Modelling population exposure to high indoor temperatures under changing climates, housing conditions, and urban environments in England

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Abstract: The exposure of an individual to heat during hot weather depends on several factors including local outdoor temperatures and possible Urban Heat Island (UHI) effects, the thermal performance of the building they inhabit, and any actions that they are able to take in order to modify the indoor thermal conditions. There is an increasing body of research that seeks to understand how housing, UHI, and occupant profiles may alter the risk of mortality during hot weather. Housing overheating models have been of particular interest due to the amount of time spent indoors and the need to improve the energy efficiency of the UK housing stock. A number of housing overheating models have been created in order to understand how changes to the building stock and climate may alter heat exposure and risks of heat-related mortality. We briefly describe the development of a metamodel – a model derived from the outputs of EnergyPlus dynamic thermal simulation models of building variants – and its application to a housing stock model representative of the West Midlands, UK. We model the stock under a ‘current’ scenario, as described by the 2010-2011 English Housing Survey, and then following a full energy-efficient building fabric retrofit or the installation of external window shutters. Initial results indicate a wide range of overheating risks inside dwelling variants in Birmingham, with flats and bungalows most vulnerable to overheating, and detached dwellings least vulnerable. Modelling of the full retrofit of buildings indicated that the stock would experience an overall increase in overheating, while external shutters were able to decrease overheating significantly.

Keywords: Overheating, England, Dwellings, Energy Efficiency

1. Introduction

Due to the effects of climate change, the UK is expected to experience an increase in summer average ambient temperatures and extreme temperature events. High temperatures have been shown to lead to an increased mortality risk to the UK population (Armstrong et al., 2011), particularly for those most vulnerable, such as the elderly, isolated, or those with chronic health problems (Hajat et al., 2007). Since the UK population as a whole, and the vulnerable in particular, spend the majority of their time indoors and inside their own homes (ONS, 2005), the overheating risks inside dwellings are likely to be important.

The role of housing as an important contributor to heat exposure has been characterised by a number of different monitoring (Beizaee et al., 2013; Lomas and Kane, 2012) and modelling (Mavrogianni et al., 2012; Peacock et al., 2010; Taylor, Davies, et al., 2016) studies. Both monitoring and modelling studies indicate that there is a range of building performances under hot weather, with certain property types more prone to overheating than others. In the UK, the above studies suggest that flats and more modern dwellings have higher internal temperatures during hot weather, while older detached properties have been found to be cooler. This evidence appears to be supported by epidemiological studies following the heatwave in France, where greater risk of mortality was found in occupants in top-floor flats, as well as in dwellings with a lack of insulation, smaller dwellings, and those with larger windows (Vandentorren et al., 2006). The potential for building retrofits or adaptation to reduce indoor temperatures has been examined using a modelling approach for a selection of buildings (Gupta and Gregg, 2013; Porritt et al., 2010), which indicate that adaptations such as the installation of external shutters and shading due to vegetation may help to reduce indoor temperatures during hot weather. Other studies have indicated that some energy efficient retrofit measures of buildings may increase the risk of overheating if not combined with sufficient means of ventilation or shading (Mavrogianni et al., 2012; Taylor et al., 2015).

Several studies have sought to incorporate housing into models of population heat exposure and subsequent health risks. Wolf and McGregor (2013) used principle components analysis to study heat vulnerability across London. Taylor et al. (2015) combined building simulation outputs for individual buildings, census age and population data, and Urban Heat Island (UHI) maps to predict where heat-related mortality would be greatest across London. Other studies incorporating building characteristics into models of heat vulnerability include those in Birmingham, UK (Tomlinson et al., 2011), and Melbourne, Australia (Loughnan et al., 2012). Housing modification of heat exposure has been estimated at postcode-level across the UK (Taylor, Davies, et al., 2016), and work is ongoing to incorporate this into health models to estimate the role of housing on mortality. There has, however, been relatively little work done on determining how wide-scale adaptations to the building stock or occupant behaviour may be used to reduce indoor temperature exposure, and consequently population mortality.

In this paper, we assess how housing, and changes to housing energy efficiency or occupant shading behaviour may alter exposure to indoor heat. A new metamodeling framework, derived from EnergyPlus (US-DOE, 2013) simulations, is briefly described, which aims to predict how changes in factors associated with climate change, building stock energy-efficiency improvements and replacement, and population adaptation may influence indoor temperature exposure. This metamodel has been used to estimate the overheating risk in the spatially-referenced Homes Energy Efficiency Database (HEED) (EST, 2013) for the West Midlands under current conditions (Taylor, Symonds, et al., 2016). Here, we use the metamodel to derive initial estimates of indoor overheating risks for pre and post-retrofit dwellings in the 2010-2011 English Housing Survey (EHS) (DCLG, 2011) located within the West Midlands Government Office Region (GOR). We explore how simple adaptations, such as installing external shutters on dwellings, may allow the risk of mortality to be significantly reduced, while energy-efficiency upgrades may increase exposure.

2. Methods

Indoor overheating predictions are made using a metamodelling framework – a series of metamodels derived from outputs of another model, in this case EnergyPlus. Details of the metamodelling framework development can be seen in Symonds et al (2016). Characteristics of the dwellings within the West Midlands subset of the EHS were input to the metamodel in order to determine the overheating risk to the current building stock and possible changes (interventions) to the stock.

2.1 Metamodel

The metamodel used Artificial Neural Networks (Schaul et al., 2010) to model overheating using as inputs categorical, discrete and continuous variants related to the building and occupancy behaviour. Briefly, building and household characteristics were divided into categorical (e.g. built form, solid or cavity wall, occupancy type, climate region) and continuous (e.g. wall, roof, floor, and window U-values, building fabric permeability, orientation, and wind exposure) variables. Continuous variables were sampled from ranges defined in Table 1 using a Latin Hypercube method, creating a total of 600 EnergyPlus simulation files for each combination of categorical variable. Simulations were then run in parallel on the UCL High Performance Computing system, Legion, outputting hourly indoor temperatures. In this initial application of the model, categorical variables were limited to current-day climates for Birmingham, West Midlands and occupancy profiles for two people who are at home during the day. Window-opening temperature threshold and thermostat setting were also varied, but not implemented in the work described here. Details of the metamodel performance, including goodness-of-fit to testing runs, can be found in Symonds et al (2016).

The EnergyPlus models included a number of assumptions, namely: trickle vents were implemented in dwellings where window U-values were consistent with a post-2002 installation, as per Building Regulations (HM Government, 2010); solid walls were modelled with internal wall insulation when selected U-values were consistent with retrofits, as internal wall insulation has been associated with increased overheating risk (Mavrogianni et al., 2012; Taylor et al., 2015); and internal gains and occupancy schedules were the same for all dwelling types modelled. Built forms were modelled using the archetypes derived by Oikonomou et al (2015), with the size and layout of buildings held constant due to the complexity of varying them individually with floor area.

Table 1 – The distribution of building parameters from which EnergyPlus simulation files were created using Latin Hypercube Sampling

Parameter	Range	Distribution	Reference
Wall U-value	0.15-2.55 W/m²K	Uniform	(BRE, 2009)
Roof U-value	0.10-2.25 W/m²K	Uniform	
Window U-value	0.85-4.80 W/m²K	Uniform	
Floor U-value	0.15-1.30 W/m²K	Uniform	
Fabric air permeability	0-∞ m³/h/m² @ 50 Pa	Truncated Normal (μ = 20; σ = 10)	(Stephen, 2000)
Orientation	0-360	Uniform	-
Wind Exposure	City/Urban/Rural	Discrete	-

The metamodel computes the mean of the daytime maximum living room temperature when the two-day rolling mean outdoor temperatures exceeded the regional mortality threshold for the West Midlands (23.0ºC) (Armstrong et al., 2011); this is herein referred to as MDTTX. For flats, we took the average MDTTX for top, middle, and bottom-floor flats.

2.2 Application to housing stock

The EHS is a national survey of housing condition, energy-efficiency, and household characteristics. Weighting factors enable the households and dwellings detailed in the survey to be used to estimate nationally representative results. A total of 1,558 dwellings in West Midlands were described in the EHS.

For each EHS dwelling, U-values for fabric elements and building permeability were derived using SAP methodologies (Hughes et al., 2012) from variables available within the EHS, while terrain was informed by a parameter describing the building location. Trickle vents were assumed to be present in dwellings with double-glazed windows at a rate of 5% in dwelling constructed prior to 1990, and 100% in those constructed post-1990 (DECC, 2011). The metamodel was then used to calculate the indoor overheating metric at four different orientations (0, 90, 180, and 270 degrees East of North) for an occupancy scenario representative of two pensioners at home all day, for each entry in the EHS for the West Midlands. Results were analysed using the dwelling weighting to examine the range of overheating risks across the stock.

2.3 Intervention scenarios

Retrofit scenarios were also simulated in order to see what effect these had on the overheating risk of the housing stock. Two separate retrofit scenarios have been modelled:

1. A complete retrofit was assumed, including adding cavity or solid wall insulation, insulation to the roof and floor, and new triple-glazed windows with trickle vents. For each retrofit, the maximum possible U-value for the fabric type, given the building age and construction, was obtained from SAP, while permeabilities were assumed to be reduced by 5% as per Milner et al. (2014).
2. The installation of adaptable external shutters has been applied to windows. Shutters were modelled as closed between 9am and 6pm, with internal lights on.

Metamodel results were analysed to show the impact that these retrofits have on the MDTTX of the buildings within the stock.

3. Results

The distribution of overheating risks for the West Midlands housing stock under current, retrofit, and external shutter scenarios can be seen in Figure 1. While MDTTX estimates for different built forms showed a normal or unimodal distribution (not presented here), the distribution for the stock as a whole was multimodal. This is likely due to the fact that the geometry of built forms were not varied in the metamodel development. Under current housing conditions, detached dwellings were found to have lower MDTTX estimates, while flats and bungalows had higher MDTTX estimates. Following the modelled retrofit scenario, the distribution of MDTTX for the West Midlands housing stock shifted right, showing a relative increase in the overheating risk (median retrofit=28.1ºC, compared to median current=27.1 ºC). The largest increase was for low-rise flats, which saw an average increase of 1.4ºC MDTTX (1.35-1.52 ºC, 95% CI) following retrofit, while the lowest was for high rise flats which saw an average increase of 0.3ºC MDTTX (0.21-0.31 ºC, 95% CI). These estimates account for current levels of retrofit, and the small average increase in high rise flats is likely attributable to the already high levels of energy-efficient adaptations in that dwelling type.

Employing external shutters was able to significantly reduce the MDTTX (median shutters=24.3 ºC versus median current =27.1 ºC), as has been suggested in past studies (Gupta and Gregg, 2013). Semi-detached dwellings saw the largest average decrease (3.85ºC MDTTX, 3.81-3.88 ºC, 95% CI) while highrise flats saw the lowest average decrease (1.37ºC MDTTX, 1.28-1.45 ºC 95% CI).

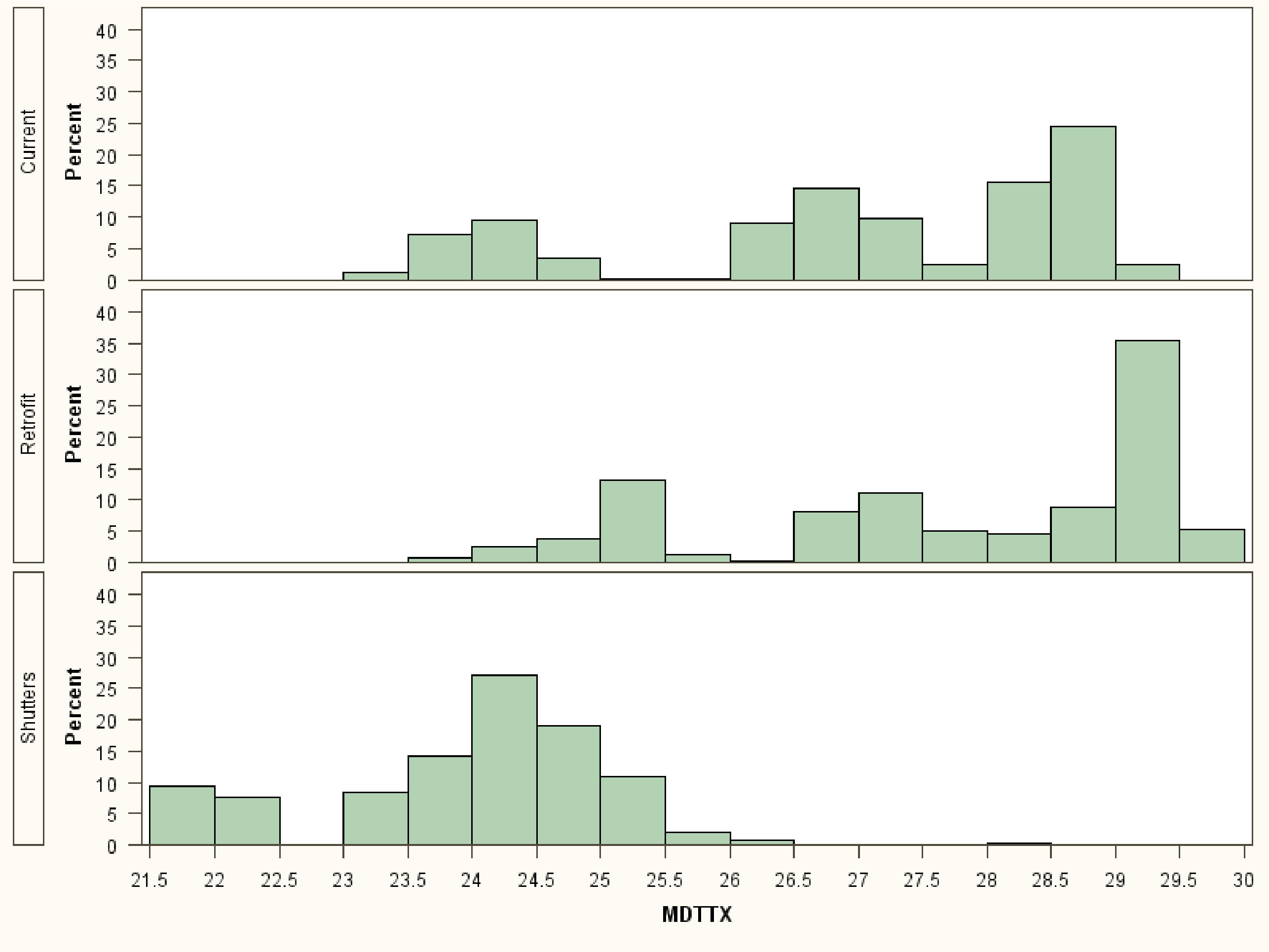

Figure 1 - Distribution of estimated MDTTX for dwellings in the West Midlands, UK under current conditions, folloiwng a complete retrofit, and with external shutters on the windows

4. Discussion

The described metamodel was able to rapidly calculate an overheating metric for a large number of dwellings, that can be used to estimate the indoor temperature impacts of energy-efficient retrofits or shutters. Further work will expand the model to include other regions in England, future climate scenarios, and occupancy scenarios reflecting a family. The outputs from this metamodel will be incorporated into a health risk assessment model to estimate how the housing stock may influence heat-related mortality, and what consequences the building and occupant adaptations may have on health.

The metamodel and its underpinning EnergyPlus models have a number of limitations. We consider a complete retrofit, but do not model the installation of any Mechanical Ventilation and Heat Recovery (MVHR) systems. The metamodel does not allow for the installation of Air Conditioning systems, which would likely reduce heat-related risk significantly but would not be compatible with energy reduction goals. The built forms have been developed from the EHS to be representative of the average for the English stock, but individual buildings are likely to differ from the modelled archetypes. This is likely to be the main reason for the observed multimodal distributions, and further work may examine means of varying building geometry within EnergyPlus and the incorporation of geometry as an input into the metamodel. While the trends in relative overheating performance of buildings in the metamodel are similar to those from monitoring studies (Beizaee et al., 2013; Lomas and Kane, 2012), further work is required to compare modelled data to actual data. Work is currently being undertaken to compare the model results against a large set of monitored indoor temperatures from the Energy Follow Up Study (EFUS) (BRE, 2013); consequently, the results of this study should be considered preliminary until appropriate model calibration is carried out. While the application of the described metamodel to the HEED database allows results to be mapped at postcode-level (Taylor, Symonds, et al., 2016), the EHS is likely a more representative sample of the regional housing stock than HEED.

The initial application of this model has estimated the indoor overheating risk assuming a spatially constant outdoor temperature, without accounting for local outdoor temperatures caused by the UHI. Previous studies (Taylor et al., 2015; Wolf and McGregor, 2013) have incorporated modelled or satellite-derived estimates of UHI temperatures in their risk estimates. Further work will incorporate estimates of UHI variation across the stock, and the consequent impact on indoor temperatures and health. In addition, the model will be expanded to cover additional climates throughout the England and future weather scenarios. Future work will integrate the model results into health impact calculations that will predict any changes to population mortality that may occur due to climate change, the retrofit of existing and construction of new buildings, and potential occupant adaptations. The metamodel will be a useful means of informing policy decisions, urban planning, and building design.

5. Conclusions

We have presented initial overheating results for the West Midlands, developed using a metamodeling framework derived from a large number of dynamic thermal simulations of the English housing stock. The model is able to rapidly calculate a health-relevant metric for a large number of existing and possible future building variants, enabling an estimate of population mortality to be quickly obtained. Results indicate a possible increase in overheating following building retrofits, and a significant decrease in overheating if external shutters are employed. Future work will incorporate local outdoor temperature variations from the UHI, other regional and future climates, and occupancy scenarios for families. In addition, mortality rates will be derived based on the modelled indoor temperatures.

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