Urban Heat Islands and their Associated Impacts on Health

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Summary

Towns and cities generally exhibit higher temperatures than rural areas, for a number of reasons, including the effect that urban materials have on the natural balance of incoming and outgoing energy at the surface level, the shape and geometry of buildings, and the impact of anthropogenic heating. This localized heating means that towns and cities are often described as 'Urban Heat Islands' (UHIs). Urbanised areas modify local temperatures, but also other meteorological variables such as windspeed and direction, and rainfall patterns. The magnitude of the UHI for a given town or city tends to scale with the size of population, although smaller towns of just 1,000s of inhabitants can have an appreciable UHI effect. The UHI 'intensity' (the difference in temperature between a city centre and a rural reference point outside the city) is on average, on the order of a few degrees Celsius, but can peak at as much as 10ºC in larger cities, given the right conditions. UHIs tend to be enhanced during heatwaves, when there is lots of sunshine and a lack of wind to provide ventilation and disperse the warm air. The UHI is most pronounced at night time, when rural areas tend to be cooler than cities, and urban materials radiate the energy they have stored during the day into the local atmosphere.

As well as affecting local weather patterns and interacting with local air pollution, the UHI can directly affect health through heat exposure, which can exacerbate minor illnesses, affect occupational performance, or increase the risk of hospitalization and even death. Urban populations can face serious risks to health during heatwaves whereby the heat associated with the UHI contributes additional warming. Heat related health risks are likely to increase in future against a background of climate change and increasing urbanisation throughout much of the world. However, there are ways to reduce urban temperatures and avoid some of the health impacts of the UHI, through behavioural changes, modification of buildings, or by urban scale interventions. In order to best evaluate the potential for interventions to reduce heat related impacts in future, it is important to understand the physical properties of the UHI, and the impact of the UHI on health.

Keywords

urban heat island, heat related mortality, urban environmental health, temperature, cities, climate change, land use change

The Significance of the Urban Heat Island (UHI)

Humans are responsible for causing significant modifications to the natural environment, most notably through large scale land use changes and the emission of greenhouse gases throughout the industrial era, which have led to increasing global temperature and more frequent extreme weather events (Field et al., 2012; IPCC, 2013). Local or regional modifications to land surfaces such as replacing vegetation with man-made materials, contributes to global climate change, but also has more local impacts. One of the most easily observed impacts of replacing natural surfaces with man-made materials such as concrete, tarmac and asphalt, is an increase in local air temperature, which can turn towns and cities into 'urban heat islands' (UHIs). This excess heat in urban areas is driven by the fact that urban materials modify the natural exchange of energy between the atmosphere and the surface of the Earth (the surface energy balance), as urban materials generally absorb and store solar energy during the daytime and release it at night. The lack of vegetation in urban areas also reduces evaporation rates so that local air temperature is increased through sensible heating. The geometry of buildings in cities means that heat gets trapped close to the surface and is not easily radiated to space (a reduced sky-view factor); anthropogenic heating also contributes to the UHI. The urban heat island intensity (the difference in temperature between the centre of a town or city and a rural reference point) is on the order of a few degrees on average, and usually reaches a maximum value at night time, when urban materials release their stored energy, warming the local environment, compared with natural environments, where heat storage is much lower.

The harmful effects of heat on human health are well documented, and include impacts ranging from mild illness and reduced occupational efficiency, to severe illness (e.g. cardiovascular, respiratory), hospitalization and even death (Basu, 2009). The UHI therefore poses a particular risk to health in terms of heat-related illness. This risk from heat is compounded by the fact that urban populations are often exposed to other hazards, such as air pollution, noise exposure, poor housing and social or economic disadvantages (Patz, Campbell-Lendrum, Holloway, & Foley, 2005). On a global scale, many cities are expanding, and urban populations are growing, driven by economic and environmental pressures (United Nations, 2014). In the future, the pressures of climate change and increasing urbanisation will lead to increased risks to health through overheating in cities worldwide.

The risk to health from the UHI is not always easily captured, particularly when using global climate models, where the resolution is generally too coarse to resolve fine details such as urbanized areas. Increasing resolution comes at the cost of the requirement for increased computing power. This means that the UHI is a large source of uncertainty in terms of projecting future temperatures (Sherman & Archibald, 2019) and we could potentially be under-estimating local or urban temperature impacts in future. Given the changing climate and with increasing pressure on urban communities, it is imperative that research continues to increase understanding of the physical processes driving the urban heat island, in order to quantify the likely impacts on health.. Implementation of potential solutions to reduce health risks in urban environments depends on successful understanding of the impacts.

Measuring and Characterising the Urban Heat Island

The UHI phenomenon was noted in the 1800s by Luke Howard, a pioneer of urban climate studies, who analysed the temperature in different parts of London (Howard, 1833). Despite extremely limited observations, Howard recognized the impact that London had on local climate, noting the artificial warmth induced by its structure, the population and consumption of fuel in fires. Howard defined the urban effect as the temperature difference between weather stations in comparatively urban and rural areas, denoted by ΔT_{u-r}, and defined the 'intensity' of the UHI effect in the same terms. The phenomenon of the urban effect on local climate became widely recognised, although a lack of observations meant that more in depth study of the urban heat island effect did not begin in earnest until the 1960s (Bornstein, 1968; Lowry, 1977; Oke, 1982). There is a wealth of research articles covering many aspects of the UHI. Only a selection is included here, and where possible, sources included have a health aspect.

What causes the UHI effect?

The UHI is largely driven by the fact that urban materials and morphology modify the natural surface energy balance (Oke, 1982). Urban geometry can limit the amount of heat radiated towards the sky, and surface roughness (the deviation from a flat surface due to objects like buildings), can reduce ventilation by disrupting wind flow, so that warm air does not get replaced by cooler air. The lack of moisture availability in towns and cities, means that less energy is used up by evaporation, and anthropogenic sources such as heating and air conditioning systems can contribute to local heating. All these factors contribute to the UHI effect to a greater or lesser extent (Oke, 1987).

During the daytime, urban materials such as concrete tend to store heat, which is released at night time in the form of long wave radiation, warming the local environment. In rural areas, when the incoming solar energy is 'switched off' after dark, temperatures drop, tend to reach a minimum and then start to climb again when the sun rises the next day. This differential heating of the local environment during night time is a key characteristic, making the UHI effect a nocturnal phenomenon, whereby urban temperatures tend not to fall as low as rural temperatures. A typical profile of temperature from a rural to an urban area is shown in Figure 1.

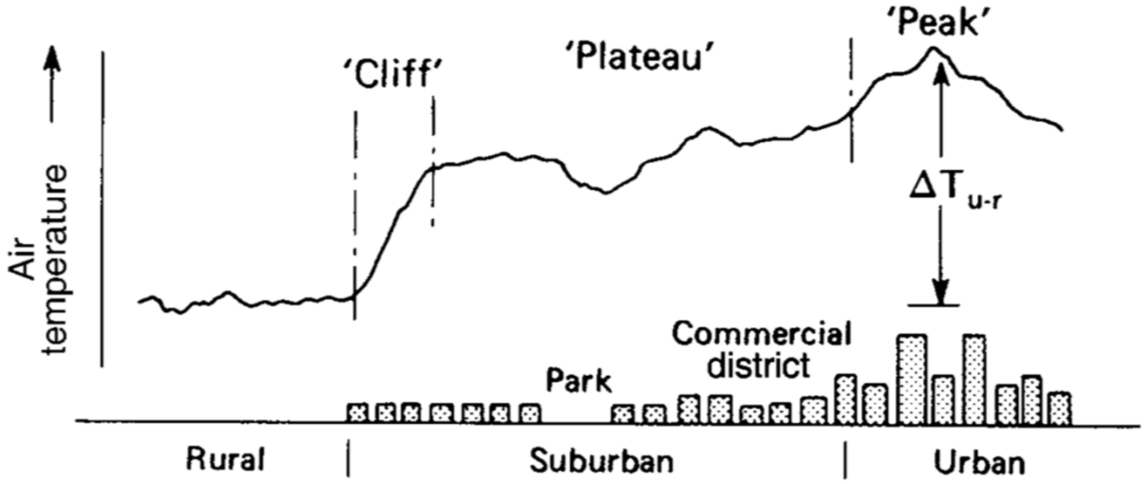

Figure 1. The classical illustration of a cross section of the urban heat island, showing temperature features such a temperature cliff at the edge of the urbanised area, a cooler spot coincident with a park, the plateau through the more densely populated parts of the city, and a temperature peak in the city centre. Reproduced from (Oke, 1987).

Certain weather conditions such as anticyclonic (high pressure) weather systems are particularly conducive to the formation of a strong UHI. Here, there is generally substantial solar heating in the daytime, low wind speeds, so that the warm air is not dispersed downwind of cities, and is instead trapped near the surface. In contrast, when there are strong winds and large amounts of cloud, the UHI tends to be weaker (Arnfield, 2003). The UHI can also interact with weather systems, affecting rainfall patterns and flood risk, disrupting surface winds and worsening air pollution (Collier, 2006). Under moderate wind conditions, urban heat can be advected horizontally away from cities, affecting areas downwind of the urban area (Heaviside, Cai, & Vardoulakis, 2015a). Local weather and climate, and the particular physical characteristics of individual cities means that the UHI is unique to each town or city.

How large can the UHI intensity be?

When averaged over time periods of a day or more, the UHI intensity is typically on the order of a few degrees. During the night time, however, UHI intensities can reach much larger maximums, particularly in large cities; if conditions are favourable, the intensity may reach 5 or 10^{o}C (Bohnenstengel, Evans, Clark, & Belcher, 2011; Gedzelman et al., 2003; Macintyre et al., 2018). The intensity of the UHI depends on various city specific factors such as urban density, local climate and land use, and tends to scale with the size of the population of an urban conurbation (Oke, 1973). However, cities or towns do not have to be particularly large, and may contain only a few thousand inhabitants in order to exhibit an UHI effect. Settlements which are clustered close together, separated by more natural land surfaces can lead to the formation of an urban heat 'archipelago', with localised hotspots, rather than a simple isolated heat island (Taha 2017).

During extreme environmental conditions such as heatwaves, where regional temperatures are already anomalously high, temperatures in cities can reach levels which pose serious risks to health. Since the UHI is generally a nocturnal effect, there may be little respite from high temperatures, even during the night. Air pollution levels are often elevated during heatwaves, and in urban areas, which leads to further health risks (Fenech et al., 2019; H. Li et al., 2018).

Challenges associated with measuring the UHI

The UHI can be characterised as a surface or an air phenomenon, depending on whether the focus is on differences in temperature of the surface of the earth, of the air in the urban canopy layer (below roof height) or in the urban boundary layer (up to around 1km above the surface) (Oke, 1987). The most relevant type of UHI in terms of effects on human health is usually defined in the air temperature of the canopy layer, which is represented by traditional static observations from weather stations measuring temperature at around 1.5 m above the ground (Grimmond, 2006).

Challenges arise because temperature monitoring sites tend to be sparsely situated, which makes measurements of the spatial features of the UHI difficult. Historically, weather stations were sited outside of the hottest parts of cities, as scientists recognised that urban effects were likely to have an impact on local temperatures. For example, in central London, one observation station is based in St James Park, where there is much more vegetation compared with the surrounding urban area. Measurements of the UHI intensity defined as the difference in temperature between urban and rural stations, may therefore be underestimated. Similarly, it is important that the rural station is sited in a truly rural location to capture the full intensity. A systematic review investigated 190 heat island studies and found that around half of them were lacking in quality, through measurement errors and by not fully reporting details of the methodology used (Stewart, 2011).

The advent of low-cost temperature sensors has enabled dense networks of temperature sensors to be deployed across cities. The relatively lower quality of the sensors compared with traditional weather stations is partly compensated by better spatial coverage; however this type of network can be expensive to set up and maintain (Bassett et al., 2016; Chapman et al., 2015; Sun et al., 2019). Networks of privately owned weather stations like Weather Underground (www.wunderground.com) can help to fill in the gaps and make use of citizen collected observations but it is difficult to measure the quality of this type of data. Moving transects (for example using vehicles) can provide observations in the form of a cross section of an urban area (D. B. Johnson, 1985; Taha et al., 2018). Transects give more spatial information than point measurements (albeit in only 2 dimensions) although there may be some error associated with the timing of measurements as the vehicle moves along a section.

Satellite data can support UHI studies, since they have the potential to provide detailed spatial information over large geographic areas, provide multi-spectral information and track changes over time. It is also possible to use sensors mounted on aircraft to provide custom high-resolution data, limited to small areas. Satellites measure the surface (skin) temperature of the earth, which has less relevance to human health, compared with air temperature. There are other limitations in using satellite data to characterise urban temperatures: there may be a lack of temporal information, as satellites typically only pass over an area once a day; data capture is limited to clear sky conditions, since clouds can block the satellite images; the angle of a satellite may affect which surface is being measured; and there is some uncertainty over retrieval of data – or the process of interpreting the data received by satellites, after attenuation in the atmosphere, in order to produce relevant temperature data. Some of the shortcomings described here may be overcome by employing a range of methodologies and using data from different sources, to help achieve effective characterization of the UHI.

Using modelling techniques to characterize the UHI

Increasingly, limitations in traditional observational techniques have been addressed by advances in weather and climate models. General Circulation Models (GCMs) generally provide global-scale simulations of weather and climate, and as such, are not able to resolve small scale features such as towns and cities. However regional models can be run at relatively high spatial and temporal resolution over discrete areas of interest and for specific time periods, which makes them highly suitable for urban heat island studies. Generally, these are referred to as mesoscale models, which relates to their horizontal resolution which ranges from a few km to a few hundred km, so that they are on a smaller scale than (synoptic) weather systems, but larger scale than micro-climates.

Since land surfaces play such a important role in driving local climate conditions, it is essential that local land use is well represented in regional models, and that atmospheric processes near to the surface are well simulated. This can be achieved by employing boundary layer schemes within mesoscale models, which are designed to simulate local atmospheric conditions in the urban canopy layer (Barlow, 2014). One of the first mesoscale models to investigate the UHI of New York using a boundary layer scheme was the URBMET Urban Boundary Layer Model, a 2 dimensional scheme (Bornstein, 1975). Increased computing power and advances in modelling techniques have allowed boundary layer schemes in mesoscale models to parameterize turbulent fluxes in the lower boundary layer, enabling more detailed information about urban morphology and materials to be input, and for the option to include directly emitted anthropogenic heating sources (Salamanca et al., 2011).

In order to simulate conditions in the local boundary layer as accurately as possible, input data on a wide range of properties relating to building geometry and materials needs to be input into the boundary layer scheme (Grimmond & Oke, 1999). Urban classification may be further broken down into more detailed urban sub categories, which reflect differences in building and street morphology between suburban and commercial neighbourhoods (Martilli, Clappier, & Rotach, 2002). Since each city is unique in terms of land use, input data should be specific to the town or city to be modelled; there are also systematic differences in building types in different parts of the world, for example some cities are characterised by high rise reflective buildings, and some contain low rise or more dispersed clusters of buildings. Comparisons of model output with existing weather observations is essential to ensure satisfactory model performance.

In an attempt to standardise the process for classifying urban land use types for any city in the world, methods such as the Local Climate Zone mapping initiative have been developed, whereby land use classes have been extensively expanded to better represent urban areas anywhere in the world, and to provide some consistency for urban climate modelling studies (Stewart & Oke, 2012). Detailed land use information can be derived from satellite images or vector data sources, and manipulated using Geographical Information Systems (GIS) to produce data suitable as input to a boundary layer scheme in a mesoscale model. A particular advantage of the use of mesoscale models with urban boundary layer schemes is the ability to vary parameters to test the potential impacts of various urban planning measures on the local climate.
Other types of models which do not explicitly attempt to simulate local weather and climate, use local observations, neural networks or artificial intelligence to predict local variations in temperatures across cities (Kolokotroni, Zhang, & Giridharan, 2009; Theeuwes, Steeneveld, Ronda, & Holtslag, 2017)

Climate change and the UHI

Urban areas both contribute to global climate change, through land use changes and greenhouse gas emissions, and are affected by it, through changing weather patterns. The UHI effect is likely to exacerbate the impacts of climate change, particularly in terms of increased temperatures and heatwaves. Although maximum temperatures in cities are likely to rise as a result of increasing global or regional temperatures, the effects of climate change on UHI intensity is less clear, and it is likely to depend strongly on the city in question, and local weather and climate at that particular location. One study for 54 US cities suggests that UHI intensity is not increasing with higher temperatures since rural areas are warming at a faster rate, potentially because rural areas are more sensitive to changes in larger scale weather conditions (Scott, Waugh, & Zaitchik, 2018). Despite there being no clear signal of a relationship between climate change and UHI intensity, the urban temperature increment needs to be considered against a background of rising global temperatures. It is therefore necessary to combine projections of temperatures in urban areas with those of projected changes in global temperatures to anticipate the full extent of urban temperatures in future.

Trends in global mean temperatures derived from the global instrumental temperature record are routinely compiled by a number of international organisations around the world, including the Met Office in the UK, and NASA in the US. Although observational sites tend to be placed away from the densest urban areas, even slightly urbanised land use can positively bias temperature measurements, so these effects need to be corrected for (Bassett, Cai, Chapman, Heaviside, & Thornes, 2017). Any changes to land-use throughout the instrumental record period which may influence surface air temperature are dealt with using statistical methods to correct any bias introduced by carefully comparing data from remote sites, uninfluenced by human activities, with urban sites. This careful handling and analysis of observations ensures a level of confidence that recent observed anthropogenic warming is not related to land use changes (Peterson, 2003). The IPCC stated that although the instrumental record over the last century did include urban heat island effects, these were mainly local effects, with a negligible influence on the global temperature trend (IPCC, 2007).

Despite these reassurances, in 2010, a Californian based independent organisation named Berkeley Earth, with large amounts of donated funding, set about analysing land surface temperature data in order to determine whether or not urban temperatures, and changes in land use over recent decades, influenced the observed rise in global temperatures. The BEST (Berkeley Earth Science Temperature) Project reported that the observed warming trend was real, and that the results of their analysis echoed those of existing international published datasets (Tollefson, 2011). These results came as no surprise for climate and meteorological institutes, but were significant since the BEST Project was set up based on criticisms and concerns of the quality of climate change research and the reliability of the instrumental record. Many climate scientists saw the independent analysis of data as a positive addition to the literature, and the analysis of data by those with genuine scepticism of climate change was encouraged. Recent research suggests that because parts of the world which are warming most rapidly tend to have poor observational coverage (e.g. the Arctic), the temperature trend derived from global temperature records may actually underestimate the true temperature rise over the last century (Benestad, Erlandsen, Mezghani, & Parding, 2019).

How the Urban Heat Island Affects Health

The impacts of heat on health

The effects of temperature on health are well researched and include mild illness through to increased risk of hospitalization and death (Basu, 2009; Guo et al., 2017, 2014). The health effects of heat and cold differ: cold tends to affect health over longer timescales (typically up to a few weeks) than heat, which is more immediate (effects up to a few days). Short periods of extreme heat can therefore lead to a spike in health effects, including increased mortality. For heat effects, mortality tends to increase above a threshold temperature; the shape of the response curve, and the position of the threshold temperature varies depending on the population in question. In countries with below average ambient temperatures, the threshold is often lower than in warmer countries, however, there are many factors which influence the shape of the temperature-mortality curve, including housing characteristics and socio-economic status of the population (Baccini et al., 2008; A Gasparrini et al., 2015).

Climate change will mean increases in ambient temperature in future, which is likely to increase the risk of heat-related health impacts, globally, and particularly in already hot countries (Antonio Gasparrini et al., 2017; Hajat et al., 2014; Huang et al., 2011). Heatwaves lead to widespread health impacts, for example the heatwave of 2003 was thought to be responsible for around 70,000 deaths across Europe (Robine et al., 2008), and heatwave mortality in cities has been attributed to anthropogenic climate change (D. Mitchell et al., 2016). There is some evidence that people have adapted slightly to high temperatures over time, although it is unlikely that humans will be able to adapt at the observed rate of increasing temperatures (Arbuthnott, Hajat, Heaviside, & Vardoulakis, 2016).

Health risks in urban populations

In 2007, for the first time, more of the world’s population were classed as residing in urban than rural areas, and projections suggest that 66% of the world will live in urban areas by 2050 (United Nations, 2014). As well as growth in the proportion of urban vs rural dwellers, the total global population is increasing steadily and ageing, and urban areas are expanding, which puts increasing pressure on health care systems in many cities.

Urban heat poses a risk to health for urban populations, but there are many other risk factors which make urban populations particularly susceptible to the detrimental effects of the UHI.

These include exposure to high levels of air pollution, traffic noise, poor water quality, poor housing and overcrowding (Heaviside, Macintyre, & Vardoulakis, 2017; Vardoulakis, Dear, & Wilkinson, 2016). Often, the areas of cities which are most affected by urban heat, are co-located with areas where housing is of poor quality and where the populations may be more deprived in terms of social status, meaning the impacts of urban heat may disproportionately affect already vulnerable groups. Air conditioning (for those who can afford it) can be an effective way of reducing heat-related health impacts, however the downsides of implementing air conditioning run on non-renewable energy sources are overwhelming, in terms of greenhouse gas emissions and local anthropogenic heating (Lundgren-Kownacki, Hornyanszky, Chu, Olsson, & Becker, 2018).

Quantifying direct, heat related health impacts of the UHI

Existing studies have quantified the impact of heat on health outcomes such as mortality or morbidity burden, but there are fewer which have attempted to quantify the direct impact of the UHI intensity on health. Quantification of this type requires combining health outcome data with exposure data. For example, analysing health data such as hospital admissions alongside urban temperature data can help to quantify the relative risk of morbidity or mortality depending on local heat exposure. When analysing mortality and morbidity statistics alongside temperatures in large cities such as Philadelphia and Massachusetts in the US, and Brisbane in Australia it was revealed that heatwave deaths and emergency hospitalisations are co-located with areas of the city with not only the highest exposure to heat, but also high population density, and with demographic indicators of susceptibility, such as the lowest incomes, and highest ages (Hattis, Ogneva-Himmelberger, & Ratick, 2012; Hondula & Barnett, 2014; D. P. Johnson & Wilson, 2009). A health impact assessment for the whole of the US estimated that the impact of the UHI on heat related mortality was around 1.1 deaths per million population, although this was based on information from death certificates specifically highlighting temperature related effects, and is therefore likely to under-estimate the number of deaths where heat was a contributing factor (Lowe, 2016).

A small area cluster analysis across the city of Paris calculated health impacts from heat on the elderly (Benmarhnia, Kihal-Talantikite, Ragettli, & Deguen, 2017). Results showed the adverse effects of particulate air pollution, which increased the risk of mortality during heatwaves, and the protective effect of green space. Another study used a case-control analysis to highlight urban-rural differences in health impacts (Laaidi et al., 2012). In Cyprus, the effects of heat stress on mortality has been quantified and the likely increased impacts due to climate change assessed (Heaviside, Tsangari, et al., 2016). By comparing cardiovascular and respiratory mortality counts in urban and rural parts of Cyprus during heatwave conditions, it was found that women in particular had an increased mortality risk from heat, in urban areas (Pyrgou & Santamouris, 2018).

In an epidemiological study of London, the population was designated into 3 urban zones, from inner, mid and rural populations, and the relationship between temperature and mortality, and hence susceptibility to heat and cold for each separate group, was assessed to determine the level of adaptation to the effects of heat (Milojevic et al., 2016). There was some evidence of acclimatisation to heat in London, since susceptibility varied between the 3 zones. Another study in London provided quantitative estimates of heat-related mortality using high resolution modelling, and showed that different dwelling types, as well as UHI intensity were strongly related to the extent of health impacts (Taylor et al., 2015).

One study used regional meteorological modelling simulations and epidemiological relationships for the West Midlands, the 2nd most urbanised region, and Birmingham, the 2nd largest city in the UK in order to quantify the direct effect of the UHI intensity on heat-related mortality (Heaviside, Vardoulakis, & Cai, 2016). By simulating local temperatures in the region during the 2003 heatwave for two scenarios – one with, and one without the effects of urban surfaces – and comparing the results of the two health impact assessments, it was reported that up to half of the heat-related mortality was associated with the UHI. This study also included projections of future temperature for the UK due to climate change, and including the UHI effect, and estimated a threefold increase in mortality for a 2003 type heatwave occurring in the 2080s (Heaviside, Vardoulakis, et al., 2016). Similarly, in the US, an analysis which included projections of urbanisation and climate change showed projected increased in heat-related mortality of up to 300% by the 2050s (Hondula, Georgescu, & Balling, 2014).

Identifying spatial variation in risk using mapping techniques

Mapping how temperatures vary across urban areas can provide evidence for targeted, local action to minimise the effects of the UHI where it is most required. There is a wealth of temperature mapping studies for cities, globally, using a range of environmental data sources and techniques including satellite imagery and regional models with urban boundary layer schemes. However, increasingly, researchers have incorporated additional datasets with information about the local population, in order to give further knowledge on the potential spatial variations in health risks and vulnerability across a city.

Parts of cities with the highest UHI intensities tend to be more centrally located, with high population density and where populations are more likely to be socially disadvantaged, whereas suburbs tend to house more affluent populations (B. Mitchell & Chakraborty, 2015). Social factors can modify an individual's risk or increase their vulnerability to the UHI. By including information about social and economic status of the population, it is possible to highlight parts of cities where populations are likely to be particularly susceptible to the impacts of heat. Many different indicators have been mapped alongside temperature and other exposure data in cities worldwide; examples of exposure metrics and susceptibility indicators are given in Table 1. By including multiple factors, researchers can help to identify areas most at risk from heat impacts, and can help policy makers to focus adaptation measures where the highest returns can be expected in terms of reducing health impacts.

Table 1. examples of metrics used for heat risk mapping studies

Example exposure metrics	Susceptibility indicators
Daily mean air temperature (population weighted)	Age
	Dwelling type
Daily maximum temperature	Housing quality
Daily minimum temperature	Poverty
Summer mean/maximum temperatures	Social isolation
Urban Heat Island intensity	Ethnicity
Number of hot days	Education
Land surface temperature	Languages spoken
Air pollution concentration	Indices of multiple deprivation
Noise levels	Underlying health status
Vegetation index	Access to greenspace or cool areas

Local land use	Access to air conditioning Fuel poverty Behavioural habits Density of households Diabetes Income level Welfare dependency

Accounting for population density, by weighting temperature metrics by population density is a more accurate measure of heat exposure, since population weighted temperature is likely to be higher than temperatures derived based on area averaging, for example by around 1^{o}C in Birmingham, UK (Heaviside, Vardoulakis, et al., 2016). In the same city, satellite imagery illustrating the UHI intensity, combined with commercial data from a credit reference company was used to map vulnerability based on age and underlying illness (Tomlinson, Chapman, Thornes, & Baker, 2011). High resolution regional modelling of this region showed that increasing levels of social vulnerability, based on indices of multiple deprivation, were correlated with increasing UHI intensity (Macintyre et al., 2018). Results also highlighted that housing types which are most associated with overheating (e.g. flats and apartments) tended to be located in the hottest parts of the city, as were hospitals and care homes.

In London, Taylor et al. mapped the 'triple jeopardy' that comes from the UHI, population age and dwelling type for a single hot day, based on a simulation from a regional climate model (Taylor et al., 2015). They found that dwelling type and UHI intensity were both strong determinants of heat-related mortality risk. Similar work comparing London and Madrid highlighted the highest levels of vulnerability were linked with summer energy poverty (Sanchez-Guevara, Núñez Peiró, Taylor, Mavrogianni, & Neila González, 2019). Whilst wintertime poverty is more common in London, summertime poverty may become an increasing risk in the future in northern European cities.

In the US, research has targeted social vulnerability at the neighbourhood level for the New York area (Karimi, Nazari, Dutova, Khanbilvardi, & Ghandehari, 2018), and looked at the potential for or difficulty in gaining refuge from heatwaves in Oregon (Voelkel, Hellman, Sakuma, & Shandas, 2018). Mapping studies in China have highlighted the vulnerability of the elderly and those in mountainous regions (Hu, Yang, Zhong, Fei, & Qi, 2017; W. Zhang, Zheng, & Chen, 2019) and intra-urban comparisons have been carried out in Korea (Jänicke et al., 2019). One of only a few studies to look at heat risks in urban slums used remote sensing to characterise the locally high temperatures experienced in large and small slum areas in Ahmedabad, India, a risk factor which is likely to impact on an already vulnerable portion of the city population (Wang, Kuffer, Sliuzas, & Kohli, 2019).

Heat vulnerability indices

Sometimes, vulnerability mapping is taken a step further for particular cities, and indices of risk or vulnerability are produced (Bao, Li, & Yu, 2015). These are highly localised, as risks vary between cities and populations, so that the exposure and susceptibility indicators are different for each index derived (Table 1). The most appropriate vulnerability factors for each location may be determined through reviews of epidemiological literature or based on expert opinion. Indices are either constructed based on weighting all factors equally and normalising, by undertaking some weighting of the index through expert judgement, or by principle component analysis (PCA) or cluster analysis.

One study used PCA based on 9 proxy measures of heat risk for the city of London, which were weighted according to their relative health impact (Wolf & McGregor, 2013). The results showed evidence of clustering of multiple risks in areas of high vulnerability, such as high population density, welfare dependency and poor underlying health status. Similar PCA techniques were used to create a heat vulnerability index based on 5 classes for Puerto Rico, developed using satellite images and census data. The most relevant classes indicating vulnerability for this region were age, unemployment, education, health insurance coverage and social isolation (Méndez-Lázaro, Muller-Karger, Otis, McCarthy, & Rodríguez, 2018). Similar indices have been constructed for China (Q. Chen, Ding, Yang, Hu, & Qi, 2018) and Chicago in the US (D. P. Johnson, Stanforth, Lulla, & Luber, 2012). The number of heat vulnerability index studies is increasing. However, in order to identify real risks from heat, it is important to validate the suitability of heat vulnerability indices by using recorded health data, such as emergency calls or hospitalizations (Bao et al., 2015). Multi-criteria decision analysis can be a valuable tool for policy makers, and allows them to apply weights of varying importance to a number of factors. These can then be tailored for different cities and population groups (Woods et al., 2016).

Mitigation and Adaptation Measures to Reduce Urban Overheating

The pressures of climate change, population growth and increasing urbanization will require concerted efforts to mitigate the UHI in order to try to avoid dangerous heat-related risks in the future. In the last decade, there have been a number of notable, deadly heatwaves throughout the world, and temperature records are regularly being broken. Since the Earth is committed to a certain level of global temperature rise already, even if greenhouse gas emissions were to stabilise (IPCC, 2019), adaptation measures will need to be deployed to prepare for anticipated changes as a matter of urgency, to minimise health impacts.

Once quantification of the risks and impacts of urban heat has been undertaken, it is possible to investigate the potential for interventions to reduce negative health impacts. Mitigation measures to reduce the intensity of the UHI can take a number of forms, but are broadly aligned with modifying the surface energy budget. For example, measures may reduce local heating through processes such as reflection of incoming solar energy, and minimising absorption of heat by urban materials, or by increasing evapotranspiration by providing more natural, green surfaces and increasing water availability. These interventions may be at the urban scale, for example, employing different types of road surfaces, providing shading by improved building design, or by increasing tree cover, which increases evapotranspiration and provides shade. At the building scale, UHI mitigation methods may include implementing green or reflective roofing materials, providing shutters on windows, or incorporating energy solutions by retrofitting dwellings and reducing local anthropogenic heat sources (Akbari & Kolokotsa, 2016).

Adaptation of the population to increased risk of heat in future can be aided by public health interventions such as heat-health warning systems (Hajat et al., 2010). Ultimately, the level of adaptation of the population will be heavily influenced by population behaviour, and how people carry out their daily activity in general, as well as national and local policy measures. In order to reduce impacts and switch to sustainable, healthy cities, urban planners and local authorities should focus on the myriad health ‘co-benefits’ from policy decisions which aim to reduce the impacts of climate change in future whilst increasing population health, and potentially bringing economic benefits (Haines et al., 2009; Harlan & Ruddell, 2011).

Increasing the reflectivity of urban materials to reduce urban heat

Urban materials tend to absorb and store energy throughout the day, and release it at night, leading to warming of the local environment. Modification to urban materials, for example by employing ‘cool’ (reflective) coatings for buildings and roads, has the potential to reduce the amount of energy stored and can therefore can help lower urban temperatures in summer time (Pasetto, Pasquini, Giacomello, & Baliello, 2019; Pisello, 2017). Mitigation of urban heat by modification of the urban landscape is a heavily researched topic in itself and has been reviewed extensively elsewhere, e.g. (Salata et al., 2017). According to reviews of costs and benefits, one of the most cost-effective methods to reduce urban heat for UHI mitigation is through the use of cool roofs (Phelan et al., 2015; Zinzi & Agnoli, 2012). An urban climate modelling study suggested that temperatures can be reduced by up to 4^{o}C in the daytime and 1^{o}C at night in Rome, by increasing the albedo of roofs, walls and roads (Morini, Touchaei, Rossi, Cotana, & Akbari, 2018). In Stuttgart, the UHI intensity was reduced by more than 1^{o}C in a similar modelling study, although there were potential impacts on increased local air pollution, when increasing the albedo of roofs (Fallmann, Forkel, & Emeis, 2016).

There have been attempts to explicitly estimate the health impacts of various UHI mitigation strategies. This kind of assessment is essential in order to best inform policy makers and town planners of the relative costs and benefits of interventions. For example, modelling the potential numbers of deaths avoided based on maximising reflectivity of roofs reveals that up to 45 deaths per year could be avoided in the city of New York (Susca, 2012). It was also reported that cool roofs were the most effective UHI mitigation method in terms of reducing numbers of emergency service calls in Arizona (Silva, Phelan, & Golden, 2010). When including climate projections into an assessment of health impacts of changes in surface reflectivity and vegetation cover, it was estimated that 40-99% of the projected impacts of climate change on health could be offset by a combination of UHI mitigation schemes (Stone Jr et al., 2014). There is likely to be disparity in the effectiveness of urban heat management schemes by age, income, ethnicity and other factors (Vargo, Stone, Habeeb, Liu, & Russell, 2016).

In the UK, modelled simulations of the effect of cool roofs have shown health benefits, with increasing reflectivity in a UK city leading to reduced daytime maximum temperatures, and a corresponding decrease in heat related mortality of up to 25% of the total estimated heat mortality associated with the UHI intensity (Macintyre & Heaviside, 2019). The largest health benefits were seen when implementing cool roofs on commercial and industrial properties, rather than residential areas. In London, the impact of a range of building level modifications was simulated in terms of indoor temperature and heat-related mortality impacts, with the main result showing that adding and using shutters on windows can be an extremely protective adaptation measure (Taylor et al., 2018).

Urban greening and the benefits of green infrastructure to health

Whilst the impacts of reflective surfaces bring about direct benefits to health through reduced local temperatures, the health implications of various types of green infrastructure are more complex, and there are likely to be health benefits in addition to heat reduction. Green infrastructure to mitigate UHI effects may include increasing the areas of parks and recreational areas, increasing the green fraction of existing urban areas, the use of green walls and roofs and the planting of trees (Marando, Salvatori, Sebastiani, Fusaro, & Manes, 2019; Price, Jones, & Jefferson, 2015). The use of water bodies (sometimes called 'blue spaces') can also mitigate urban heat (Steeneveld, Koopmans, Heusinkveld, & Theeuwes, 2014). These nature-based solutions can reduce local temperatures through increased evapotranspiration, but are likely to have other benefits. For example, there are reported benefits to mental health and wellbeing from access to green spaces and increased levels of activity and recreation from parks and gardens (Fleming et al., 2018; Livesley, McPherson, & Calfapietra, 2016; Wheeler et al., 2015).

It is important to consider the optimum location or formation of green infrastructure. For example, a study in Phoenix, Arizona found that optimal positioning, and adding only 1% of new green space could cool surface temperatures by 1-2°C, and that dispersed patterns lead to regional cooling, whereas clustered patterns are better for more local cooling. (Y. Zhang, Murray, & Turner, 2017). For Chicago in the US, a multi-disciplinary approach used urban climate modelling combined with social and economic data to identify vulnerable population groups who would be most likely to benefit from green roofs (Sharma et al., 2018).

Combinations of changing roofs to green or cool surfaces may be appropriate in different cases; structural factors, local humidity and the ease of irrigation should be taken into consideration when planning green roofs (D. Li & Bou-Zeid, 2013). Although the impacts on health of green infrastructure appear to be overwhelmingly positive, there may also be some risks to health through increased aeroallergens or disease vectors such as urban ticks or mosquitoes when increasing urban greenery (Salmond et al., 2016).

The benefits of green infrastructure are difficult to quantify but estimating the health or economic value of policies which use green infrastructure to reduce the impacts of the UHI can be useful to urban planners, and these resources are growing in number. For example, a comprehensive health impact assessment for the city of Melbourne in Australia modelled the effect of increasing the numbers of trees throughout the city, finding substantial reductions in heat-related mortality (D. Chen et al., 2014). A cost-benefit analysis of implementing green roofs in the city of Lisbon, Portugal looked at financial, economic and socio-environmental aspects of implementing green roofs. The results suggested that there were positive social benefits, but these came at a financial cost for implementation (Teotónio, Silva, & Cruz, 2018). Also in Lisbon, it was found that living near to green and blue space in urban areas was associated with decreased mortality for elderly populations (Burkart et al., 2015). Although positive health effects have been observed in relation to green and blue spaces, it is not always easy to determine a causal relationship (de Keijzer et al., 2016; Wheeler et al., 2015).

Planning for Future Urban Environments: Challenges Ahead

The effects of climate change are already apparent, as demonstrated through increasing global temperatures, and more frequent heatwave events. Temperature records are being broken with increasing frequency, and by wider margins; for example, June in 2019 was the hottest ever recorded, with temperatures at around 2°C higher than usual in Europe (https://climate.copernicus.eu/record-breaking-temperatures-june). Projections show that the warmest parts of the world are likely to see the largest heat-related health impacts in coming decades (Antonio Gasparrini et al., 2017), and increasing populations and greater degrees of urbanisation will expose more of the earth's population to dangerous levels of urban heat in future. Humankind is already committed to a certain level of climate warming, but in order to avoid catastrophic and irreversible effects in the future, it will be necessary to employ major, and integrated changes to our environment and way of life, particularly in our towns and cities.

As research outputs give us more insight into urban environmental health risks, and climate models are able to capture urban effects on climate more clearly, the risks will become clearer. An effective public health response will become increasingly important, with widespread heat-health warning systems employed where they were previously absent, and with acknowledgement that urban populations are likely to be more at risk (Public Health England, 2015).

Development of new urban areas should be carefully designed and as sustainable as possible in order to avoid the mistakes of the past. As far as possible we should retrofit and improve our urban environments, treating the causes of ill health in an integrated manner. There are considerable co-benefits to be had from living in sustainable cities, such as increased active travel, improved air quality, and improved mental health and wellbeing (Haines et al., 2009).

Multi-disciplinary collaborations, and effective communication between different sectors, including scientists, architects, engineers and public health professionals, will ensure research recommendations are acted on. Research outputs need to be accessible to policy makers in order to have the biggest impact. Public knowledge of environmental issues such as climate change is increasing. The scientific and public health communities should build on this public engagement to drive widespread behavioural changes and to help influence policy and planning measures.

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