Cool cities by design: Shaping a healthy and equitable London in a warming climate

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Abstract

This chapter examines the concept of urban heat resilience in the context of the current research and policy trend towards the creation of healthy cities. This is achieved through the lens of research work carried out at the UCL Institute for Environmental Design & Engineering that focuses on urban climate risk, heat vulnerability mapping and co-creation with policy stakeholders in London. The chapter first sets out the challenges associated with healthy urban environments in a warming climate. It then proceeds with outlining the opportunities that arise from scientific advances in this area and the potential for knowledge exchange and co-design between academia, policy and citizens. The chapter closes with an exploration of solutions and pathways forward identified in past and ongoing research work.

Key messages

- It is broadly recognised that the design and planning of buildings and cities are key factors for human health and wellbeing.
- Future cities will have to be resilient to urban heat risk, which will be exacerbated by the combined effects of climate change, the urban heat island and population ageing.
- Temporal-spatially explicit models of urban heat risk, often combined with mapping tools, are widely used nowadays by planners and public health policymakers to identify urban areas where environmental, personal and social determinants of heat risk coincide across a city.
- Recent research work has demonstrated that older people in the centre of London are vulnerable to heat events due to a combination of heat risk factors, such as being more likely to suffer from health and mobility issues and live in a highly populated and built up area; however, once building characteristics are factored into the evaluation of urban heat risk, heat related mortality is likely to be higher in the outskirts of London.
- A participatory, systems-based approach could be instrumental in addressing health inequities related to heat risk in urban environments.
- Enabling co-creation of solutions and effective communication between academics, planners, building construction practitioners, policymakers and communities is of fundamental importance for the mitigation of urban heat risk.

Keywords

cities; health; wellbeing; urban heat island; climate change; overheating; heatwave; vulnerability

1. Introduction: Healthy city design in a climate of change

The recent rise in the political economy of 'wellness' and the wellbeing agenda among building designers and urban planners has emerged from a powerful shift in health policy that focuses on preventing ill health rather than curing disease. Urban design and planning is fast becoming a key instrument in promoting health and wellbeing in cities, and tackling the social determinants of health whilst achieving current climate change mitigation targets (Northridge *et al.* 2003; PHE 2018; Pineo *et al.* 2018b). This was reflected in the 2009 Zagreb Declaration for Healthy Cities that set healthy urban environment and design as one of the three core themes of Phase V of the World Health Organization (WHO) European Healthy Cities Network, alongside creating caring and supportive environments, and healthy living (WHO Regional Office for Europe 2009). Initiatives such as the WHO Healthy Cities programme have greatly contributed to a paradigm shift in academic research, urban planning and policy by highlighting the role that built environment design plays in forging healthy, sustainable and people centred cities (WHO 2018).

The climate change induced increase in the frequency and magnitude of hot episodes is expected to lead to a wide range of adverse effects on human health and wellbeing (IPCC 2014). These range from thermal discomfort, sleep disruption, reduced human performance, heat stroke and hyperthermia, to the exacerbation of certain chronic medical conditions and even death. According to WHO (2011), these effects are largely preventable. Following the deadly 2003 and 2006 heatwaves, European public health protection networks have greater preparedness to minimise heat risk than a few decades ago (Menne & Matthies 2009). Although recommended immediate response actions commonly triggered by extreme heat events feature meteorological early warning systems and public health advice, emphasis is now placed on building design and urban planning, such as the provision of shading and the improvement of green and blue infrastructure (Santamouris & Kolokotsa 2013).

As climate change, urban design and wellbeing are closely connected, the aim of this chapter is to place urban heat resilience in the context of the global Healthy Cities movement using London as a case study. It is divided into three parts:
(a) challenges,
(b) opportunities and
(c) solutions.

The first part establishes the background guiding initiatives that aim to create climate resilient, sustainable, healthy and equitable urban environments. It outlines current urban transformation trends, including climate change, the Urban Heat Island (UHI) phenomenon, urbanisation, demographic change and population ageing, building stock changes, public health awareness and governance issues, and the root causes underlying the production of climate injustices in urban settings. The second part identifies key opportunity areas across research and policy arenas, including advances in urban climate science, the assessment of positive effects of urban warming (such as potential reductions in cold related mortality and increases in physical activity), the development and mainstreaming of urban heat vulnerability mapping tools, 'choice architecture', systems thinking, and knowledge exchange between academia, policy and citizens. The third part offers a synopsis of past and ongoing London focused academic research projects developed in close collaboration with city level and local government policymakers. Particular emphasis is given on successful applications of built environment and climate related knowledge to the formulation of healthy urban design policies and solutions through co-creation processes that foster interdisciplinary and intersectoral partnerships.

2. Current and future challenges to cities

Anthropogenic global climate change is now a well-established and unequivocal fact. According to the Intergovernmental Panel on Climate Change (IPCC 2013, 2018), extreme weather events, such as heatwaves, will become both more frequent and severe in the future, with potentially catastrophic impacts to public health and the economy. The UK experienced a 10-day heatwave in August 2003, which resulted in more than 2,000 excess deaths in England and Wales, with similar thermal conditions being observed in July 2006 (Kovats & Hajat 2008) and, more recently, in the summer of 2018. Heat events of this magnitude will have become the norm by the middle of the century (Christidis *et al.* 2015). According to the UK Climate Projections (UKCP 2018), under the Representative Concentration Pathway 4.5 (RCP4.5), the projected 50th percentile change of mean summer temperature in the UK is 1.6 °C by the 2050s compared to the 1961-1990 baseline, with heatwave periods similar to 2018 likely to occur during half of the summers by the middle of the century. There is, as a result, increasing concern that ongoing and future warming trends pose unprecedented challenges to our communities. A recent inquiry by the Environmental Audit Committee (EAC 2018) highlighted the need for Government leadership and cross-departmental collaboration to prepare for heatwaves at multiple scales.

The negative effects of regional warming are exacerbated in urban areas due to the UHI phenomenon, an inadvertent modification of the local urban climate linked to urbanisation (Grimmond 2007). Heat islands are reported when temperatures are higher in an urban area relative to the surrounding rural environment as a result of more heat absorbed and trapped within urban environments due to high built densities, the substitution of natural surfaces with humanmade surfaces, and human activities generating additional heat; generally, the UHI effect is more pronounced during clear and calm nights (Oke 1982, 1987). London's UHI intensity markedly increases during heatwave events, with differences between central London and surrounding rural areas reaching 8-9 °C during the 2003 heatwave (MOL 2006) when, out of the around 2,000 heatwave attributed deaths recorded nationwide, more than 600 were recorded in the London region (Kovats & Hajat 2008).

The urban heat risk increment is a pertinent issue in the context of global urbanisation trends. According to the most recent World Urbanization Prospects by the United Nations (UN DESA 2018), 55% of the world's population lived in urban areas in 2018 and this proportion is projected to increase to 68% by the middle of the century compared to only 34% in 1960. Urban population increases and the creation of new megacities will be predominantly concentrated in low income and lower middle income settings, mainly in Asia and Africa. In such settings, as well as in higher income global cities, such as London, urbanisation is likely to escalate heat stress risks amongst the most vulnerable segments of the population that will not have the means to adapt to a warming climate, thus jeopardising urban inclusivity and magnifying health inequities (Heaviside *et al.* 2017).

Epidemiological studies of heat related health risk conclusively indicate that the most heat-vulnerable group is older people, with people over 65 being susceptible to heat related illnesses, such as heat stroke and exhaustion, and heat related death (Kovats & Hajat 2008). The annual population growth rate of people aged 60 or older is around 3% and it is expected that by 2050 all regions in the world apart from Africa will nearly have a quarter of their population aged 60 or above (UN DESA 2017). Other heat risk factors include pre-existing illnesses, in particular cardiovascular and respiratory diseases, and social isolation, both of which are likely to increase with older age. The combined phenomena of climate change, the UHI, urbanisation and an ageing world will, therefore, result in an increasing

number of people being exposed and vulnerable to climate change impacts in cities in the future. This will be especially relevant in major cities that have large numbers of older people (Smith *et al.* 2014; WHO 2017).

Despite the fact that people vulnerable to heat are likely to spend more time indoors compared to the rest of the population, the role of buildings as modifiers of exposure to high temperatures has remained an under-researched area to date. Epidemiological and built environment studies in Europe and the UK suggest that indoor heat exposure may be higher for people living in residential or care settings with one or more of the following characteristics (DCLG 2012; Hajat *et al.* 2007; Kovats & Hajat 2008; Vandentorren *et al.* 2006; ZCH 2015):

- top floor,
- purpose built,
- single aspect flats,
- with restrictors or other barriers to window opening,
- no shading,
- low ceilings,
- large glazing areas (especially if they are south or west facing),
- high internal heat gains,
- Mechanical Ventilation with Heat Recovery (MVHR) with no summer bypass,
- community heating systems with high heat gains through corridors and
- lack of air conditioning or other active cooling systems.

This highlights the contribution of building characteristics to aggravating heat risk. In climates where wintertime heating is required, such as the UK, the focus of building stock transformation agendas has understandably been on winter energy efficiency, which aims to achieve two targets of fundamental importance: 1) climate change mitigation through the reduction of carbon emissions mainly related to space heating and 2) the elimination of fuel poverty. But as building fabrics become more insulated and airtight, the risk of overheating increases if appropriate passive cooling measures are not included at an early design and retrofit stage (Fosas *et al.* 2018; Mavrogianni *et al.* 2012).

Another challenge in heat risk mitigation in the UK is the social and cultural lack of knowledge of how to tackle heat related hazards. Recent studies have suggested that vulnerable individuals perceive neither heat risks nor cold risks as potentially threatening to them and, due to the unprecedented nature of hot spells, they often do not know how to operate their homes during an extreme heat episode (Abrahamson *et al.* 2009; White-Newsome *et al.* 2012; Wolf *et al.* 2010). This underscores the importance of both public health initiatives aiming to increase risk awareness but also social cohesion and local knowledge bases that could help identify heat-vulnerable individuals and promote best practice advice during heat events.

The discussion above raises questions about how external stresses, such as urban warming and demographic trends, convert into a decline in population wellbeing and health. Many have argued that extreme weather events, such as heatwaves, often reveal underlying wider inequities in the distribution of vulnerability (Friel *et al.* 2008). The distribution of climate related disadvantage varies geographically, as a function of the interplay of policy, sociodemographic and environmental factors (Macintyre *et al.* 2018). More focus should, therefore, be given to the study of unequal geographical distributions of climate risk and heat related vulnerability and disadvantage in cities. According to Lindley et al. (2011), although significant research efforts have been made in recent years to identify the patterns

of climate hazard exposures, the social, personal and environmental determinants of climate related risk are less well understood or recognised in adaptation policy. Social and personal factors include age, income and education levels but also access to social networks and public health infrastructure that will have a protective effect during an extreme weather event. Environmental factors include the characteristics of the buildings and neighbourhood an individual inhabits, such as the presence and operationality of cooling building strategies, the surrounding microclimate, the type of amount and quality of accessible greenspace and other public spaces, the levels of noise, air pollution and perceived risk of crime that may inhibit natural ventilation through window opening in the summer. Hajat and Kosatsky (2010) argue that an enhanced understanding of the determinants that explain heat risk heterogeneity is a fundamental prerequisite for the development of targeted climate change adaptation responses in cities. In a large and diverse city such as London, attention needs to be paid to the full gradient of inequality and its impact on the spatial variation of population vulnerability to heat risk. Socioeconomic status has not been shown to be a risk factor for heat mortality in the UK due to the low penetration of air conditioning across the building stock. However, Bundle et al. (2018) argue that it is plausible that there is a social gradient in indoor overheating risk as a result of a correlation between deprivation and heat risk factors, such as prevalence of long term health conditions and neighbourhood crime rates, which may inhibit night cooling through window opening.

There is significant need to integrate overheating solutions into built environment policies for the planning and design of new development and infrastructure (including green spaces), building regulations and regeneration programmes. There are two categories of policy approaches to climate change adaptation: 1) 'mainstreaming' of adaptation solutions into existing policy domains and programmes and 2) 'stand-alone' adaptation policies (Runhaar *et al.* 2018). Mainstreaming solutions benefit from existing resources and the potential to develop co-benefits with other policy objectives; while stand-alone options may receive more attention and dedicated funding. Research by Cortekar et al. (2016) notes that adaptation policy efforts often start with a vulnerabilities assessment using locally-specific climate impact resources, such as the UKCIP Adaptation Wizard, followed by the development of appropriate policy responses. Cortekar and colleagues noted significant challenges for adaptation policies related to unsuitability of a 'one-size-fits-all' solution due to local variations, human and financial resource constraints, and lack of a systems approach to account for interconnections across climate change impacts and adaptation measures.

Such challenges tend to persist because urban environments are dynamic complex systems in a state of constant flux. They are a 'drama in time' (Geddes 1904). The determinants of urban heat risk are commonly interconnected and counterintuitive phenomena. For example, if people use air conditioning to protect themselves from heat, at an aggregated level their decisions increase energy consumption and thus global warming as well as the UHI because air conditioning generates heat directly outside the conditioning units. In addition, if policymakers and planners take measures to build more densely, they may also increase the UHI effects locally. Mainstreaming of adaptation solutions and stand-alone adaptation policies rarely have merely technical dimensions and often require that people also change their behaviour. Yet, it is a true challenge to anticipate whole-system effects of potential policies, people's decisions and behaviour. Consequently, the study of urban environments and heat risks requires a whole-systems perspective for a broader understanding of effects in space and time.

3. Research directions and opportunities for change

Local urban climate modification is a well-documented phenomenon worldwide (Arnfield 2003; Oke 1987). UHI studies have traditionally been observational and increasingly include remote sensing but advances in computing and big data analytics in recent years have also allowed the generation of prediction modelling frameworks. Modelling studies encompass a wide range of methods, including both deterministic and stochastic modelling approaches (Mirzaei 2015; Mirzaei & Haghighat 2010; Santamouris 2007; Stewart 2011). Deterministic approaches mainly include modelling of urban canyon temperature regimes, modelling of the urban canopy layer and dynamic numerical modelling. Stochastic approaches include statistical correlation analysis and Artificial Neural Network (ANN) modelling.

The development of these models paves the way for the evaluation of the impact of urban planning decisions on urban heat risk, energy use and health outcomes, hence facilitating informed policymaking (Wolf *et al.* 2015). For example, temporal-spatially explicit models of urban heat risk could enable planners and public health policymakers to identify 'hotspots', i.e. areas where environmental, personal and social determinants of heat risk coincide across a city (Preston *et al.* 2011; Romero-Lankao *et al.* 2012; Wilhelmi & Hayden 2010). The fine scale mapping of local urban climate variables and heat risk factors is underpinned by the wide use of Geographic Information Systems (GIS) in research and practice (Aubrecht & Özceylan 2013; Boumans *et al.* 2014; Dugord *et al.* 2014; Harlan *et al.* 2013; Merbitz *et al.* 2012; Taylor *et al.* 2015; Tomlinson *et al.* 2011; Van Der Hoeven & Wandl 2015; Wilson *et al.* 2010; Wolf *et al.* 2013; Wolf & McGregor 2013). Maps can be a powerful communication tool when engaging with policymakers and other stakeholders with the aim to identify the ways built environment design impacts on health and wellbeing, for example by allowing the quick ranking of risk factors for an individual, i.e. age, housing type, location etc. Nonetheless, there are inherent challenges related to the difficulty to convey nuances or limitations in the underlying data, which further pinpoints the need for effective communication between academic researchers and policy stakeholders. Additional challenges may often emerge due to data-scale issues given that many attempts to map fine scale variations in vulnerability and risk encounter ethical issues related to data acquisition.

Despite the current focus on its physical determinants, urban heat risk is a sociotechnical problem, which necessitates the adoption of an interdisciplinary approach in order to tackle it. For instance, the role of built environment design is indeed acknowledged by recent developments in the behavioural sciences. There is increasing recognition that human behaviour is often driven not by conscious, deliberative cognitive processes but instead by non-conscious, automatic responses that may be triggered by characteristics of, or cues within, our surrounding environment (Hollands *et al.* 2017; Marteau *et al.* 2012). Appropriate design strategies at different scales or, in other words, interventions to alter 'choice architecture' - ranging from changes to the microenvironment of indoor spaces to the neighbourhood level could be employed to encourage healthy behaviours and social practices, thus reducing urban climate related risks. This could include, for example, integrating passive cooling strategies, such as natural ventilation and shading, and green and blue infrastructure in the design of buildings and cities in such a way that they are intuitive and easy to implement, thus limiting or avoiding the use of active cooling.

This is very much echoed in the recent trend to adopt systems thinking and participatory research in built environment and urban health research (Eker *et al.* 2018; Homer & Hirsch 2006; Macmillan *et al.* 2016; Pineo *et al.* 2018b; Shrubsole *et al.* 2018). This trend is illustrated, for instance, by recent citizen science attempts to collect data related to urban

heat risk factors, such as urban microclimate data (Rajagopalan *et al.* 2017) and building construction age (CASA 2019). Mapping interactions between various heat risk factors at the urban scale in collaboration with stakeholders will allow the identification of feedback interaction between drivers, barriers, and behaviours in space and time. It will also enable the identification of possible unintended consequences through this process and the potential reduction or elimination of negative consequences through the application of systems knowledge.

A participatory, systems-based approach could be an invaluable tool to addressing health inequities related to heat risk by enabling solution co-creation processes between academics, planners, building construction practitioners, policymakers and communities as described by Raven *et al.* (see Chapter 3). In the past, research project outputs were mainly published in academic outlets, hence limiting their accessibility to a wider audience. A two-way dialogue has thankfully been initiated in recent years between researchers and decision makers, whereby scientific evidence on the factors that may contribute to heat vulnerability is gradually but steadily being translated into policy action and industry best practice. The next section will offer some examples of research projects aiming to improve London's urban heat risk resilience with strong impact pathway plans.

4. Solution pathways

The challenges and opportunities outlined in the previous sections have triggered a series of past and ongoing interdisciplinary London-focused research projects undertaken by University College London's (UCL) Institute for Environmental Design and Engineering (IEDE) in conjunction with other institutions. These projects have tackled various factors of urban heat risk, including the role of the UHI, building fabric characteristics, and social determinants of heat vulnerability, with a particular focus on older and ageing populations. Whilst the main emphasis has been placed on residential environments, current research aims to expand existing methodological frameworks to assess the heat vulnerability of care settings. Translational work carried out in collaboration with London boroughs and the Greater London Authority (GLA) are presented at the end of the section.

4.1 London's local urban climate

London's local urban climate and its impacts were the focus of the four-year research project *'The development of a Local Urban Climate model and its application to the Intelligent Design of cities'* (LUCID) (Mavrogianni *et al.* 2011). This project improved our understanding of London's UHI through the development of a suite of local urban climate models spanning three scales: 1) citywide, 2) neighbourhood and 3) street level (Figure 1). Data outputs from the local urban climate models were imported into a second suite of models aiming to assess the impacts of London's UHI on 1) energy use, 2) thermal comfort and 3) health.
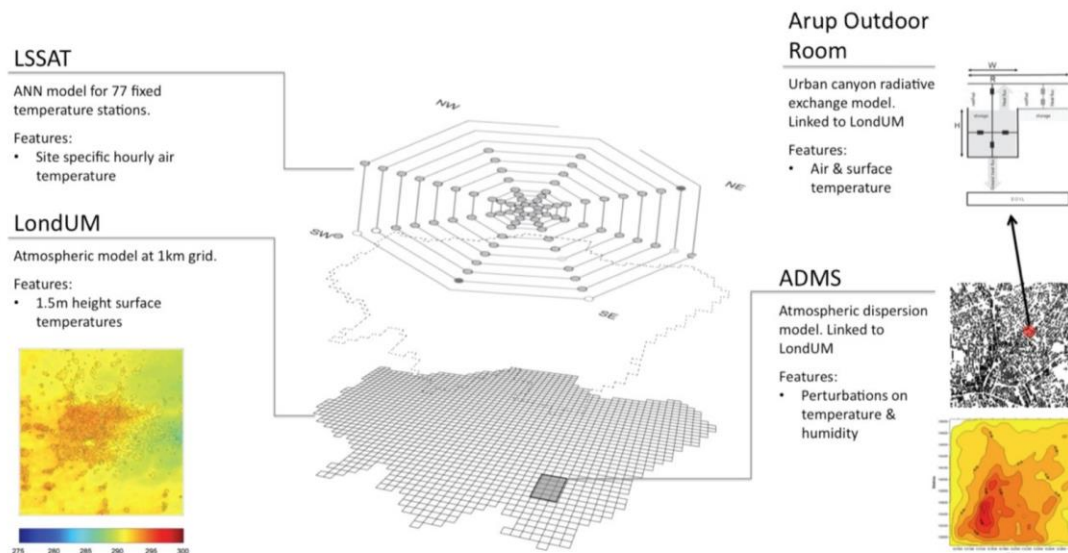
Figure 1. Urban climate models developed within the context of the LUCID project (Source: EPSRC LUCID project)

Previous monitoring studies have demonstrated that London experiences a significant UHI (Watkins *et al.* 2002). Modelling work carried out as part of the LUCID project has allowed the exploration of the spatiotemporal variation of local temperatures across the city, including the effect of variables such as urban materials, land use and anthropogenic heat. The citywide London Unified Model (LondUM) was constructed as part of LUCID and is based on the MetOffice Unified Model (MetUM), a numerical weather prediction model (Bohnenstengel *et al.* 2011). LondUM represents the Earth's surface using a variation of vegetated and non-vegetated surface properties (such as thermal reflectivity, emissivity and capacity), thus estimating the effect that the surface properties have on the local climate.

Figure 2 illustrates an example of LondUM's outputs. It was found that a heat island intensity (i.e. a temperature difference between core urban and rural locations) of 5 °C during the hours after sunset occurs frequently. The intensity peaks on nights with low winds and clear skies. A considerable variation of local urban temperatures over short distances was also observed; external air temperatures may vary by 3-4 °C within only a kilometre. This is attributed to the heterogeneity of the local microclimatic characteristics, including land use and surface properties as well as urban morphology. Although on average the thermal centre of London's UHI is located around the British Museum, the advection of cool rural air changes its pattern on windier days and redistributes heat across London. Modelling also demonstrated that the spatial distribution of London's green infrastructure has a significant cooling effect for London, reducing citywide night time temperatures by up to 2-3 °C compared to a hypothetical scenario in which all London green surfaces were replaced by built up areas. Anthropogenic heat, on the other hand, generated from traffic, industry, space heating and other human activities, was shown to increase the night time heat island intensity by up to 2 °C on average over a year. Such temperature differences are important in a health impact context taking into account that an increase in relative risk of heat related death of 3.8% per °C above a 24.8 °C mean maximum ambient daily outdoor temperature threshold has been estimated for London (Armstrong *et al.* 2011).
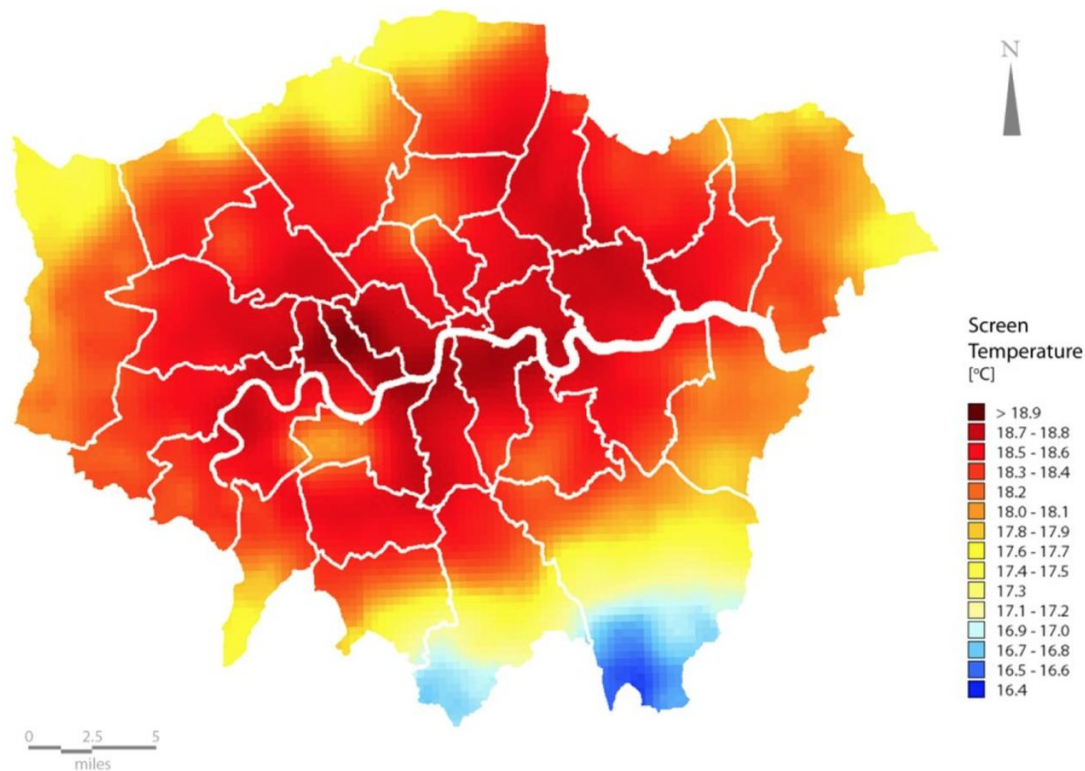
Figure 2. Screen level temperature at 1.5 m height, 26 May - 19 July 2006 (LondUM simulation) (Source: EPSRC LUCID project)

According to LUCID's impact assessment models, the UHI currently has an appreciable net energy benefit for London resulting in around a 13% reduction in residential space heating loads (Mavrogianni *et al.* 2009). However, these benefits might be offset by increased cooling loads if there is a significant uptake of air conditioning in the future. Although the vast majority of London homes are currently naturally ventilated, temperature monitoring studies have shown that bedrooms in almost half of the homes in the monitored sample overheated even during a mild summer (Pathan *et al.* 2017). The heat island also has a substantial impact on the burden of heat related mortality. An epidemiological study using LondUM outputs estimated that the proportion of heat related deaths attributable to the London's heat island increased by 9.5% as one moves from outer to central London (Milojevic *et al.* 2011). It was demonstrated that heat related mortality risk increases in London areas with high average building height, potentially due to the high prevalence of overheating in top floor flats which are prone to heat exposure from radiation loading in these areas. This is in agreement with previous studies (Mavrogianni *et al.* 2009). In winter, nevertheless, the heat island has a protective effect as it results in decreased cold related mortality (Milojevic *et al.* 2011).

Embedding passive cooling strategies in urban design is important and measures such as the improvement and expansion of London's green infrastructure will have co-benefits for health and wellbeing (Fairbrass *et al.* 2018). However, Oikonomou *et al.* (2012) found that the most effective way of reducing indoor heat exposure is the provision of high quality building envelopes that can cope with excess temperatures. This is because the relative contribution of the thermal quality of domestic buildings on internal temperatures is higher than that of the building's location within the heat island.

4.2 London buildings as modifiers of heat exposure

There has been increasing recognition in the last few decades of the indoor environment's impact on human health and wellbeing. Building envelopes can indeed act as modifiers of human exposure to heat, light, noise and air pollution. Nevertheless, in contrast to the wealth of epidemiological research focusing on outdoor climate and air pollution and their influence on health outcomes, indoor environmental quality remains a relatively under-researched field to date. Taking into account that the UK population spends around 90% of their time indoors on average, it is imperative that we estimate the modifying effect of buildings on human exposure to harmful environmental conditions (Vardoulakis *et al.* 2015).

This has been the remit of the *'Air Pollution and WEather-related Health Impacts: Methodological Study based On spatio-temporally disaggregated Multi-pollutant models for present day and futurE'* (AWESOME) project, which developed a building physics based indoor environment model of the UK housing stock (Taylor *et al.* 2016) to examine the contribution of the building envelope as a modifier of exposure to outdoor pollutants and heat, and to provide an integrated assessment of the associated health risks. These estimates were based on a large number of simulations using the building physics tool EnergyPlus, with input data derived from national housing surveys and energy efficiency retrofit databases (Mavrogianni *et al.* 2012; Oikonomou *et al.* 2012). The model outputs were applied to a geographically referenced housing stock model and aggregated at the postcode level. The National Institute for Health Research (NIHR) *Health Protection Research Unit* (HPRU) *in Environmental Change and Health* built on this work with the aim to evaluate more broadly the impact of urban stock heat adaptation transformations, housing energy retrofit strategies and urban greening on indoor environmental quality and health. For the HPRU project, a meta-modelling framework based on the outputs of multiple EnergyPlus runs was developed using Artificial Neural Networks (ANN) (Symonds *et al.* 2016) (Figure 3). This model framework significantly reduces the computing time required for the calculation of occupant exposures to indoor overheating or pollutants with a reduced number of housing inputs, facilitating rapid estimation of exposure at the housing stock or population level.
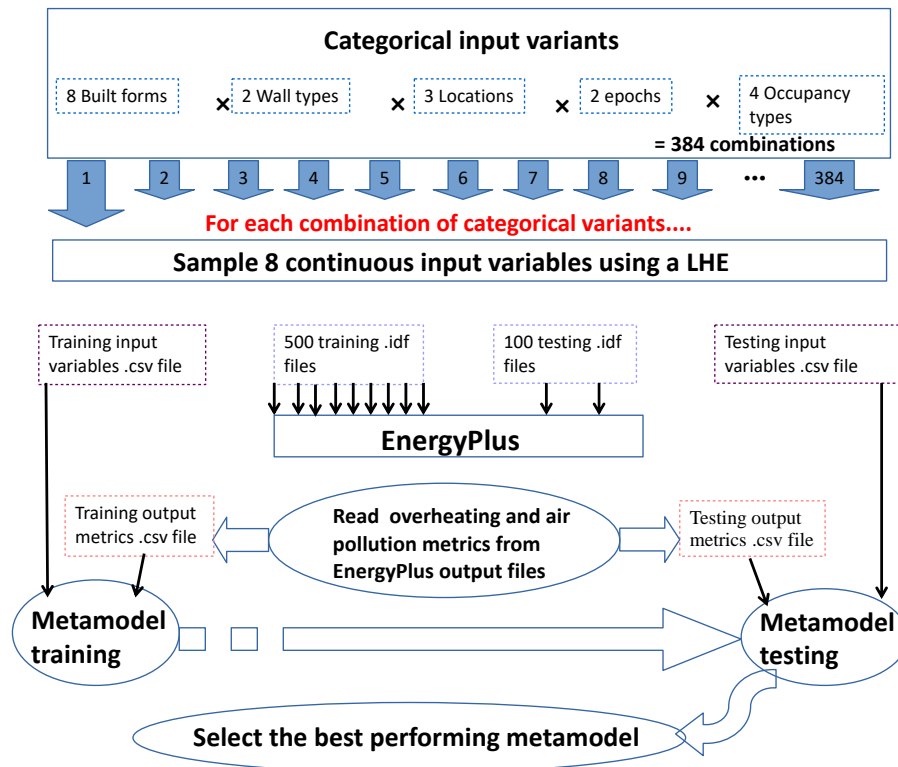
Figure 3. The meta-modelling framework underpinning the HPRU housing stock model
(Source: Symonds *et al.* 2016)

The relative internal heat and air contaminant exposure levels across the UK housing stock, as derived from the AWESOME project, are mapped in Figure 4 (Taylor *et al.* 2016). It was shown that people living in flats and newly built properties are exposed to lower indoor air pollution from outdoor sources. This could possibly be attributed to the fact that the majority of newer, purpose built flats are characterised by higher levels of building air tightness and feature smaller exposed surface areas compared to older houses. Additional work by Taylor et al. (2016) has, however, indicated that they are also exposed to higher air pollution from indoor sources. In terms of indoor overheating risk, flats, bungalows and more recently built, and highly airtight dwellings were amongst the building types that were most at risk of overheating. As a result, people living in urban flats, such as London, are on average exposed to higher levels of overheating and indoor air pollutants due to the higher number of flats in urban areas.
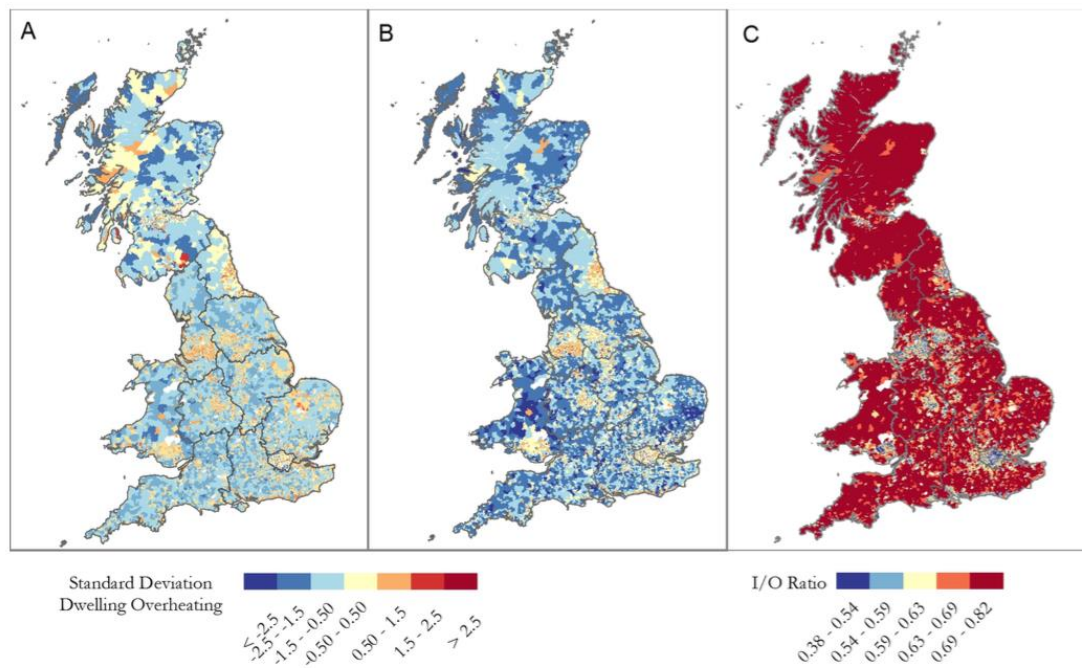
Figure 4. A) Mean Maximum Daytime living room Temperature (MMDT, ^{o}C),
B) Mean Maximum Night time bedroom Temperature (MMNT, ^{o}C), and
C) Indoor/Outdoor ratios for $PM_{2.5}$, for the pensioners' occupancy assumption aggregated at
the Lower Super Output Area level (Source: NERC AWESOME project)

4.3 Identifying heat-vulnerable older Londoners

The importance of an individual's age for heat vulnerability is well established in epidemiological literature (Kovats & Hajat 2008). Although a plethora of existing studies have evaluated the impacts of climate change on urban environments, and population susceptibility to adverse health effects, there are relatively few studies currently that specifically focus on older people and ageing populations in cities. In a similar manner, climate adaptation strategies are rarely tailored to older citizens. The *'Seasonal Health and Resilience for Ageing Populations and Urban Environments'* (SHARPER) two-year project aimed to fill this knowledge gap. The project studied three global cities: London, New York and Shanghai (Arup & Partners 2016).

The heat vulnerability maps and assessment tools developed for SHARPER were heavily based on the London urban heat vulnerability index developed by Wolf and McGregor (Wolf *et al.* 2013; Wolf & McGregor 2013). The index used a Principal Components Analysis (PCA) for socioeconomic determinants of heat risk to develop a Heat Vulnerability Index (HVI). This includes population density, and health status (including mobility levels). The HVI was subsequently overlaid on top of UHI satellite data to identify 'hotspots' of heat risk. For the purposes of the SHARPER project, the index was expanded and revised to include updated Census data as shown in Figure 5. This allowed the identification of areas where the population is most at risk from heat, and provided estimates of the resilience of ageing and older populations in each city at a high spatial resolution (Arup & Partners 2016).
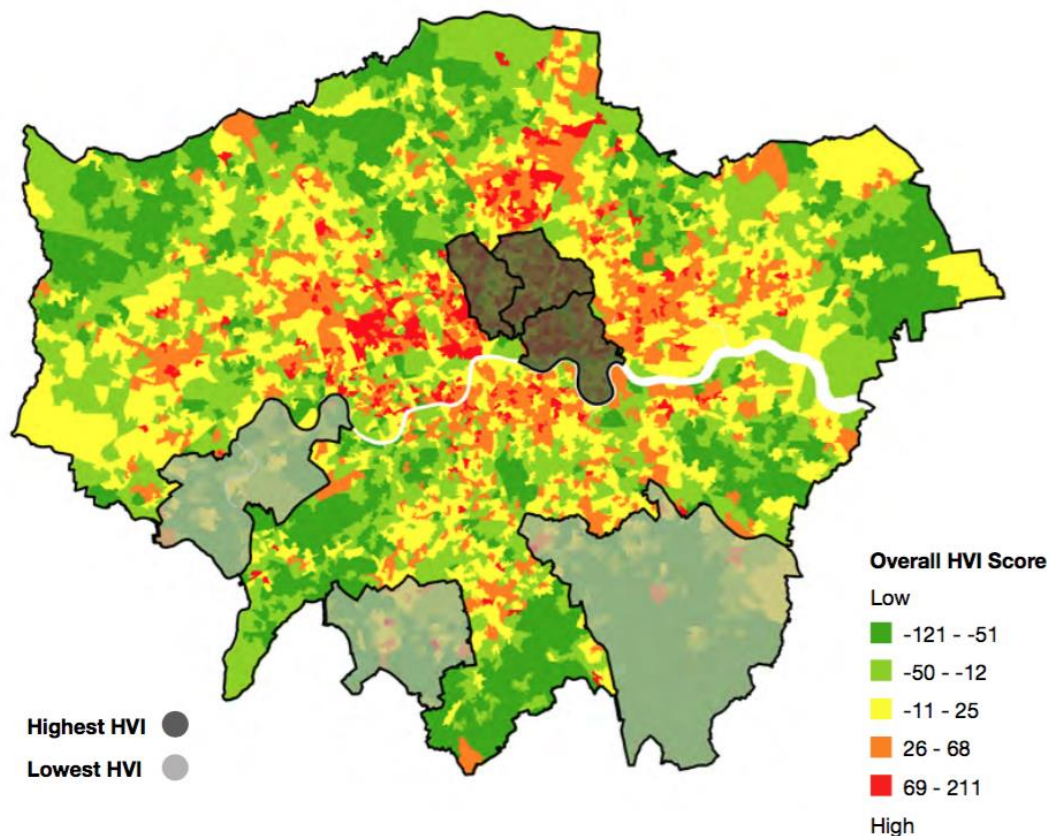
Figure 5. Heat vulnerability index for London (Source: Arup & Partners 2016, © Dr Tanja Wolf / King's College London)

The study found that inner city older people aged 65+ are at high risk from a rise in the frequency of heatwaves. The London Boroughs of Hackney, Islington and Tower Hamlets, in particular, are characterised by the highest number of heat vulnerability areas. This is due to a combination of heat risk factors such as high population density, and a greater proportion of older people with health and mobility issues in these boroughs. Although the borough of Hammersmith and Fulham has high land surface temperatures, the socioeconomic heat vulnerability factors are lower here. Richmond upon Thames, Bromley and Sutton contained the lowest concentration of populations at heat risk.

Similarly to the assessment of urban heat vulnerability, the design of adaptation measures often focus on the general population and only a small body of literature is concerned with the development of targeted responses for urban older and ageing populations. Many authors have argued that the identification of urban design and planning strategies to reduce the heat exposure and associated risks for older people in cities should become a research priority (Gamble *et al.* 2013). The SHARPER project went a step further by outlining a range of practical interventions targeted to older and ageing populations in cities aiming to alleviate heat vulnerability. The interventions were identified and evaluated through detailed stakeholder consultation. It was recommended that 'win-win' measures that improve the resilience of older people to both extreme heat and cold, as well as contributing to the wider agenda of healthy and sustainable building design, should be prioritised.

Examples of such measures include:
- drawing upon the wealth of knowledge and skills that older citizens have, identifying and using existing community networks, and empowering citizens by involving them in the development of heat resilience plans,
- supporting and expanding the role of social care services in providing access to energy, food, water, sanitation and medicines during and after a heatwave,
- enhancing existing and creating new green and blue infrastructure across the city,
- implementing passive cooling strategies at the microclimatic level through the introduction of shading structures, trees, ventilation pathways through buildings, courtyards etc.,
- climate proofing new build as well as retrofitted buildings by introducing passive cooling building design strategies at an early design stage, and
- improving existing heatwave alert systems and streamlining communication channels to ensure that timely information and advice reaches vulnerable people during a hot episode.

4.4 London's Triple Heat Jeopardy

A limitation of the Wolf and McGregor and SHARPER heat vulnerability indices is that the role of building characteristics as modifiers of heat exposure was not taken into account fully. The 'Triple Heat Jeopardy' mapping framework was developed by Taylor et al. (2015) with input from GLA policymakers, who have been at the forefront of climate change adaptation at an urban scale. To identify locations at greatest risk of heat related mortality, the Triple Jeopardy Index combines three data layers: 1) population age, 2) local urban temperature and 3) indoor temperature estimates for over 2.6 million residential addresses in London (Figure 6). An epidemiologically based mathematical relationship was then used to estimate heat deaths during a hot episode based on an individual in the population's age and age-specific heat mortality risk, and the UHI and housing components of heat exposure. The methodological approaches taken by Wolf and McGregor and Taylor et al. are fundamentally different. The models include different inputs, for example: 1) Taylor et al. do not include multiple social determinants of heat risk like Wolf and McGregor, and 2) Taylor et al. include more detailed estimates of heat exposure, both from housing and the UHI. Calculation outputs are also different, with the Taylor et al. model estimating population mortality risk, while the Wolf and McGregor model estimates a vulnerability index, which was subsequently demonstrated to be more aligned to ambulance callouts than mortality (Wolf *et al.* 2013).
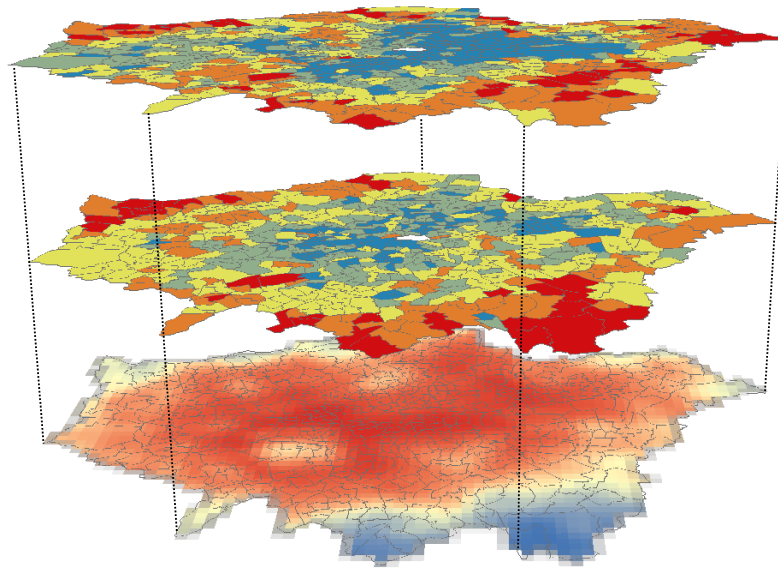
Figure 6. The London Triple Heat Jeopardy mapping framework combining (from top to bottom) age-related relative risk of heat mortality, dwelling temperature anomaly, and local urban temperature data (Source: NERC AWESOME project)

Interestingly, the findings by Taylor et al. indicate that once building properties are factored into the evaluation of urban heat risk, heat related mortality is likely to be higher in the outskirts of London rather than the centre of the city despite the increased external temperatures (Figure 7). This is mainly attributed to the high proportion of older people in the outer boroughs, as well as the makeup of their housing stock, which includes poorly insulated bungalows. The contradictions between the Taylor et al. and SHARPER indices should not be seen as a weakness of either approach but rather as an indication of the complexity of urban heat vulnerability assessment. The comparison of varying approaches is a valuable step towards the integration of multiple heat risk determinant factors in GIS-based risk assessment frameworks. Such tools can become a great asset for urban planners and policymakers aiming to quantify the reduction in heat related health risks resulting from climate adaptation policies and compare their relative advantages in cost benefit analyses.
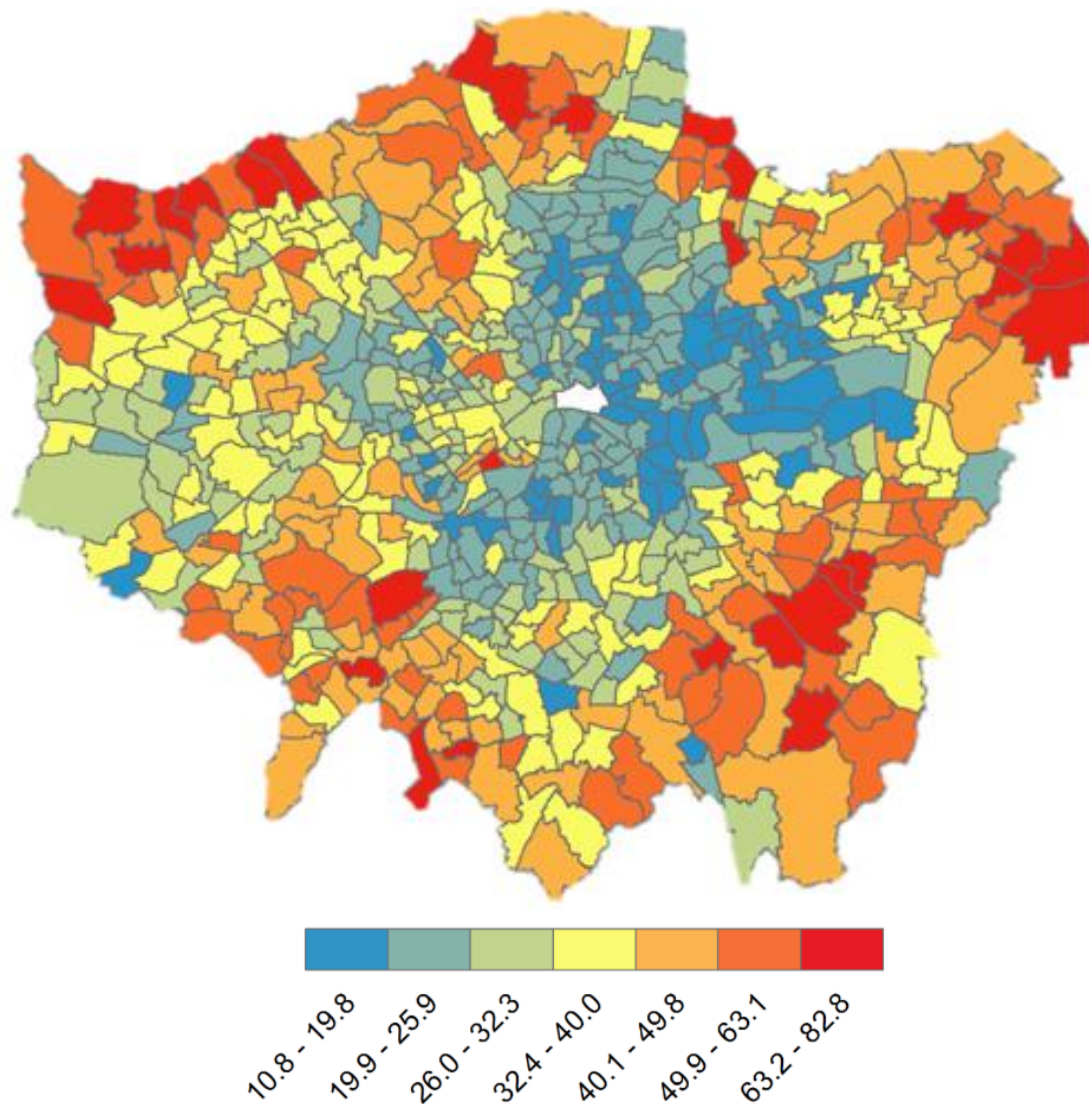
Figure 7. Estimated mortality per million population during a warm 55-day period in London (Source: Taylor *et al.* 2015)

4.5 Climate proofing London care homes

In recent years, there has been an increasing interest in the climate resilience of the care and extra care sector in the UK. This discussion is underpinned by the findings of a recent project commissioned by the Joseph Rowntree Foundation (JRF, Gupta *et al.* 2016; Gupta & Gregg 2017). The study suggested that the health risks associated with heat exposure are not adequately recognised by social care practitioners, potentially due to ingrained habits, norms and the prevalent 'culture of warmth' that dictates that older people need to be kept warm at all times. In addition, poor building design and the lack of effective heat management in care and extra care settings may contribute to increased indoor heat exposure that could have detrimental impacts for the most vulnerable residents. This was further reflected in the UK Government's 2017 Climate Change Risk Assessment (CCRA) produced by the Committee on Climate Change (CCC, Kovats *et al.* 2016), which identified overheating risk in care homes as a key risk and research priority for the health and social care system.

The interdisciplinary pilot project *'Mapping Climate Disadvantage for London's Care Provision'* was an one-year pilot project (Mavrogianni *et al.* 2018a; Oikonomou *et al.* 2018). Its overarching aim was to accelerate the development of equitable responses to climate change for care provision in urban environments, with a focus on overheating risk using Greater London as a case study. A meta-analysis of outputs of existing housing research using building physics-based models was carried out specifically focusing, for the first time, on care settings. This quantified the impact of building geometry and physical properties on the current and future overheating risk of London care home typologies. The location of London care homes was then mapped and information layers of the spatial variability of climate disadvantage in these areas was overlaid on them using spatial analysis techniques. Preliminary mapping suggests that 20% of London care homes are located in areas of 'extremely high' or 'acute' socio-spatial vulnerability (Figure 8), defined by the ClimateJust framework as the result of 'an equally weighted combination of neighbourhood level scores for indicators including population sensitivity to heat, exposure, ability to prepare, respond and recover' (Climate Just 2018).
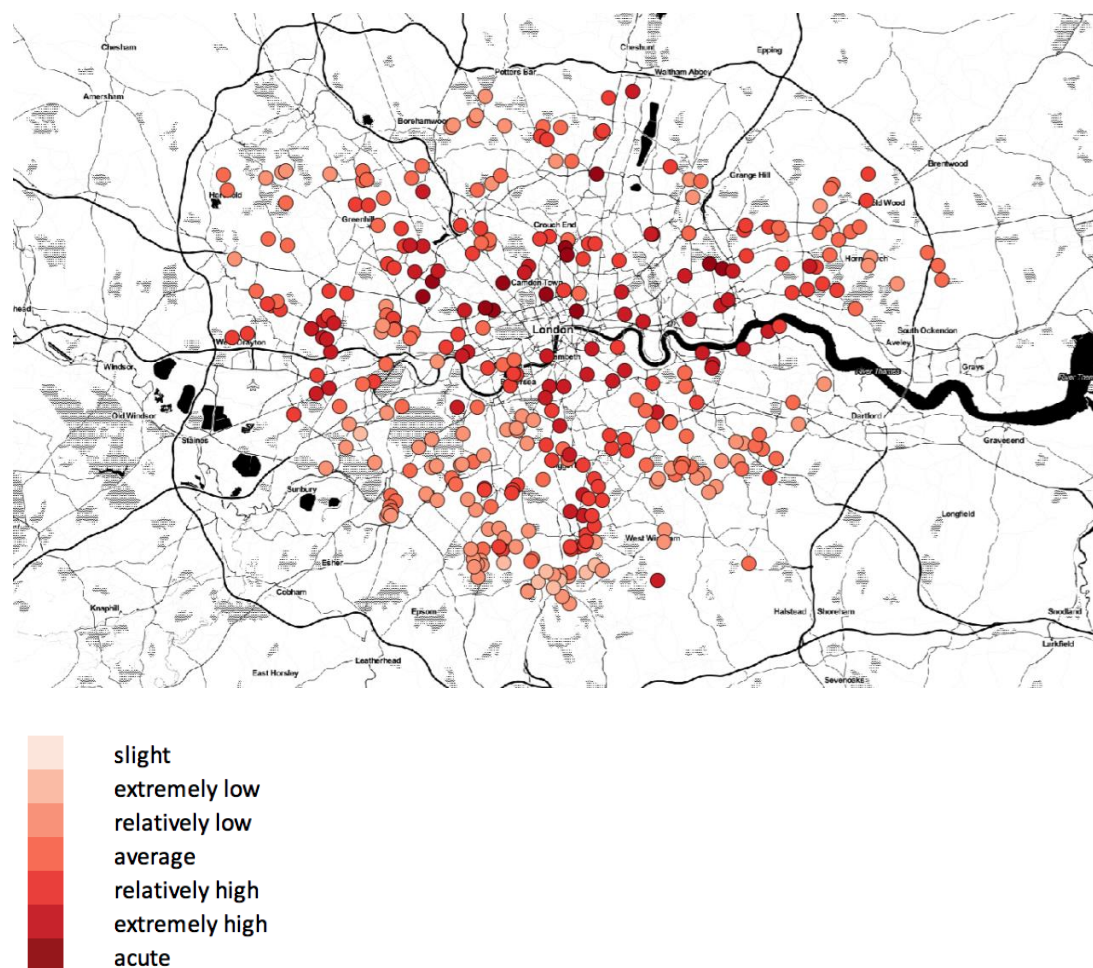

slight
extremely low
relatively low
average
relatively high
extremely high
acute

Figure 8. Location of London care homes in relation to socio-spatial vulnerability indicators (Source: Mavrogianni *et al.* 2018a; Oikonomou *et al.* 2018)

It is envisaged that ongoing and future work in this area will have important implications for building designers, social care providers and managers by helping making suggestions on how to modify existing inspection processes and management practices in order to identify and combat overheating risks for care home residents.

4.6 Working with London Local Authorities

As discussed earlier, the promotion of collaborations between academics, policymakers and the wider public and the operationalisation of research outcomes have a pivotal role in the development of effective urban heat risk mitigation plans. Two examples of such successful translational studies are the UCL Institute for Environmental Design & Engineering (IEDE) projects carried out in collaboration with two London Local Authorities, the London Boroughs of Islington and Hounslow.

The *'Climate Resilience South Islington Project'* (CRISP) was led by the Borough of Islington and assessed levels of awareness, attitudes and habits of older social housing residents in the south of Islington using a questionnaire survey (Kolm-Murray *et al.* 2013). As a follow-up to this study (Makantasi & Mavrogianni 2016; Mavrogianni *et al.* 2015), the UCL team undertook monitoring of indoor temperatures in a small sample of flats across three estates (a 1900s low-rise, a 1950s mid-rise and a 1960s high-rise building). It was found that vulnerable social housing tenants already experience indoor overheating even during a not particularly warm summer, with the flats located in the 1960s high-rise buildings being most prone to high temperatures. Building performance simulation was subsequently used to test the effectiveness of a range of retrofit interventions under current and future climate, thus generating useful guidance for the Borough's housing team. One key finding was that future urban warming could inhibit the cooling potential of natural ventilation beyond a certain time point. In other words, natural ventilation alone may not be able to cool dwellings in the future, with noise and air pollution concerns further limiting its feasibility.

The collaborative project with Hounslow Council (Mavrogianni *et al.* 2018b; Taylor *et al.* 2017) disseminated research outputs of the HPRU project, described above, and tailored them in such a way so as to facilitate their integration into the Borough's existing emergency management systems. This included modelled overheating risk indicators produced at individual physical address level for a range of external weather conditions. 2D and 3D visualisations and animations of the spatio-temporal variation in dwelling overheating risk and UHI intensities during hot spells were also produced (Figure 9).

Figure 9. A 3D visualisation of the area around Worton Way, Hounslow showing the overheating risk of dwellings at 28 °C outdoor temperature (blue dwellings represent the coolest, while red are the hottest) (Source: Taylor *et al.* 2017)

The broader lessons learnt during these two collaborative projects on urban heat risk can be summarised as follows:

- It is of paramount importance to engage with all key stakeholders from the early stages of the project; a co-design element is essential.
- Flexibility is required on the researchers' end to allow for work to be performed within the time and personnel resource constraints experienced by the Borough.
- It is vital to achieve a good understanding of the Borough's datasets (including GIS), procedures and emergency planning tools at an early stage to allow for the effective integration of new data.

4.7 Complex urban systems

To improve the situation locally, it is important to not only integrate the research on the spatial and social characteristics of climate and heat vulnerability, respectively, but to also incorporate a whole systems perspective and to collaborate with local decision makers and stakeholders. The *'Complex Urban Systems for Sustainability and Health'* (CUSSH) project is a four-year Wellcome Trust funded project that aims to develop critical evidence on how to achieve the far-reaching transformation of cities needed to address vital environmental imperatives for population and planetary health. Only launched in 2018, it has started to use cutting edge science and systems-based participatory methods to articulate visions of development, help shape policy decisions, and accelerate the implementation of transformational changes for health and sustainability in low, middle and high income settings (Belesova *et al.* 2018; Zimmermann *et al.* 2018a). Across the six partner cities (London, Rennes, Nairobi, Kisumu, Beijing and Ningbo), the CUSSH project will be supporting city decision makers in developing ambitious urban sustainability and health policies. The project assembles a multidisciplinary team of experts in participatory system dynamics, behaviour change, microsimulation, air pollution modelling, and urban systems complexity and public engagement. In London, CUSSH is initially focussing on green infrastructure with its connections to environmental quality, sustainability, population health and health equity.

Although green infrastructure has the potential to attenuate the UHI effect, it is important to establish potential synergies and unintended consequences of this approach as well as understanding how such green infrastructure can be provided and managed. In collaboration with GLA policymakers, a systems approach was adopted using participatory system dynamics modelling. A causal diagram of potential cause, effect and feedback relationships associated with the provision, maintenance and health impacts of green infrastructure in London was developed. Figure 10 shows a selected number of these relationships; it reveals that the existence of municipal and other green infrastructure tend to increase their use, with positive effects on physical activity and health. At the same time, they reduce the UHI effect, with beneficial health effects, at least under warm conditions (Zimmermann *et al.* 2018b).
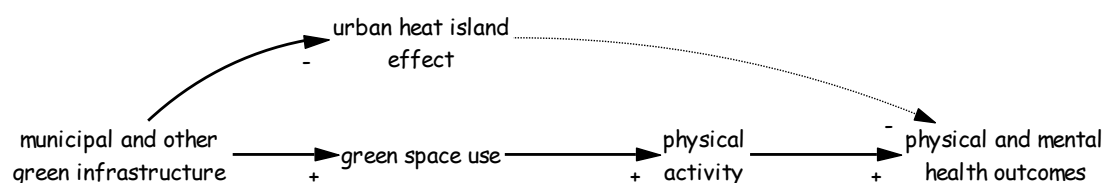

Figure 10. Selected causal effects of adding municipal and other green infrastructure
A plus (minus) next to an arrow indicates a same (inversely) directed causal relationship. A

dashed arrow indicates the high ambiguity of the adverse summer and useful winter effects of the UHI. (Source: Zimmermann *et al.* 2018b)

This approach revealed explicitly that green infrastructure and the UHI are interconnected in a complex system. It brought together the multiple perspectives of the participating stakeholders. The visual nature of this approach allowed policymakers to see the interconnection of variables and their dependencies, including unintended consequences and synergies (Black 2013).

A key finding arising from the CUSSH work is that researchers can provide policymakers with an evidence based assessment of heat vulnerability, enabling policymakers to direct scarce resources toward design and retrofit measures that have the best chance of reducing the health impacts of extreme heat events. Such collaboration would benefit from researchers gaining greater understanding of policymakers' constraints and opportunities. Ongoing research in IEDE shows that there is an increasing number of urban health indicator tools displaying data about built environment exposures at low spatial scales (Pineo *et al.* 2018a), and climate vulnerability tools were among the indicator tools identified. Research into local decision makers' use of evidence in the UK found that participants were interested in qualitative data (alongside quantitative data), data displayed on maps, case studies and indicators that could help build a business case for particular interventions (McGill *et al.* 2015). The modelling results from the various research projects discussed in this section are an example of research outputs that might be useful for practitioners as they include maps, images and locally specific data.

5. Summary

The role of building and urban design in public health promotion has been elevated in recent decades. This chapter set out to discuss a series of UCL IEDE research projects focusing on London's urban heat resilience in the context of an urban health research and policy agenda. The current and future challenges to global megacities, such as London, were explored. This was followed by a discussion of how advancements in a wide range of scientific fields, such as climate science, built environment studies, GIS, behavioural psychology, and systems thinking could be harnessed to develop evidence based and solution driven decision frameworks for policymakers working in the area of urban climate resilience. It is widely recognised that we live in a warming, ageing and increasingly urbanised world and that certain segments of the population will be hardest hit by the effects of these major changes to our urban environments. In London, academic research has been centred around modelling the external environment and the modifying effect of the building stock on indoor environment exposures, and mapping the environmental, social and personal determinants of climate related risk. This work is co-created with public health bodies, city level and local government policymakers. Further translational work is needed to strengthen the collaborations between academic teams and stakeholders, thus bridging the fields of climatology, building and urban design, and public health in order to increase climate resilience, erase climate injustice and promote health equity in urban settings.

Acknowledgements

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