# The development of a heat wave vulnerability index for London, United Kingdom

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## ABSTRACT

The health impacts of heat waves are an emerging environmental health concern. This is especially so for large cities where there is a concentration of people and because of the urban heat island effect. Temperatures within cities can reach stressful levels during extreme temperature events. To better manage heat related health risks, information is required on the intra-urban variability of vulnerability to heat wave events. Accordingly a heat vulnerability index (HVI) is developed and presented for Greater London in the United Kingdom. The approach to HVI development adopted is an inductive one whereby nine proxy measures of heat risk are extracted from the 2001 London census for 4765 census districts and subject to principal components analysis. Scores for the emergent principal components are weighted according to the variance they explain and summed to form the HVI. Although mapping of the HVI shows what appears to be a heterogeneous heat "risk-scape" statistical testing reveals significant spatial clustering of areas of high heat vulnerability in central and east London which also co-occur with areas of potentially high heat exposure. Drivers of the spatial pattern of heat vulnerability are discussed as are the implications of study results for heat risk management in large cities.

## 1. Introduction

The health impacts of heat waves are an emerging environmental health concern. Recent heat wave events, in particular the 2003 European event with up to 80,000 victims (Robine et al., 2008) and the 2010 Russian event with an estimated 54,000 fatalities (Revich, 2011) have highlighted this problem across the European continent (Kosatsky, 2005). As climate change is expected to increase the intensity and frequency of periods of extremely hot weather with resulting significant effects on human health (Confalonieri and Menne, 2007; IPCC, 2012), large cities are of special concern in a potentially warmer world because of the urban heat island (UHI) effect (Oke, 1973; Souch and Grimmond, 2006). One adaptation response to heat as a hazard in cities has been the development of heat health warning systems (Hajat et al.,

2010; Matthies and Menne, 2009). While the purpose of these is to produce information on the implications for health of emerging hot weather conditions, the associated alerts/warnings lack geographical or spatial specificity at the sub-city scale; vulnerable groups of the population, such as the elderly, are usually targeted rather than specific areas that may have a number of physical and social characteristics that conspire to elevate vulnerability to heat. Further, if heat and health are placed in a climate risk management framework, then information on vulnerability to heat at spatial resolutions finer than the regional or city scale is required to assist decision makers with the allocation of resources in the preparation for and response to extreme heat events.

London has experienced a number of heat events with significant health impacts. Especially severe were events in 1976 (MacFarlane, 1977), 1995 (Rooney et al., 1998), 2003 (Johnson et al., 2004) and 2006 (Health Protection Agency, 2006) with evidence emerging for distinct health effects of heat waves in July 2009 (Health Protection Agency, 2010) and June 2011 (Green et al., 2012). Beyond these acute events there is clear evidence for a climatological relationship between heat and mortality with studies suggesting that for London average temperatures above 19 °C result in significant increases in mortality (Hajat et al., 2002). Because of the clear health effects of heat events, especially those experienced in August 2003, a number of heat-health related actions have been implemented, such as the development of heat

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plans (Green et al., 2012; Department of Health, 2012; Kovats and Bickler, 2012). While these represent a step towards heat risk management there is general acknowledgement that if heat health prevention actions are to be effective, there is a need to know the location of communities that may be vulnerable to heat in London (Abrahamson and Raine, 2009; Mavrogianni et al., 2009; Oven et al., 2012) and large cities in general (Bassil et al., 2009; Blättner et al., 2009; Dolney and Sheridan, 2006; Harlan et al., 2006; Hondula et al., 2012; Johnson and Wilson, 2009; Reid et al., 2009; Rinner et al., 2010; Smargiassi et al., 2009; Smoyer, 1998; Tomlinson et al., 2011; Uejio et al., 2011; Vescovi et al., 2005; Wilhelmi, 2004).

A common approach to characterisation of vulnerability and its subsequent mapping has been the development of vulnerability indices. The purpose of these is to highlight areas with elevated vulnerability so that specific mitigation and adaptation strategies can be designed to reduce the likelihood of an event related impact such as death, illness, loss of livelihood or damage to property and infrastructure. Vulnerability indices related to floods, drought, environmental change and a range of other geophysical hazards have traditionally been the focus of the hazards community with heat as a hazard receiving little attention. Fortunately this situation is changing as manifest by a gradual increase in the number of studies focused on understanding the climate and socio-economic drivers of intra-city variations in heat related health outcomes and the development of heat vulnerability indices, albeit with mainly a North American focus. For example, in a sentinel paper, Smoyer (Smoyer, 1998) described and offered explanations for the spatial variation of heat related deaths in St. Louis, Missouri, USA. This early paper stimulated the interest of a number of researchers in the social determinants of heat vulnerability and associated health outcomes, in particular Wilhelmi (2004) who, building on the broader ideas of Cutter et al. (2003) related to mapping quantitative vulnerability indices, encouraged the heat hazard community to consider the power of Geographical Information Systems and associated indices for understanding the geography of heat and health at a variety of spatial scales. As a consequence a number of studies, focusing on the development and mapping of heat vulnerability indices, have emerged over the past few years (Johnson and Wilson, 2009; Reid et al., 2009; Tomlinson et al., 2011; Uejio et al., 2011; Wolf et al., 2009). These have largely followed the inductive methodology of Cutter et al. (2003). The main purpose of this paper therefore is to add to the emerging body of knowledge associated with heat vulnerability index development with a particular focus on London, UK and in doing so to shed light on the nature of the heat "risk-scape" for London. A subsidiary purpose is to provide the requisite background for a follow up paper on testing the heat vulnerability index using mortality and ambulance call out data.

For the purposes of this study, vulnerability to heat is conceptualized as a function of exposure to heat and the sensitivity of people (Fig. 1). Physical factors and processes such as radiation, elevation, wind and land use determine the outdoor temperature. These, in addition to the orientation of houses and windows, ventilation and heat protection measures, influence the indoor temperature. Both indoor and outdoor temperature influences human exposure to heat. At the same time, the sensitivity of people to heat depends on a range of individual factors, which may well influence adaptive capacity and the ability to cope with extreme temperatures. Adaptive capacity is influenced by demographic characteristics (age, gender, family status), health status (pre-existing illness), access to resources, support and information (e.g. with regard to heat protection measures) and mobility. Often referred to as heat risk factors these determine sensitivity to heat and form the basis of the heat vulnerability index presented in this study.

## 2. Materials and methods

The approach taken to developing the heat vulnerability index presented here is an inductive one (Tate, 2012) in which Principal Components Analysis (PCA) is used to identify groups of covariant heat risk factors as represented by a number of principal components (PC). In this way vulnerability is viewed as a latent, as opposed to a directly measurable, variable represented by the synergistic effects of several variables. The inductive approach to vulnerability index building in general was first introduced by Cutter et al. (2003) and to the best of our knowledge was applied quite independently to the issue of heat as a hazard for the first time by Wolf (2009)) and Wolf et al. (2009) in the UK at the city scale and Reid et al. (2009) in the US at the national scale. The methodology applied in the development of the HVI is presented in Fig. 2. Informed by the approach of Cutter et al. (2003), the methodology followed was originally outlined in Wolf (2009)) and Wolf et al. (2009) and parallels the approach adopted by Reid et al. (2009), but unlike Reid, focuses on the city scale.

Table 1 summarises the factors considered as important determinants of heat risk. As not all factors are represented in the 2001 Census for London, proxies of these were used in the development
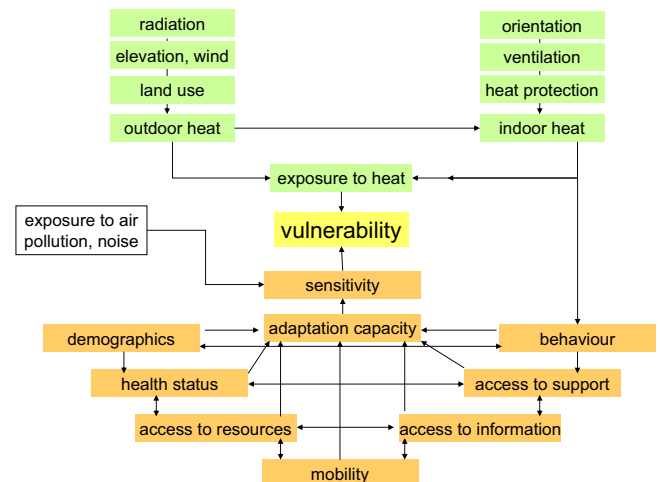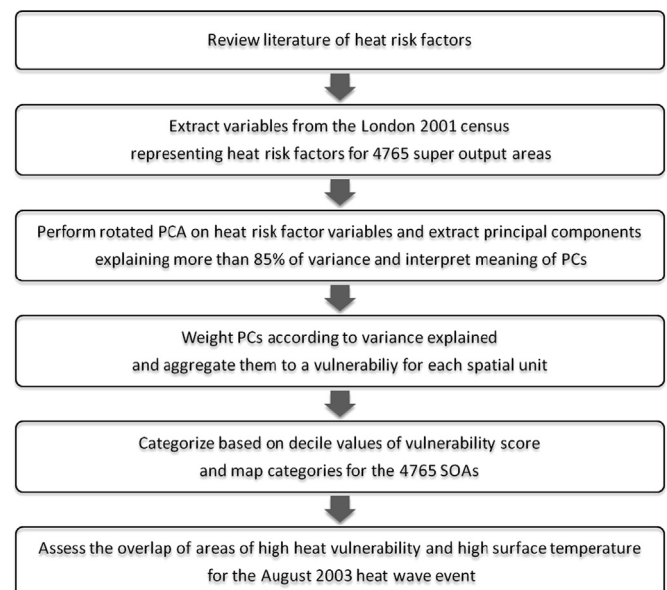


**Fig. 1.** Conceptualisation of vulnerability.



**Fig. 2.** Methodology applied in the development of the HVI.

**Table 1**
Literature based heat risk factors, associated heat risk factor proxy variables as represented by variables available in the London census, principal component loadings for each of the heat risk proxy variables with associated principal component indicated in brackets and percentage variance explained by each principal component.

| Category | Risk factor from literature listed at bottom of table as indicated by . bracketed number | Census data variables used as risk factor proxies expressed as percentage values | Principal component loading and number (bracketed) | Variance explained by principal component |
|---|---|---|---|---|
| Heat exposure | Living in inner city thus being exposed to UHI (Greenberg et al., 1983; Martinez et al., 1989; Kilbourne et al., 1982) | *(Population density and overlay with MODIS image)* | | |
| | Thermo isolation of home (INVS, 2004) | Households in rented tenure | 0.725 (1) | 25.8% |
| | Living on a high floor of multi storey buildings (Semenza et al., 1996) | Households in a flat | 0.896 (1) | |
| | High population density | Population density (pers/ha) | 0.778 (1) | |
| | Not having working air conditioning (Semenza et al., 1996; Kaiser et al., 2001; Naughton et al., 2002; CDC, 2002; Kilbourne, 2002) | Households without central heating | 0.980 (4) | 11.5% |
| Sensitivity | Being elderly (Garssen et al., 2005; Johnson et al., 2005; Hajat et al., 2007) | Population above 65 years old | 0.864 (2) | 25.2% |
| | Pre-existing illness, impaired health, including mental or psychiatric illness (Reid et al., 2009; Ballester et al., 2003; O"Neill et al., 2003) | Population with long-term limiting illness; population with self-reported health status "not good" | 0.929 (2) | |
| | Low economic status, worker, low education (Michelozzi et al., 2005) | Receiving any kind of social benefit | 0.905 (2) | |
| | Living alone, social isolation (Klinenberg 2003; Fouillet et al., 2006) | Single pensioner households | 0.924 (3) | 23% |
| | Minority status (Curriero et al., 2002) | Ethnic group other than "white British"; | − 0.603 (3) | |
| | Confined to bed, not leaving home daily (Semenza et al., 1996; Naughton et al., 2002) | *(no data)* | | |
| | Living in institutions, often in relation to several of the above factors (Kovats et al., 2006; Holstein et al., 2005; Misset et al., 2006; Vandentorren et al., 2004) | Population living in any kind of communal establishment | (excluded from PCA) | |

of the index based on available social and economic variables measured in the census. Eleven proxy variables are assumed to represent the majority of heat risk factors and these are presented in Table 1. Data for the eleven proxy variables were extracted from the 2001 Census at the spatial scale of the Super Output Lower Level (SOA) resulting in eleven data points for each of the 4765 SOA units across London. Kaiser–Meyer–Olkin and Barthlett's tests were carried out on the inter-variable correlation matrix in order to test for the appropriateness of undertaking a PCA by checking for sufficient correlation in the dataset and a clustering of correlations. Consequently two proxies (living in communal establishment and long term limiting illness) were excluded to improve the suitability of the dataset; nine variables were in included in the subsequent PCA. A PCA was performed as the aim was to find a structure that reduces the complexity of the variables; the SOA are considered as fixed parameters and the heat risk factors as variables. The PCA was conducted based on a correlation matrix given that some of the input variables had different units of measurement; using the correlation matrix standardises the data. To improve the interpretation and maximise the dispersion of loadings across the PCs, an orthogonal (Varimax) rotation was undertaken. An issue when conducting PCA is how many PCs to retain. In this analysis the PC selection criteria outlined by Jolliffe (2002) were followed such that PCs with eigenvalues greater than 1.0 were selected, the reason being that such PCs account for more variance than the original variables which have a variance of 1.0. For the $n$ retained components, PC scores were generated for each SOA so that all 4765 SOAs possessed $n$ PC scores. These were then weighted by the variance explained by the respective components and aggregated to produce a combined PC score, which was treated as the SOA heat vulnerability index value; 4765 HVI values were produced equivalent to the total number of SOA. This approach was taken to reduce any subjectivity introduced by *a priori* assumptions relating to the relative importance of the original variables in terms of their contribution to vulnerability and is in line with the so-called variance weighted approach (Schmidtlein et al., 2008), which acknowledges that not all components contribute equally to explaining the spatial pattern

of vulnerability. The 4765 HVI values were organised into deciles with the result that ten HVI categories were produced. The HVI category values were mapped so as to portray the spatial distribution of heat vulnerability across London.

Beyond describing the spatial distribution of vulnerability, of interest is whether there is any evidence of clustering of areas with high or low social vulnerability. To explore the spatial dimension of patterns of vulnerability, the Hot Spot Analysis Getis-Ord Gi* tool within ArcGIS 9.1 software from Environmental Systems Research Institute (ESRI) was applied. This identifies spatial clusters of statistically significant areas with high or low attribute values. This tool calculates the Getis-Ord Gi* statistic (Ord and Getis, 1995) which indicates whether high values or low values tend to cluster. The G-statistic is useful for identifying the presence of clusters of extremely high or low vulnerability values. The output of the Gi function is a z-score for each SOA. The z-score represents the statistical significance of clustering for a specified distance. At a significance level of 0.05, a z-score would have to be less than − 1.96 or greater than 1.96 to be statistically significant. Here, only "hot spots" (z-score > 1.96) are considered.

In order to build a picture of the thermal climate of London, quality assured daily temperature data were obtained from the British Atmospheric Data Centre (BADC). While it is recognised that heat is a product of the synergistic effects of the radiation, thermal and wind environments, in this study temperature is used as a proxy of heat. The description of the thermal climate of London presented in the next section relates to the period 1990–2006 for which health data was available.

Of interest in vulnerability studies is whether areas of high social vulnerability co-occur with areas where exposure is high, or in the case of heat events, where high temperatures may be experienced. So as to establish whether there is a convergence of "hot spots" of vulnerability with areas of high temperature, the HVI map was overlaid on a Moderate Resolution Imaging Spectroradiometer (MODIS) satellite image of surface temperature, fortuitously available for August 7, 2003 during clear sky conditions, coincident with the early stages of the August 2003 European heat wave event. The MODIS image provides coverage of London with

ten thermal infrared bands at 1 km spatial resolution. The algorithm used for estimating land surface temperature from the infrared data gathered by MODIS is described in Wan (Zhengming, 1999) while the contribution of MODIS imagery to understanding land surface temperature climatology and the relationship between surface and air temperature is discussed in Lin and Dickinson (Jin and Dickinson, 2010). The MODIS image was used in this way because the requisite climate station density for resolving intra-urban variations in temperature does not exist for London.

## 3. Results

### 3.1. London's thermal climate

In terms of heat risk, of relevance is the occurrence of extreme temperature values and extended periods of anomalous heat. Fig. 3 plots the 95th percentile of summer maximum, minimum and average temperatures from 1977 to 2006. A noticeable feature is the inter-annual variability of the 95th percentile temperature values. The years for which significant heat related health impacts have been reported for London, namely 1976, 1995, 2003 and 2006, are clearly evident as anomalous 95th percentile maximum temperature values. A distinct feature of the climate of southeast England is London's urban heat island which may well play a role in enhancing heat related stress during extreme temperature events (Kovats et al., 2006). For the 1990–2006 study period the difference in the mean summer temperature between central London and nearby rural locations, as represented by temperatures recorded at the London Weather Centre and Wisley (32 km south of London) respectively, was 2.8 °C. This difference, often referred to as the urban heat island (UHI) intensity, becomes large during periods of anomalous heat as exemplified by the contrast in urban and rural temperatures for the period of the 2003 European heat wave, August 3–13 (Fig. 4). During this event, nocturnal temperatures in central London reached levels 6–8 °C higher than rural environments. Also of note for this period is the persistence of high nocturnal temperatures in central London, beyond the time for which maximum temperatures began to fall. While temperature measurements at single urban and rural sites may be sufficient for establishing the magnitude of the UHI intensity, a dense network of climate stations is required for developing an idea of urban canopy heat island morphology. As few large cities possess the requisite climate station networks for this, increasingly satellite images of surface temperature are being used for gaining insights into surface heat island morphology. For London there are few good images of surface temperature because of cloud cover but fortuitously one good MODIS image is available for the early parts of the August 2003 heat wave (Fig. 5). Although the
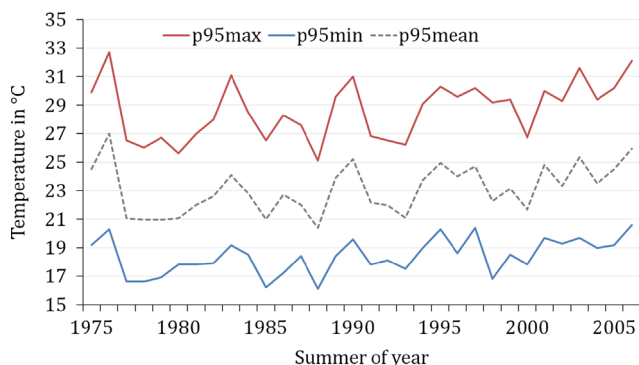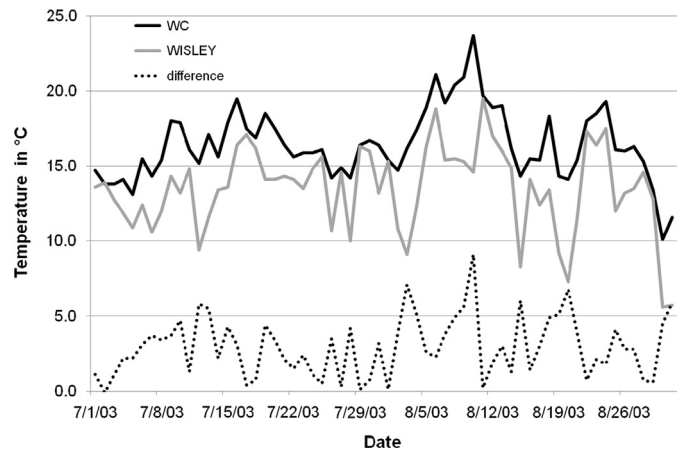


**Fig. 4.** Urban and rural temperatures 3–13 August 2003 in London as represented by the London Weather Centre (WC) and Wisley respectively. The dotted line represents the urban heat island intensity calculated as the difference in temperature between the London Weather Centre and Wisley (WC – Wisely).

1 km spatial resolution does not reveal the fine-grained structure of the surface heat island, it provides an insight into the spatial distribution of heat exposure for this heat event. What is clear is a concentration of heat in central London with surface temperatures at 2130 h exceeding 19 °C, matched with air temperatures of 20–22 °C (Fig. 4) 2–3 °C beyond the temperature – mortality threshold identified for London (Hajat et al., 2002). Areas with high nocturnal surface temperatures are associated with areas of high population density (Fig. 6) where during the day land surface temperatures may have reached as high as 30–34 °C (Holderness et al., 2013). Away from central London, temperatures decrease quickly interrupted by anomalous cool spots associated with large parks southwest and northeast of the city centre. The temperature contrasts between the "cool" park and "hot" central London areas reach 7–8 °C and are similar to the nocturnal urban canopy heat island intensity noted above based on London Weather Centre (WC) and Wisley air temperature differences, comparable to the AVHRR (Advanced Very High Resolution Radiometer) derived daytime (1400 h) UHI for August 8, 2003 noted by Holderness et al. (2013) and exceed those found by Tomlinson et al. (2012) using MODIS for Birmingham, UK's second largest city. While the land surface temperature image presented in Fig. 5 connotes a sense of symmetry to the heat island morphology, and in some ways portrays what might be perceived as a "model" heat island, it should be emphasized that the shape and intensity of the heat island and therefore the distribution of heat exposure will change with different large scale weather conditions McGregor et al. (2007).

### 3.2. Principal Components analysis of heat risk factors

Application of the eigenvalue 1 criteria (Field, 2005) resulted in four principal components being retained for analysis. These explained 85% of the variance. The percentage variance values for each PC were used as the weights in the calculation of the HVI value for each SOA. Consideration of the component loading matrix (Table 1) indicates that component 1 relates to housing condition (flat, population density, rented) while component 2 loads heavily on poor health status and people receiving benefit and to a lesser extent on rented housing. Based on these variable loadings PC1 and PC2 are taken to represent crowded high density housing conditions and poor health and welfare dependency respectively. The third component loads on single pensioner households, high age and negatively on ethnic minorities. The fourth component loads on housing without central heating.
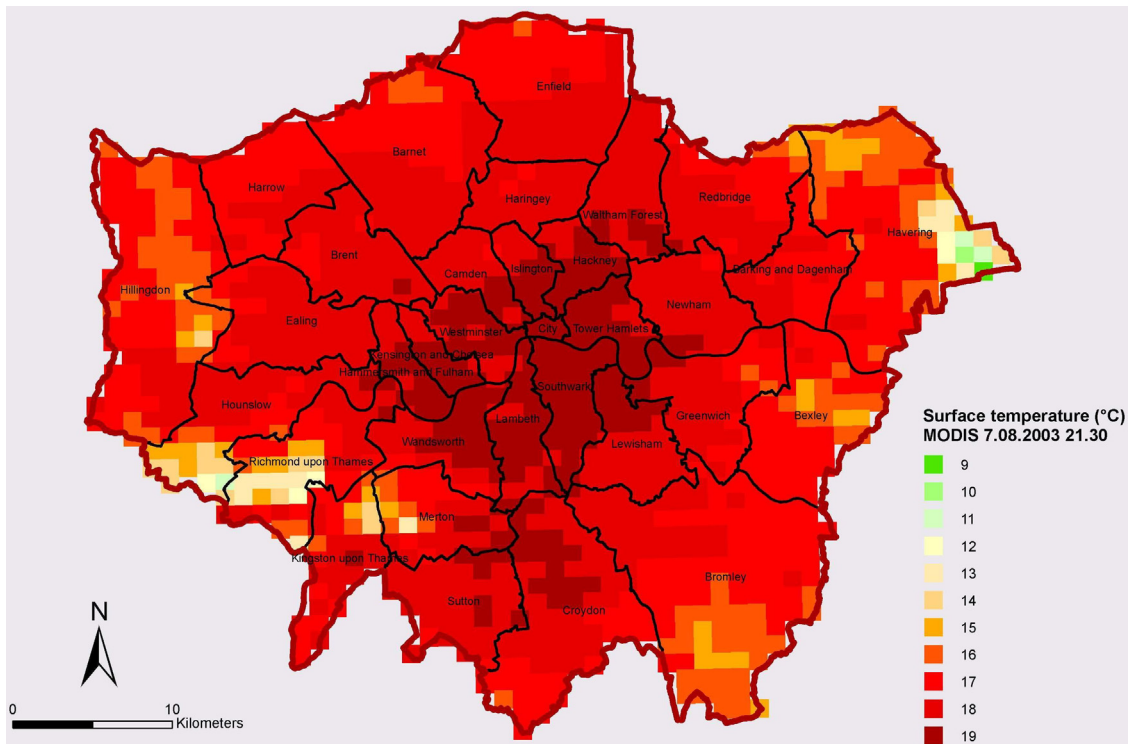


**Fig. 3.** 95th percentile summer maximum, minimum and mean temperatures from 1977 to 2006.

**Fig. 5.** Surface heat island London, August 7, 2003 at 2100 h GMT (MODIS Image). Legend shows surface temperature in degrees celcius. The surface temperature pattern should be compared with that of population density in Fig. 6.
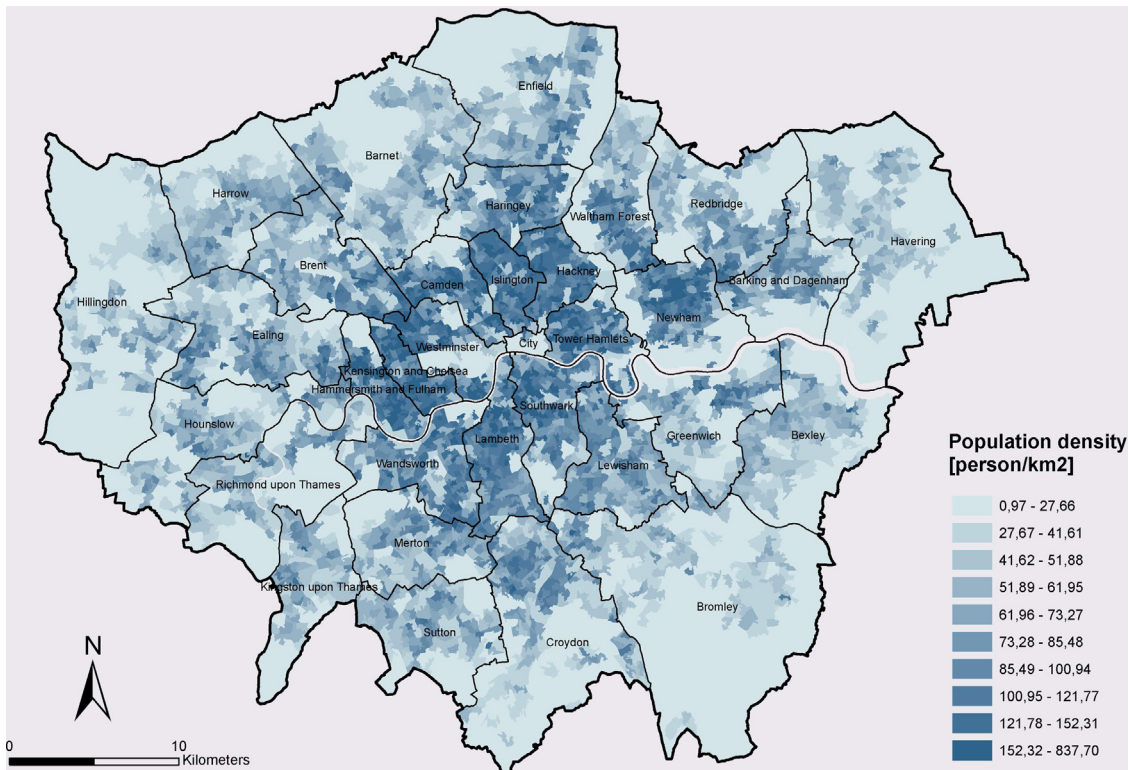


**Fig. 6.** Spatial pattern of population density. When compared with the MODIS surface temperature image there is a close coincidence of areas of high surface temperature and high population density.

Accordingly PC3 and PC4 are interpreted as representing elderly and isolated and poor housing quality respectively.

The distribution of vulnerability index values is shown in Fig. 7. Strong positive (negative) values represent SOA with high (low) vulnerability to heat as described by the heat risk factors represented by the four PCs. Although skewness ($Sk$) and kurtosis ($K$) statistics point to a weak positive skew ($Sk=0.55$) and a weak peaked distribution ($K=0.33$), overall the distribution of HVI values approximates a normal distribution. The 1st, 5th, 50th, 95th and 99th percentile HVI values are $-80$, $-65$, $-4$, 78 and

121, respectively. Taking the 5th and 95th percentiles as indicators of extreme values at either end of the vulnerability score distribution indicates that 238 SOAs possess low and high vulnerability respectively. The HVI values were grouped into deciles to produce ten vulnerability classes. Fig. 8 shows the spatial distribution of the ten classes across Greater London with class 10, related to HVI values greater than 60, indicating the highest vulnerability class. The distribution of heat vulnerability is quite heterogeneous. Overall, vulnerability is higher in central London, including the

SOAs in the central boroughs and in particular areas north of the Thames. In addition, there are single pockets of high vulnerability throughout the GLA. While this general trend partially reflects the spatial patterns of the input heat risk factors, the fine scale heterogeneity of heat vulnerability is unique. Of note is that many SOAs with high vulnerability fall in prestigious areas of London (e.g. in Westminster). Further many highly vulnerable SOAs are located in the area where the surface urban heat island was most intense during the August 2003 event.

Consideration of the spatial distribution of vulnerability classes reveals two distinct patterns. First is a pattern in the form of a ring of SOAs with high sensitivity to heat in central London, especially in the boroughs north of the Thames (Hammersmith and Fulham, Kensington and Chelsea, Westminster, Camden, Islington, Hackney, Tower Hamlets). The second pattern consists of a cluster of small pockets of high sensitivity dispersed in several SOAs across the area of Greater London. These are often surrounded by SOAs with low sensitivity.

Although the pattern of vulnerability is quite heterogeneous, qualitatively there appears to be some spatial clustering of areas of similar levels of vulnerability as evident from Fig. 8. In order to test whether spatial clustering exists amongst the 10 vulnerability classes, the Hot Spot Analysis tool in Arc-Info and the Getis-Ord Gi statistic were applied to the 4657 SOA vulnerability values as described above. This revealed 168 vulnerability "hot spots" statistically significant at 0.05 level of significance, that is, 168 SOAs, which have a close affinity with their neighbours in terms of vulnerability characteristics. Further analysis revealed that all 168 statistically significant SOAs fall within vulnerability class 10 indicating that there is a strong tendency for spatial clustering of areas with very high sensitivity to heat but no so for SOAs with lower sensitivity. Many high vulnerability hot spots are located in the central boroughs of London north of the Thames. Other clusters are in Barking and Dagenham and along an axis that runs from Barking and Dagenham to the northeast and from Greenwich to the southeast.
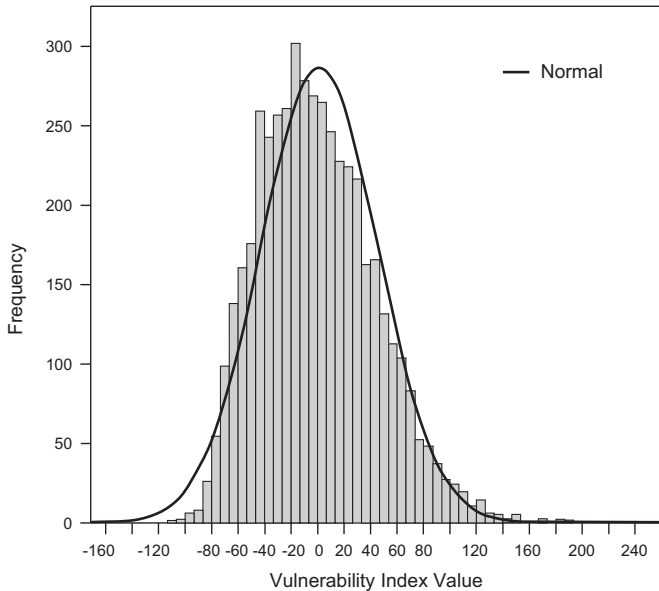


**Fig. 7.** Distribution of HVI values. Solid line is the fit of the normal curve to the distribution. The 1st, 5th, 50th, 95th and 99th percentile HVI values are −80, −65, −4, 78 and 121, respectively.
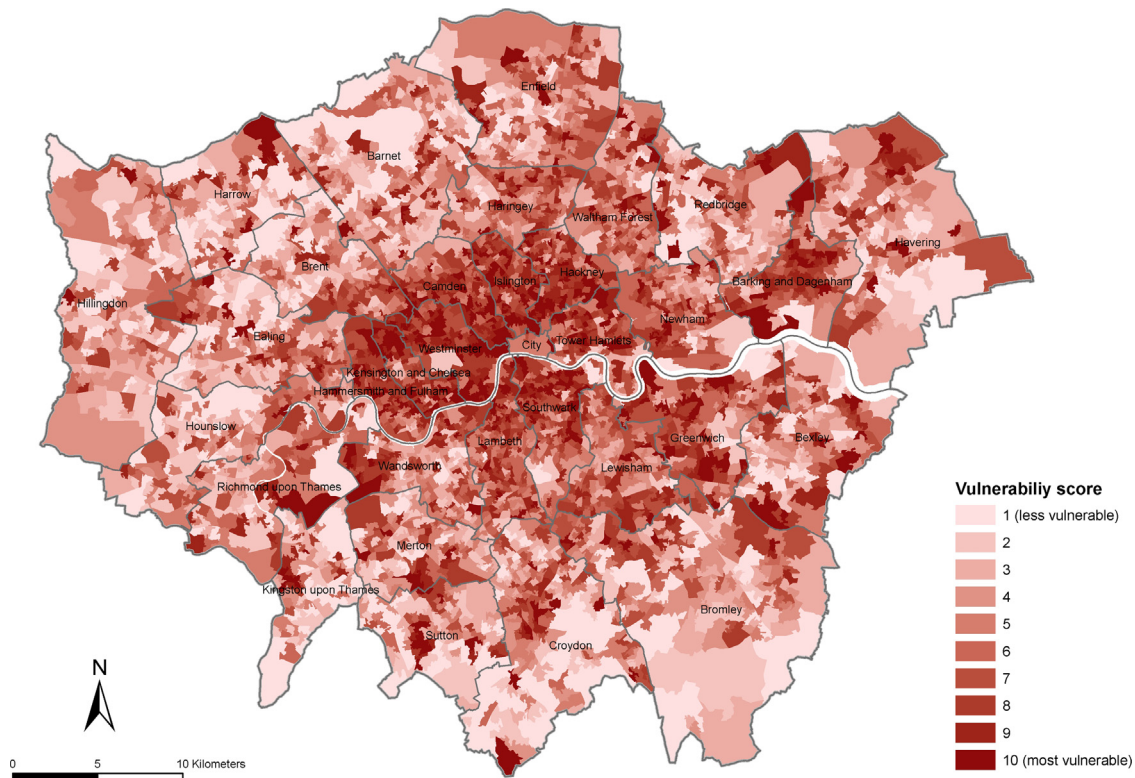


**Fig. 8.** Spatial distribution of the heat vulnerability across Greater London as categorised by 10 heat vulnerability classes. Heat vulnerability increases from 1 (lowest) to 10 (highest).
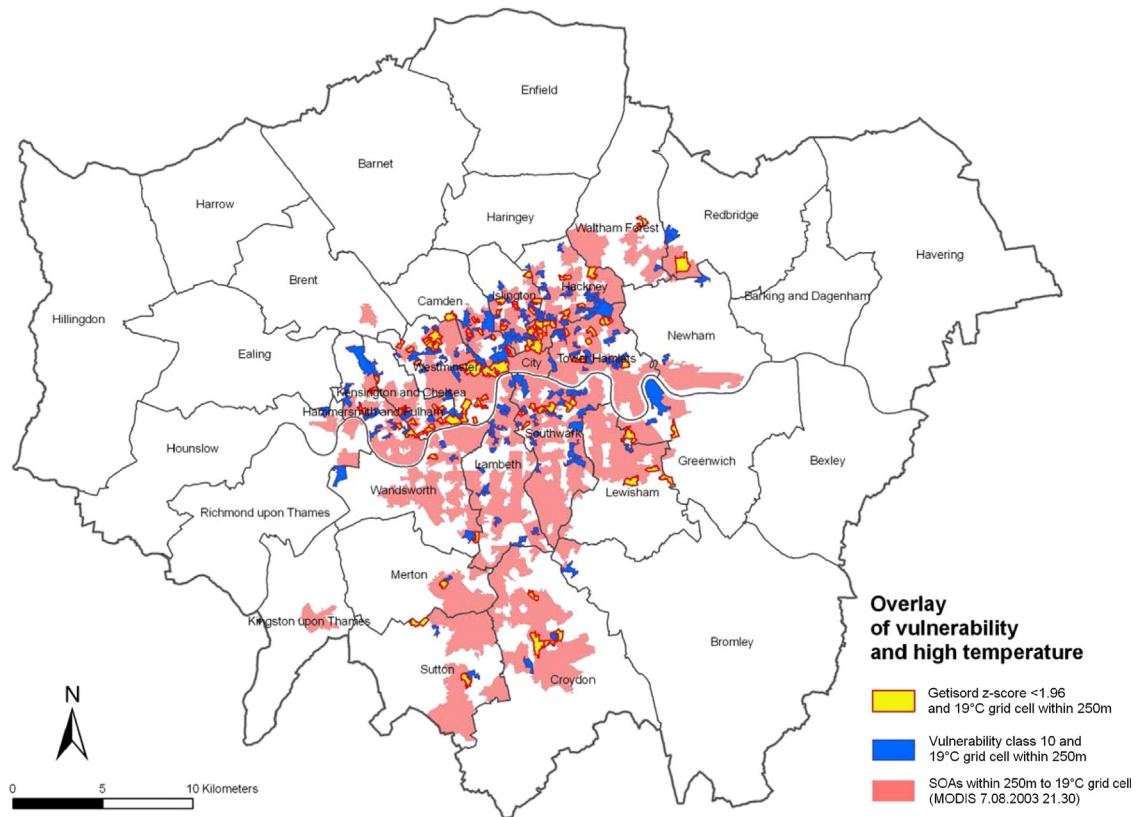
**Fig. 9.** Census districts with co-occurrence of high vulnerability (HVI class 10) and areas with surface temperature equal to or greater than 19 °C or so called "hot hot spots".

From a risk management perspective of particular interest is whether there is co-occurrence of areas of high vulnerability and heat exposure, the theoretical result of which will be a high risk of heat related health effects. In order to examine this, the SOAs with high vulnerability, as well as the "vulnerability hot spots", were overlaid on the August 7, 2003 MODIS image and the number of SOAs falling within 250 m of a MODIS grid cell with a surface temperature of 19 °C or higher, considered to represent a high level of exposure to heat, were counted and identified. This revealed 262 "high exposure high vulnerability SOAs" (vulnerability class 10 and surface temperature 19 °C or greater), which included 94 "high exposure high vulnerability hot spots" (Getis Ord $z$-score $> 1.96$ and surface temperature 19 °C or greater). Fig. 9 maps the high exposure high vulnerability hot spots "hot hot spots". The pattern of SOAs with high exposure and high vulnerability differs somewhat from the vulnerability class 10 pattern and that for the vulnerability hot spots (Getis-Ord zscore > 1.96). This is most likely due to the form of the urban heat island and its connection with population and urban density.

## 4. Discussion

A clear characteristic of London's thermal climate is periods of extreme heat that result in discernible heat related health impacts. In this way London is no different to a number of other large mid-latitude cities that over recent decades have suffered high death and hospitalization rates as a result of periods of extreme heat; Chicago 1995 (Klinenberg, 2003), Paris and western Europe 2003 (Kosatsky, 2005), Melbourne 2009 (Victoria Government, 2009) and Moscow, 2010 (Revich, 2011) are good examples. As London is a large city characterized by high urban densities, buildings and construction materials with a high thermal mass and increasingly important anthropogenic heat inputs into the urban atmosphere,

the urban heat island is likely to play a role in elevating temperatures above broader regional temperatures during periods of extreme heat. The extent to which such "extra" urban heat might contribute to higher mortality rates in London and other large urban areas compared to nearby rural surrounds or smaller built up areas is somewhat contested and remains a fruitful area of future research (Hajat et al., 2007; Oikonomou et al., 2012; Sheridan and Dolney, 2003).

While vulnerability is conceptualized in a variety of ways by different communities (Cardona et al., 2012), it is a population characteristic widely recognized as a critical player in the degree of impact experienced, anywhere from the individual to country scale, as a result of exposure to extreme geophysical events. Deciphering the drivers of vulnerability is key to understanding the social construction of risk, how this might play out on in terms of environmental justice and ultimately explaining the differential societal impact of extreme weather and climate events. While risk mapping has become embedded as a component of risk assessment for extreme hydrometeorological events, only recently has it emerged as a clearly visible area of research in the field of extreme heat events. As for other hydrometeorological hazards, heat risk mapping is concerned with establishing the extent to which a high level of exposure to extreme temperatures in conjunction with susceptibility, in the assembly of heat vulnerability, might conspire to create "hazardousness" of a place (Hewitt and Burton, 1971) in terms of heat related mortality and morbidity. This study falls firmly within the hazard of place paradigm. It has taken an inductive approach (Tate, 2012) to the creation of a heat vulnerability index for London and has been informed by the general methodology outlined by Cutter et al. (2003) regarding the development of quantitative vulnerability indices. The work presented here builds on that of Wolf (2009) and Wolf et al. (2009) and in some respects is similar to the methodology applied by Reid et al. (2009, 2012) in an assessment of US national vulnerability to

heat stress using census track data. Notwithstanding these similarities, this study differs from the majority of other studies that adopt an inductive approach to vulnerability index development in general and centred on the use of PCA in at least four aspects. Firstly, a variance weighted approach is applied to the calculation of vulnerability values, secondly vulnerability values are mapped at a fine spatial scale, thirdly a specific attempt is made to establish the degree to which spatial clustering of areas of like vulnerability occur and lastly an assessment of the degree to which areas of high heat vulnerability coincide with possible areas of high heat exposure is made.

Although vulnerability to heat in London is characterized by its spatial variability, there is strong statistical evidence for the clustering of high vulnerability areas in the central and eastern parts of London. Although other studies have not assessed in a statistical sense the existence of spatial clustering of areas of high vulnerability it can be inferred from these that this may well be a characteristic of large urban areas, as it is for London. For example Vescovi et al. (2005) in an assessment of vulnerability to heat stress in Quebec found that areas with high population density on Montreal Island, which tend to be located geographically close to each other, have high heat related mortality rates compared to other districts. Similarly Johnson and Wilson (2009) for Philadelphia, USA, Tomlinson et al. (2011) for Birmingham, UK, Gabriel and Endlicher (2011) for Berlin and Loughnan (Loughnan et al., 2011, 2012) for Melbourne all report the spatial concentration of higher than normal mortality rates and thus vulnerability during heat wave events.

Importantly this study has been able to reveal the geographical variation in the constituent components of high vulnerability such that central areas of London derive their high vulnerability from factors associated with high density housing while in east London poor health status and welfare dependency are important. Because other studies have used different variables to describe vulnerability to heat, it is difficult to compare the relative importance of these with what has been found for London. Notwithstanding this, study results in many ways confirm an emerging pattern of association found in a number of heat risk mapping studies such that spatial clustering of heat related health effects are closely related to poor socio-economic conditions or concentrations of particular ethnic groups or people that might experience difficulties accessing information (Romero-Lankao et al., 2012). Further the location of these particular population groups is often in areas of high heat exposure. For example Johnson and Wilson (2009) find for Philadelphia that the spatial distribution of the urban poor matches closely the pattern of heat exposure, the net effect of which is high mortality rates. Studies focusing on Phoenix in the USA, because of its extreme thermal climate and a number of heat related health events, have been particularly useful in revealing some of the socio-spatial determinants of vulnerability to heat and associated outcomes. For example, Harlan et al. (2006) found that the resources people possess to cope with the extreme climate of Phoenix was an important determinant of heat vulnerability. Further, Uejio et al. (2011) report the importance of socioeconomic vulnerability (living alone, linguistically isolated) and neighbourhood stability (vacant housing) for explaining the spatial pattern of heat related ambulance call outs for a heat wave in 2005, while Chow et al. (2012) found that the spatial distribution of vulnerability to extreme heat and thus mortality in 1990 and 2000 was related to high concentrations of Hispanic people and the elderly in urban-fringe retirement communities. In possibly the first ever study on a Southern Hemisphere city Loughnan et al. (2011, 2012) identified areas within Melbourne, Australia with high heat related mortality as being typified by care facilities for the aged, higher proportions of older people living alone and areas with large proportions of people who spoke a language other than English at home.

While requisite data, often in the form of population census information, is widely available for undertaking assessments of the spatial variability of heat vulnerability, although the spatial resolution of the data can constrain the scale of analysis (Hondula et al., 2012), problematic has been the spatial assessment of heat exposure. As in studies for Phoenix, USA (Chow et al., 2012) and Birmingham, UK (Tomlinson et al., 2011) the approach adopted in this study for gauging the spatial distribution of exposure has been the use of a satellite image of surface temperature for a single day embedded in a longer heat wave event. There are of course a number of assumptions associated with this approach including surface temperature is a good proxy of overlying air temperature and thus exposure, a single image is a robust climatological representation of the spatial distribution of high temperature areas within an urban area and heat related outcomes measured at the scale of mortality/morbidity data are a response to temperature anomalies at the scale of the satellite record. These are issues that the heat risk mapping community will need to confront over the coming years.

The vulnerability index developed in this study uses the variance weighted method as an approach for dealing with the relative importance of the statistically derived components of vulnerability. While this approach may be statistically pragmatic, it may discount the importance of socio-economic variables that represent consistent and dominant heat risk factors, such as age, which in this study combines with other variables on the third most important component in terms of the total variance explained. Accordingly, an issue that needs to be grappled with in the further development of the vulnerability index presented here is that of the relative qualitative or quantitative weighting of variables and thus population characteristics that are known to be important in determining the nature of heat health outcomes. The matter of the stationarity of current patterns of vulnerability and thus risk also presents a challenge. This is because socio-economic and demographic patterns change over time in large cities so that current patterns of vulnerability may not represent those of the future. This is especially relevant in the case of vulnerability-based assessments of the impacts of projected climate change on future health outcomes. Further the relationship between climate and society will alter as climate change adaptation strategies are mainstreamed into urban design and planning and individual to community behaviours change due to the implementation of heat risk reduction strategies during periods of extreme heat. In short, the present may not be the key to the future as far as the relationship between spatial patterns of vulnerability; exposure and thus risk are concerned.

## 5. Conclusion

London as a "world city", with its advanced economy and relatively high standard of living, is not immune to the impacts of extreme heat with noteworthy levels of heat related deaths and hospitalisations recorded for a number of heat wave events, the most significant of which was in August 2003. The realisation that extreme heat events are a feature of London's climate and periods of intense heat are likely to become more common with climate change, has triggered a number of actions including the development of a National Heat Plan for England. This encompasses both public education information about heat, and weather related criteria used for issuance of heat warnings. Despite these developments and the existence of a substantive body of research work on the epidemiology of heat at the Greater London scale, no explicit attempt has been made to map heat risk across London with a view to understanding the spatial distribution of population vulnerability to heat as one dimension of heat risk.

So as to understand the nature of the potential heat "risk-scape" for London, a heat vulnerability index has been developed using an inductive approach based on principal components analysis of a range of heat risk factors with a subsequent summing of associated weighted PC scores to provide a heat vulnerability index value for each of 4765 small census districts across London. The four PCs that are combined to produce the heat vulnerability index values represent the covariance of sets of individual heat risk factors. These are interpreted to represent high-density housing, poor health and welfare dependency, being elderly and isolated and poor housing quality. Mapping of the heat vulnerability index values into ten categories revealed that not only are there spatially contiguous areas of high heat vulnerability in London but these co-occur with areas that are likely to possess anomalous temperatures during extreme heat events at the regional scale. In addition to providing insights into the nature of London's heat "risk-scape" for the first time, study results add to a growing body of evidence that a range of heat risk factors coalesce spatially to form areas of high heat vulnerability in large urban areas. This study also adds support to the view that place-based approaches for assessing the spatial variation of heat vulnerability should form the basis of future heat risk mapping efforts.

While the vulnerability index presented in this study can be applied to academic analyses of the relationship between heat and health it also has applications for heat (climate) risk management. However, before such applications are undertaken, due diligence is required regarding proof of concept, such that the index presented here needs to be tested as a reliable *a priori* predictor of health outcomes such as mortality or ambulance call out. This will be the focus of future work.

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