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Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a European city

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ABSTRACT

Hot weather can exacerbate health conditions such as cardiovascular and respiratory diseases, and lead to heat stroke and death. In built up areas, temperatures are commonly observed to be higher than those in surrounding rural areas, due to the Urban Heat Island (UHI) effect. Climate change and increasing urbanisation mean that future populations are likely to be at increased risk of overheating in cities, although building and city scale interventions have the potential to reduce this risk.

We use a regional weather model to assess the potential effect of one type of urban intervention – reflective ‘cool’ roofs – to reduce local ambient temperatures, and the subsequent impact on heat-related mortality in the West Midlands, UK, with analysis undertaken for the summer of 2006, as well as two shorter heatwave periods in 2006 and 2003.

We show that over a summer season, the population-weighted UHI intensity (the difference between simulated urban and rural temperature) was 1.1 °C on average, but 1.8 °C when including only night times, and reached a maximum of 9 °C in the West Midlands. Our results suggest that the UHI contributes up to 40% of heat related mortality over the summer period and that cool roofs implemented across the whole city could potentially offset 18% of seasonal heat-related mortality associated with the UHI (corresponding to 7% of total heat-related mortality).

For heatwave periods, our modelling suggests that cool roofs could reduce city centre daytime 2 m air temperature by 0.5 °C on average, and up to a maximum of ~3 °C. Cool roofs reduced average UHI intensity by ~23%, and reduced heat related mortality associated with the UHI by ~25% during a heatwave. Cool roofs were most effective at reducing peak temperatures during the daytime, and therefore have the potential to limit dangerous extreme temperatures during heatwaves. Temperature reductions were dependent on the category of buildings where cool roofs were applied; targeting only commercial and industrial type buildings contributed more than half of the reduction for heatwave periods. Our modelling suggested that modifying half of all industrial/commercial urban buildings could have the same impact as modifying all high-intensity residential buildings in the West Midlands.

1. Introduction

Hot weather can have a negative impact on human health and can exacerbate conditions such as cardiovascular and respiratory diseases, and also lead to heat stroke and death (Basu, 2009; Basu and Samet, 2002). The heatwave that affected Europe in August 2003 broke many temperature records, and was thought to be responsible for 70,000 deaths (Robine et al., 2008). In the future, anticipated changes to the climate include an increase in the frequency, intensity, and duration of heatwaves (Kirtman et al., 2013).

Around 54% of the world's population currently reside in urban areas, projected to increase to 66% by 2050 (United Nations, 2014); In the UK 82% of people presently reside in urban areas (ONS, 2011). Urbanisation has led to a number of environmental changes: land use changes have often meant that native rural land types (such as forest, wetlands, and cropland) are replaced by urban surfaces, such as buildings, roads, and other paved areas, using materials like concrete, tarmac and asphalt, which generally absorb and retain more heat from

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the sun than vegetation does. Paving over vegetated areas also reduces surface permeability and reduces evapotranspiration. Energy use in cities, such as power for lighting and heating (or cooling) in buildings, as well as vehicles, can also add heat to their surroundings. All these factors can lead to higher air temperatures in cities, an effect known as the Urban Heat Island (UHI). The UHI has been well observed and documented (Arnfield, 2003; Oke, 1973) and is defined as the difference in temperature between urban and rural areas. It may be quantified by comparing ambient air temperature measurements in the middle of an urban area, and at a location in surrounding rural areas (Bassett et al., 2016; Oke, 1973), or from satellite observations (Azevedo et al., 2016). However, data from measurement stations may have limited geographical and time coverage, while satellite measurements record land surface 'skin' temperature (rather than air temperature), and may have missing data if it is cloudy. The use of meteorological computer simulations makes it possible to quantify the UHI intensity in space and time, by comparing temperatures simulated both with and without urban surfaces such as buildings and roads (Heaviside et al., 2015; Macintyre et al., 2018), and to extrapolate to other scenarios.

Heatwaves can interact non-linearly with the UHI, generating very high heat stresses (Founda and Santamouris, 2017; Li and Bou-Zeid, 2013). The UHI has, and will continue to have, effects on health, especially with an ageing population (Heaviside et al., 2017). Additionally, climate change is estimated to increase global cooling energy demand by 72% by 2100 (Isaac and van Vuuren, 2009). Some research exclusively in US cities suggests no trend in UHI intensity from 2000 to 2015 due to an increasing trend in rural temperatures, although urban temperatures have increased over the same period (Scott et al., 2018). Modifying the urban fabric of cities through various interventions in the built environment is a potential method to mitigate the impact of the UHI, and as well as reducing heat exposure and potential negative health outcomes, may also bring co-benefits such as reduced summer energy demands (Akbari et al., 2016; Synnefa et al., 2007).

Various studies have investigated the relationship between heat and health effects, now and for future projected conditions (Gasparrini et al., 2015; Hajat et al., 2014; Hondula et al., 2014; Vardoulakis et al., 2014), with some focusing on heatwave events (Arbuthnott and Hajat, 2017; Laaidi et al., 2012), or adaptation and acclimatisation (Arbuthnott et al., 2016; Milojevic et al., 2016). Generally heat-health effects occur above a threshold temperature, with effects often rising steeply as temperatures increase. Previous work estimated that around 50% of heat-related mortality in the West Midlands could be attributed to the UHI during the heatwave of 2003 (Heaviside et al., 2016). In addition, health impact assessments based on geographically averaged temperatures under-estimated heat-related mortality by around 20% compared with population weighted temperature, highlighting the need to include urban effects and demographics for health impact assessments (Heaviside et al., 2016). Taylor et al. (2018b) also estimated heat mortality in the same region, using a different temperature metric based on indoor maximum temperatures, and found the UHI effect contributed to around 21% of heat related mortality for the same period. Macintyre et al. (2018) investigated spatial variability of the UHI in the West Midlands region, finding that higher UHI intensities were co-located with areas with higher deprivation scores, and that around 90% of care homes and 94% of hospitals (both locations with more at-risk populations) are located in areas warmer than the city mean temperature.

This study aims to quantify what proportion of heat related deaths which have been attributed to the UHI could potentially be avoided by implementation of cool roofs across the West Midlands region, focusing on the whole summer of 2006 as well as two distinct heatwave periods in August 2003 and July 2006, two of the most significant heatwave periods in recent decades in the UK.

1.1. Roofing interventions to reduce urban heat

Reflective 'cool' roofs have a higher albedo (i.e. reflectivity) compared with ordinary roofs, which increases the amount of reflected solar radiation. This can potentially reduce urban temperatures, and may also reduce building energy consumption for cooling demand, both of which are projected to increase in future (due to rising temperatures and income growth in developing nations), as well as helping reduce formation of urban smog (Akbari et al., 2001; Davis and Gertler, 2015; Isaac and van Vuuren, 2009; Kolokotroni et al., 2013). The roof is a good area to target for this type of cooling intervention as it receives the largest incident solar radiation, and can be the largest area of internal heat gain to the building. The impacts of the UHI and potential mitigation measures have been explored through direct observational studies as well as using modelling techniques (Heaviside et al., 2017).

Typically the mean albedo of urban surfaces is taken to be around 0.2 (i.e. 20% of incoming radiation is reflected, with the rest being absorbed), but can range from 0.1 to 0.3 (Silva et al., 2010; Wang et al., 2016). Cool roofs themselves have a range of albedos depending on the type of coating or roofing material, and typically have albedos in the range 0.65 to 0.8 (and a few newer technologies can reach 0.85 or even higher) (Santamouris et al., 2011). Modelling studies of cool roofs typically include albedos in the range 0.5 to 0.9, with 0.7–0.8 being around average (Imran et al., 2018; Silva et al., 2010; Taylor et al., 2018a; Zhang et al., 2018). Relatively high albedos are achievable (e.g. 0.85–0.9) though there is evidence that cool coatings degrade with time, possibly on the order of 0.15 in the first year alone due to the accumulation of dirt (Bretz and Akbari, 1997).

The surface 'skin' temperature of cool roofs has been observed as cooler than other roofing types (including vegetated roofs) by a number of studies (Jenerette et al., 2016; Seungjoon et al., 2015; Taleghani et al., 2014). Overall, observational studies find that reflective cool roofs tend to perform more efficiently than vegetated roofs in reducing air temperatures, and even more so when all costs and maintenance are included. The effectiveness of white roofs in reducing air temperature can be modified by the presence of clouds, and green roofs often require irrigation to maintain cooling ability (Seungjoon et al., 2015). Some studies suggest that cool roofs may be more effective at cooling the outdoor environment than reducing indoor temperatures (though this may depend on roof properties such as amount of insulation).

Modelling studies using simulations of the built environment at individual building or neighbourhood scale have been used to assess the impacts of UHI mitigation measures such as albedo modification, cool or vegetated roofs, or urban vegetation and greenspace, on local conditions. Increasing albedo is generally the most effective strategy for reducing near-ground air temperature (Imran et al., 2018; Silva et al., 2010), and may reduce ground surface 'skin' temperature by up to around 10 °C (Wang et al., 2016). A study in London found that implementing cool roofs could reduce maximum air temperature by 1 °C in summer (Virk et al., 2015). Computational fluid dynamic (CFD) modelling found cool roofs have the greatest effect on mean near-surface air temperatures when used on buildings 1–2 storeys high, and while the effect was negligible on buildings taller than 4 storeys, a tall building downwind could counteract this by mixing cooled air down to street level (Botham-Myint et al., 2015).

Modelling the effects of UHI mitigation methods on indoor temperatures generally find that green roofs cannot match the hazard reduction potential of cool roofs unless they are well irrigated, but irrigation may place increased demand on water resources (which are likely to already be stressed in hot areas) (Buchin et al., 2016). For cool roofs, the adjacent top floor rooms will benefit the most, which is also where the greatest hazard is (indoor temperatures are generally higher for the top-floor of buildings) (Mavrogianni et al., 2012). However, this effect is diminished if the building is very well insulated (Virk et al., 2015).

The WRF (Weather Research Forecasting) model is a weather forecasting and analysis model that has been used to look at the impact of building interventions to modify the UHI at local city-wide or regional scales (Chen et al., 2011; Li et al., 2014). Modelling cool roof deployment across different cities finds maximum local air temperature reductions in the range of 0.5 °C to 5.5 °C, depending on level of implementation, with the most common reductions being in the range 1 °C to 2 °C (Imran et al., 2018; Jacobs et al., 2018; Morini et al., 2016; Morini et al., 2017; Smith and Roebber, 2011; Touchaei et al., 2016; Vahmani et al., 2016). Some studies find that a 95% cool roof cover was needed to reduce average maximum 2 m air temperature by 0.5 °C (Li et al., 2014). The effect appears to be roughly linear with increasing levels of coverage across a city (Li et al., 2014), though other studies have found sub-linear relationships (Imran et al., 2018); a recent review found approximately a 0.1 °C to 0.33 °C decrease in mean ambient temperature for each 0.1 rise in albedo (Santamouris, 2014a).

Increasing the albedo of urban surfaces in a modelling study from 0.2 to 0.8 in two Italian cities was found to reduce air temperature by up to 2.5 °C, and increasing the albedo of the most industrial area reduced air temperature by up to 2 °C during the daytime (Morini et al., 2016; Morini et al., 2017). In Montreal, increasing the albedo of roofs, walls and roads led to a peak reduction in 2 m air temperature of 1 °C during three hot days in July 2015 (Touchaei et al., 2016). Deployment of cool roofs across all of the city of Los Angeles could reduce daytime air temperature by 0.9 °C, averaged over the month of July according to simulations (Vahmani et al., 2016).

As well as affecting temperature, building modifications also impact energy consumption within the building itself. Building energy load is often increased in areas with high urban temperatures, due to the increased demand for cooling; for US cities, for every 1 °C rise in daily maximum temperature above a threshold, peak urban electricity demand rises by 2–4% (Akbari et al., 1992), and can be as high as 8.5% for southern US states (Santamouris, 2014b), and even 11–25% in apartment buildings in China (Yang et al., 2017). However, in some scenarios, increased urban temperatures can reduce heating load in winter for current climate, but in future it is expected that the increase in cooling load will outweigh this effect (Kolokotroni et al., 2012; Santamouris, 2014b). Cool roofs may reduce building energy demand for cooling by 17% to 41% in summer in warm dry climates (Baniassadi et al., 2018; Kolokotsa et al., 2018) but in winter heating energy use increased slightly (~4%) for temperate climates (Taylor et al., 2018a; Virk et al., 2015). A recent review found that increasing the albedo of a city could achieve a direct energy saving of 20–70% (Gago et al., 2013). Microclimatic and building energy modelling studies suggest that cool roofs in London could reduce maximum air temperature by 1 °C in summer, but due to their performance in winter, actually result in an energy penalty over a full year; however, in a 2050 climate scenario, cool roofs resulted in a net reduction in annual energy use (Virk et al., 2015). Additionally, annual building energy demand modelling in London found that cool roofs are preferable to natural ventilation, as there was a lower winter penalty for heating demand (Kolokotroni et al., 2013).

Cool roofs generally have a premium over conventional roofing materials; estimates suggest cool roofs may cost \$8–\$32 per m^2 (U.S. Environmental Protection Agency, 2008). Cool roofs may be installed on roofs that are flat or steeply pitched, and in general result in net annual energy savings in the US where electricity prices are relatively high, though they may deflect some desired heat gain during the winter. Other types of surface building modifications are being developed and tested though they are not currently widely used. Retro-reflective materials (i.e. where reflection is back in the direction of the source, such as a bike reflector) have been investigated in the lab and are found to generally stay cooler than traditional surfaces, but only in sunny conditions (Qin et al., 2016). A concern for reflective roofs is the aesthetics of having a white roof, and as a consequence, reflective coloured tiles have been investigated (Castellani et al., 2017). Phase Change Materials (PCMs) absorb energy from the environment via changing phase (e.g. changing from solid to liquid). These are usually capsules of material built into the building fabric or installed on surfaces (Lu et al., 2016; Roman et al., 2016); however, there are some issues surrounding their degradation in UV light, and they have not been widely tested.

To summarise, building modifications such as cool roofs have a significant impact on the building surface temperature (of several °C), and a smaller impact on 2 m air temperature (usually up to 1 °C). The change in air temperature may appear small but is often significant portion of the UHI intensity, and the presence of thresholds in heat-health effects should not be ignored. In addition to temperature, other factors such as humidity, wind speed, and exposure to sunlight can influence heat stress a person may experience (Steadman, 1984). Vegetated surfaces in cities generally cool via evaporation of moisture (rather than reflecting energy as cool roofs do), and their presence can increase humidity and possibly reduce the ability of the human body to cool itself (though this only significantly influences comfort above about 26 °C).

1.2. *Health impacts*

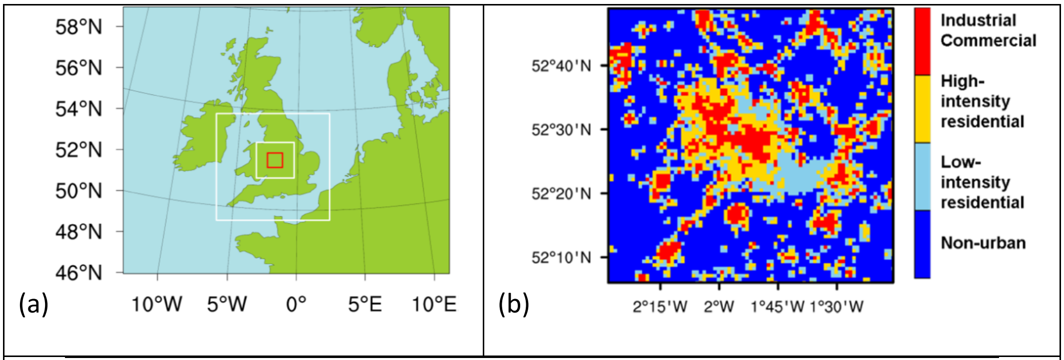
For most populations, the relationship between temperature and mortality can be characterised by a ‘U’,‘V’ or ‘J’ shaped curve, with the risk of heat-related mortality only increasing above a temperature threshold (Gasparrini et al., 2015). For example, in the UK, the threshold temperature for increased risk of mortality is typically around 18 °C for daily mean temperature threshold, with mortality increasing by around 2.5% for every 1 °C above this (Hajat et al., 2014; Vardoulakis et al., 2014). Health impacts are relevant to a value of ΔT (i.e. daily mean temperature – threshold temperature), which may be comparable with the scale of the UHI intensity.

While much research has addressed temperature changes and impact on energy demand of UHI mitigation techniques, fewer studies have quantified the health impacts of these changes. A life-cycle analysis of albedo changes to mitigate the UHI in New York City found near-surface summer air temperature was reduced by 0.5 °C by making all roofs albedo 0.9 (from 0.32); the authors estimate this would lead to 751 annual avoided disability-adjusted life years lost (DALY – defined by WHO as the lost years of healthy life) (Susca, 2012). Combining vegetation (roof greening and street trees) and albedo enhancement (albedo 0.9) could offset projected increases in heat-related mortality by 40% to 99% across three metropolitan regions (Stone et al., 2014). For US cities it was found that a 20% increase in surface reflectance could reduce heat-related mortality by between 5% and 21% depending on city over a 10-year period (Vanos et al., 2014). Increasing the albedo of roof and paved surfaces across three US cities could avoid 1 per 100,000 deaths in 2050 (Vargo et al., 2016). There is some consistency between observed daytime land surface temperatures and residents' perceptions about their environment and self-reported symptoms of heat-related illness, suggesting there is value in consulting residents on heat mitigation strategies (Jenerette et al., 2016). A review of the health impacts of UHI interventions is given in Heaviside et al. (2017).

Here, we quantify the effectiveness of cool roofs at reducing ambient temperature in an urban area, and estimate the associated impact on temperature-related health effects.

2. Methods

We first modelled the 2 m air temperature across the West Midlands using a regional configuration of the WRF mesoscale meteorological model; then by comparing simulations that included urban land cover with simulations that included only rural land cover, we quantified the UHI intensity over a summer season. We then adjusted roof albedo in the model to simulate the effect of cool roofs on 2 m air temperatures. The impacts on heat-related mortality over this period were then



(c)

Category	1: Industrial/ commercial	2: High-intensity residential	3: Low-intensity residential
Albedo (roof, wall, ground)	0.1989	0.1997	0.2027
Surface emissivity (roof, wall, ground)	0.9239	0.9274	0.9292
Average building height	25 m	15 m	10 m

(d)

Model setting	Option	Reference
Long wave radiation	Rapid Radiative Transfer Model (RRTM)	Mlawer et al. (1997)
Short-wave radiation	Dudhia scheme	Dudhia (1989)
Boundary layer physics	Bougeault–Lacarrere (designed for use with BEP urban scheme)	Bougeault and Lacarrere (1989)
Urban physics	BEP urban scheme	Martilli et al. (2002)

Fig. 1. (a) Modelled domains in the WRF simulation. The central (red) box is expanded in (b); (b) Urban categories used in the inner domain; the area covered is ~80 × 80 km. (c) Details of default urban categories used in BEP (Building Energy Parameterisation). (d) General WRF model set-up details, using schemes detailed in Mlawer et al. (1997), Dudhia (1989), Bougeault and Lacarrere (1989), and Martilli et al. (2002). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

estimated.

2.1. Urban temperature modelling

We used the WRF regional weather model version 3.6.1 (Chen et al., 2011) with four nested domains, with horizontal grid resolutions of 36 km, 12 km, 3 km, and 1 km in the inner (smallest) domain, with feedback of variables between grids (Fig. 1). The model time-step in each domain was 180, 60, 15 and 5 s respectively, while gridded meteorological variables, including 2 m air temperature were output at hourly time-steps. Boundary conditions are from the ERA-Interim reanalysis at 0.5° every 6 h (Dee et al., 2011), and there were 39 pressure levels above the surface, up to 1 hPa. Sea-surface temperatures are allowed to vary for longer simulations based on those in the ERA-Interim boundary meteorology. We found that using the ERA-Interim dataset as initial and boundary conditions led to better agreement with observations for the simulated output, however, we also ran the simulation for the 2003 heatwave period using the NCEP Final Analysis (GFS) dataset (NCEP FNL, 2000), as a sensitivity test. This gives some information on one source of uncertainty when modelling at fine resolution in a nested set-up.

We used an urban canopy scheme, the Building Energy Parameterisation (BEP) scheme, which models the effect of buildings on energy and momentum fluxes inside and immediately above the urban street canyons (Martilli et al., 2002; Heaviside et al., 2015). Information on building and road properties (e.g. building height, street canyon width, material properties such as albedo, thermal conductivity and heat capacity) is included for three urban categories: Industrial/commercial, High-intensity residential, and Low-intensity residential, across the West Midlands region (Fig. 1b). Details of parameters used for each urban category are given in Fig. 1c, d. Land-surface data used as an input to WRF for all domains were based on the US Geological Survey (USGS) 24-category land-use data, and for the inner domain we used two local datasets to generate the 3 separate urban categories (Owen et al., 2006). We used the Noah Land Surface Model, a relatively complex model, which is often coupled with an urban canopy scheme, and has four layers of soil moisture and temperature (Tewari et al., 2004).

The model was run for the summer 2006 season (1 June – 31 August). The first day of simulation was discarded as a spin-up period to remove the effect of initial conditions. The model has been previously run and evaluated in this configuration, details of which may be found in Macintyre et al. (2018), and for the 2003 heatwave (Heaviside et al., 2015). The model was first run with urban surfaces included, as described above ('URBAN'). This simulation was evaluated against hourly observations from weather stations in the region, extracted from the Met Office Integrated Data Archive System (MIDAS) (Met Office, 2012) obtained from the Centre for Environmental Data Analysis (CEDA) web portal. Then to simulate the effect of cool roofs being introduced across the West Midlands, we altered albedo of all roofs from the default values (~0.2, Table 1a) to 0.7 ('COOLROOF') within the BEP scheme (with walls and ground surfaces unchanged). The value 0.7 was chosen as a compromise between the fact that higher albedos are achievable, but reflects the fact that cool roofs will degrade with time. A simulation was also performed where urban categories are replaced by the surrounding rural cropland/pasture ('RURAL') for comparison. By taking

Table 1
Model validation of 2 m temperature for the seasonal urban simulation based on MIDAS meteorological station observations.

	Edgbaston (EB)		Coventry (CV)		Coleshill (CH)		Church Lawford (CL)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled	Observed	Modelled
Mean (°C)	17.66	17.56	17.76	17.47	17.53	17.23	17.77	17.09
Standard deviation (°C)	4.28	4.31	4.44	4.32	4.60	4.39	4.67	4.61
RMSD (°C)	–	1.40	–	1.53	–	1.59	–	1.69
Correlation	–	0.95	–	0.94	–	0.94	–	0.94

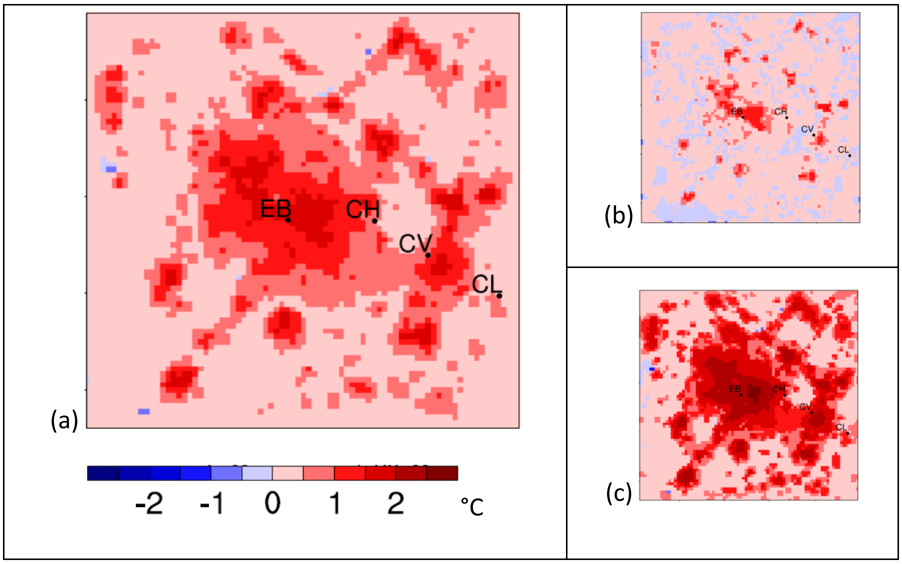


Fig. 2. Urban Heat Island intensity for June–July-August 2006. (a) Mean 2 m temperature difference for the whole period; (b) daytime average (8 am – 8 pm); (c) night-time average (8 pm – 8 am). The UHI intensity in the centre of the domain (Birmingham City centre) in this figure is +2.0 °C (+1.5 °C daytime, +2.6 °C at night). Lettered points refer to observation stations (refer to Table 1).

the difference in temperature between the 'URBAN' and 'RURAL' simulations, the UHI intensity can be quantified (as in Macintyre et al. (2018) and Heaviside et al. (2015)).

We also focus specifically on a heatwave period (16–27 July 2006) within this season and the summer 2003 heatwave (2–10 August 2003). The model was re-run for these periods in the 'URBAN', 'RURAL' and 'COOLROOF' configurations, and also three additional scenarios where cool roofs are applied to each urban category individually (Industrial/commercial, High-intensity residential, and Low-intensity residential, hereafter known as categories 1, 2 and 3 respectively, Fig. 1b). Additionally, we performed simulations with an albedo of 0.45 to simulate the effect of only half of buildings having cool roofs, for the two most urbanised categories (categories 1 and 2). Due to computational time demands, different albedos for individual urban categories were only simulated for the heatwave periods, with all urban categories changed together for the longer summer period.

2.2. Health impact calculations

We calculated the heat-related mortality for each heatwave period, under each scenario ('URBAN', 'RURAL', 'COOLROOF'). Daily all-cause mortality counts for 2006 were obtained from the Office for National Statistics, UK. We used the exposure-response coefficient derived in Vardoulakis et al. (2014), for the West Midlands region, which is approximately a 2.5% (95% CI: 2.0%, 3.0%) increase in mortality for every 1 °C increase in daily mean temperature above the threshold of 17.7 °C (representing the 93rd centile daily mean temperature for this region). Exposure was calculated based on gridded hourly 2 m air temperature output from WRF to calculate daily mean temperatures, and population weighting was by using a gridded 100 m residential population database (ONS, 2011; ONS, 2015). For comparison purposes, we also performed a calculation using the coefficient derived in (Armstrong et al., 2011), which is based on daily maximum temperatures during summer months. For the West Midlands, they calculated a 2.2% (95% CI: 1.9% to 2.6%) increase in mortality for every 1 °C increase in daily maximum temperature above the threshold of 23.0 °C.

3. Results

The model was run first for a summer period (June to August) in 2006. Hourly data from available MIDAS stations within domain four were used, with modelled data extracted by bilinear interpolation from temperatures at the nearest four grid points in the 1 km grid-spacing. The key statistics on the comparison between modelled and observed temperatures are shown in Table 1. Further figures for model comparison against observations can be found in the supplementary material (Fig. S1, S2, Table S1, S2). The modelled 2 m air temperature compares well with observations, demonstrating that the model is able to capture diurnal variation in temperature at these sites, with correlation being 0.94 or higher (Table 1, Fig. S1). The comparison with windspeeds is more variable, but the model is still able to broadly capture the variation at an hourly timescale, with the comparison generally better for urban sites (Fig. S2).

3.1. Seasonal analysis of UHI and cool roofs

The UHI intensity (calculated by taking the difference in 2 m temperature between the 'URBAN' and 'RURAL' simulations) over summer 2006 is shown in Fig. 2, with the average over all times shown (Fig. 2a) as well as broken down to day (Fig. 2b) and night time (Fig. 2c) averages (day time is defined as 8 am-8 pm, and night time is from 8 pm-8 am). The effect of cool roofs (the difference in 2 m temperature between 'COOLROOF' and 'URBAN' simulations) is shown in Fig. 3 (again for all hours, day, and night times), and temperature statistics for the 'URBAN', 'COOLROOF' and 'RURAL' simulations for this period are

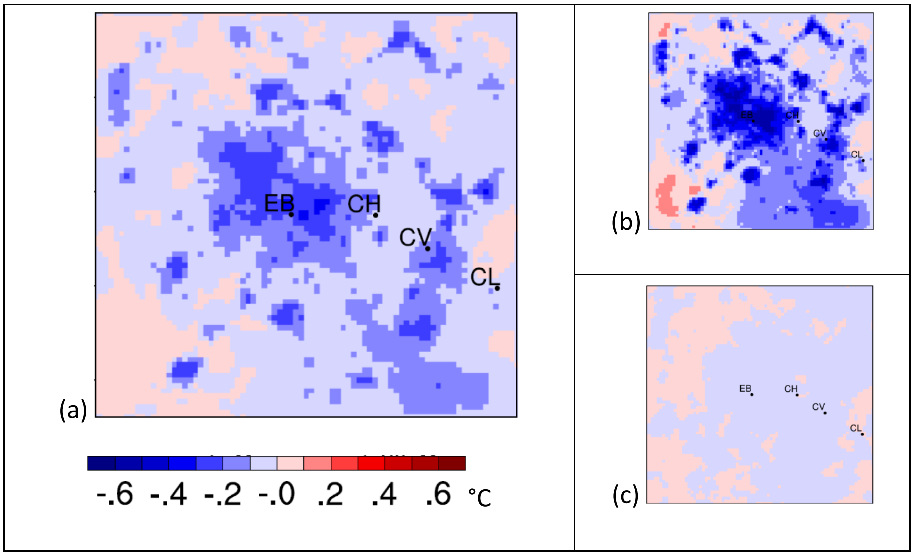


Fig. 3. Impact of cool roofs for June–July-August 2006 in terms of reduction of 2 m temperature. (a) Average for the whole period; (b) daytime average (8 am – 8 pm); (c) night-time average (8 pm – 8 am). City centre in this figure is −0.3 °C (−0.6 °C daytime, −0.1 °C at night). Letters refer to observation stations (refer to Table 1).

shown in Table 2.

The mean temperature across the domain for the summer of 2006 was 16.9 °C (19.5 °C during the day, and 14.2 °C at night) from the 'URBAN' simulation. Comparison with the 'RURAL' simulation shows that the urban surfaces raised the mean temperature of the whole domain by 0.5 °C over the summer on average (0.9 °C at night) (see supplementary Table S1a). However, the population weighted average UHI intensity is higher: 1.1 °C (1.8 °C at night) (Table 2). The greatest mean UHI intensity is seen in the city centre, being 2 °C on average, and 2.6 °C at night (Fig. 2, and Table S1a), and reached a maximum of ~9 °C during an evening in mid-July. Our estimates of the UHI intensity in Birmingham are comparable to historical observations of the difference in temperature between urban or semi-urban sites and largely rural stations (summer mean of 1.08 °C and a mean of 2.26 °C for anticyclonic conditions (Unwin, 1980), and 2.5 °C (reaching up to 7 °C) during anticyclonic conditions (Zhang et al., 2014)), and when using heating and cooling rates derived from observations made by transects across the city (Johnson, 1985), which found the UHI to be around 4.5 °C at night during July 1982. There is also good agreement with observations from a high-density network of ground-based sites (1.5 °C daytime and 2.5 °C at night, Azevedo et al., 2016) compared with 1.5 °C daytime and 2.6 °C at night in our study, although our estimates are slightly lower than those observed by Bassett et al. (2016), possibly due to different choice of averaging periods for day and night times, and a different experimental period.

Cool roofs can reduce mean population-weighted 2 m air temperatures by 0.17 °C, which corresponds to 15% of the UHI intensity over the summer. The effect of cool roofs is greatest during the daytime, where the reduction in temperature is 0.3 °C (Fig. 3a, Table 2) and up to 0.6 °C in the city centre (Fig. 3b, Table S1a). Since the UHI is relatively small during the day, this corresponds to 64% of the UHI at this time. At night, cool roofs only reduce population-weighted temperature by 0.03 °C (Fig. 3c, Table 2).

3.2. Impact of cool roofs for heatwave period

We now focus the analysis on a heatwave period within summer 2006 (16–27 July 2006). July 2006 holds the record for the warmest calendar month ever recorded in the UK (Prior and Beswick, 2007). We also look at the August 2003 heatwave period (2–10 Aug 2003) to provide a comparison with previous work (figures and tables for August 2003 may be found in the supplementary material). For the 2003 heatwave period, we also performed a sensitivity analysis, whereby WRF was driven by the NCEP reanalysis dataset, in comparison with ERA-Interim. We found small differences in the absolute values calculated (mean population-weighted temperature of 20.1 °C with GFS compared with 20.7 °C with ERA-Interim), and found that temperatures simulated with ERA-Interim boundary meteorology provide a better comparison with observations (Fig. S12, Supplementary).

During the July 2006 heatwave, the mean daily maximum temperature was 28.5 °C across the domain, and reached 35 °C on 19 July (not shown); over the August 2003 heatwave, average daily maximum temperatures were 26.5 °C, reaching 33 °C on 10th August (more general statistics are given in Tables S2 and S3, supplementary). Figures of the UHI intensity for the two heatwave periods (similar to Fig. 2) are shown in supplementary Figs. S1 and S2. Population-weighted UHI intensity over the region in July 2006 is 1.3 °C (2.2 °C at night), and in the city centre, the mean UHI intensity over these heatwave periods is 2.3 °C (3.0 °C at night time) (Fig. S1 and S2, Table S2).

The effect of cool roofs is shown in Fig. S9 of supplementary

Table 2

Temperature statistics for different model simulations for the summer period (June-Jul-Aug 2006). Values are population weighted averages across the whole modelled domain, and broken down for day and night times. Geographical (non-population weighted) averages may be found in supplementary Table S1.

Population weighted	'URBAN' run T 2 m (°C)	'COOLROOF'		'RURAL'		% of UHI offset by cool roofs
		T 2 m (°C)	ΔT (°C) ('COOLROOF' – 'URBAN')	T 2 m (°C)	ΔT (°C) ('RURAL' – 'URBAN')	
Mean	17.38	17.21	−0.17	16.24	−1.14	15%
Day	19.60	19.29	−0.30	19.13	−0.47	64%
Night	15.17	15.13	−0.03	13.36	−1.80	2%

Table 3
Temperature statistics for different model simulations for the July 2006 heatwave period (16–27 July 2006). Values are population weighted averages across the whole modelled domain, and broken down for day and night times.

Simulation type	URBAN	COOLROOF						RURAL
Urban category altered*	n/a	Cat 1 2 3	Cat 1	Cat 2	Cat 3	Cat 1	Cat 1 2	n/a
Albedo of roof	n/a	0.7	0.7	0.7	0.7	0.45	0.45	n/a
(a) Population-weighted 2 m temperature (°C)								
All times	22.35	22.07	22.19	22.25	22.32	22.25	22.22	21.10
Day	25.74	25.22	25.42	25.54	25.66	25.55	25.50	25.41
Night	18.96	18.91	18.95	18.95	18.97	18.96	18.95	16.79
(b) Difference from the 'URBAN' simulation (°C)								
All times	–	−0.28	−0.16	−0.10	−0.03	−0.10	−0.13	−1.25
Day	–	−0.52	−0.32	−0.20	−0.08	−0.19	−0.24	−0.33
Night	–	−0.05	−0.01	−0.01	0.01	−0.01	−0.01	−2.17
(c) Percent of UHI intensity that could be offset								
All times	–	23%	13%	8%	3%	8%	10%	100%
Day	–	158%	96%	60%	23%	58%	73%	100%
Night	–	2%	1%	1%	0%	0%	1%	100%

*Category 1 = Industrial/commercial; Category 2 = High-intensity residential; Category 3 = Low-intensity residential.

material (for all hours, day, and night times), and temperature statistics for the 'URBAN', 'COOLROOF' and 'RURAL' simulations for this period are shown in Table 3. Population-weighted daytime temperatures were reduced by 0.3 °C over the heatwave, with peak cooling reaching up to 3.1 °C in the city centre (not shown). Again, the effect of cool roofs is much more apparent during the daytime, with a small effect at night. Applying cool roofs to the industrial/commercial urban category (Cat 1) has the most significant impact on temperatures, due in part to the greater density of buildings in this category (Table 3).

Our analysis for the July 2006 heatwave period shows cool roofs can reduce mean population-weighted 2 m air temperatures by around 0.3 °C, corresponding to 23% of the mean UHI intensity, and can reduce daytime population-weighted temperatures by around 0.5 °C (Table 3). Analysis shows similar results for the August 2003 heatwave simulations (Table S4). This is a greater impact than for the seasonal simulation, due to heatwaves generally having more cloud-free conditions, which is when cool roofs are most effective.

There are also differences in the spatial distribution of cooling corresponding to different urban categories. For the 2006 heatwave, applying cool roofs to all categories can reduce the average population weighted UHI intensity by 23%. Applying cool roofs to the industrial/commercial category only can still offset 13% (high intensity residential only can offset 8%, and low intensity residential only can offset just 3%). This demonstrates the most effective way for applying the intervention is to target the most built-up areas and commercial buildings.

For the 2006 heatwave period, during the daytime the 'COOLROOF' simulation actually had a slightly *lower* 2 m air temperature than the 'RURAL' simulation (25.2 °C vs 25.4 °C). This could be in part due to the very dry conditions (i.e. low soil moisture) at this time. Vegetated areas cool their surroundings mainly through evaporation (latent heat transfer). However, this particular heatwave occurred after an extended period of drought where groundwater recharge was very low (Marsh, 2007), and vegetated areas became so dry that they were not as effective at cooling the air as buildings with reflective roofs, as buildings generally have a higher albedo than soils and also shaded areas around them. This daytime 'urban cool island' has been observed for densely built cities in dry locations (Johansson, 2006; Rasul et al., 2015).

There are small differences between the 2003 and the 2006 heatwaves, which could be partially due to the amount of cloud, as this influences the effectiveness of cool roofs at reducing air temperature. During both heatwave periods there was almost no cloud during the daytime over the modelled domain, and only a small amount very early in the mornings; small differences in the distribution and amount of cloud can lead to differences in peak reduction in temperatures by cool roofs during both heatwaves (3.1 °C in 2006 vs 2.3 °C in 2003).

3.3. Health impact calculations

We applied a health impact methodology to estimate the potential heat-related mortality associated with each modelled simulation, by applying existing exposure-response coefficients to the temperature data generated by the model simulations (see Section 2.2; Table 4 and Fig. 5).

For the 'URBAN' simulations, population weighted results are 27% higher (seasonal) and 17% higher (heatwave periods) than those based on a geographic mean temperature only. Using the coefficient based on maximum temperature (from Armstrong et al. (2011)), population-weighted results are just 6% higher (seasonal) and 10% higher (heatwave) than geographic mean only for the 'URBAN' simulation, as this coefficient is applied to the daily maximum temperature (which is less spatially varying than the daily mean), as the influence of the UHI is largest at night.

Comparing 2 m temperature in the 'URBAN' and 'RURAL' simulations, we estimate that the UHI effect accounts for about one-third of heat-related deaths across the domain (Fig. 4).

We find that in our study, cool roofs may reduce total heat-related deaths by up to 8%, and reduce those attributable to the UHI by up to 25% during heatwave periods.

Estimates of heat-related mortality based on the maximum temperature coefficient derived by Armstrong et al. (2011) are broadly similar, being a little lower seasonally (272 deaths compared with 305) due to the higher threshold temperature for effects, and a little higher during heatwaves (e.g. 101 deaths compared with 96) as heatwave periods are generally defined by periods of high maximum temperatures. However, when quantifying the health impact of cool roofs as a fraction of that due to the UHI, the results are quite different. This is likely to be because the UHI intensity is greatest at night, and has only a small impact on daily maximum temperatures (Fig. 2). Seasonally, results using daily mean temperatures suggest that of the 119 deaths attributed to the UHI, 21 (27%) could be avoided by implementing cool roofs, whereas the analysis using daily maximum values suggests that of the 40 deaths attributable to the UHI, 33 (81%) could be reduced by cool roofs (Fig. 4). In this study, using the maximum temperature rather than the mean leads to fewer deaths being attributed to the UHI (since the UHI is larger at night and influences minimum temperatures more than maximum), and predicts a larger influence of cool roofs on health

Table 4
Estimated heat-related mortality for summer 2006, and heatwave periods in July 2006 and August 2003. Numbers in brackets represent the 95% confidence intervals based on the exposure-response coefficients.

	Exposure-response coefficient* metric	Estimated total number of heat-related deaths		
		URBAN (95% CI)	COOLROOF[a] (95% CI)	RURAL (95% CI)
Jun-Jul-Aug 2006 (seasonal)	Mean T	305 (248–360)	283 (231–334)	185 (151–219)
	Maximum T	272 (237–318)	240 (209–280)	232 (202–272)
16–27 July 2006 (heatwave)	Mean T	178 (146–209)	167 (137–197)	131 (107–154)
	Maximum T	188 (164–220)	172 (150–201)	178 (156–208)
2–10 August 2003 (heatwave)	Mean T	96 (78–113)	88 (72–104)	66 (53–78)
	Maximum T	101 (89–118)	89 (77–104)	83 (73–97)

*Mean temperature metric used with Vardoulakis et al. (2014): 2.5% (CI: 2.0%–3.0%) increase in mortality for every 1 °C increase in daily mean ambient temperature above 17.7 °*C. maximum* temperature used with Armstrong et al. (2011): 2.2% (CI: 1.9%–2.6%) increase in mortality for every 1 °C increase in daily maximum ambient temperature above 23.0 °C.

[a] 'COOLROOF' in this case corresponds to all three urban categories being adjusted together.

effects attributed to the UHI, due to the small background UHI during the daytime.

4. Discussion

According to the UK Climate Projections (UKCP09), for a medium emission scenario the West Midlands is likely to see a 2.6 °C increase in summer mean temperatures by the 2050s, and 3.7 °C by the 2080s, relative to the 1961–90 baseline (Murphy et al., 2009). The corresponding number of deaths for a 2003 type heatwave event in future in the West Midlands were estimated at 200 and 278 deaths in the 2050s and 2080s, respectively, compared with around 90 in August 2003 (Heaviside et al., 2016). These projected temperature increases are similar in magnitude to the current UHI intensity experienced in the centre of Birmingham city during heatwaves (Fig. 2, Fig. S1 and S2), meaning that in Birmingham, cool roofs could offset about 25% of the projected warming. Cool roofs could play an important role in mitigating the UHI effect, and offsetting near-term warming from climate change. However, these climate projections do not typically include the effect of the UHI (due to limitations of spatial scale). It has been shown that excluding the effect of the UHI in future decades could underestimate heat-related mortality by around one third (Heaviside et al., 2016). Future projections of heat health effects are challenging to estimate, due to population demographic changes, increasing rates of comorbidities, and potential population adaptation and/or acclimatisation, but further action is likely needed to offset or adapt to the potential effects of a warming climate.

The effect of cool roofs on reducing ambient temperature is greatest during the daytime, as the cooling mechanism is via reflection of sunlight. As the UHI is greatest at night time and only relatively small during the day, cool roofs have a modest effect on the average UHI intensity, however they help reduce maximum daily temperatures. This has important implications for thermal comfort as well as energy demand for cooling. The reductions in ambient temperature during heatwaves compare well with those from previous similar studies; we find a mean air temperature reduction of 0.3 °C during heatwaves, compared with 0.2 °C to 0.44 °C for summer periods in London (Virk et al., 2015), and ~0.5 °C during the day by Li et al. (2014). Additionally, a study in New York City suggests a mean summer reduction of 0.5 °C by applying cool roofs across the city, and while their estimate of 0.6 °C reduction for daytime is close to ours, their estimates for night are larger (0.3 °C), which could be due to differences in city characteristics, or the very high albedo chosen in their study (Susca, 2012). Peak temperature reductions of 3.1 °C compare well with estimates by Morini et al. (2016, 2017) who find between 1 °C and 4 °C maximum daytime reduction for Italian cities, as well as a maximum 3 °C cooling estimated for cool roofs in Chicago (Smith and Roebber, 2011), and city-scale 1.1 °C peak reduction found by Imran et al. (2018). Our results also fall in the middle of the range summarised in a recent review, which found mean ambient reductions of 0.11 °C to 0.8 °C for deployment of cool roofs across urban areas (Santamouris, 2014a).

We chose to apply an albedo of 0.7 across all roofs across the region to simulate the theoretical temperature reductions, and thus mortality reductions that implementing cool roofs might achieve. While higher

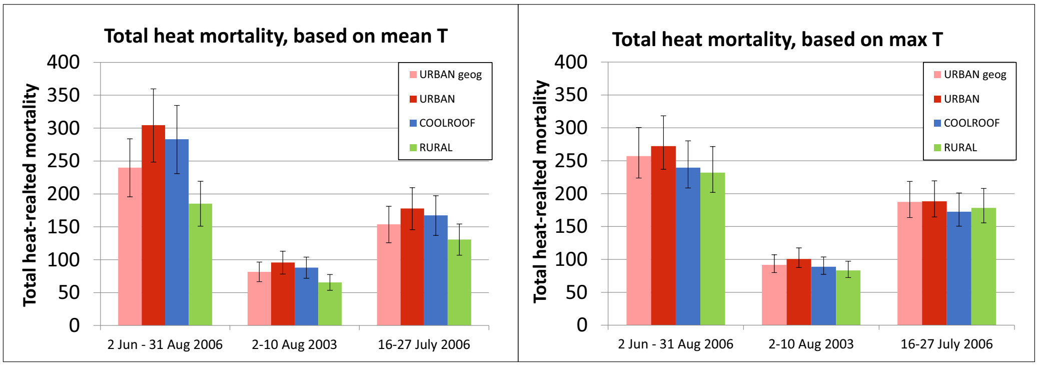


Fig. 4. Heat-related mortality for each period calculated using the different coefficients for the West Midlands. Results are derived from population-weighted temperatures, except for the 'URBAN geog' (lighter-red bars), which are based on geographical mean only. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

albedos are possible (e.g. 0.85 or higher), the albedo is likely to reduce over time as the surface becomes aged or dirty. While applying 0.7 uniformly to all roofs is a simplification, our aim is to demonstrate a realistic maximum potential impact on the UHI (a city-wide phenomenon), to give an upper limit for a cooling effect, and the associated impacts on heat-related health effects.

Our analysis shows that cool roofs may reduce overall heat-related mortality during a heatwave by up to 8%, and offset up to 25% of that attributable to the UHI in our study area. The HIA results for August 2003 for the 'URBAN' simulations here compare well with those of Heaviside et al. (2016) for the same period, when the same coefficient from Hajat et al. (2014)[1] is applied (Table S4). However, for the 'RURAL' simulations our study finds around 60 deaths, as opposed to about 40 in the Heaviside study. The differences in the 'RURAL' simulations could be due to different WRF model versions used in the two studies, and some updates to the newer version may have affected vegetation parameters. Differences in the boundary meteorology could also play a role, as well as model initialisation. The estimated reduction in mortality that we find is comparable to those estimated from previous studies. Altering roofs in New York City from an albedo of 0.32 to 0.9 could reduce 45 deaths over the summer (Susca, 2012), which is comparable to the 32 calculated in this study (using maximum temperatures as their study did, and considering the much higher albedo used in their study). A study in Greece suggests that a reduction in temperatures similar to that achievable by reflective coating could alter conditions to reduce heat-related mortality by ~38%, though this study only focused on cardiovascular and respiratory mortality in the over 65 s (Paravantis et al., 2017). A modelling study for Baltimore, Los Angeles and New York found that increase average urban albedo from 0.15 to 0.35 (by implementing cool roofs with albedo of up to 0.6 and roads of 0.3) could save up to 32 lives in Baltimore, 22 lives in Los Angeles, and 219 lives in New York over a 10-year period, corresponding to a 5%, 21% and 10% reduction in heat-related mortality (Vanos et al., 2014), which compares with our value of ~8% reduction in overall heat-related mortality.

We explored the effect of using different exposure-response coefficients, using daily mean and daily maximum temperature metrics and different thresholds for effects. Using maximum temperatures in the health impact assessment tends to lead to lower overall seasonal heat mortality heat compared with using the mean temperature (due to the higher threshold for effects, 23 °C vs 17.7 °C). However, during heatwaves daily maximum temperatures tend to be much higher than the threshold for effects, whereas daily mean temperatures are not as high above the threshold (as it is an average and therefore moderated by overnight temperatures). In terms of the distribution of heat-related mortality over the course of a year, this would suggest that using the daily maximum temperature would lead to annual heat-related mortality being attributed mainly to periods of heatwave conditions with little occurring outside of these periods, whereas using the daily mean temperature would have heat-related mortality spread across more days and not concentrated during heatwaves. This could be important for targeting interventions and health messaging. Previous studies have used heat-health relationships based on maximum ambient temperatures to assess the effectiveness of building modifications at reducing exposure to high indoor temperatures (Taylor et al., 2018a; Taylor et al., 2018b). There is no clear consensus on which temperature metric is most relevant for health effects, with maximum, mean, and overnight temperatures having been related to health effects (Armstrong et al., 2011; Gasparrini et al., 2012; Laaidi et al., 2012; Hajat et al., 2014; Murage et al., 2017). As different types of interventions may have more influence over different temperature metrics, care should be taken when choosing methods to assess the effectiveness of interventions to reduce exposure to high temperatures, especially for future projections (Hondula et al., 2014). However, since the UHI effect is mainly a night time phenomenon, we believe that the use of a daily mean temperature is appropriate for this study, which is in the context of summer temperatures, and particularly in the urban environment and associated with the UHI effect. Mean daily temperature therefore reflects the peak temperatures as well as the high nighttime minimum temperatures likely to be experienced in cities during heatwaves, which do not provide respite from heat, and which are thought to exacerbate health impacts during heatwaves, for example in Paris in 2003 (Laaidi et al., 2012). There is potential to apply the results of simulations to epidemiological analyses based on a range of health endpoints and temperature metrics in the current study area to gain more insights as to health effects associated with different exposure variables.

Implementing cool roofs on commercial buildings has the biggest effect on ambient temperatures, as commercial areas tend to have the highest density of buildings. The health impact assessment shows that adaptation of commercial buildings could still reduce heat related mortality, despite expectations that populations might not reside as heavily in these areas. With inner city developments of new blocks of flats and conversions, reducing temperatures close to urban centres is still important (Macintyre et al., 2018).

July 2006 was at the end of an extended general drought period from 2004 to 2006 (Marsh, 2007). During dry periods when soil moisture is low, vegetated areas have a reduced cooling effect on the surrounding air, due to reduced evapotranspiration. Our analysis using daily maximum temperatures show that urban areas with reflective roofs resulted in lower maximum temperatures than when all urban surfaces were replaced with vegetation. This demonstrates the effectiveness of shading by urban infrastructure, particularly in dry conditions, as well as high-albedo roofs absorbing less heat than dry, dark coloured soils. Summer mean precipitation over the West Midlands is projected to be 20% lower by the 2080s for a medium emissions scenario, though large uncertainties and geographical variation exist (Murphy et al., 2009). Future changes in rainfall patterns and drought frequency due to climate change may impact the effectiveness of various urban interventions to reduce heat; urban green spaces may be less effective at cooling their surroundings without additional irrigation.

The UHI intensity is the difference between urban and rural temperatures, and as such, a small UHI intensity does not preclude high maximum temperatures in cities. Identifying locations with large UHI intensity and high temperatures would be beneficial to target modifications of the urban fabric to try to reduce local air temperatures, particularly where more vulnerable populations may reside (Macintyre et al., 2018). Together with underlying vulnerabilities, health effects from heat are determined by exposure, which is more likely to be related to indoor temperatures. Limited or indirect evidence on indoor exposures means there is currently no overheating threshold for health risk in relation to indoor temperatures (Vardoulakis et al., 2015), though there is a relationship between indoor and outdoor temperature, particularly for warmer conditions (Nguyen et al., 2014), and the epidemiology models will incorporate the influence of buildings on exposure to some extent.

Personal heat exposure of individuals is currently sparsely observed, though a few studies have achieved this, finding that for the south eastern US, individual exposures are generally lower than those predicted by weather stations (Bernhard et al., 2015; Kuras et al., 2017; Sugg et al., 2018). The epidemiological studies used in this study are based on outdoor temperatures, partly due to more data being available, and also that indoor temperatures can vary strongly depending on a range of building attributes such as materials, insulation, south facing glazing, occupant behaviour such as window opening, shading by trees, etc., making indoor temperatures of all dwellings difficult to predict. Sufficient data on indoor temperatures and exposure would be challenging and costly to obtain at scales useful for population

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[1] Hajat et al. (2014) find a 2.3% (95% CI: 1.6% - 3.1%) increase in mortality for every 1 °C increase in daily mean ambient temperature above 17.7 °C. Results of a HIA with this coefficient may be found in the supplementary material.

epidemiology.

Winter mortality is a serious issue for the UK, and fuel poverty may exacerbate this risk; interventions to reduce effects from heat should be carefully chosen so they do not overly exacerbate risks from cold, and vice versa. Cool roofs may impact on indoor temperatures during the cool season; Taylor et al. (2018a) show that there is indeed a 4% increase in energy use for heating during the winter months when cool roofs are applied to a building, and a small change in associated temperature-related mortality (though there is uncertainty around the threshold for cold effects on health). Improvements in home energy efficiency (insulation and heating) could potentially offset this increase in cold mortality in winter. However, indoor temperature modelling is beyond the scope of what can be investigated with a regional weather model.

Future work will investigate the effects of cool roofs and the UHI on indoor temperatures which would require additional simulations using building physics models. The UHI and its effects in wintertime are currently under-examined, and future work should address this issue, particularly the impact of the wintertime UHI effect on cold related mortality, and the potential modification by cool roofs or other types of interventions.

The WRF model is a useful tool for simulating meteorological variables at this scale. While city-scale effects are simulated in the high resolution innermost domains, the initial and boundary meteorological conditions need to be specified at the edge of the outer domains. Choice of boundary conditions are a source of variability in models such as WRF, and therefore are an additional source of uncertainty in assessments such as this one. We found that using the ERA-Interim reanalysis as boundary and initial conditions led to simulations with the best comparison with observations. When using the NCEP Final Analysis (GFS) dataset instead of ERA-Interim, we found slightly reduced model performance, and small differences in the temperature, generally the GFS runs showed slightly lower temperatures, suggesting that higher temperatures are not captured as well by WRF when using this dataset. This could be due to differences in reanalysis resolution, and differences in soil levels and soil moisture values. This is an indication of one source of uncertainty in a set-up such as ours, and shows that temperatures in the innermost domain of WRF can be around 0.5 °C different, depending on choice of larger scale initial and boundary conditions (Fig. S12, supplementary). We used the BEP multi-layer urban canopy scheme to simulate the effect of buildings on energy and momentum fluxes in the lower atmosphere (accounting for shading and reflections by buildings) at sub-grid scale, providing a suitable representation of how urban areas influence meteorology. However, individual building level microclimates are not explicitly captured as our regional weather models are run at ~1 km horizontal grid scale, and therefore results for specific locations may have additional variation on finer scales. Built environment modifications such as cool roofs may also alter local winds, ground surface temperatures, and sensible heating fluxes. Other modelling techniques may be able to capture the effect on local conditions of altering roofs of individual buildings, and while a more in-depth study of local meteorological effects such as on local winds would be interesting, it is beyond the scope of this current work which focuses on population heat-related health effects and the UHI, which is a city-scale phenomenon.

5. Conclusions

We used a detailed regional meteorological model to simulate ambient temperatures, quantify the UHI intensity, and also estimate the effect of applying cool roofs to an urbanised area in the UK. We find that summer mean UHI intensity in Birmingham city centre was 2.0 °C (2.6 °C at night), and reached up to a maximum of 9 °C during one evening. Our simulations showed that applying cool roofs (albedo 0.7) across all buildings reduced population-weighted temperature by 0.3 °C, corresponding to 23% of the UHI intensity, and could potentially offset 18% of seasonal heat-related mortality associated with the UHI (corresponding to 7% of total heat-related mortality). During heatwave periods, we find that covering all buildings with cool roofs could reduce overall heat-related mortality by ~8%, and offset 25% of that attributable to the UHI.

Although the UHI effect is most pronounced at night time, our results showed that the effect of cool roofs was largest in the daytime, reducing average daytime temperatures by 0.5 °C, and up to a maximum of ~3 °C reduction. Therefore, the reduction in the UHI intensity offered by cool roofs is mainly related to the daytime component of the UHI intensity, and cool roofs reduce the night time UHI intensity far less. In terms of health protection, cool roofs therefore have the potential to limit dangerous high temperatures experienced in daytime during heatwaves, on the order of a few degrees.

By modifying the albedo of different urban categories, our modelling shows that applying cool roofs to half of commercial buildings could be as effective at reducing ambient temperatures as applying them to all high-intensity residential areas in the West Midlands. As cool roofs affect local conditions by reflecting more sunlight, the maximum reduction in ambient temperature occurs during the daytime, when temperatures are highest. The efficacy of cool roofs at reducing maximum temperatures is also important for cooling loads which are expected to increase significantly in future.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.02.065.

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