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Probabilistic spatial risk assessment of heat impacts and adaptations for London

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Abstract High temperatures and heatwaves can cause large societal impacts by increasing health risks, mortality rates, and personal discomfort. These impacts are exacerbated in cities because of the Urban Heat Island (UHI) effect, and the high and increasing concentrations of people, assets and economic activities. Risks from high temperatures are now widely recognised but motivation and implementation of proportionate policy responses is inhibited by inadequate quantification of the benefits of adaptation options, and associated uncertainties. This study utilises high spatial resolution probabilistic projections of urban temperatures along with projections of demographic change, to provide a probabilistic risk assessment of heat impacts on urban society. The study focuses on Greater London and the surrounding region, assessing mortality risk, thermal discomfort in residential buildings, and adaptation options within an integrated framework. Climate change is projected to increase future heat-related

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mortality and residential discomfort. However, adjusting the temperature response function by 1–2 °C, to simulate adaptation and acclimatisation, reduced annual heat related mortality by 32–69 % across the scenarios tested, relative to a no adaptation scenario. Similar benefits of adaptation were seen for residential discomfort. The study also highlights additional benefits in terms of reduced mortality and residential discomfort that mitigating the urban heat island, by reducing albedo and anthropogenic heat emissions, could have.

1 Introduction

Projections of future climate change suggest that it is very likely that the frequency and/or duration of warm spells and heatwaves will increase over most land areas by the late 21st century. Warmer and/or more frequent hot days are also likely over most land areas in the early 21st century, and virtually certain by the late 21st century (IPCC 2013). Increases in summer mean daily maximum temperature in the range of 1.2 to 7.3 °C (central estimate 3.7 °C) have been projected by the 2050s for the South-East of England (medium emission scenario) relative to the 1961–1990 baseline (UKCP09 2012).

High temperatures and heatwaves are associated with significant impacts on society. Healthy individuals have efficient heat regulation mechanisms to help cope with increasing temperatures (Hajat et al. 2002), yet there are limits to the amount of heat exposure an individual can tolerate. Beyond this threshold people can suffer from heat exhaustion and heat stroke which can result in death, with older people, babies and young children particularly at risk (Department for Health 2013). During the 2003 heatwave studies of London estimated an increase in daily deaths of 42–60 % (Kovats et al. 2006; D'Ippoliti et al. 2010). Heat-related mortality is also projected to increase steeply in the 21st century, with London projected to be highly vulnerable to future effects of high temperatures (Hajat et al. 2012). Hot conditions have also been associated with an increase in hospital admissions due to sunburn, heat exhaustion, and respiratory disorders due to deteriorated air quality, placing additional strain on the health service during these periods (Cabinet Office 2010).

Linked to heat-related mortality is the issue of overheating of buildings in summer, and the associated thermal discomfort people face, a problem which is likely to become increasingly severe under future climate change (Hacker et al. 2005). Buildings have the potential to amplify outside temperatures, dependent on architecture, building type, construction material, ventilation, and external weather characteristics. This results in a complex response function which cannot be easily characterised (Coley and Kershaw 2008). As such, most heat-related impact studies focus on external environmental conditions and exclude the influence of building structures and characteristics on internal temperatures and impacts (Mavrogianni et al. 2012). Whilst there are no set building regulations related to overheating risk to guide residential building design in England, internal temperature thresholds above which people will feel discomfort have been established as guidelines, for example 26–28 °C for bedrooms and living space (CIBSE 2006).

Urban areas are considered particularly vulnerable to impacts of climate change due to their high concentrations of activities, people and assets (Hall et al. 2009), whose homes, workplaces, public buildings, and infrastructure may not be designed for the high temperatures projected to occur in the future. Those living within urban areas are also particularly vulnerable to high temperatures due to the Urban Heat Island (UHI) effect, whereby temperatures are higher than in surrounding rural areas due to the heat storage of paved and built up areas, reduced radiative cooling efficiency, and waste heat from buildings, transport, and industry.

The risk of high and potentially extreme temperatures in urban areas therefore requires consideration of multiple factors, including the frequency and severity of heat events, the UHI effect, and the vulnerability of different sectors of the urban population. All of these factors are expected to change in the future, in ways which are not necessarily independent of one another. This study utilises an urban integrated assessment framework (UIAF) for analysing scenarios of climatic and socio-economic changes in urban areas (Hall et al. 2009) to quantify the risks and uncertainties of high temperatures, for a range of different scenarios, and the potential effectiveness of adaptation options. The UIAF couples outputs and data from multiple models to provide system-scale understanding of the inter-relationships between climate impacts, the urban economy, transport and the built environment.

2 Modelling framework

An overview of the model framework and components facilitating the mortality and residential discomfort risk assessment is illustrated in Fig. 1. The framework incorporates probabilistic projections of daily maximum (TMax) and minimum temperature (TMin) from a spatial version of the UKCP09 Weather Generator (WG) (Kilsby et al. 2011) (outlined in Section 2.1). This facilitates a probabilistic analysis of heat events, as well as providing an assessment of underlying climate model uncertainties. For each impact the hazard is assessed in terms of the exceedence of temperature thresholds, defined based on estimates from impact

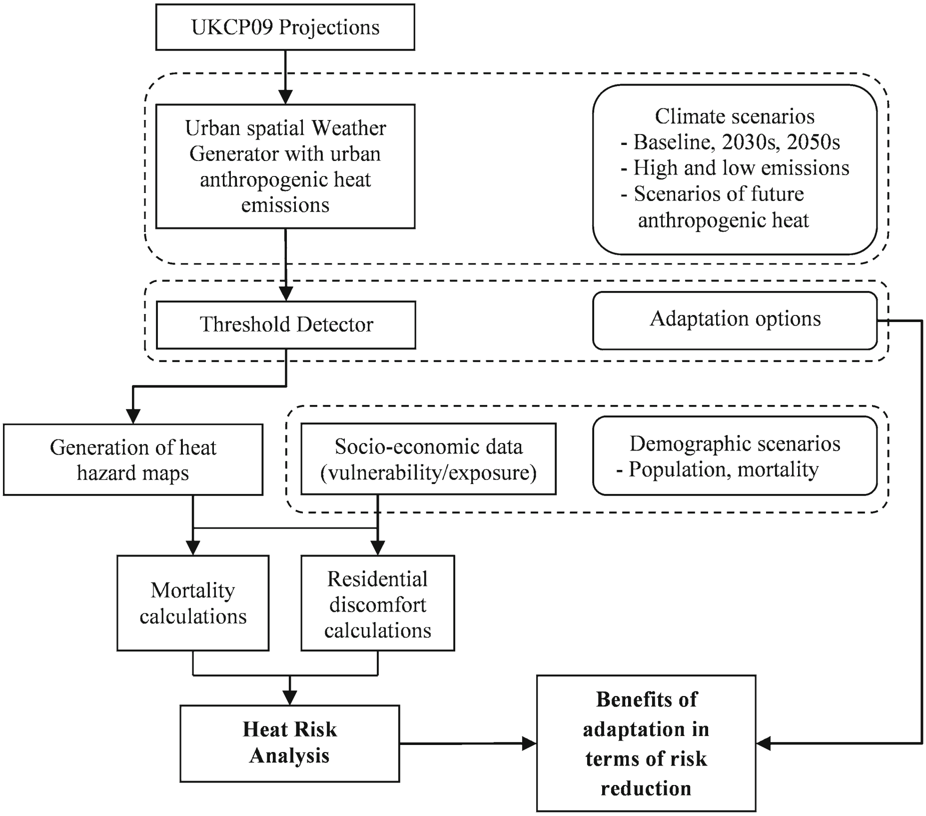

Fig. 1 Overview of the risk based modelling framework

studies and literature. The threshold values, methodology for each impact, and results are outlined in Section 3. Adaptation options are represented by adjusting the temperature threshold values. Based on the exceedence of temperature thresholds heat hazard maps are created using Arc-GIS. These reflect both daily data on the intensity and spatial pattern of events and summary statistics (e.g. the annual number of days exceeding set thresholds per year). The heat hazard maps are then overlaid onto maps containing demographic and socio-economic data to estimate impacts as a function of the hazard, vulnerability and exposure.

The study focused upon Europe's largest city, London, and its surrounding region, defined as communities where more than 10 % of the commuting trips were destined for employment locations in Greater London. Raw commuting thresholds produce an uneven and discontinuous boundary, and so the boundary line was cleaned to define the final study area (Fig. 2). This approximates to the London Outer Metropolitan Area boundary, as defined in publications such as the London Office Policy Review (GLA 2009). It encompasses an area of 13,238 km^2, a population of approximately 13.9 million people (7.5 million within Greater London), and 5.7 million residential dwellings (ONS 2001).

2.1 Spatial weather generator for urban areas

The spatial and temporal scale of climate model outputs is often inconsistent with that required for climate change impact studies. More spatially explicit climate projections can be produced by incorporating downscaling techniques that account for local climatological features. The most recent UK climate scenarios (UKCP09) have been accompanied by a stochastic Weather Generator (WG) which can provide daily and hourly time series of weather variables for present and future conditions at a 5 km^2 resolution (Jones et al. 2009). The WG incorporates a

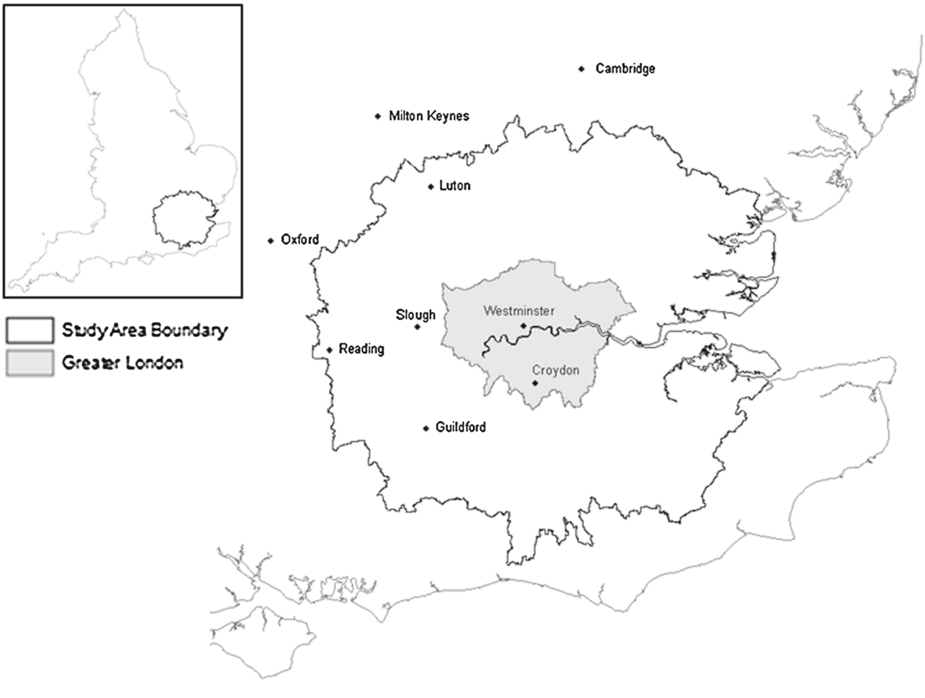

Fig. 2 The boundary of the study area surrounding Greater London, and location in England (*inset*)

stochastic rainfall model, which simulates future rainfall sequences, and then generates other weather variables according firstly to the rainfall state and then to other inter-variable relationships which are represented as regression relationships. The WG has been well validated against observed data from 1961 to 1990 (*ibid.*).

The UKCP09 scenarios were novel in their representation of climate model uncertainties, based on the range of climate model responses from a large perturbed physics ensemble (Murphy et al. 2009). Results are presented as probability distributions of projected changes which can be used to parameterise changes in the WG. In practice this is achieved by providing a Monte Carlo sample of 10,000 equiprobable vectors of change factors that are used to parameterise the WG. This leads to a two-level sampling scheme in which (i) repeated representations of the WG for a given vector of input parameters can be used to explore the effects of natural variability and (ii) sampling different vectors of change factors explores the effect of climate model uncertainty in projected future impacts. In the results reported here we refer to the median or other quantiles in the range of the climate projections explored via (ii).

The UKCP09 WG simulates weather sequences at a single site so does not provide spatial consistency in time across neighbouring grid cells (Jones et al. 2009). The lack of spatial coherence limits the use of the WG for analysing aggregate impacts over several grid cells. In this study a modified version of the UKCP09 WG is used to provide spatially coherent time-series data. In addition the effects of the UHI due to urban land use and anthropogenic heat flux is incorporated as an additional change factor to the WG. This component is based on the study by McCarthy et al. (2012), downscaled for integration in the spatial WG, which yielded relationships for the strength of the UHI as a function of urban land cover and anthropogenic heat emissions (see supplementary material for a summary of the method). The effects of climate change were found to be additive to these local urban temperature effects in London.

In this study TMax and TMin time-series data for 30 year stationary sequences are taken from the WG for each grid cell in the study area. These series are generated 100 times each based on a different randomly sampled vector of change factors, to allow probabilistic analysis. In this study, daily time-series data is generated for the baseline period (1961–1990) and for the 2030s and 2050s under high and low emission scenarios (equivalent to the IPCC SRES B1 and A1FI scenarios). Each future scenario is also run assuming that (i) the ratio of urban land use and anthropogenic heat emissions remain the same as the baseline period (1.0) or (ii) that urban land use and anthropogenic heat emissions increase by 50 % from the baseline (1.5).

2.2 Demographic data and projections

Vulnerability to high temperatures will not only be a factor of climate change but will also be affected by socio-economic change. The UIAF integrates demographic data and projections which can be combined with the hazard maps to facilitate a more comprehensive risk analysis. In this study population and mortality data are used to assess heat related mortality and residential discomfort.

Population projections from the Office of National Statistics (ONS) were only available until 2033 thus projections for the 2030s and 2050s at a borough and district level were taken from a geo-demographic model. The geo-demographic model closely follows the methodology employed by the ONS in the generation of their national and sub-national population projections with each projected year based on trends from the previous 5 years (ONS 2010a). To estimate future projections firstly the population is aged. For each age group the number of births is calculated by multiplying an age-specific fertility rate by the number of women in that age group. Mortality is calculated in a similar way in the model using an age and gender specific mortality rate calculated for each age group and multiplied by the number of people in that age group to calculate the number of deaths. Migration is the most complicated of the processes in the ONS projections and much of the data required to estimate migration is not available. Consequently migration is estimated by calculating the difference in the size of the projected population (by age group) for a given region compared to the expected ONS subnational projection in the demographic model. In this study the principal scenario is used, which reflects the ONS typical baseline projection under normal conditions. For the study area this represents a population increase from a baseline of 13.9 million to 17.4 million in 2030, and to 19 million by 2050. For each borough and district the data was disaggregated to a ward scale based on the present day population distribution.

To estimate heat related mortality a baseline daily mortality rate was ascertained from data on annual mortality rates in 2008 at a ward level. This data was available directly from the ONS (2010b) for Greater London, based on death registrations by area of residence. For the wider study region district level data from the ONS (2010c) for the South East and East of England was used, disaggregated equally across the wards within those districts. Due to the difference in mortality rates between Greater London and the surrounding region a separate daily mortality rate has been defined for both. Additionally, trends in monthly mortality from 2006 to 2010 were investigated to estimate mortality in each season. On average 23 % of deaths in the study area occurred in summer (June to August). The daily mortality rate was weighted accordingly as the largest impact from heat events occur during summer. For the 2030s and 2050s annual mortality projections, used in the generation of the principal population projections, have been used to calculate daily mortality rates. This resulted in an estimated rate of 127, 117, and 107 deaths per day in summer in Greater London for the baseline, 2030s and 2050s periods respectively, and 160, 172, and 188 deaths per day in the study region surrounding Greater London, replicating the general trends seen in the ONS projections.

3 Risk assessment

3.1 Heat related mortality

Heat related mortality is calculated based on epidemiological studies which link mortality to temperature. This approach can be applied to isolated events, however a more objective method for assessing the temperature mortality relationship is to investigate longer-term time-series data (Gosling et al. 2009). Heat related mortality has recently been investigated for England and the UK by Armstrong et al. (2010) and Hajat et al. (2012). Gosling et al. (2009) also reviews multiple studies to highlight average temperature thresholds of minimum mortality across a range of locations, including London. These include studies by Pattenden et al. (2003) and Hajat et al. (2002, 2006) which have been utilised here. Averaging the temperature response functions provides a mean daily temperature threshold of 20 °C above which heat related mortality increases on average by 3.1 % per 1 °C rise. It is assumed that there is no lag effect between high temperatures and mortality as previous evidence suggests that heat impacts are mostly immediate, occurring on the same or following day of exposure (Armstrong 2006). Daily mean temperature (TMean) is estimated using TMax and TMin values from the WG, with the number of days which exceed each 1 °C temperature interval above 20 °C estimated for each scenario.

Annual average heat-related mortality is calculated for each grid cell in the study area with a background daily mortality rate r (Eq. 1). The number of heat related excess deaths is calculated based on the percentage increase in heat related mortality of 3.1 % (p) for each

1 °C temperature interval (i) above 20 °C, where n represents the number of intervals i. The total number of days (d_i) in the simulation in which the daily average temperature falls in interval i is divided by the number of years (y) in the simulation.

$$M = \sum_{i=1}^{n} \frac{p \cdot i}{100} \cdot r \cdot \frac{d_i}{y} \tag{1}$$

For each scenario heat related mortality was estimated for Greater London, the surrounding region, and the whole study area. While there is limited evidence on the effects of autonomous and planned adaptation on temperature-related mortality, with no generally accepted method as to how adaptation can be modelled, one approach is to shift the exposure-response threshold (Gosling et al. 2009). Here the threshold has been shifted by 1 °C and 2 °C to investigate potential implications of autonomous or planned adaptation on heat related mortality. The values of 1 °C and 2 °C have been selected as proxies to investigate adaptation based on various estimates in the literature (e.g. see review by DCLG 2012) which suggests that this could be a reasonable, and not overly optimistic, range to represent decreasing external or internal temperatures or through increased personal resilience due to behavioural changes. The median (50th percentile) results are presented assuming the ratio of urban land use and anthropogenic heat emissions remain the same as the baseline period (Fig. 3a) and that they increase by 50 % from the baseline (Fig. 3b), with probabilistic results illustrated in Fig. 4.

If the present day level of urban land use and anthropogenic heat emissions were to remain unchanged in the future, the median results suggest there will be an additional 603 heat related deaths per year in Greater London by the 2050s (high emission scenario), regardless of the declining mortality rate, and 1,262 across the whole study area. If, as is anticipated, urban land use and anthropogenic heat emissions are increased by 50 % from the present then 842 and 1,643 additional heat related deaths are estimated. By way of comparison, in a recent study Hames and Vardoulakis (2012) estimated additional annual heat related deaths in the range of 96–619 (10th to 90th percentile) for London by the 2050s under a low emission scenario, and 187–951 under a high emission scenario. Comparably, this study estimates additional annual deaths in the range of 377–1103 and 445–1,314 for London. The higher values reflect the inclusion of urban land use and anthropogenic heat emissions in the temperature data (using the previous version of the WG, which does not incorporate the additional urban heat change factors, results in additional annual deaths in the range of 125–675 and 189–941 for the 2050s for low and high emission scenarios respectively).

Increasing the mortality based temperature threshold by 1 °C resulted in declines in annual heat related mortality ranging from 32 to 42 % across the scenarios, and from 57 to 69 % for an adjustment of 2 °C (Fig. 3). Such adjustments could be associated with, and used to illustrate, benefits of adaptation options on heat related mortality (e.g. associated benefits of heatwave warning systems and increased use of air conditioning). There is no good empirical evidence to quantify the benefits of these adaptation options. A sensitivity analysis is therefore presented here.

The analysis also highlights that potential benefits, in the form of reduced mortality, that stabilising or reducing anthropogenic heat emissions could have at a city level, for example through urban greening schemes and reduced energy use. Figure 5a illustrates the spatial pattern of annual mortality for Greater London at a ward scale for the 2050s high emission scenario assuming a 50 % increase in present day urban anthropogenic emissions and no adaptation. Figure 5b highlights the potential benefits, in the form of reduced heat-related mortality, if anthropogenic heat emissions were to remain at the present day level and adaptation increased resilience to heat by 1 °C. As such, it is important that heat-related

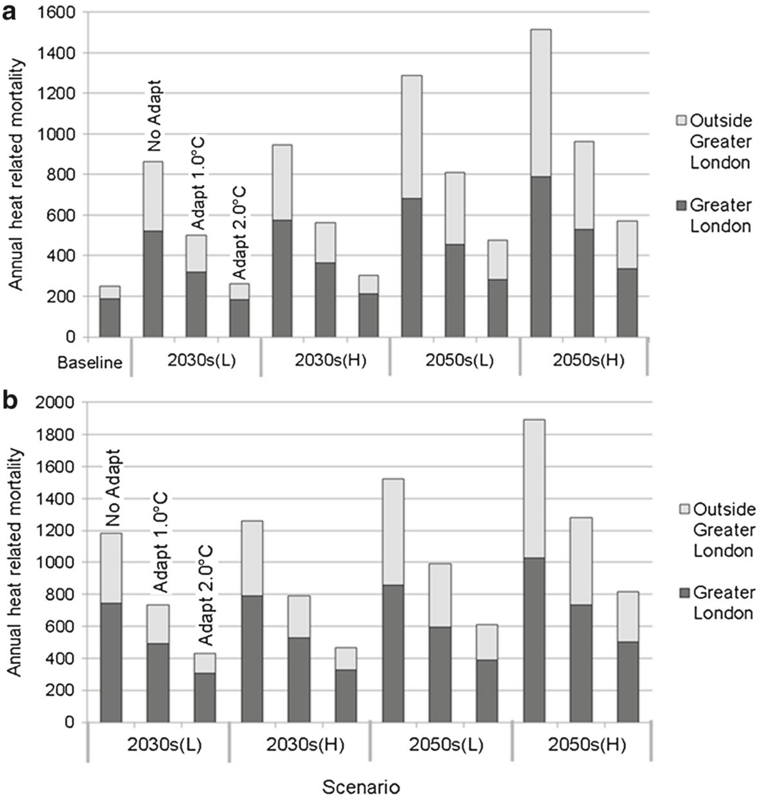

Fig. 3 Estimated annual heat related mortality (50th percentile) with and without adaptation assuming **a** present day urban land use and anthropogenic heat emissions remain stable, and **b** a 50 % increase in present day urban land use and anthropogenic heat emissions

adaptation is considered in terms of measures to restrict temperatures in urban areas as well as implementing impact specific adaptive measures to deal with residual temperature increase.

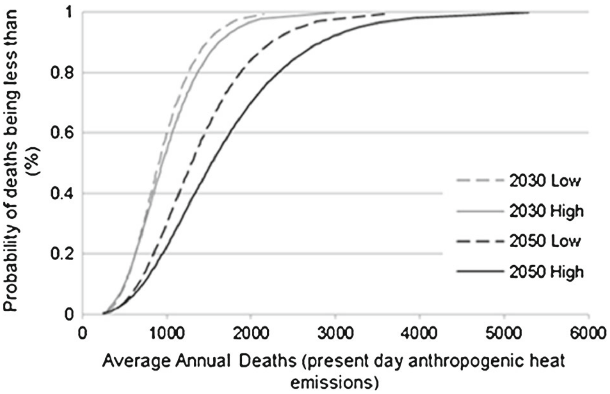

Fig. 4 Probability of average annual heat related mortality for the 2030s and 2050s under low and high emission scenarios, assuming present day urban land use and anthropogenic heat emissions remains constant

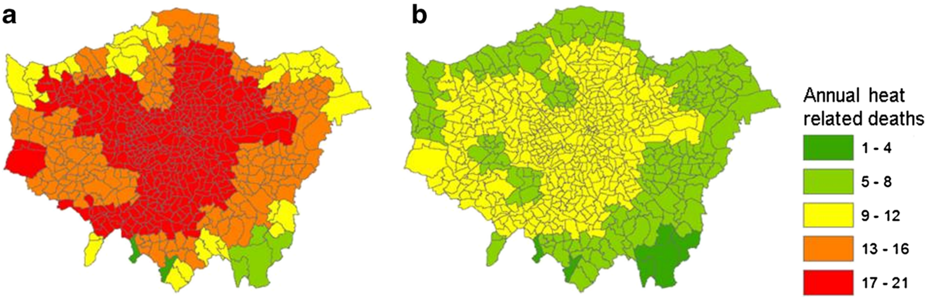

Fig. 5 Spatial pattern of annual heat related deaths in Greater London (50th percentile) for the 2050s (high emissions) assuming **a** no adaptation and a 50 % increase in present day urban land use and anthropogenic heat emissions, and **b** assuming adaptive responses increase resilience to heat by 1 °C and urban land use and anthropogenic heat emissions remain stable

As well as focusing on annual results it is also important to note that heat related mortality may vary widely on any given day. The spatial WG is advantageous in this regard as it provides spatially coherent data across neighbouring grid cells. This means that information on daily heat events (defined here as any day where one or more grid cells exceed the TMean threshold of 20 °C by 1 °C or more) in Greater London and the surrounding region can also be assessed in probabilistic terms.

3.2 Residential discomfort

Mavrogianni et al. (2012) assessed the effect of different building stock characteristics and thermal properties on internal living room temperatures in London, with results highlighting a potential amplification in daily maximum temperatures of 0.7–1.5 °C for terraced buildings; 1.7 °C for semi-detached buildings; 0.7–1.5 °C for detached buildings, and −0.8–2.7 °C for flats. Whilst such estimates simplify processes that relate external to internal temperatures at an individual building level, they do provide an indication of the overheating risks related to different residential building types (assuming natural ventilation and no air conditioning), and how such risks could change in the future. Based on the internal temperature threshold of 28 °C above which people will feel discomfort in living spaces (CIBSE 2006) the above amplification values are used as proxies to estimate a range of external temperature thresholds above which residential discomfort could occur in each building type (Table 1). Mavrogianni et al. (2012) also noted a strong correlation between daytime living room and night-time bedroom temperatures, with night-time bedroom temperatures about 1 °C lower. This can also be linked to night-time bedroom temperatures of 27 °C, which would also cause thermal

Table 1 Amplification values and temperature thresholds used to define residential discomfort

Building type	External to internal temperature amplification range	Lower limit for external TMax threshold	Upper limit for external TMax threshold
Terraced	0.7–1.5	26.5	27.3
Semi-detached	1.7	26.3	26.3
Detached	0.7–1.5	26.5	27.3
Flats	−0.8–2.7	25.3	28.8

discomfort (based on the exceedence of the temperature threshold of 26 °C for thermal discomfort in bedrooms (CIBSE 2006)).

The number of people subject to residential discomfort was estimated based on the TMax temperature pattern for each day of the spatial WG simulation. Spatial footprints of heat events, defined here where one or more grid cells in the study area exceeded the thresholds for each building type (Table 1), were created. The daily heat maps were overlaid to maps showing the number of buildings of each type per grid cell, and the average number of occupants per building. This was estimated using data on the number of residential buildings of each type from the (ONS 2001), and the population projections (outlined in section 2.2). Whilst population change is captured in the future estimates the number of properties is assumed to remain constant. London has a slow turnover of building stock with the net conventional housing supply falling from 2008/09 to 2009/10, with 10,070 new build homes delivered in 2009/10 concentrated primarily in central London (GLA 2011).

Thus, the potential number of people subject to residential discomfort (RD) is calculated as $RD = a_t\, n_t : \text{TMax} \geq \text{Threshold}$ where a_t is the average number of occupants of building type t and n_t is the number of buildings of type t in the given cell. The spatial coherence of the WG allows data to be aggregated across the study area for each daily heat event and assessed in probabilistic terms. Median results are shown in Fig. 6, represented as a percentage of the total occupants per building type in the study area at risk from thermal discomfort.

The difference in results across building types represents the underlying characteristics and thermal properties of the buildings factored in the amplification values; the location, concentration, and number of residents living in each property type; and the spatial pattern of the temperature regime.

The results highlight the relative effects of climate change and changes in the UHI effect on potential future residential discomfort. Comparing the results generated using the low and high temperature thresholds demonstrates the potential benefits of adaptation options to increase building resilience to high temperatures (e.g. through structural modifications such as improved ventilation and increased shading to reduce the temperature amplification level of buildings). For example, in the 2030s for flats a shift in the temperature threshold of 3.5 °C

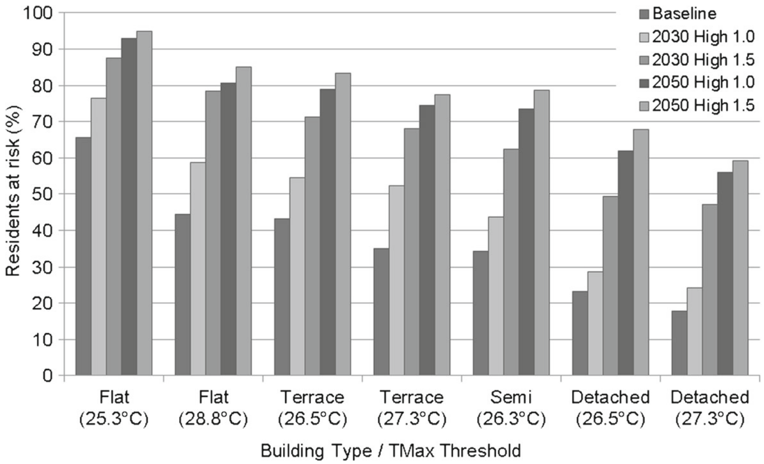

Fig. 6 Percentage of total occupants per building type at risk from thermal discomfort per daily event. Median results are presented for the baseline, 2030 high and 2050 high scenarios assuming urban land use and anthropogenic heat emissions remain at the present day level (1.0) and that they increase by 50 % (1.5)

would reduce the percentage of people at risk by 9 % (high emission scenario, median result). Additional benefits of stabilising urban land use and anthropogenic heat emissions (e.g. through urban greening schemes and reduced energy use) are also evident. If urban land use and anthropogenic heat emissions are assumed to remain at the present day level, alongside adaptations at a household level, then the percentage of people in flats at risk would be reduced by 29 % compared to a scenario with no adaptation. Although this assumes a relatively large change in the temperature threshold benefits were seen across all the scenarios and building types. For detached buildings an increase in the external temperature threshold of just 0.8 °C reduced the percentage of people at risk by 2 %, increasing to 25 % if stabilisation of urban land use and anthropogenic heat emissions were considered in parallel.

4 Conclusions

Social vulnerability to heat events will be influenced by future climate change, social factors, conditions of the built environment, and the spatial configuration of urban systems. For Greater London and the surrounding region climate change is projected to have a negative impact on future heat related mortality and the frequency with which people could be affected by residential discomfort. By the 2050s (high emission scenario, median result) climate change and changes to urban land use and anthropogenic heat emissions could result in 842 additional heat related deaths in Greater London, and 1,643 additional deaths across the wider study area. However, adjusting the temperature response function by 1–2 °C, to simulate adaptation and increased resilience to heat, reduced annual heat related mortality by 32–69 % across the scenarios tested.

By the 2030s 59–76 % of flat based residents and 24–29 % of residents in detached properties could be affected by thermal discomfort per event (high emission scenario, median result). If urban land use and anthropogenic heat emissions are also assumed to increase by 50 % from the present day then 78–88 % and 47–49 % of residents in flats and detached properties could be affected respectively. The range in results highlights the potential benefits which could be seen from adaptations aimed at increasing building resilience to high temperatures and stabilising urban land use and anthropogenic heat emissions.

The study highlights the potential risks that high temperatures pose to residents within urban areas, and the negative effects that future climate change and an intensification of the UHI could have. Whilst studies such as those undertaken as part of the UK Climate Change Risk Assessment (DEFRA 2012) do highlight the potential additional impacts that the UHI could have on climate related risks in urban areas, urban fabric, land use and anthropogenic heat emissions are not explicitly modelled within the climate scenarios. As such, these studies are likely to underestimate temperatures and impacts in urban areas, as well as overlooking potential benefits that could be gained through integrated adaptation strategies. The incorporation of urban land use and anthropogenic heat emissions within the WG scenarios, and the ability to provide probabilistic risk based information is a novel component of the modelling framework.

Furthermore, the integrated modelling approach is beneficial in that it facilitates a range of impacts and adaptation options to be considered within a single framework. The spatially coherent time-series data allows the user to map and identify risk hot spots, whilst vulnerability due to socio-economic change as well as climate change can be captured through the incorporation of different demographic scenarios. The modelling approach is also flexible in its potential to build in more specific information on adaptation policies and pathways as and when more quantitative information on the effects of specific adaptation options on temperature based resilience becomes available.

Overall, the UIAF provides a comprehensive method to assess and quantify the risks of future climate change and socio-economic change; benefits of adaptation options to help increase urban resilience to high temperatures; and associated social consequences. Using an integrated urban modelling approach highlights the importance of mainstreaming adaptation across different policy areas, such as health and urban planning; provides information to help facilitate the coordination of policy makers from different areas; and highlights potential benefits of adaptation which may cross policy areas to provide win-win situations. Such probabilistic information will be useful for governments and policy makers as they prepare for future climate risks, and aim to improve the resilience of urban areas and their inhabitants.

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References

Armstrong BG (2006) Models for the relationship between ambient temperature and daily mortality. Epidemiology 17:624–631

Armstrong BG, Chalabi Z, Fenn B, Hajat S, Kovats S, Milojevic A, Wilkinson P (2010) Association of mortality with high temperatures in a temperate climate: England and Wales. J Epidemiol Community Health. doi:10.1136/jech.2009.093161

Cabinet Office (2010) National risk register of civil emergencies. The Stationery Office Limited, London

CIBSE (2006) Environmental design: CIBSE guide A, 7th edn. The Chartered Instistion of Building Services Engineers, London

Coley D, Kershaw T (2008) Climate change, thermal comfort and building design. Paper presented at the Presented at Thermal Comfort for Building Occupants, CIBSE, London, 18th November 2008

DCLG (2012) Investigation into overheating in homes: literature review. DCLG, London

DEFRA (2012) The UK climate change risk assessment 2012: evidence report. DEFRA, London

Department for Health (2013) NHS heatwave plan for England 2013: protecting health and reducing harm from severe heat and heatwaves. Department of Health, London

D'Ippoliti D, Michelozzi P, Marino C, de'Donato F, Menne B, Katsouyanni K, Kirchmayer U, Analitis A, Medina-Ramón M, Paldy A, Atkinson R, Kovats S, Bisanti L, Schneider A, Lefranc A, Iñiguez C, Perucci CA (2010) The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. Environ Heal 9:37, 9pp

GLA (2009) London office policy review 2009. Greater London Authority, London

GLA (2011) Housing in London. The evidence base for the London Housing Strategy. GLA, London. Available online at: http://www.london.gov.uk/sites/default/files/Housing%20in%20London%20Dec11.pdf. Accessed 10th October 2013

Gosling S, Lowe J, McGregor G, Pelling M, Malamud B (2009) Associations between elevated atmospheric temperature and human mortality: a critical review of the literature. Clim Chang 92:299–341

Hacker JN, Belcher SE, Connell RK (2005) Beating the heat: keeping UK buildings cool in a warming climate. UKCIP Briefing Report. UKCIP, Oxford

Hajat S, Kovats RS, Atkinson RW, Haines A (2002) Impact of hot temperatures on death in London: a time series approach. J Epidemiol Community Health 56:367–372

Hajat S, Armstrong BJ, Baccini M, Biggeri A, Bisanti L, Russo A, Paldy A, Menne B, Kosatsky T (2006) Impact of high temperatures on mortality. Epidemiology 17:632–638

Hajat S, Vardoulakis S, Heaviside C, Eggen B (2012) Temperature effects of climate change on human health. In: Vardoulakis S, Heaviside C (eds) Health effects of climate change in the UK 2012: current evidence, recommendations and research gaps. Health Protection Agency, Oxford

Hall J, Dawson R, Walsh C, Barker T, Barr S, Batty M, Bristow AL, Burton A, Carney S, Dagoumas A, Evans S, Ford AC, Glenis V, Goodess CM, Harpham C, Harwatt H, Kilsby C, Kohler J, Jones P, Manning L, McCarthy M, Sanderson M, Tight MR, Timms PM, Zanni AM (2009) Engineering cities: how can cities grow whilst reducing emissions and vulnerability? Newcastle University, Newcastle

Hames D, Vardoulakis S (2012) Climate change risk assessment for the health sector. UK 2012 climate change risk assessment. Defra, London

IPCC (2013) Working group I contribution to the IPCC fifth assessment report climate change 2013: the physical science basis summary for policymakers. Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf. Accessed 8 Oct 2013

Jones PD, Kilsby CG, Harpham C, Glenis V, Burton A (2009) UK climate projections science report: projections of future daily climate for the UK from the Weather Generator. University of Newcastle, Newcastle upon Tyne

Kilsby C, Jones P, Harpham C, Glenis V, Burton A (2011) Spatial urban weather generator for future climates. ARCADIA task 3 report. Available at: http://www.arcc-cn.org.uk/wp-content/pdfs/ARCADIA-7.pdf

Kovats RS, Johnson H, Griffiths C (2006) Mortality in southern England during the 2003 heat wave by place of death. Health Stat Q 29:3

Mavrogianni A, Wilkinson P, Davies M, Biddulph P, Oikonomou E (2012) Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings. Build Environ In Press:1–14. doi:10.1016/j.buildenv.2011.12.003

McCarthy MP, Harpham C, Goodess CM, Jones PD (2012) Simulating climate change in UK cities using a regional climate model, HadRM3. Int J Climatol 32(12):1875–1888

Murphy JM, Sexton DMH, Jenkins GJ, Boorman PM, Booth BBB, Brown CC, Clark RT, Collins M, Harris GR, Kendon EJ, Betts RA, Brown SJ, Howard TP, Humphrey KA, McCarthy MP, McDonald RE, Stephens A, Wallace C, Warren R, Wilby R, Wood RA (2009) UK climate projections science report: climate change projections. Met Office Hadley Centre, Exeter

ONS (2001) Census: standard area statistics (England and Wales). ESRC/JISC Census Programme, Census Dissemination Unit. Mimas, University of Manchester

ONS (2010a) Subnational population projections, 2008-based projections. Available at: http://www.ons.gov.uk/ons/publications/re-reference-tables.html?edition=tcm%3A77-163339. A National Statistics publication, Crown copyright

ONS (2010b) Birth and death rates by ward. Available at: http://data.london.gov.uk/datastore/package/birth-and-death-rates-ward. A National Statistics publication, Crown copyright

ONS (2010c) Mortality statistics: deaths registered in England and Wales by area of usual residence—data tables, 2008. Available at: http://www.ons.gov.uk/ons/rel/vsob1/deaths-registered-area-usual-residence/2008/index.html. A National Statistics publication, Crown copyright

Pattenden S, Nikiforov B, Armstrong BJ (2003) Mortality and temperature in Sofia and London. Epidemiol Community Health 57:628–633

UKCP09 (2012) South East England key findings. UK Climate Projections. http://ukclimateprojections.defra.gov.uk/content/view/2200/499/. Accessed 21 March 2012