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# Comparison of built environment adaptations to heat exposure and mortality during hot weather, West Midlands region, UK

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ABSTRACT

There is growing recognition of the need to improve protection against the adverse health effects of hot weather in the context of climate change. We quantify the impact of the Urban Heat Island (UHI) and selected adaptation measures made to dwellings on temperature exposure and mortality in the West Midlands region of the UK. We used 1) building physics models to assess indoor temperatures, initially in the existing housing stock and then following adaptation measures (energy efficiency building fabric upgrades and/or window shutters), of representative dwelling archetypes using data from the English Housing Survey (EHS), and 2) modelled UHI effect on outdoor temperatures. The ages of residents were combined with evidence on the heat-mortality relationship to estimate mortality risk and to quantify population-level changes in risk following adaptations to reduce summertime heat exposure. Results indicate that the UHI effect accounts for an estimated 21% of mortality. External shutters may reduce heat-related mortality by 30–60% depending on weather conditions, while shutters in conjunction with energy-efficient retrofitting may reduce risk by up to 52%. The use of shutters appears to be one of the most effective measures providing protection against heat-related mortality during periods of high summer temperatures, although their effectiveness may be limited under extreme temperatures. Energy efficiency adaptations to the dwellings and measures to increase green space in the urban environment to combat the UHI effect appear to be less beneficial for reducing heat-related mortality.

## 1. Introduction

The evidence that climate change will increase ambient temperatures in the UK, as elsewhere, has focused attention on how to protect against the health risks of summer heat. In England and Wales, heatwaves in 2003 and 2006 were associated with 2000 and 680 excess deaths, respectively (Johnson et al., 2005; PHE, 2015). These will not be exceptional events by mid-century (Murphy et al., 2009), and potential vulnerability to similar heatwaves is expected to increase as the population ages (Gasparrini et al., 2012; Hajat et al., 2014).

Among the possible measures to protect against such risks are adaptation of the housing stock to reduce indoor temperatures and actions aimed at reducing the Urban Heat Island (UHI) effect. Indoor heat exposures are likely important, given that the English population is estimated to spend 70% of their time in their own homes, increasing to 82% in the elderly population (ONS, 2005). As in many temperate regions around the world, buildings in England have not been designed for high outdoor temperatures, and English dwellings vary in their response to high external temperatures (Beizaee et al., 2013; Mavrogianni et al., 2012) with overheating in housing considered a future risk (Vardoulakis et al., 2015). Potential dwelling adaptation measures to reduce indoor overheating include external shutters, shading, high albedo surfaces, and low-e glazing (Gupta and Gregg, 2012). In addition, there is a critical need to reduce the carbon emissions of the housing stock through energy-efficient retrofits of existing dwellings, which may impact on dwelling overheating risks (Mavrogianni et al., 2012; Taylor et al., 2015b). The UHI effect describes the occurrence of higher outdoor temperatures in metropolitan areas compared with those of the surrounding countryside. It is caused by the thermal properties (heat absorption, capacity, conductance and albedo) of the surfaces and materials found in urban landscapes, the reduced evapotranspiration from reduced natural vegetation and increased impervious surfaces, and the waste heat production from anthropogenic activities (Oke, 1982). Urban land use changes are therefore a primary means for UHI

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mitigation (Heaviside et al., 2017).

The relationship between heat and excess mortality in the UK has been derived for different regions (Armstrong et al., 2011), and age classifications (Gasparrini et al., 2012) using a two-day rolling mean maximum outdoor temperature. Hajat et al. (2007, 2014) also derived regional relationships between excess mortality and heat for England, instead using two-day mean daily outdoor temperature. Estimates of the relationship between *indoor* temperatures and heat-related mortality in the UK have heretofore relied on the application of the above models to make estimates of indoor temperature exposure. Such studies include Taylor et al. (2015a), who estimated the spatial variation of summertime mortality across London using building physics-derived indoor temperatures and modelled UHI temperatures; and Liu et al. (2017), who used building physics models and high spatial resolution climate projections to map heat mortality risk across the city of Sheffield under current and future conditions. Similarly, the spatial variation of UHI-related mortality has been estimated using the Hajat model and simulated outdoor temperatures for the West Midlands by Heaviside et al. (2016).

The impact that housing heat adaptation, energy efficient retrofit, and the UHI may have on temperature exposure and mortality risk remains a focus of continuing research. In this paper, we use modelling methods that draw on current evidence to quantify the potential impact of external shutters, complete energy efficiency retrofit, and the UHI, using the West Midlands region of the UK as the setting. The West Midlands is a region of 5.6 million people (ONS, 2011) comprising the city of Birmingham and the West Midlands conurbation (which includes the city of Wolverhampton and the towns of Dudley, Solihull, Walsall and West Bromwich).

## 2. Methods

The study is based on a set of in silico experiments to estimate the impact on population temperature exposure and subsequent heat-related mortality of:

(1) Energy efficiency upgrades to the entire housing stock, including the installation of floor, roof, and wall insulation, triple glazed windows, and a corresponding increase in air tightness;
(2) The installation of external shutters/shading in the entire stock, assumed to be used in all dwellings between 9 a.m. and 6 p.m. during the summer months; and
(3) The UHI effect, estimated by assuming all current built structures (including all buildings, roads and artificial surfaces) are replaced by natural vegetation.

Implementing housing adaptations across the entire stock is ambitious, and are specified to represent the theoretical upper limit of the impacts on temperature exposure and health of these types of intervention. The removal of urban surfaces is an unrealistic adaptation, and would indeed result in a significantly reduced exposed population; therefore, this is presented as an investigation of mortality attributable to the UHI rather than an adaptation. The steps entailed in the quantification of the impact of the adaptation measures are shown schematically in Fig. 1. For the adaptations above, the steps were:

(1) The use of a) building physics simulation studies to generate patterns of indoor temperatures based on different outdoor temperatures for a representative sample of dwellings in the region, or b) regional meteorological models to generate spatial and temporal variations in UHI;
(2) The use of these data to estimate a 'temperature anomaly' for each individual in the West Midlands population to quantify temperature exposure modification. These are defined as a) the difference between the average indoor temperature of an individual's dwelling and the regional population-average indoor temperature exposure, or b) the difference between an individual's outdoor temperature exposure and the regional population-average outdoor temperature.
(3) The use of published (outdoor) temperature-mortality relationships (Armstrong et al., 2011) - previously used in studies that use modelled indoor temperatures in England (Taylor et al., 2015a; Liu et al., 2017) - to quantify the associated impact of summer heat on deaths. Here, it assumes that adaptation-related changes to the temperature anomaly defined in (2) lead to a corresponding shift in personal temperature exposure.

### 2.1. Modelling indoor temperatures and dwelling type-specific temperature anomaly

Indoor temperatures for each of the 1558 West Midlands region dwellings included in the statistically-representative 2010–11 English Housing Survey (EHS) (DCLG, 2011) were estimated using a metamodel that predicts (using a limited set of dwelling characteristics) indoor temperatures simulated by the validated building physics model *EnergyPlus* using detailed dwelling data (Symonds et al., 2016a). The steps were as follows.

First, *EnergyPlus*, was used to simulate hourly indoor (living room) temperatures across a calendar year for each of the 14 dwelling archetypes listed in Table 1. We used Latin Hypercube sampling to select, for each dwelling type, random combinations of the other dwelling characteristics listed in Table 1 (wall construction, surrounding terrain, orientation, permeability, U-values, glazing ratio, ceiling height and floor area) as the data inputs for the model runs. This generated a total of 19,200 simulations with unique dwelling type/characteristics combinations. These simulations were run using UK Climate Projections (UKCP09) baseline weather data from the Birmingham airport monitoring station for the year with the fourth hottest summer over the period 1961 to 1990 (1970), chosen to represent the conditions of a warm, but not extreme, summer under 'base' climatic conditions (Eames et al., 2010). A neural network metamodel was then developed using the Python tool PyBrain (Schaul et al., 2010) to predict the average of the simulated daily two-day rolling mean maximum living room temperatures ($T_{\max,in}$) within incremental ranges of two-day rolling mean maximum outdoor temperatures ($T_{\max,out}$) for each dwelling type (Symonds et al., 2016a).

The metamodel outputs were then used to estimate the daily $T_{\max,in}$ for each West Midlands dwelling in the EHS for the summer (1 May to 31 August) using the daily $T_{\max,out}$ of the base weather file. From this, a dwelling-specific daily temperature anomaly was calculated:

$$T_{max,anomaly} = T_{max,in} - \overline{T_{max,in}} \tag{1}$$

where $T_{\max,in}$ is the dwelling-specific temperature for a given day, $\overline{T_{max,in}}$ is the occupant-weighted mean $T_{\max,in}$ for the region as a whole (calculated using EHS household occupancies and weighting values), and $T_{\max,anomaly}$ represents the building's positive or negative indoor anomaly relative to the regional mean.

These estimates of temperature anomaly were derived for each dwelling assuming no adaptations and then after each of the two forms of adaptation described above: i.e. (1) full energy efficiency retrofit to all dwellings, including cavity and/or internal solid wall insulation, loft and floor insulation, triple glazed windows, and air-tightening equivalent to reducing permeability[1] by 5 $m^3/h/m^2$ and (2) application of shutters/shading to all dwellings from 9 am to 6 pm. In both 1) and 2), dwelling-specific anomalies were calculated relative to the mean of the un-adapted stock. Active cooling measures such as air conditioning (A/C) or ceiling fans were not considered due to their energy demand, and - in the case of A/C - the assumption that the ideal operation of A/C

[1] Permeability is defined here as the volume of air leakage through the building envelope per hour at 50 Pa pressure differential.