05$) and mirrors previous research findings (Casa, 1999; Ely *et al*., 2007; Helou *et al.,* 2012; Hodgson *et al*., preprint).

From ANOVA analysis, Paris is the quickest event for male and female mean times when compared to a number of the slower locations. Paris has the lowest O_3 and highest NO_2 levels, significantly so when compared to the highest and lowest locations respectively (p=<0.01). Consequently, this may explain why the male event at Paris is the quickest of the nine. However, for female events, pollutant and meteorological conditions don't show any significantly high or low values for Paris.

3.1.8. Shanghai

Shanghai only has meteorological data available and the male subset showed no significant relationships whilst female events are slower under windier conditions (p=0.04, Figure 9). This reduction in running speed under higher wind speeds is to be expected (Davies 1980). The lack of significant relationships with temperature or relative humidity could be attributed to Shanghai not having particularly high or low temperatures, instead having the highest relative humidity of around 90%. Shanghai is also around the mean run time of all events, suggesting that the meteorological conditions are not extreme enough, in a detrimental capacity, to have a clear impact on the overall finishing times compared to other locations.

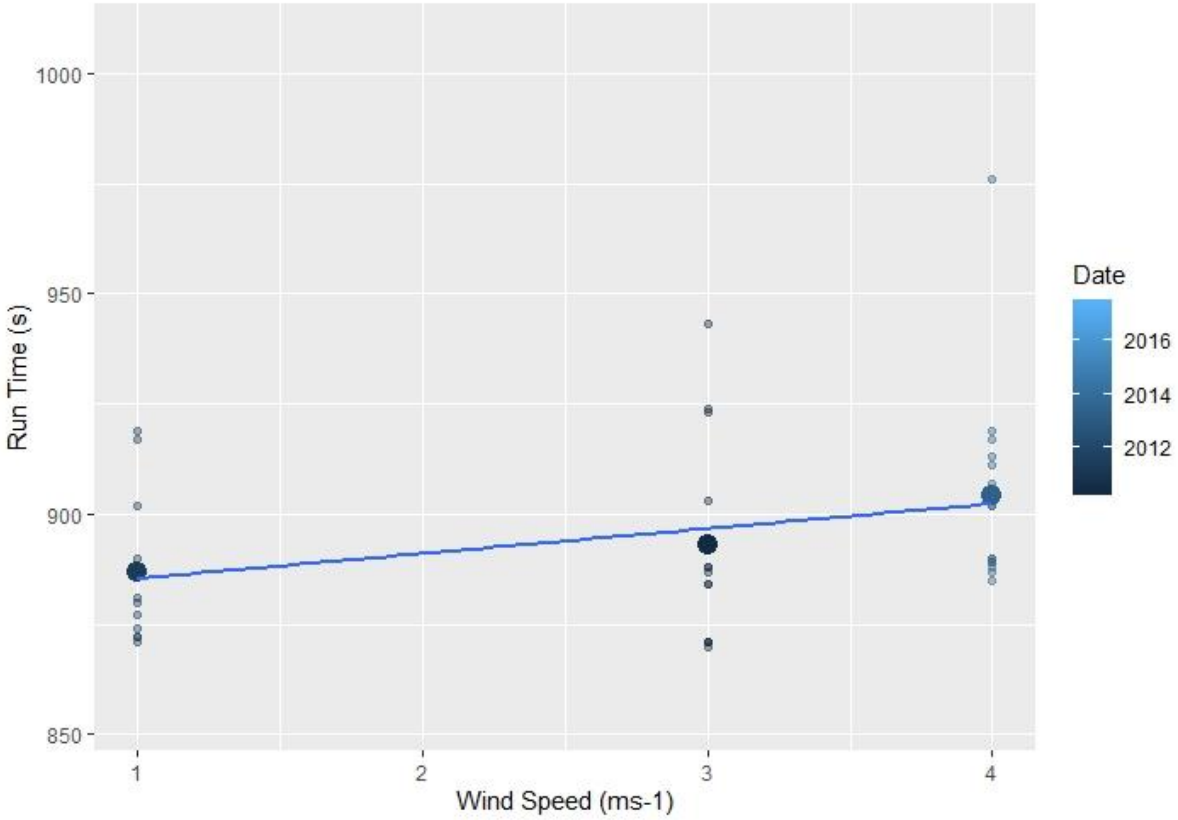

Fig 9 The effect of increasing wind speeds on female races held in Shanghai. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

3.1.10 Stockholm

For the male subset at Stockholm, only $PM_{2.5}$ had a significant relationship with finishing times, improving them under elevated levels ($p=0.04$). There were no female events to analyse. Despite this unusual relationship with $PM_{2.5}$, Stockholm generally has the lowest readings at its events ($p=<0.03$) as well as significantly low NO_2 levels ($p=<0.05$). O_3 concentrations are also low. Temperature, relative humidity and wind speeds are not particularly extreme in either direction, suggesting that other factors may be influencing performance or that in this instance, the meteorological and air quality conditions are not great enough to impact elite athletic performance.

3.1.11. Zurich

Zurich’s male subset conformed to previous research with higher temperatures slowing performances, whilst relative humidity was beneficial ($p=<0.01$, Figure 10). Heat index was also detrimental to performance ($p=<0.01$). The female subset showed no significant results. Generally, Zurich is one of the colder and more humid events, as well as having the lowest wind speeds ($p=<0.01$). This could suggest that under 'normal' conditions Zurich is below an optimum race temperature for sufficient muscular performance as well air density being higher and thus providing increased resistance. Also, without air quality data, full conclusions as to the influence of variables on performance cannot be drawn.

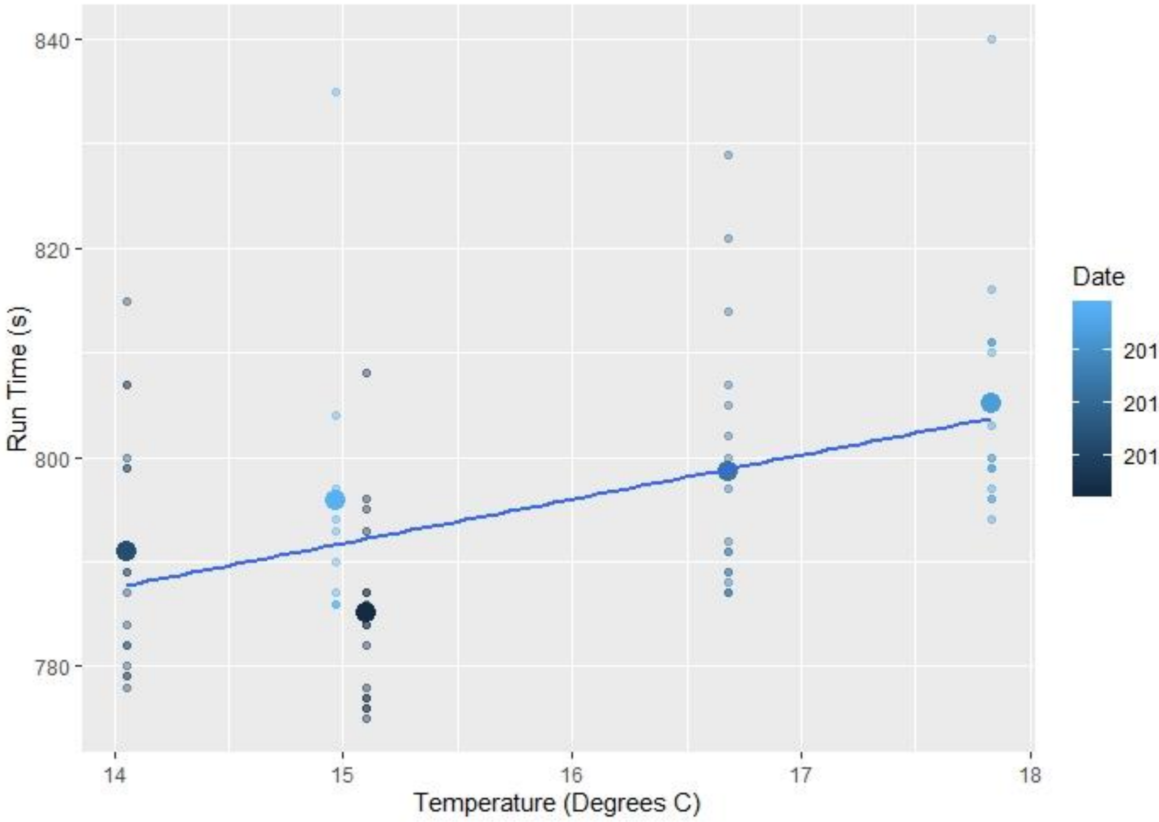

Fig 10 The effect of increasing temperatures on male races held in Zurich. The smaller points show the individual finishing times whilst the largest points are the mean time for each race.

4. Summary and Practical Applications

Overall, there is a lot a variability in results when examining different locations that host Diamond League events. This is to be expected with distances between events and monitoring locations and the highly spatial variability of pollutants, particularly PM and NO_2 (Duyzer *et al.*, 2015; Ferradas *et al.*, 2010; Kaur *et al.*, 2005; 2007). With respect to meteorology, windier conditions and higher temperatures are most detrimental to performance, with the latter inversely correlated with relative humidity and quicker finishing times coming from events with low temperatures and high relative humidity. With regards to track surfaces, Diamond League venues have to meet and maintain IAAF standards, so although there might be some small difference between track age and composition there is unlikely to contribute to vastly different running performances.

Paris and Birmingham show the most promising results. Paris has the quickest finishing times, whilst also having the lowest O_3 conditions and second highest NO_2 levels. Additionally, events are held under lower than average temperatures and regression results suggest that low O_3, temperatures and higher NO_2 levels will result in the quickest times. For Birmingham, the slowest event, high O_3, PMs and temperatures result in slower performances, and events are generally held under high levels of the first two variables. This potentially suggests that despite elite athletes training for high temperatures, they are not as well conditioned to high pollution levels, particularly PM, which will generally be low at high altitude training locations.

Although attention has previously been drawn to concerns regarding air quality at the previous Olympic Games held in Athens, Beijing and Rio, along with the methods used by host nations to improve conditions prior to events, there has to date been no consideration of the impact of environmental conditions on performances (De La Cruz *et al*., 2019; Donnelly *et al*., 2016; Florida-James *et al*., 2011; Wang *et al*., 2009). It is hoped that this research will prompt further investigation into the influence of air quality and meteorology variables on elite athletic performance and health, as well as scheduling events at times when pollution is lowest not only for athletes, but also spectators who will also be influenced by air pollution. This has previously occurred with regards to temperature with the (now) 2021 Tokyo Olympics endurance events being scheduled to avoid the warmest of temperatures, but additional mitigation measures could also be implemented (BBC Sport, 2019). For instance, road closures along and around events as well as the provision of public, active or 'green' transport options for spectators and officials may help reduce pollution levels at the event whilst Kosaka *et al*. (2018) suggested that increased shading along the Tokyo marathon route may reduce the likelihood of heat stress related medical incidents (Morici *et al.*, 2020). This is especially so when research has highlighted the positive relationship between increased temperatures, associated medical incidents and the total number of 'did not finish' participations (Carlstrom *et al.*, 2019; Khorram-Manesh *et al.*, 2020; Schwabe *et al.,* 2014). Given the research evidence, there is a real opportunity for organisers to consider making changes, not only from a health perspective, but also for PR as optimising environmental conditions will inevitably lead to an improved chance of new records adding to the legacy of the event.

Finally, with over half the world's population currently live in urban areas, the majority of whom are under air quality conditions that exceed the World Health Organisation's guidelines, consideration of not only elite athletic event locations and timings but also recreational exercisers should be considered (Hewitt et al., 2020; Marmett et al., 2020). Prior to the COVID-19 pandemic, participation at parkrun events (weekly, timed 5000m running events) and mass participation runs across a variety of distances were incredibly popular (Scott, 2021; Yankelson et al., 2014): parkrun reached over six million registered runners in 2019, Helou et al. (2012) showed that marathon entries increased over a ten year period and

Brocherie et al. (2015) also found a 26% increase in the American running population between 2007 and 2012 (Parveen, 2019). This has the potential for a greater number of people being exposed to harmful pollution levels, putting greater strain on population health, associated health services and productivity (Kumbhakar et al., 2021). This highlights the need for additional research into the effect of air pollution and meteorology on athletic performance and health, as well as the best methods to mitigate detrimental outcomes at local and international sporting events and during recreational exercise.

5. Conclusions

Following on from previous research into marathon studies and examination of parkrun events, this research has looked to examine the influence of meteorology and air quality on elite 5 km running performance at Diamond League events. Although analysis results vary across event locations, the influence of meteorological parameters correlates well with previous research and suggests that they are the most influential on elite athletic performance. Of pollutants, O_3 appears to be the greatest influencer on performance, with NO_2 seeing improved finishing times. This correlates with previous research and is likely linked to the relationship between these two pollutants, sunlight (temperature) and VOCs. Although specifically aimed at elite athletes, this study helps support research in the air quality and physical activity field, as well as providing insights into the timing of events for both elite and recreational athletes to best minimise potentially detrimental impacts on athletic performance as well health related effects of air pollution.

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