Front. Eng. Manag.
https://doi.org/10.1007/s42524-025-4029-y

RESEARCH ARTICLE

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Urban heat stress, air quality and climate change adaptation strategies in UK cities

Abstract Consistently threatened by climate change, cities need to adapt to emerging hazards and risks. One such risk relates to extreme heat, which is a particular problem in urban areas and is also linked to air pollution. Together, these risks can have a substantial impact on human health. Our analysis of air quality, ambient temperatures, and climate change adaptation plans in 30 UK cities found strong evidence that London and Cambridge exhibit the highest risk of both extreme temperature and air pollution. Furthermore, although a heatwave in London led to lower levels of PM_{10} and NO_2, it was highly correlated with increased levels of O_3, a low-level pollutant that exacerbates respiratory problems. We also found a lack of data availability (e.g., O_3, PM_{10}) in some local authorities and inconsistencies in their climate change adaptation strategies. We therefore identify a clear need for standardised assessment of hazards at the city level, and their incorporation into local adaptation plans. Further assessment of climate hazards and risks at the city level are required for effectively adapting to a changing climate in the UK and other cities worldwide.

Keywords climate change, cities, hazards, adaptation, heat stress, air quality

Received May 1, 2023; revised Oct. 12, 2024; accepted Dec. 8, 2024

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Open access funding provided by University of Nencastle upon Tyne.

1 Introduction

Cities (urban areas) around the world emit gigatons of Greenhouse Gases (GHGs) annually and are major drivers of climate change. Simultaneously, the specific characteristics of cities make their populations and assets particularly vulnerable to multiple, complex, and dynamic climate hazards (Smid and Costa, 2018). Large urban areas located near coasts and on riverbanks are vulnerable to hazards such as pluvial/fluvial flooding and sea level rise (CCC 2021; CCC, 2023). However, almost all urban and rural areas are highly vulnerable to the risk of heat waves, urban floods, drought, and air pollution (Gasper et al., 2011; CCC, 2023), and therefore require the capacity to adapt to a changing climate (IPCC, 2022). Adaptive capacity is the ability of systems and humans to adapt to potential damage caused by climate change or to respond to the consequences (IPCC, 2023a). The recent Climate Change Committee Report to the UK Parliament highlighted that there is limited evidence that adaptation planning and implementation by UK cities, communities and infrastructures is effectively dealing with risks such as flooding, coastal erosion, heatwave, and specifically the interactions between heat and air pollution (CCC, 2023).

Additionally, the relationship between urban and climate systems is dynamic and complex. For example, climate change can have direct impacts on the functioning of urban systems, such as through the urban heat island effect. However, because cities can also be affected by various other indirect climate change threats, we also need to assess the interrelationships between different hazards and multiple urban systems. Rapid urbanisation also increases the exposure to climate change hazards in urban populations, irrespective of global climate change (IPCC, 2022). As such, urban areas around the globe are focusing increasingly on adaptation planning across different sectors (Mendizabal et al., 2021). Risk identification, proposed adaptation measures, and climate actions determine the effectiveness of adaptation plans (Fig. 1).

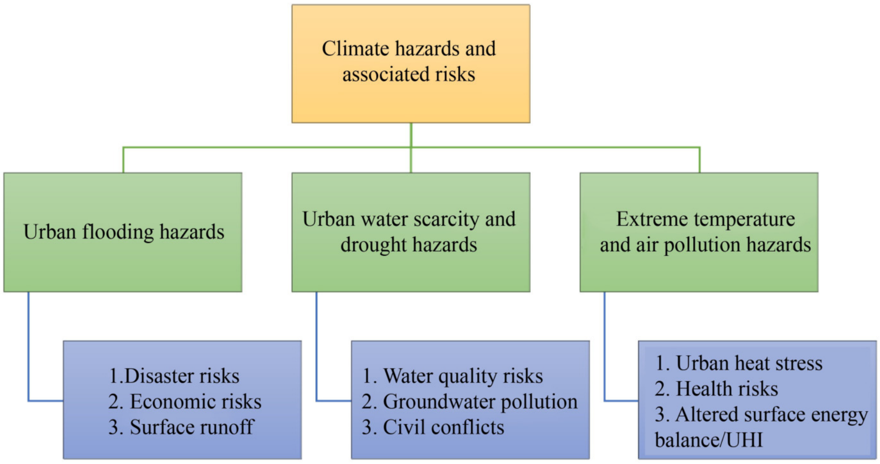

Fig. 1 Climate hazards and risks in cities and settlements (IPCC, 2022). Extreme temperature and air pollution hazards (in bold) are analyzed in this study.

The consistent monitoring and evaluation of these plans can help to assess the interrelationships between different hazards and multiple urban systems (Reckien et al., 2023; Buzási et al., 2024).

The urban heat island effect has long been recognized in cities and built environments, with temperature in urban systems being 5 °C–6 °C warmer than surrounding areas (Wilby, 2003). Urban areas retain more solar energy during the day due to having less vegetation cover and more building material, and experience lower rates of radiant cooling at night (Kamara et al., 2020). Urban areas also exhibit lower evapotranspiration and convective heat losses due to higher impervious cover and thus contributing to more surface warming. Additional heat in urban environments is released from various anthropogenic activities including transportation, industries, and air conditioning, thereby yielding variations in heat intensities (Wilby, 2008). Further, heatwaves in urban areas can increase air pollutant concentrations of ozone (O_3) (Susca and Pomponi, 2020). These pollutants are a consequence of combined high temperatures and solar radiation resulting in the production of photochemical smog in the urban atmosphere (Williams, 2012).

Observed trends in the UK have reflected an increase in climate induced hazards. Heatwaves have increased in duration during the past 10 years, while extreme cold events have decreased in terms of intensity and frequency. On the other hand, increase in the intensity and frequency of heavy rainfall has led to a higher number of very wet days. Overall, human-induced climate change has had a significant impact in terms of extreme temperatures and precipitation events in the UK (Guerreiro et al., 2018).

Annual variations in local weather, land use patterns, and difficulties associated with predicting the frequency and intensity of severe weather events make it difficult to investigate climate hazards in urban systems. Moreover, a complex mesh of drivers exacerbate the climate change risks that people and infrastructures are exposed to (Bozeman et al., 2023). This is particularly the case in cities and urban areas (IPCC, 2022) where hazards are unevenly distributed (Walsh et al., 2022). There are significant gaps in climate change adaptation across the world, and several critical gaps in the local adaptation plans of UK cities that impede implementation and progress (CCC, 2023). These relate to: the capacity to implement specific adaptation strategies for existing hazards, the ability to identify relationships between multiple hazards that exist simultaneously and to provide adaptation strategies for specific hazards at the city level (Buzási et al., 2024), and barriers to the dissemination of local knowledge to support implementation of adaptation strategies (Reckien et al., 2023). Moreover, levels of tropospheric ozone are often higher on very hot days; hence climate change can exacerbate the public health risks of air pollution; however, we do not know enough about whether and how cities may be considering these issues together. Therefore, this paper reports and analyses selected risks in the form of heat waves and air pollution across 30 UK cities and reports on how some of these cities have set out to address these risks in their climate adaptation strategies.

2 Background

2.1 Climate change impacts and risks in urban areas

Approximately, 4.2 billion of the world's population reside in urban areas (cities). Many of these cities are vulnerable and exposed to severe weather events that will become more extreme and frequent as climate change progresses (IPCC, 2022). Climate change risk is defined as the potential for occurrence of adverse consequences from climate change. It arises from dynamic interactions of climate change hazards combined with the exposure and vulnerability of the affected entities (IPCC, 2023a). Exposure is defined as the presence of resources, infrastructure and population in areas impacted by climate change or affected by climate change hazards directly or indirectly. Whereas vulnerability is the tendency or susceptibility of resources, infrastructure, and population that can be negatively affected by climate change impacts (IPCC, 2023b).

Natural resources, urban infrastructure, and financial capital can be damaged or severely affected by weather extremes (Walsh et al., 2022). Stress induced by climate hazards such as extreme heat, severe weather events, and air pollution can have immediate and long-lasting impacts on a population's physical and psychological health (Ballester et al., 2023). Moreover, urban infrastructures exacerbate the adverse health impact of climate hazards through the urban heat island effect, extreme precipitation or extreme drought, and reduction in natural drainage (Wilby and Dessai, 2010).

Different climate change impacts and risks in urban areas are closely connected to social and economic challenges (IPCC, 2022). For example, climate change will make it more difficult to address poverty, hunger, and resource demand in cities and urban areas by further straining resources (IPCC, 2022; Bozeman et al., 2023). Furthermore, the combination of these challenges with population growth, increasing demand for drinking water, food, and energy will magnify the social and economic impacts of climate change. Ultimately, it could alter the functioning of urban areas (Gasper et al., 2011; Mendizabal et al., 2021). Therefore, it is imperative to analyze climate risks and key vulnerabilities to people and infrastructure. The climate hazards included in this study are heat waves and urban air pollution, which are described in the following section.

2.2 Heatwaves and their impact on cities

The World Meteorological Organization (WMO) defines a heatwave as a phenomenon when a day's maximum temperature exceeds the average daily maximum temperature by 5 °C for a minimum five consecutive days. This definition is based on the normal measuring period from 1961 to 1990 (Kalisa et al., 2018). The surface characteristics of urban areas can alter temperatures; the geographical and spatial features of the built environment influence the intensity of heat wave events. As mentioned earlier, due to cities having less vegetation, 'urban heat island' (UHI) effect (Zaidi and Pelling, 2015) can take place. One common response to this is, an increased demand for building cooling mechanisms, which results in higher GHG emissions and further increase in outdoor air temperature (Kalisa et al., 2018).

Although heatwaves in the UK are currently rare (Howarth and Brooks, 2017), their intensity, frequency, and length are likely to be intensified due to changes in demography and future climate change. Indeed, 'urban heat risk' is already a prominent concern in UK cities, and the UK's third Climate Change Risk Assessment (CCRA 3) produced by its Climate Change Committee (CCC, 2021) predicts that heatwaves will become common by the 2040s and heat related deaths are forecast to triple relative to the 2020s. During a hot spell in August 2003, deaths in London increased by 42%, compared to an average figure of 17% over the previous five years. The study by Wolf and McGregor (2013) attempted to develop a heatwave vulnerability index for London. The study shows that 95th percentile temperature values of London demonstrate a noticeable interannual variability. In terms of heat risk, the studied years are shown to have maximum heat related health impacts in London. These anomalous 95th percentile temperature values provide evidence of the risk of extreme temperatures in London. A study conducted by Wilby (2003) for UHI effect also in London shows that the intensity of UHI depends on the maximum daily temperatures. June, July, and August are expected to exhibit maximum UHI intensity. Thus, Wolf and McGregor (2013) confirmed Wilby (2003) findings of the occurrence of maximum hourly temperatures in these months over a 12-year period (2010–2021).

2.3 Urban air pollution

Air pollution is one of the environmental factors that has the greatest impact on global health and mortality. As the major air pollutants in urban areas, tropospheric ozone (O_3), nitrogen dioxide (NO_2) and particulate matter (PM) pose adverse impacts on human health. Ambient concentrations of these three trans-boundary urban air pollutants are affected by local and regional emissions and their long-range air transport from upwind concentrations and the stratosphere (Doherty et al., 2009). Global background ozone concentration levels have increased due to rapid population growth, industrialisation, and vehicular expansion in urban areas. Annual averages of 8-h ozone concentrations in European and UK cities have also risen (Williams, 2012). The pattern of future GHG emissions and ozone precursor emissions have the potential to exacerbate existing climate hazards, and their concomitant health impacts in urban populations, by raising urban temperatures and increasing air pollution (Doherty et al., 2009). At the same time, concentrations of NO_2 often fall during warmer weather, due to a photochemical reaction in the atmosphere caused by the accumulation of other pollutants. A photochemical reaction requires NO_2 as a precursor in O_3 formation, when in the presence of sunlight. Thus, the concentration of oxides of nitrogen decreases with a rise in temperature, while forming O_3 as a product and a secondary pollutant (the following reaction:

$$NO_x + CO/VOCs + hv = O_3,$$

where, NO_x – oxides of nitrogen (NO_2), CO – carbon monoxide, *hv* – sunlight, and VOCs – volatile organic compounds.

Ozone is generated through a typical urban photochemical process on hot sunny days, associated with slow moving, stable and anticyclonic weather systems. This particular type of weather system impedes the movement of air pollutants in the boundary layer. Hence, high ambient temperatures can potentially result in higher concentrations of O_3 pollutants in the urban atmosphere. In one instance, 2,045 deaths were recorded in England and Wales due to the elevated O_3 levels above a threshold of 100 μg/m^3 in the heatwave of August 2003 (Doherty et al., 2009). This heatwave event swept across most of Europe, and climate change modeling studies suggested that the extreme temperatures experienced in the summer of 2003 will become the norm from 2060 onwards. Furthermore, the temperature inversion layer in the urban atmosphere retains a higher pollutant concentration compared to rural areas. This increases the health risk for urban populations. Strong solar radiation, high air temperatures and the presence of primary air pollutants such as volatile organic compounds (VOC's) and NO_2 are typical features of UHIs. These factors combine and start a complex chemical reaction to give rise to secondary air pollutants like O_3 (Susca and Pomponi, 2020)， albeit often accompanied by a fall in the level of NO_2 concentrations. Indeed, site-specific air quality studies in Europe have shown a perfect linear correlation between increasing O_3 concentrations and increasing ambient temperatures (Susca and Pomponi, 2020).

The adverse impacts of particulate matters (PM) on human health are widely known. PM are categorised into PM_{10} and $PM_{2.5}$ based on the diameter of the particulates in question. Sources of PM in urban areas include windblown dust, industrial emissions, and vehicular emissions (exhausts and brake/tire wear). PM is known to have adverse impact on respiratory and cardiovascular systems (Kirešová and Guzan, 2022). A few studies have investigated the correlation between the occurrence of heatwaves and elevated air pollutant concentrations for metropolitan cities. For example, correlations between temperature and air pollution (O_3, PM_{10}, and NO_2) have been studied for Birmingham (Kalisa et al., 2018). However, because interannual variabilities and correlations vary in different cities, it is important to assess the frequency and intensity of air pollution as a climate change hazard in a range of urban areas.

2.4 Urban areas and climate change adaptation strategies

The Organisation for Economic Cooperation and Development (OECD, 2009) defines climate change adaptation as a continuous process with frequent revisions in development plans, with policies and projects subjected to changing climate and socio-economic conditions. It emphasizes the importance of risks and vulnerability assessments for adaptation studies, as well as the need to combine urban development strategies with climate change policies. Integrating adaptation into development process requires an evolving framework in terms of urban development and dynamicity (Dawson et al., 2014). It should promote flexible and efficient adaptation strategies to address all forms of urban growth and development that can be utilized by the public, planners, stakeholders, and policymakers (Sanchez-Rodriguez, 2009).

Cities act as an interface between local, national, and international level climate change mitigation and adaptation strategies (Butt et al., 2022). Cities host more than 80% of the UK's population, a figure that is projected to increase by 3.2% in the next 10 years, reaching an estimated 69.2 million individuals (ONS, 2021) who may face increased exposure to climate threats (IPCC, 2022).

The UK's Climate Change Act (Committee on Climate Change, 2017) sets out the legislative framework to reduce GHG emissions and to adapt to the risks and vulnerability caused by the changing climate (UK Government, 2008). In terms of adaptation, the Act requires the government to undertake a country-wide assessment of risks and opportunities every five years and a National Adaptation Programme (The National Adaptation Programme, 2018) identifies and addresses climate change vulnerability and risks. The NAP is also reviewed every five years to increase resilience by setting out objectives, proposals, and policies to address climate risks. The NAP primarily concerns England, but similar programmes have been established for Wales, Scotland, and Northern Ireland. The NAP takes a sectoral approach to address the risks to natural environments, health and emergency services, agriculture and forestry services, businesses, and building and infrastructures (Walsh et al., 2022).

Local governments around the world have documented adaptation and mitigation activities in local climate plans as a way to mainstream these efforts within municipalities (Reckien et al., 2019; Butt et al., 2022). The UK is no exception; according to Heidrich et al. (2016), in 2015 approximately 80% of a sample of 24 Urban Audit (UA) UK cities had an adaptation strategy or adaptation framework documents. These municipalities report a range of risks and strategies to deal with the effects of climate change (Berrang-Ford et al., 2015; Adger et al., 2018; Reckien et al., 2023; Magnan et al., 2020), however there have been very little analysis of whether and how these strategies address the combined impacts of high temperatures and air pollution. Therefore, the aim of this research was to identify and analyze urban heat and air pollution risks using a systematic and methodological framework to assess associated adaptation plans published by selected UK cities.

3 Materials and methods

Two separate analyses were undertaken in this study. The first examines trends of temperature and pollutants across key UK cities over a decade, examining aggregated data over several months/years, followed by an assessment of each city's climate adaptation plan. The second focuses on the unique case study of London during its 2014 heat-wave; this was selected due to the data availability and importance of London as it is the capital and biggest city of the UK. Figure 2 presents an overview of the research design for this study.

We first selected 30 cities from the Eurostat database (Urban Audit- see below) and then retrieved the air quality data, temperature data, and adaptation strategies. We then explored the four aspects using data gathered from published climate change adaptation strategies/plans that were available from UK government and city council databases.

3.1 Urban audit cities in the UK

In this study, we assessed whether and how 30 UK cities are addressing the combined risks of extreme temperatures and air pollution in their climate adaptation plans. We selected our 30 cities from the statistics database of the "European Statistics Office (Eurostat)," which was previously known as the "Urban Audit" (Eurostat, 2019). The Urban Audit (UA) database is run by the European Commission and provides data on demography, housing, health, environment and education to enable comparative analysis of different EU cities. The cities are selected in close collaboration between the Directorate-General for Regional Policy, Eurostat and the national statistical institutes (Eurostat, 2010), according to the following rules set by (Eurostat, 2007); the cities in each country's sample should be home to approximately 20% of the national population; the database includes all capital cities and, where possible, also of regional capitals; including both, large (more than 250,000 inhabitants) and medium-sized (between 50,000 and 250,000 inhabitants) cities. Ultimately the cities selected in the UA should be a representative sample of the cities in the country. The 30 cities chosen from the UA database represent around 17.3 million of the UK population (~29%) and include the capitals of the four countries of which the UK comprised: England, Northern Ireland, Scotland and Wales (Table 1). UA covers core cities, urban zones, and metropolitan areas in Europe and the UK, including 23 cities in England, 3 in Scotland, 2 in Wales and 2 in Northern Ireland. Notably, local government units in the UK are significantly larger than in any other European country, which means that data are not available for smaller towns: most UK municipalities have larger populations than some of those included in our selection (Stevenage, for example, has fewer than 90,000 inhabitants).

3.2 Data sources

Our assessment of climate hazards is based on the urban environmental indicators selected from the Eurostat database. Our data sources include air quality from DEFRA and local authorities, temperature from DEFRA and the Met Office (Met Office, 2022), and city adaptation strategies for policy analysis. Although there are clear crossovers between climate change mitigation and air pollution policies (Roggero et al., 2023), we focused solely on adaptation plans to examine whether and how the cities may be connecting these strategies with air quality concerns (for example, to address concerns around public health).

3.2.1 Adaptation strategy collection procedures

We collected and downloaded local adaptation strategies and other documentation by searching municipal

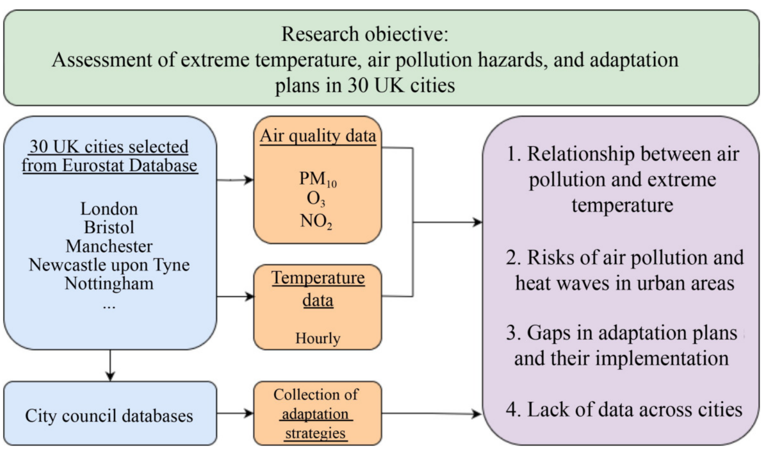

Fig. 2 Research design and objectives.

Table 1 The 30 core UK cities surveyed (Eurostat Urban Audit (UA) database). Size and population statistics are retrieved from Standard Area Measurements (SAM) published by Office of National Statistics (ONS, 2023) and population census by ONS (2021), respectively.

City	UK Country	Size (km^2) (ONS, 2023)	GHG emissions (kt CO_{2e} in 2022) (UK Government, 2023)	Population (Office for National Statistics, 2021)
Aberdeen	Scotland	186	1,165	221,200
Belfast	Northern Ireland	138	1,632	345,418
Birmingham	England	268	4,316	1,121,408
Bradford	England	366	2,009	333,931
Bristol	England	110	1,570	425,232
Cambridge	England	41	540	145,700
Cardiff	Wales	141	1,707	362,400
Coventry	England	99	1,293	344,322
Derry	Northern Ireland	1,251	1,634	85,279
Edinburgh	Scotland	263	2,192	514,990
Exeter	England	47	461	126,156
Glasgow	Scotland	175	2,607	635,130
Gravesham	England	99	402	106,900
Kingston upon Hull	England	71	1,031	270,806
Leeds	England	552	3,693	536,321
Leicester	England	73	1,361	406,588
Lincoln	England	36	351	103,813
Liverpool	England	112	1,746	506,552
London	England	1,572	28,400	8,776,535
Manchester	England	116	2,141	470,411
Newcastle upon Tyne	England	113	1,307	286,468
Nottingham	England	75	1,334	299,797
Portsmouth	England	40	753	223,312
Sheffield	England	368	2,211	500,552
Stevenage	England	26	363	94,456
Stoke-on-Trent	England	93	1,136	260,602
Wirral	England	157	1,125	320,200
Wolverhampton	England	69	974	234,015
Worcester	England	33	361	105,455
Wrexham	Wales	503	1,097	135,100

websites (but not those of higher-level bodies such as county councils or regional strategies), in particular their environment, sustainability, energy and/or climate departments (or equivalent) and examining their policy and planning strategies and documents. Where feasible we conducted additional desktop and internet searches or contacted the Local Authorities, city representatives or the relevant departments directly. For the desktop and internet search, we used a common search engine (Google, Yahoo or equivalent) and followed the search procedures e.g. ‘climate’ and ‘adaptation’ in the title, local authority name, subtitle or introduction and the scope was then widened to all dedicated ‘climate’ documents.

3.2.2 Air quality data

Air quality data was collected by contacting the authorities, and through the Department for Environment, Food and Rural Affairs (DEFRA) website, downloading material from municipal websites or gathering strategies from data depositories (European Local Climate Plans, 2020). Urban indicators for assessing air pollution hazards were O_3 concentration (μg/m^3) and annual average concentration of PM_{10} and NO_2 (μg/m^3). These were extracted from the UK Air Information Resource (AIR), an archive database published by DEFRA that includes data from 1972 to 2022 (DEFRA, 2019). The data type for O_3 was selected as daily max 8-h ozone, and daily mean for PM_{10}

and NO_2. The UA cities of Worcester, Gravesham, Stevenage, and Wolverhampton were not included in the NO_2 monitoring network of DEFRA. Therefore, 'Air Quality Annual Status Reports' published by these local authorities were used for NO_2 monitoring data (City of Wolverhampton Council, 2022, Worcestershire Regulatory Services, 2022, Gravesham Borough Council, 2022, and Stevenage Borough Council, 2022). PM_{10} monitoring data for Lincoln, Bradford, Stevenage, and Worcester was downloaded from city council websites (City of Lincoln Council, 2022 and City of Bradford Council, 2021). The date range was defined from 1st January 2010 until 31st December 2021, providing us with 12 years of data. The Supplementary Material (ESM) illustrates the annual average concentration of air pollutants (PM_{10}, NO_2 and O_3) in the 30 UA cities (ESM Table S1).

3.2.3 Temperature data

The urban indicators considered for assessing heatwaves used the hourly measured temperature data for 30 UK cities from the UK-AIR database published by DEFRA (2019). The data type was selected as measured data to access hourly temperature data from 2010 to 2021 for each UA city. To illustrate annual variation, we converted hourly data for each year into annual average temperature (ESM Table S4). In the SI we also present the additional maximum monthly temperature data, based on the Met Office database archive of historic monitoring stations in the UK for the climate period 1990–2021 (ESM Table S2).

3.3 Data analysis

This research required data analysis to investigate the relationship between air pollutants and ambient temperatures in our selected cities. Initially, Microsoft Excel and IBM's Statistical Package for Social Sciences (SPSS) were used to generate descriptive statistics for annual averages, yearly variation, outliers, and standard deviation. Through this analysis, we observed a pattern of relationship between temperature data and air pollutants. We further hypothesized a linear relationship between temperature and air pollutants. Many studies have shown that fluctuations of certain air pollutants levels are associated with the variation in atmospheric temperature (Kalisa et al., 2018; Susca and Pomponi, 2020; Doherty et al., 2009). Thus, to measure a linear relationship, we conducted a Pearson correlation analysis to further investigate the relationship between varying temperature and air pollutants. Pearson correlation was selected as it specifically measures the strength and direction of a linear relationship between two continuous variables, that is temperature and air pollution in our study. Additionally, Pearson correlation is a suitable statistical measure when it is assumed that two variables directly influence one another.

The analysis was conducted using SPSS between hourly measured temperature and air pollutant concentrations in London during the UK's 2014 heatwave (Fig. 3). The Pearson correlation coefficients implied positive correlations between the variables. As a result, a regression analysis was conducted in SPSS, to assess how strongly the pairs of variables are related.

4 Results for climate adaptation planning in cities

4.1 Detailed analysis of temperature and heatwaves in selected cities

This research investigated whether and how the 30 UK cities address the potential impact of heatwaves and air pollution hazards in their climate adaptation plans. From the literature and our research, it is clear that extreme temperatures and resulting air pollution escalate risks to population health and burdens on city infrastructure. The assessment of these hazards gives some insights how to reduce such risks, adaptation strategies, and resisting

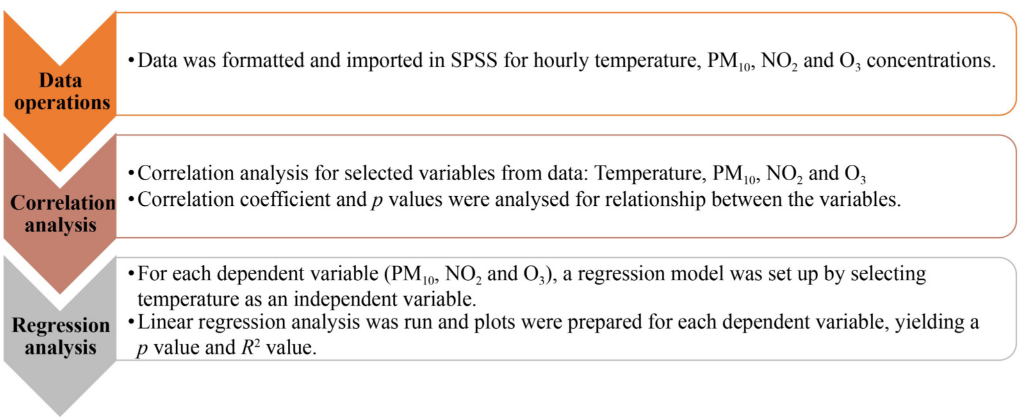

Fig. 3 Summary of analysis performed for hourly temperature and air quality data (PM_{10}, NO_2 and O_3).

climate shocks from UK, which is applicable to cities across the world.

Figure 4 shows that Portsmouth, London, Bristol, Cardiff, Exeter, and Cambridge have the highest mean annual temperatures, whereas more northern cities experience lower annual temperature ranges including Aberdeen, Glasgow, Stoke on Trent, and Edinburgh. Annual average temperatures of these cities suggest that heatwaves will be more frequent and severe in southern cities. However, temperature extremes (for example, during heatwaves) are not reflected in annual averages. Thus, a city-specific study for London (in the south) and Newcastle upon Tyne (in the north) will give plausible insights into the pattern of extreme temperatures.

Figure 5 shows the mean maximum measured temperatures in London over a period of 10 years. Most maximum temperatures in the months of January and December were scattered around 10 °C, whereas many variations in maximum temperatures can be observed in the month of April, May, June, and July. The highest peaks were in July, with significant yearly variations in the maximum temperatures. In terms of heatwave years, the highest peaks were in 2018 and 2013, when maximum measured temperatures exceeded 28 °C and 27 °C, respectively. The significant yearly variation in maximum temperatures during July suggest the city experienced heatwaves;

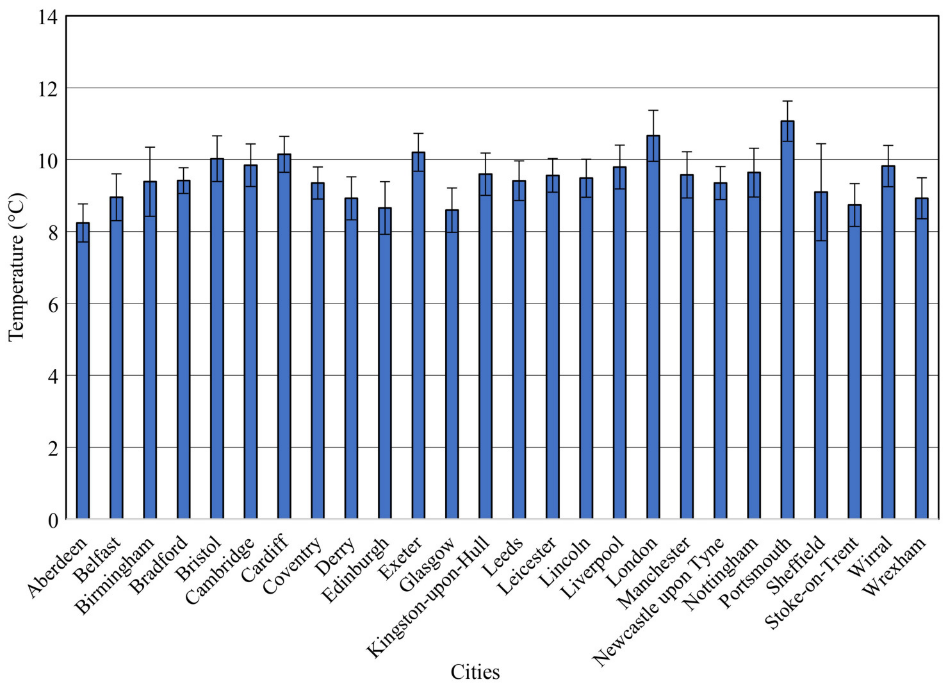

Fig. 4 Annual average temperatures of 26 UK cities between 2010 to 2021 (ESM Table S2).

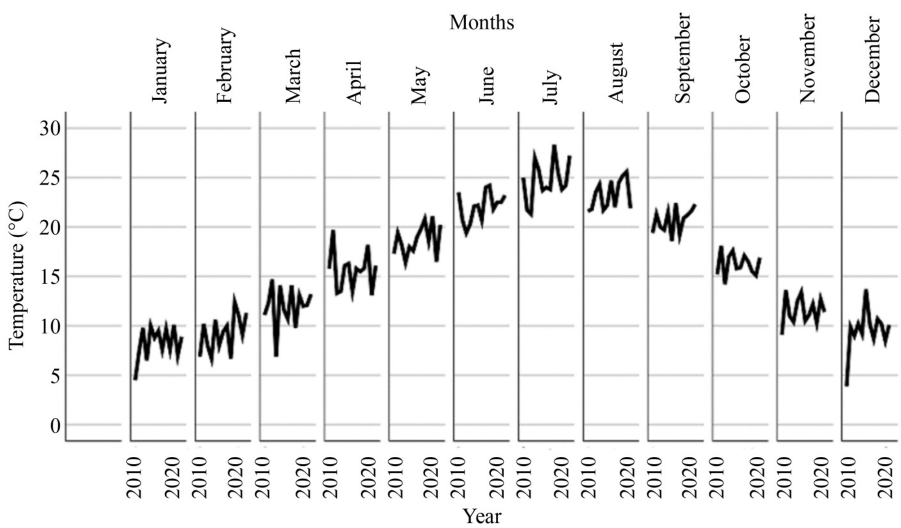

Fig. 5 Monthly mean maximum temperature (°C) in London (St James Park) from 2010 to 2020 (ESM Table S3).

specifically, in 2018 and 2013, maximum temperatures in July can be considered extreme over a period of 10 years. Given that the frequency of extreme temperatures will increase as climate change progresses, these trends suggest that city infrastructures and populations face significant temperature shocks in the future.

To illustrate the challenges related to temperature extremes we investigated the hourly data for a specific city in the North of England. Newcastle upon Tyne shows relatively low annual average temperatures (Fig. 6). The time series of hourly measured temperature data for Newcastle is shown over a period of 11 years (2011–2020). It shows most of the data points between 10 and 20°C with many observable data points exceeding 25 °C (e.g., in 2020, 2019, 2018, 2016, 2014 and 2013). Moreover, several peaks of extreme temperatures can be observed in the same year, more specifically in 2018, 2014 and 2013. In 2013, hourly temperatures exceeded 27.5 °C on multiple occasions, indicating extreme temperature hazards in the city that might otherwise be concealed in averages.

4.2 Air pollution across the 30 UK cities

Figure 7 shows annual average concentrations (µg/m^3) of PM_{10}, NO_2 and O_3 over a period of 12 years (2010–2021). The highest levels of PM_{10} concentration were in Cambridge (approximately 22 µg/m^3) and the lowest in Edinburgh. NO_2 concentrations are highest for Glasgow (approximately 61 µg/m^3) and lowest for Derry in Northern Ireland. Annual average NO_2 concentrations in Bradford, Birmingham, Wolverhampton, and Glasgow exceeded DEFRA's national air quality standard limit of 40 µg/m^3, and annual PM_{10} concentrations increased across the different cities during our period of analysis. Aberdeen at the top of the graph shows annual average concentrations of 12, 19, and 59 µg/m^3 for PM_{10}, NO_2, O_3, respectively. Whereas Kingston upon Hull in the middle shows 16, 24, and 55 µg/m^3 for PM_{10}, NO_2, O_3, respectively. Wrexham at the bottom shows 14 and 18 µg/m^3 for PM_{10} and NO_2, respectively. Coventry, Liverpool, and Wirral show the highest annual O_3 concentrations of approximately 61 µg/m^3, whereas the lowest figure was in Manchester (see Fig. 7). It is worth mentioning that the cities of Stevenage, Bradford, Lincoln, and Worcester do not have monitoring data for O_3 and PM_{10}, and thus are excluded from the study. Although air pollution levels in most cities are within the limits stipulated by DEFRA, the values are annual averages that do not reflect hourly variations. Therefore, we use data from DEFRA to present a city-specific study for London to gain insights about hourly variation and to examine the relationship between air pollution hazards and extreme temperature hazards (Fig. 8).

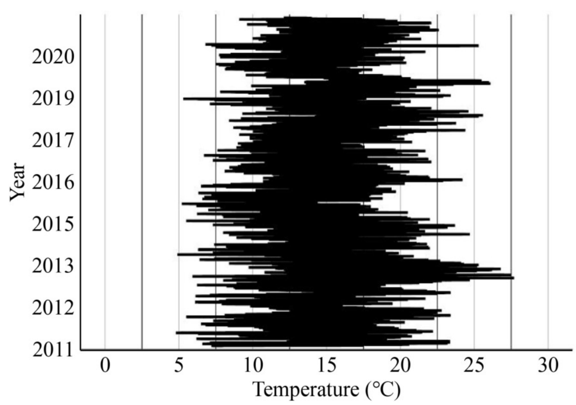

Fig. 6 Time series of hourly measured temperature in Newcastle Upon Tyne from 2011 to 2021.

4.2.1 Analysis of air pollution during London's heat wave

We now examine air pollution hazards in London during the UK's 2014 heatwave to provide greater temporal resolution in the analysis. Figure 8 presents a time series of daily mean concentrations of PM_{10}, NO_2, and max 8-h O_3 concentrations for London during this period. Air pollutant concentrations are plotted with hourly measured temperature data retrieved from DEFRA. Spikes of NO_2 concentration (of up to 90 µg/m^3) can be observed from January until March when temperature values and O_3 concentrations are comparatively lower, whereas May, June, July, and August show several peaks of hourly O_3 concentrations coinciding with temperature spikes. Again, O_3 concentrations are reduced from September until December when temperatures are lower.

A statistically significant and positive correlation between temperature and O_3 concentrations can be observed from p values of correlation analysis. The increasing trend of O_3 with increasing temperature reflects impact on tropospheric O_3 ($p < 0.001$) formation in the ambient atmosphere. Similarly, a positive correlation is observed between air pollutants PM_{10} ($p < 0.001$), NO_2 ($p < 0.001$) and temperature.

Table 2 shows the observed relationship between extreme temperatures and concentrations of PM_{10}, NO_2 and O_3 in the ambient atmosphere. However, it is worth noting that temperature variations did not instantly change the levels of pollution. In fact, there are time lags between increases or decreases in temperature and increases or decreases in air pollutant concentrations.

Figures 9–11 show linear regression plots between temperature and air pollutant concentrations. The heatwave period observed in 2014 occurred during the month of July.

Figure 10 shows there is a significant relationship between temperature and NO_2 concentrations, in that NO_2 concentrations decreasing with rises in temperature, in contrast to rising O_3 as shown in Fig. 9. The median

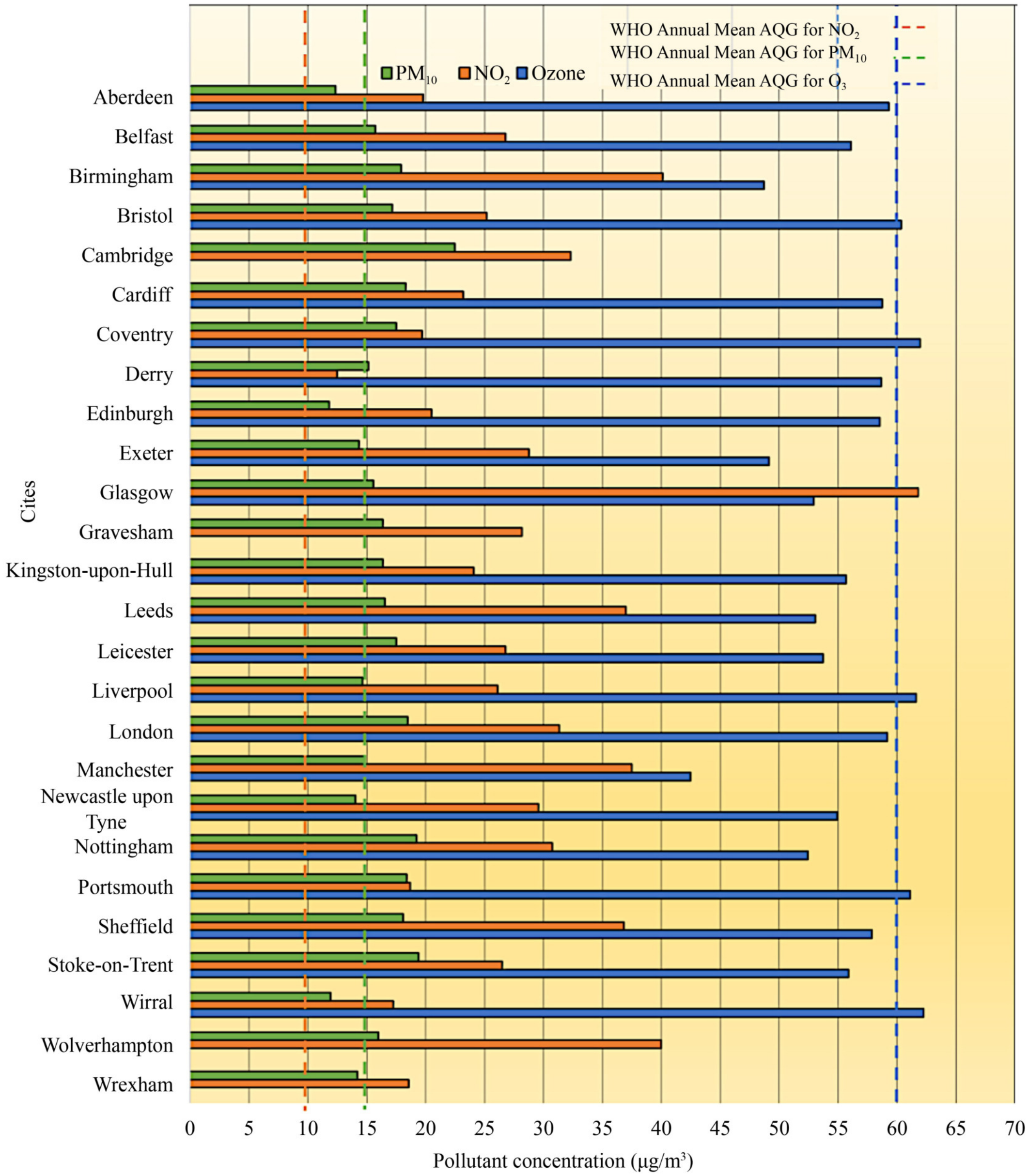

Fig. 7 Annual average concentrations (μg/m^3), PM_{10}, NO_2 and max 8-h O_3 of 26 UK cities. World Health Organisation (WHO) recommended Air Quality Guidelines (AQG) for NO_2, PM_{10}, and O_3 are 10, 15, and 60 μg/m^3, respectively (Global Air Quality Guidelines, 2021).

and mode of 16 μg/m^3 and 17 μg/m^3 is observed between 01st July 2014 and 31st July 2014. The results demonstrate the influences temperature has on the hourly and day-to-day variations in air pollution. Extreme temperatures during heat waves can influence ambient air pollutants by increasing or decreasing their concentrations.

4.3 Local adaptation plans, heat risks, and air quality across selected cities

We found that many of the 30 cities in our sample lack comprehensive adaptation strategies and a systematic framework to address the climate hazards of heatwaves and air pollution. Those plans that do exist exhibit high variabilities in risk analysis, targets, and timeframes of adaptation measures and in their implementation at local level. Most of the local climate plans we analyzed highlighted the potential impacts of severe weather on the city and included climate risk assessments and tools to inform adaptation decisions. Edinburgh, Bristol, Birmingham, and London have prioritised action plans for heatwaves, and many cities include policies (such as increasing urban tree cover and shading) that should help to reduce heat risks over the longer term. However, only Edinburgh's strategy identified air pollution as a key climate hazard. No other city in our sample incorporated air quality, and

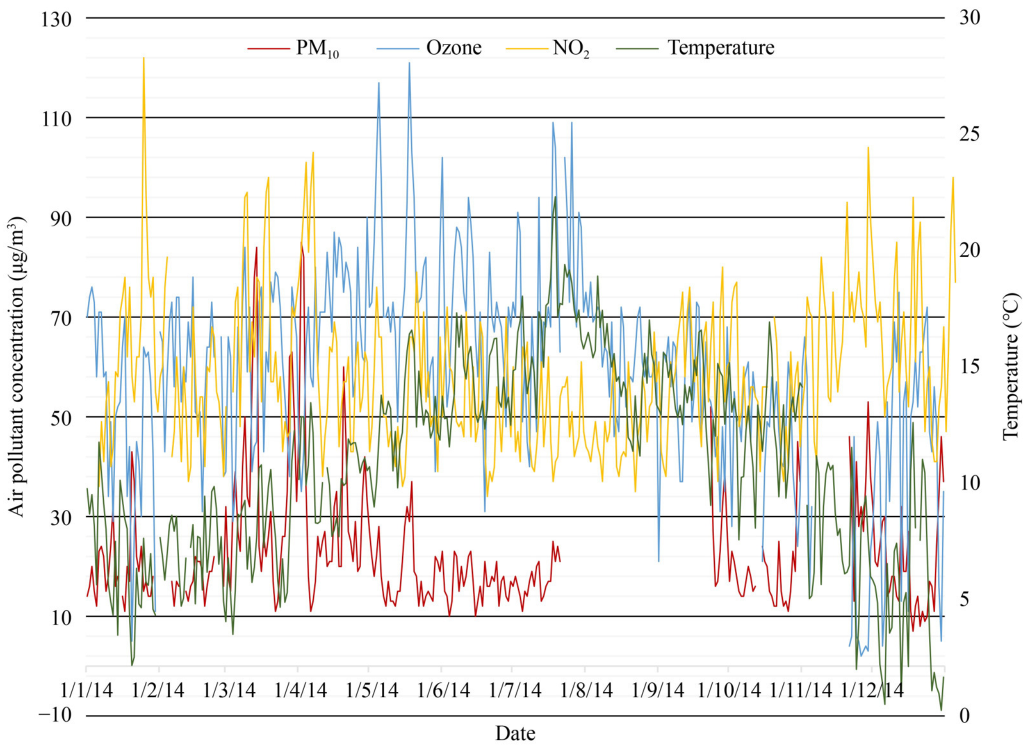

Fig. 8 Daily mean concentrations of PM_{10}, NO_2, and max 8-h O_3 concentrations with hourly measured temperature data of London in 2014 UK heatwave.

Table 2 Probability values (p) from bivariate correlation analysis between temperature and air pollutant concentration of London in 2014 UK heatwave

Independent variable	Dependent variable	p value
Temperature	PM_{10}	< 0.001
Temperature	O_3	< 0.001
Temperature	NO_2	< 0.001

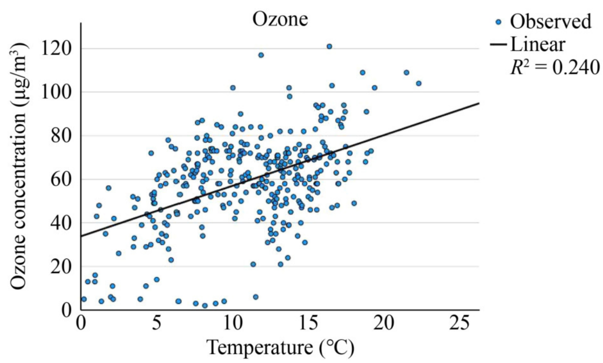

Fig. 9 Relationship between hourly measured temperature and max 8-h O_3 concentrations of London during the 2014 heatwave in the UK.

its impact on human health, into a comprehensive framework for assessing and reducing risks as climate change accelerates. This suggests that awareness of the impact that higher temperatures can have on O_3 levels is limited, at least within UK local governments. As the content of the strategies are of interest we report some key features of the selected cities.

Aberdeen City Council has implemented a Climate Change Plan with the objectives of achieving net zero targets and climate resilience by 2025. Their objectives highlight a net-zero vision for the public sector by reducing emissions from council assets. This plan highlights adaptation to climate risks by understanding climate impacts for the region, risks affecting the council, and adaptation benchmarking. It refers to the UK Climate Projections (UKCP18) for an increase in severity and frequency of heatwaves, coastal flooding, flood risks, and increased winter temperatures. Interestingly, the plan has mentioned the impacts of extreme weather events on the assets of city councils, such as buildings, roads and transport, parks and grounds, and procurement (Kamara et al., 2020). Further, the council utilizes an adaptation benchmarking toolkit to assess the planning and implementation of adaptation strategies. However, the plan is still in the initial stages of appraisal of adaptation options, development of adaptation strategies, and implementation of actions.

Belfast City Council has conducted a Belfast Resilience Assessment to identify a wide range of climate risks in the city. The assessment outlines the impact of climate stress on infrastructure capacity and public health due to flooding and extreme weather events. However, a lack of exact figures can be observed while assuming a generic term for extreme weather events in the assessment. The

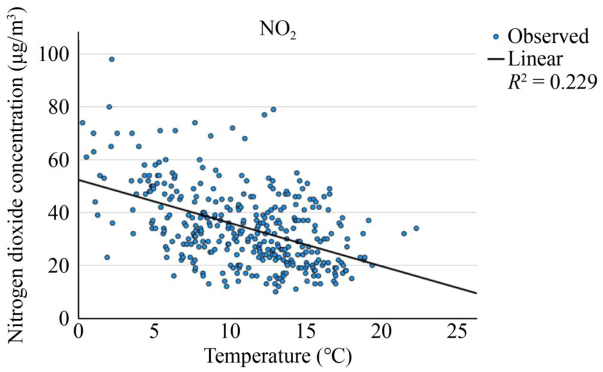

Fig. 10 Relationship between hourly measured temperature and daily mean NO_2 concentrations of London during the 2014 heatwave in the UK.

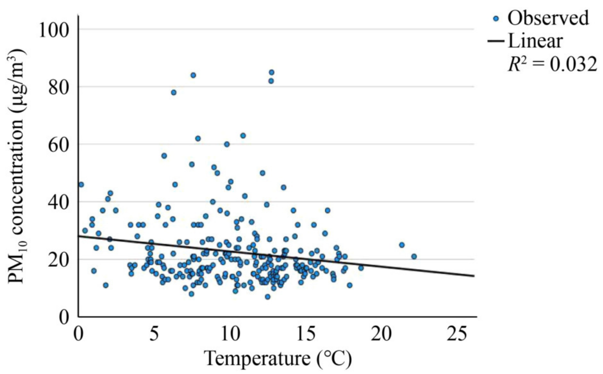

Fig. 11 Relationship between hourly measured temperature and daily mean PM_{10} concentrations of London during the 2014 heatwave in the UK.

council has outlined a case study on climate action that involved the participation of children and young people. They drew some common themes from this case study to express concerns about climate shocks and stresses on public health. The assessment emphasized the importance of urgent actions to tackle air pollution and its impact on public health. Overall, there is a lack of a systematic framework to assess climate hazards, adaptation strategies, and, most importantly, climate actions.

Birmingham's City of Nature Plan and climate adaptation aim to prepare Birmingham for the impacts of climate change and climate resilience for emerging climate risks. This plan introduced a measurement tool to identify the areas of the city that are vulnerable to climate hazards such as floods and overheating in heatwaves. This combined index also considers data from multiple deprivations and existing health inequalities. Whereas "The City of Nature Plan" is set out to implement adaptation strategies by 2045. The plan aims to modify and improve existing infrastructure and assets to reduce the impact of floods and overheating while prioritising the most vulnerable areas of the city. Interestingly, an action plan is proposed by the council for community engagement, improvements to council assets and educational establishments, and further planning. It is perceived that the plan lacks a risk assessment for existing climate hazards in the city for effective implementation of action plans.

The Bristol City Council Climate Emergency Action Plan (2022–2025) includes strategies for climate resilience to major climate risks of flooding, storms, drought, and extreme heat. The council released its preliminary climate resilience assessment in 2021. It focused on gathering data for climate hazards, the vulnerability of assets and populations to these hazards, and the city's adaptive capacity. Climate hazards included in this assessment are sea level rise, extreme precipitation, and elevated temperatures. It states that planning, funding, and detailed designs have been developed in the course of the implementation of adaptation strategies in key areas. Key actions include the flood defense scheme, the Bristol water drought plan, and the local resilience forum. It is worth noting that climate action doesn't include strategies to reduce risk from heatwaves and air pollution. Further, there is a lack of identification of areas in the plan that could be more sensitive to climate hazards and result in greater damage.

Cambridge City Council published a climate adaptation plan in 2018. This focuses on supporting council services, residents, and businesses to adapt to the impacts of climate change. The assessment of climate risks in Cambridge is drawn from the UK Climate Projections Programme (UKCP09), which provides inadequate information about local climate hazards. Major risks included in the plan are flooding, water scarcity, and overheating. The plan mentions heatwaves experienced by the city in 2003 and 2006. It further emphasizes the potential risks of increased summer temperatures. The current adaptation actions being implemented by the city councils are the application of sustainable drainage systems, advice to reduce health risks from heatwaves, and a water management plan.

The City of Edinburgh Council has followed an evidence-based and risk-based analysis to implement a climate change adaptation framework in the city. A local climate impact assessment is conducted using weather data and media searches. The LCLIP provides a baseline assessment of the city's vulnerability to extreme weather. It identified extreme weather events such as flooding, force winds, cold spells, and heatwaves as experienced by the city. Further, a climate change adaptation action plan was implemented in 2016 that highlights climate action in the city. To address the urban heat island effect and improve air quality, the council has launched an 'i-tree ecosurvey' to value ecosystem services provided by trees in Edinburgh. This survey has been implemented to calculate urban canopy and utilized in forest research. However, it doesn't contribute toward improving air quality or mitigating the urban heat island effect. In another effort, the council launched a 'Trees and Woodland Action Plan' to promote tree plantation to mitigate the impact of urban heat effects and improve air quality. Edinburgh's existing infrastructure is prone to the hazards of overheating due to heatwaves, and current action plans don't address the impact of these hazards.

The Mayor's Climate Change Adaptation Strategy (Davoudi et al., 2010) accounts for managing risks and increasing climate resilience in London. It highlights flooding, drought, and heatwaves as the key climate risks to be addressed via adaptation strategies. The strategies to manage the urban heat island effect in London are focused on increasing the green space in the city. For example, increasing the green cover to 10% by 2050 will help manage temperatures in the hottest parts of London. However, there are many current gaps observed in managing the risks of heatwaves on infrastructure and vulnerable populations. Key infrastructures lack the revision of risk assessments and the development of prioritised action plans for heatwave hazards. Thus, measures such as increasing green cover should be implemented alongside developing infrastructure resilience to combat concurrent impacts from heatwaves. Furthermore, there is a lack of a robust heatwave plan for London to address the immediate impacts of heatwaves and, subsequently, air pollution.

Manchester's climate change framework includes climate adaptation and resilience as one of the key objectives. Whereas the responses to adapt to climate hazards are solely based on the number of extreme weather events that occurred in the city, there is a lack of comprehensive risk assessment for key areas in the city, including key infrastructure and vulnerable populations. Among climate actions, the framework proposes to increase the amount of green cover to 10% by 2038. The framework doesn't provide a convincing background for adaptation strategies and their implementation.

The Net Zero Newcastle–2030 Action Plan identifies risks to infrastructure and population from hazards of heatwaves, surface and coastal flooding, droughts, and storms. Further, the plan proposes to develop a climate change adaptation working group to identify key climate change risks to city infrastructure and residents. The plan lacks targeted and effective preparation for climate hazards and the development of adaptation strategies.

The carbon-neutral Nottingham action plan mentions the current and future impacts of heatwaves and floods on the city of Nottingham. It highlights the proposed actions for land and planning policies to include adaptation for heatwaves and floods. It also proposes a local climate impact profile to understand the impact of climate hazards on citizens, businesses, and infrastructure. Thus, the Nottingham city action plan also lacks identification of key climate risks, convincing adaptation strategies, and implementation.

5 Discussion

Our study highlights the vulnerability of UK cities to extreme heat and air pollution. Heat risks are becoming more and more real: observed occurrence and frequency of extreme temperatures from June to August indicates an increase in heat wave intensities in all 30 UK cities, and other studies show how this trend is expected to increase across Europe (Guerreiro et al., 2018). City-specific studies can validate our findings: for example, a study of the urban heat island and its impact on climate change adaptation in Glasgow by Emmanuel and Krüger (2012) found a consistent increase in minimum and maximum air temperatures over 10 years. Furthermore, the study concluded that the UHI effect contributed to higher maximum temperatures in Glasgow compared to surrounding rural areas. High urban density, artificial cover through impermeable surfaces, and increasing thermal inputs in the urban atmosphere exacerbate heat stress within cities.

5.1 Implications for air pollutants

The levels of air pollution in our 30 UK cities show temporal and spatial variations due to underlying factors such as transboundary air movement, population density, geographical location, and atmospheric stability. However, although changes in temperature are also clearly linked with ambient temperature, they do not have an immediate effect. There are time lags between a rise or fall in temperature and an increase or decrease in air pollutant concentrations, which indicate the effect of the present and previous day's temperature on air pollutant concentrations (Kalisa et al., 2018). Nonetheless, a clear relationship between air pollution (specifically ozone) and temperature indicates that, together, they could constitute a self-reinforcing cycle of increased risks to human health in urban areas (both in the UK and elsewhere), because hotter days lead to higher concentrations of tropospheric ozone.

An investigation of air pollution hazards across all the 30 UK cities were beyond scope due to data limitations, and therefore we conducted a city-specific study for air pollution hazards and risks in London during the 2014 heatwave. London shows a statistically significant correlation between O_3 concentration and temperature during the 2014 heatwave, which aligns with Kalisa et al. (2018), who identified a similar relationship during a heatwave in Birmingham. Our study found that daily maximum O_3, PM_{10}, and NO_2 concentrations exhibit statistically significant correlations with daily maximum temperatures (Table 1); these are positive for O_3 but negative for NO_2 and PM_{10}. This trend reflects increased accumulation of O_3 in high temperatures likely due to transformation of NO_2, due to prolonged high temperatures in a heatwave event (per Reaction 1 in Section 2.3). The

O_3 peaks during the 2014 London heatwave are attributed to the accelerated photochemical reactions in the atmosphere, due to excessive sunlight that acts as the catalyst for reaction.

It is notable that a fall in PM_{10} concentrations (Fig. 11) coincided with an increase in temperature. PM_{10} concentrations in urban areas are affected by a number of factors: PM_{10} is positively correlated with soil cover, humidity, and vehicular emissions, but negatively impacted by temperature, wind speed, and atmospheric stability (Czernecki et al., 2017; Kirešová and Guzan, 2022). Higher temperatures during heatwaves lead to a decrease in atmospheric stability, which can cause a reduction in PM_{10} concentrations due to dispersion and wind speed. According to the Severe Weather and Natural Hazards Framework published by the Greater London Authority, high temperatures are likely to increase PM_{10} concentrations during hot and still air conditions. (London Resilience Group, 2022). However, given that both conditions need to be present, we assume that greater atmospheric instability led to PM_{10} dispersing more quickly during the London heatwaves that we examined, and therefore concentrations of this pollutant fell, despite the warmer weather. In addition, it is worth mentioning that certain limitations do exist e.g., for London, we relied solely on PM_{10} data from a North Kensington monitoring site, which may not be representative of the whole city. Nonetheless, our finding suggests that higher temperatures do not always lead to increased PM_{10} concentrations, particularly if they are accompanied by strong winds.

5.2 Deficiencies in Local Authority adaptation plans

Many local authorities have published city-specific adaptation plans to respond to and manage risks from heatwaves and air pollution. For example, the Greater London Authority recently published a London-specific framework to tackle severe weather and natural hazards due to climate change. This framework covers the risks of extreme heat and air pollution in terms of population health, utilities, transport, and environment. However, the plan shows insufficient information regarding hazard-specific impacts, case studies from previous incidents, and strategies to combat heat waves and air pollution (London Resilience Group, 2022). Newcastle City Council has published a combined Net Zero Newcastle Action Plan that includes both mitigation and adaptation approaches for tackling climate change (Net Zero Newcastle Action Plan, 2020). The plan considers heat waves among other climate hazards but does not cover the impacts of heat waves on air pollution, public health, or infrastructure. The plan relies on Heat Health Reports from the UK Meteorological Office for tackling risks due to heat waves. Given that heatwaves pose significant risks to the City of Newcastle, we suggest that the local authority should consider planning and responding to extreme temperatures accordingly.

Overall, most of the 30 cities we analyzed lack specific plans for addressing heat waves, urban drought, and air pollution within their adaptation strategies. They also do not identify vulnerable communities and critical assets within the city, and therefore it is not clear whether adaptation activities will seek to protect the most important infrastructures and most deprived communities. These shortcomings apply more generally to a range of climate threats, as well as to the specific example of increased O_3 concentrations during periods of extreme heat that we identified in London. Prolonged periods of raised ambient temperatures on the one hand, and higher levels of tropospheric ozone on the other, have substantial (and different) impacts on public health. Specifically, heatwaves increase the risks of heat exhaustion and heat stroke, particularly among older and very young people, and those with cardiovascular or renal diseases (Arsad et al., 2022). Although higher O_3 concentrations have health implications for similar groups of people (particularly the young), they exacerbate symptoms for those with respiratory illnesses such as asthma, emphysema, or bronchitis (U.S. Environmental Protection Agency, 2023), thereby increasing the size of the population at risk of health problems.

As such, because heatwaves often lead to higher O_3 concentrations, their combined impacts on vulnerable groups and public health systems will increase, along with mortality rates (Gryparis et al., 2004). Although O_3 concentrations tend to be lower in cities than in the countryside, levels are increasing in most cities (Sicard et al., 2020) and the urban heat island effect will exacerbate this trend during the summer months. Yet, we found limited evidence that UK cities were considering the public health risks of air pollution as part of their climate adaptation strategy. We also found a lack of integration between national policies and local adaptation plans, both in terms of coping with the increased risks of heatwaves and the potential impact of higher O_3 concentrations in cities. This may have contributed toward cities not considering how heat and air pollution combined represent significant risks to human health and is also likely to lead to ineffective coordination between council planners and emergency planners on hazard risk management and adaptation measures.

6 Conclusions

We found that London and Cambridge exhibited the highest risks of air pollution hazards among the 30 UK cities that were investigated. As this type of pollution is further exacerbated by anthropogenic activities and higher temperatures, we conducted a study to highlight the relationship between air pollution and heatwaves specifically for London. We found significant correlations between concentrations of O_3, NO_2, and PM_{10} on the one hand, and temperature on the other, in London during the 2014 heatwave ($p < 0.001$). Specifically, higher temperatures were correlated with higher levels of O_3, and with lower levels of NO_2 and PM_{10}. We suggest that the reduction in concentrations of PM_{10} during heat waves was due to greater atmospheric instability (which causes pollutants to disperse more quickly than would otherwise be the case), whereas the drop in NO_2 pollution is more likely to be a result of the photochemical reactions that result in higher levels of tropospheric O_3. More research is necessary to identify exactly how these variables might interact, and their concomitant impact on air pollution and human, animal and plant health. Notwithstanding this uncertainty, higher air temperatures do not always result in stronger winds, and therefore we suggest that cities should assess the extent to which concentrations of all these pollutants might increase during spells of warm weather and incorporate these hazards and risks to human health into their local adaptation plans.

We found that 29 out of our selection of 30 UK cities have a specific local climate adaptation plan or devote a section of their climate strategy to the issue of adaptation. Bristol, Edinburgh, London, Leeds, Leicester, Lincoln, Glasgow, Cambridge, Derry, and Belfast City Councils have published specific climate plans for adaptation. Wrexham county borough council did not specify any adaptation strategy or risks associated with climate change in its climate plan. There are significant gaps in how these plans identify specific hazards, assess risks, and take account of vulnerabilities and inclusivity. In particular, our analysis of the strategies and the data on local pollutants suggest that city plans do not consider specific climate change risks related to urban heat and air pollution. This is even though, barring a few exceptions caused by limited data that we excluded from our study, all 30 cities are at the risk of extreme temperatures and air pollution.

Several cities do consider some of the risks in isolation, but without significant consideration of their potential occurrence, frequency, and impact of hazards. In particular, none of our 30 UK cities had specific adaptation plans for heatwaves and air pollution. There is a clear lack of data across cities and inconsistencies in their adaptation strategies. Further assessments of climate hazards and risks on city level are required to ensure that cities are adapting to climate change effectively. Additionally, we recommend that policymakers raise awareness of the combined risks to human health that heatwaves and air pollution represent and seek to integrate these twin risks into future adaptation and emergency management planning. This would not only involve undertaking more comprehensive vulnerability assessments (for example, identifying the populations most at risk from heatwaves and from poor air quality), but also putting measures in place to reduce those risks. While we recognize that the public health impacts of climate change and air pollution will be most keenly felt at the local level, this applies as much to national as to municipal governments, particularly in countries where local authorities rely heavily on central funding.

Within this study, the boundary conditions were set by the current extent of the cities in terms of their administrative boundaries; and limited to the snapshot of the time of the study. Vulnerabilities and exposures change as city footprints grow and contract, and new technologies and management strategies are introduced. At the same time, the decision-making context is also dynamic, as policymakers prioritise different issues and become aware of emerging risks and opportunities from new data and evidence. We welcome future research to paint a more comprehensive understanding of a greater number of cities, over a longer time frame. This includes new approaches in assessing, quantifying, and understanding of their adaptive capacity, which can lead to more robust management strategies in the future.

Acknowledgements This analysis was made possible through data sets retrieved from European Commission (Eurostat), Department for Environment, Food and Rural Affairs (DEFRA), Met Office, UK City Councils, and Office of National Statistics (ONS). We want to thank the 30 cities that provided their climate change strategy documents and adaptation plans, and data sets for our analysis. Our thanks go to Dr. Craig Robson (Newcastle University), who has helped us with the map and illustrations. We also want to thank the three reviewers for their detailed and constructive comments that have helped us to improve the paper.

Electronic Supplementary Material Supplementary material is available in the online version of this article at https://doi.org/10.1007/s42524-025-4029-y and is accessible for authorized users.

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

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