

Cool roofs could be most effective at reducing outdoor urban temperatures in London compared with other roof top and vegetation interventions: a mesoscale urban climate modelling study

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Key Points:

- City scale deployment of cool roofs have the highest impact on 2 m air temperature
- Green roofs do not decrease daily average temperature but have a daytime cooling effect
- Solar PV can reduce temperatures in London by capturing sensible heat, generating electrical power and reducing sensible heat flux

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Abstract

Comprehensive studies comparing impacts of building and street levels interventions on air temperature at metropolitan scales are still lacking despite increased urban heat-related mortality and morbidity. We therefore model the impact of 9 interventions on air temperatures at 2 m during 2 hot days from the summer 2018 in the Greater London Authority area using the WRF BEP-BEM climate model. We find that on average cool roofs most effectively reduce temperatures (~ -1.2 °C), outperforming green roofs (~ 0 °C), solar panels (~ -0.3 °C) and street level vegetation (~ -0.3 °C). Application of air conditioning across London increase air temperatures by $\sim +0.15$ °C but related energetic consumption could be covered by energy production from solar panels. Current realistic deployments of green roofs and solar panels are ineffective at large scale reduction of temperatures. We provide a detailed decomposition of the surface energy balance to explain changes in air temperature and guide future decision-making.

Plain Language Summary

Multiple common city scale passive and active interventions exist to reduce urban population's exposure to extreme heat during hot spells. Nonetheless, a proper comparison of the effect that each of these interventions may have on the temperatures experienced within large cities is missing. Additionally, energetic mechanisms that lead to outdoor temperature changes are often not detailed and could lead to detrimental effects for local populations, such as indirect increase of relative humidity or outdoor temperatures. Our study, focusing over London, compares several common interventions through a modelling experiment and finds that cool roofs largely outperform other interventions during the two hottest days of the summer 2018. We also find that green roofs are ineffective on average and that solar panels and tree vegetation would only marginally change temperature exposures. Large scale deployment of air conditioning would lead to increased temperature in the core of London. Solar panels could potentially provide sufficient energy for running air conditioning all over London, creating comfortable indoor environments, and green roofs could reduce temperatures during the day. We argue that such inter-comparisons should guide future decision making.

1 Introduction

Cities have become a focus of attention for climate adaptation and mitigation solutions in the face of the increasing challenges induced by global urbanization and climate warming. More specifically, interest in urban temperatures has been growing, as cities are known to alter the local climate to which urban citizens are exposed (e.g., through the Urban Heat Island (UHI) effect (Oke et al., 2017) and thereby impact their thermal comfort and climate-related mortality (Arbutnott et al., 2016; Gasparrini et al., 2015; Masselot et al., 2023). During hot spells, higher mortality and increased likelihood of thermal discomfort are generally observed, hence calling for adaptative and mitigative measures to reduce outdoor air temperatures at the city scale (Heaviside et al., 2016; Salmond et al., 2016; Iungman et al., 2023).

To respond to these risks to public health, passive and active strategies have been proposed to cool down the urban indoor and outdoor environments, and to provide indoor sheltering for the most vulnerable. Commonly proposed urban passive cooling strategies, which should be considered as measures that directly lower the temperatures, include increased urban vegetation, roofs incorporating vegetation (known as green roofs), or the deployment of highly reflective roofs, known as cool roofs (Santamouris et al., 2017). Changes to roofs can reduce indoor temperatures or cooling needs in a building, but when deployed at scale can also reduce the outdoor air temperature and associated heat related mortality (Virk et al., 2014; H. Macintyre & Heaviside, 2019). Concerning active strategies, meaning measures that transform the incoming radiation, into energy for ex-

ample, or that mechanically change the temperatures, air conditioning (AC) is one of the most effective for protection against heat, although it can require large amounts of electrical power and increase outdoor temperatures (Salamanca et al., 2014; Stone Jr et al., 2021). Where passive strategies are unviable or insufficient, AC may be the only option, but it remains the primary solution in some high-income countries despite its problems, like in Phoenix, Arizona (Stone Jr et al., 2021). Lastly, while rooftop solar photovoltaic (PV) panels are primarily considered as a source of electrical power, they can also be considered as a passive-active strategy for impacting outdoor and indoor air temperature by increasing the roofs' albedo and by transforming incoming solar radiation into electrical power that can be used to run the AC system (Salamanca et al., 2016; Ma et al., 2017). Debate on their effectiveness as cooling strategies is currently ongoing (Sailor et al., 2021) and calls for more local studies to understand their costs and benefits at different latitudes.

In general, the impact of these strategies has been quantified for a variety of cities across the world (e.g., Chicago (Sharma et al., 2016), Madrid (Salamanca et al., 2014) or Singapore (Yang & Bou-Zeid, 2019)) and physical mechanisms that lead to the cooling/heating of the cities are well understood (Nazarian et al., 2022). Nonetheless, city-specific quantification of these impacts should still be performed to inform the general audience. In addition, few studies have explored in detail how these interventions impact the surface energy balance (SEB) and how these alterations at the city scale can relate to local changes in air temperatures (Broadbent et al., 2020; Krayenhoff et al., 2021). Furthermore, impact studies of urban scale interventions are often challenged by the lack of geographical data on realistic extent at which each intervention could be applied. This means that it is often impossible to give a realistic estimate of the potential impact that interventions can have at a city-scale.

Large-scale controlled trials of urban interventions are, so far, rare, and much of the evidence for their effectiveness comes from modelling. Urban climate models (UCMs) embedded in regional climate models (RCMs), after proper model evaluation, can provide an accurate estimation of the impact on the of urban areas on local climate, as well as the impact of interventions (Krayenhoff et al., 2021). Indeed, most UCMs are coupled to a variety of intervention strategies (e.g., green roofs and solar panels (Zonato et al., 2021) or AC systems (Salamanca et al., 2010; Salamanca & Martilli, 2010)).

In this study, we use detailed urban climate modelling, as well as recent data on the actual coverage of passive(-active) interventions, to estimate the impact on outdoor temperature of several interventions during hot summer days within the Greater London Authority boundaries. By considering a set of scenarios that include both active and passive heat adaptation strategies, our study makes a comprehensive analysis of the impact of each strategy on the outdoor air temperature and the SEB of the Greater London area. Because we expect some of these strategies to not be applicable to all buildings, like green roofs or solar PV panels, we provide realistic scenarios to compare the hypothetical maximum with realistic implementation. We also discuss the potential energy costs and benefits of air conditioning and PV, and the advantages and disadvantages of vegetation-based strategies.

2 Methods

We ran a set of regional climate simulations with a complex three-dimensional urban scheme activated on the two hottest days of the summer of 2018. Our model is based on an existing set up, run over the whole summer of 2018 (Brousse et al., 2023) and is evaluated against a set of in situ observations of air temperature. Although our model is run over the whole of south-east England to accurately represent the interaction between local interventions and mesoscale atmospheric circulations, we focus our study on

the Greater London Authority (GLA) metropolitan area only, because our realistic interventions are valid for that specific area.

2.1 Model configuration

We focus our study on the two hottest days of summer 2018, the 26th and the 27th of July, as 2018 was the hottest summer on average for the United Kingdom (McCarthy et al., 2019). Our RCM is run for 3 consecutive days, starting on the 25th of July 2018, and considers that day as spin-up time. We use the Weather Research Forecast (WRF) v4.3 RCM to physically represent the potential impact of urban temperature reduction interventions at a high spatio-temporal resolution of 1 km with hourly outputs over south-east England; following the previous model domain of Brousse et al. (2023). The impact of cities on the local climate is simulated by activating the Building Energy Parameterization (BEP; Martilli et al. (2002)) model with its coupled Building Energy Model (BEM; Salamanca et al. (2010); Salamanca and Martilli (2010)), hereafter referred as BEP-BEM.

We consider BEP-BEM to be optimal for our study as it is one of the most refined models that permits the modelling of urban areas at meso-scale. It is a complex 3-dimensional UCM that divides the urban environment and atmosphere into several key components and layers. For instance, BEP-BEM allows the users to define building characteristics at roof and wall levels and street characteristics separately and represents the building impact on the urban boundary layer with a subgrid vertical resolution of 5 m. This is particularly important for evaluation of rooftop interventions as Zonato et al. (2021) showed that the impact of interventions is dependent on building height. Using BEP-BEM thereby avoids over-simplification of the changes in urban properties induced by the intervention – something that would happen in a bulk-level UCM, for example. It also subdivides the RCM grid into an urban and a natural tile where surface fluxes are calculated separately before being merged, hence allowing for an appropriate estimation of the impact of changes in vegetation cover. In our control simulation, the natural tile is handled by the Noah-MP land surface model (Niu et al., 2011) and is considered as a mixture of cropland and grassland. Lastly, BEP-BEM offers a set of dynamic models for active and passive strategies for cooling outdoor and indoor environments, including green roofs, solar PV panels, and air conditioning (Salamanca et al., 2011; Zonato et al., 2021).

We use the same model dynamics and physics set up as (Brousse et al., 2023) as these have shown good agreement with observations for the whole summer 2018. For the urban canopy parameters and the land cover classification we use the defaults MODIS land cover from WRF and categorize the urban pixels to Local Climate Zones (LCZ; Stewart and Oke (2012)) following the WUDAPT-TO-WRF strategy (Brousse et al., 2016; Demuzere et al., 2022) to provide the WRF model with spatially explicit urban morphological parameters. The building characteristics are provided per LCZ and are the same than in Brousse et al. (2023).

2.2 Model evaluation

To evaluate the model outputs in parts of the urban environment deprived of official weather data sources, we follow the same evaluation strategy as in Brousse et al. (2023) by taking advantage of the dense network of personal weather stations (PWS) in the city of London (Brousse et al., 2022). Our model is thereby evaluated against official automatic weather stations (AWS) from the MIDAS Met Office network (Sunter, 2021; UKMO, 2021) and quality-checked crowd-sourced PWS from the Netatmo company (<https://netatmo.org>). More details on the data acquisition and on the rationale defending the use of privately owned PWS for UCM evaluation can be found in Brousse et al. (2023). All our crowd-sourced weather data has been quality-checked and filtered using a common statistical method provided by the *Crowd-QC* package from Grassmann et al. (2018); also see Napoly et al. (2018).

We evaluate our model with several statistical indicators including the squared Pearson’s coefficient of correlation (r^2), Spearman’s coefficient of correlation, root mean squared error (RMSE), mean absolute error (MAE), and mean bias (MB). The evaluation is carried out over the whole domain to ensure that the model is performing well in all urban settings and to ensure that our choice for the GLA area is not biased towards higher model performances.

2.3 Temperature interventions

We define a set of 9 passive interventions that are theoretically applicable over the Greater London metropolitan area. Most of our interventions consist of roof interventions and each intervention is compared to a control run which consists of the same model set up as in Brousse et al. (2023), and which did not consider any heat intervention strategy. Therefore, the control run is simply representative of the impact of urban areas on the local climate while all subsequent scenarios estimate the impact of each intervention on that urban climate. We also simulate the effect of widespread use of active cooling in the form of air conditioning.

Our scenarios consist of: 1) the deployment of cool roofs by increasing the albedo of each urban class to 0.85 (CR₁₀₀); 2) the deployment of green roofs composed of sedum vegetation in all urban classes by activating the green roof model from Zonato et al. (2021) with its default irrigation hours from 23.00 UTC to 01.00 UTC (GR₁₀₀); 3) the deployment of solar PV panels on all urban roofs by activating the solar PV model from (Zonato et al., 2021) in its default version (PV₁₀₀); 4) the installation of air conditioning systems in all buildings and at all floors by activating the air conditioning model embedded in the BEM model in its default version (Salamanca et al. (2010); Salamanca and Martilli (2010); AC₁₀₀); and 5) the change of the urban vegetation from cropland and grass land to urban deciduous trees as implemented in NOAH-MP (Niu et al. (2011), VG₁₀₀). These scenarios aim to represent the maximum impact that one intervention can have on the city’s temperatures and SEB. More information about each model can be found in the appendix Appendix A.

We also test the impact of certain scenarios that are based on more achievable or tailored interventions. These scenarios are: 1) the potential for solar PV deployment over roofs of existing buildings in the Greater London taking into account roof slope and overshadowing derived from the London solar opportunity map (PV_{pot}; Steadman et al. (2020)); 2) the potential for retrofit of green roofs on existing buildings in Greater London obtained through a detailed geographical information system analysis (C. Simpson et al. (2022); GR_{pot}); 3) the installation of cool roofs in compact and open mid-rise areas (Local Climate Zones 2 and 5) from the centre of London (CR_{mid}); 4) in open low rise areas (Local Climate Zone 6; CR_{low}) from the residential suburbs of London; and 5) in commercial and industrial areas of London (Local Climate Zone 8; CR_{cid}).

Potential conjoint use of green and cool roofs with solar panels have been proposed to increase solar panel efficiency while reducing urban surface temperatures in particular (Fleck et al., 2022; Schindler et al., 2018), but it was not possible to analyse this in our model. Sedum was modelled for the green roofs due to its increasing presence on new buildings in London (C. Simpson et al., 2022), but other plants such as turf may have a different impact.

To integrate the spatially-explicit variation in solar PV panels and green roofs coverage from the scenarios PV_{pot} and GR_{pot}, we adapted the code from Zonato et al. (2021) and added a field to the WRF geographical input files. These two scenarios also explain why our study focuses only on GLA area as these are bounded to its administrative boundaries and are not applicable to the whole south-east of England which composes our WRF domain. Lastly, we expect the impacts to be more prominent in London due to its higher urban heat island intensity (Bassett et al., 2021; Brousse et al., 2022).

3 Results

During the two hottest summer days of 2018, our model configuration presents a warm bias estimated at 0.72°C on average in urban PWS and of 1.76°C amongst official AWS (Fig. B1). Such a difference may be explained by the fact that official AWS are often located in open fields like parks or airports, which further supports the use of PWS for model evaluation (Hammerberg et al., 2018; Brousse et al., 2023). Metrics estimating the model error are better on average across urban PWS compared to AWS, with average values of 2.39°C compared to 2.84°C for RMSE, and of 1.94°C compared to 2.33°C for MAE. The model seems however to be better correlated temporally at AWS locations with coefficients of 0.91 against 0.88 for Spearman's r and of 0.84 against 0.81 for Pearson's r^2 . We consider our model performance to be acceptable, especially considering the high level of confidence in the temporal evolution of the air temperature at 2 m (T_2) which is directly correlated to the SEB. We thereby assume that our model is trustworthy for each SEB component as we cannot evaluate them without access to flux tower measurements.

In general, we find that cool roofs are the more effective interventions to reduce the heat in the GLA boundaries with a 2-days average cooling of $\sim 1.2^{\circ}\text{C}$ going up to $\sim 2.0^{\circ}\text{C}$ in certain locations (Fig. 1 and 2). All cool roofs interventions contribute to a reduction of T_2 on average (Fig. 2) with major impacts found in the south and the east of GLA if deployed at 100 % (CR_{100} ; Fig. 1). Horizontal advection of cooling depends on the location where cool roofs are implemented. For instance, if cool roofs are implemented in more central and mid-rise areas of London, more open and low-rise residential areas appear to benefit from this cooling by $\sim 0.15^{\circ}\text{C}$ on average. Interestingly, implementing cool roofs on residential low-rise buildings only (CR_{low}) does not cool the central parts of the cities despite providing a substantial outdoor T_2 reduction by up to $\sim 2^{\circ}\text{C}$ in the south-east. Establishing cool roofs only on industrial and commercial areas (CR_{cid}) only results in a marginal heat reduction on average over London but does lead to a heat reduction of up to $\sim 1^{\circ}\text{C}$ in large industrial areas of east-London. Compared to cool roofs, we find more minor decreases in T_2 of $\sim 0.3^{\circ}\text{C}$ on average related to both the change in natural cover from a mixture of croplands and grasslands to deciduous trees (VG_{100}) and to the installation of solar panels over the whole city (PV_{100}). Stronger cooling effects are found in the east of London for these two scenarios. Lastly, despite a high spatial heterogeneity of the cooling provided by the remaining interventions (green roofs (GR_{100} and GR_{pot}); realistic retrofit potential of solar panels (PV_{pot}), none is found to be beneficial for T_2 reduction on average for the whole metropolitan area (Fig. 2). Using air conditioning for maintaining the indoor temperature of all London's building stock to 21°C (AC_{100}) induces a heating of central London by up to $\sim 1^{\circ}\text{C}$ and of $\sim 0.15^{\circ}\text{C}$ on average for the whole city.

By relating the change in T_2 of all urban pixels in the GLA area to their relative SEB components we find that the large decrease in T_2 induced by the full scale deployment of cool roofs (CR_{100}) is linked to an increase in albedo by ~ 0.3 and a reduction of sensible heat fluxes emitted by the city of $\sim 30 \text{ W}\cdot\text{m}^{-2}$, on average. Notably, however, we observe an increase in incoming solar radiation when deploying cool roofs over the whole city (CR_{100}) and in open residential areas (CR_{low}) as well as when implementing solar panels over the whole city (PV_{100}); something that was also recently observed by Valencia et al. (2023). This could be related to a lower convection due to the cooler surfaces, although major changes in the average cloud cover in the whole atmospheric column are not perceived. Higher emissions of sensible heat fluxes by $\sim 5 \text{ W}\cdot\text{m}^{-2}$ are found in both the air conditioning (AC_{100}) and the deciduous tree (VG_{100}) scenarios. While the former is expected as AC systems remove the accumulated indoor heat outside mostly in the form of sensible heat, the latter is counter intuitive as more vegetated areas are expected to mostly transform energy in the form of latent heat fluxes via evapotranspiration – something that is modelled with an average increase of latent heat fluxes

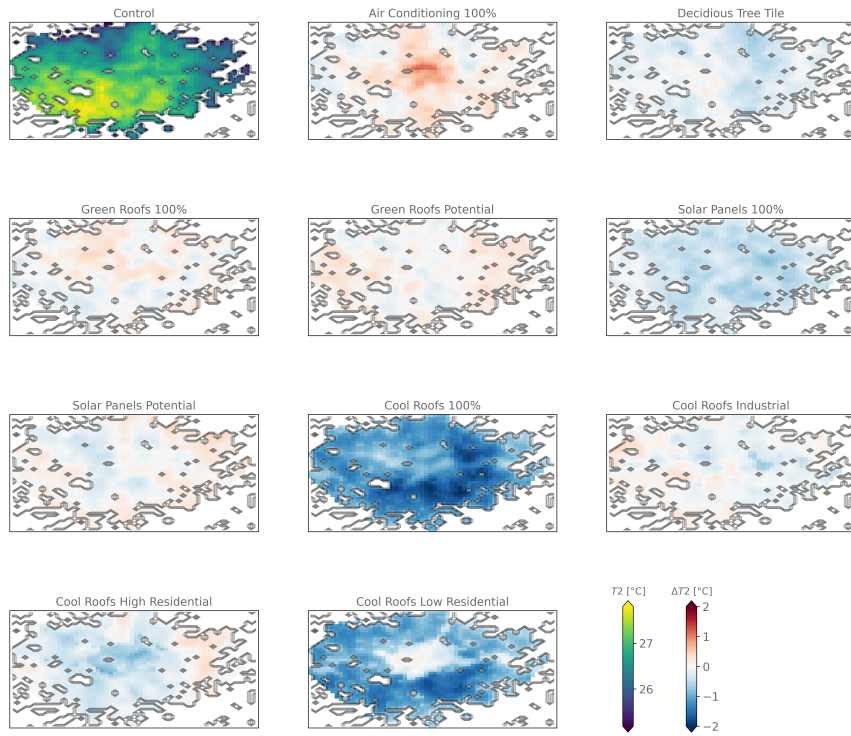


Figure 1. Average 2 m air temperature of the control run (T2; top left panel) and the average difference of each intervention ($\Delta T2$). Grey contours are WRF urban pixels (classified as an urban LCZ).

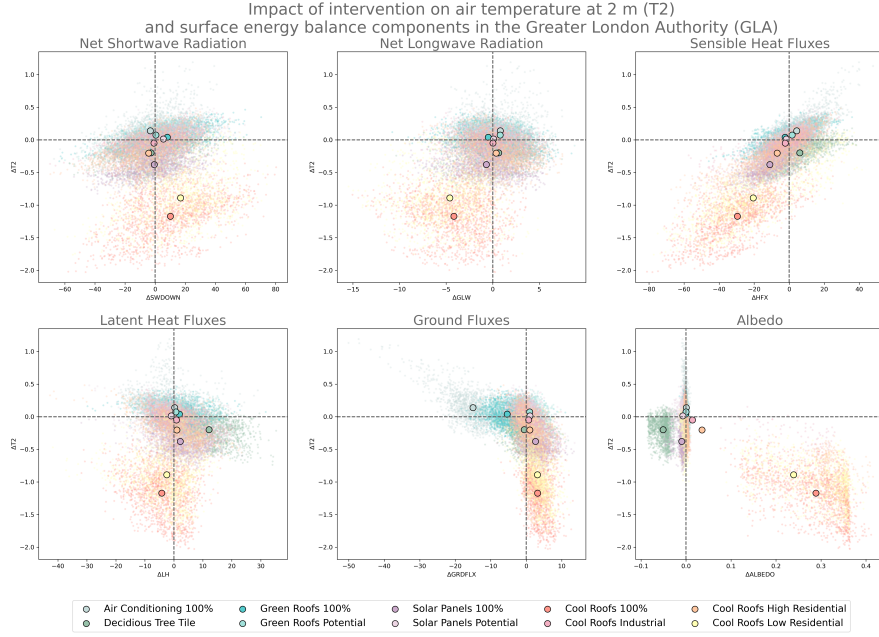


Figure 2. Time-averaged impact of each intervention on each surface energy balance component and the respective change in air temperature at 2 m for all urban pixels (small dots). Average impact is represented by the large dots.

by $\sim 12 \text{ W} \cdot \text{m}^{-2}$. We however observe a decrease in surface albedo by 0.05 on average in parallel which could explain this phenomenon.

Despite an increase of T_2 induced by green roofs of less than $0.1 \text{ }^\circ\text{C}$ on average, hourly spatial averages of changes in T_2 show that if green roofs were implemented across the whole city (GR_{100}), temperatures could be decreased by ~ 0.5 to $\sim 0.8 \text{ }^\circ\text{C}$ during hot hours of the day (11.00 UTC to 14.00 UTC; Fig. 3 and Fig. C1 to C2). Nonetheless, temperatures would also be increased at times of daily minimum T_2 by $\sim 0.5 \text{ }^\circ\text{C}$ (03.00 UTC to 06.00 UTC, Fig. 3). This is consistent with findings by Zonato et al. (2021) and explained by an increased release of latent fluxes during the day but a higher storage of heat fluxes at night due to green roofs' thermal mass. The current potential for green roofs in London (GR_{pot}) would not reduce the temperature by more than $0.1 \text{ }^\circ\text{C}$ on average across the period. During the hotter hours of the day, the impact of cool roofs (CR_{100}) can be 2.5 times and the one from cool roofs over open-low rises (CR_{low}) 2.0 times greater than the one of green roofs. Both these scenarios (CR_{100} and CR_{low}) also contribute to a constant reduction of temperature of at least $0.5 \text{ }^\circ\text{C}$ throughout the day. This is correlated to a high reduction of emitted sensible heat fluxes and of the positive intakes of ground fluxes throughout daytime hours (Fig. C1 to C2). Notably, the temperature reduction across the whole city induced by cool roofs over central mid-rises from London (CR_{mid}) reaches a peak at later hours, around 15.00 UTC, a few hours after the peak in reduction of sensible heat fluxes reached at noon. Higher temperature reduction by $\sim 0.8 \text{ }^\circ\text{C}$ is observed in the evening if vegetation is changed to deciduous trees (VG_{100}). During the day, no tangible impact is found in this case, as half of the urban pixels observe an increase in temperature while the other half observes a decrease. This may be because higher levels of sensible heat fluxes are emitted; more latent heat fluxes are also emitted throughout the day. Both full scale and realistic solar panel implementation (PV_{100}

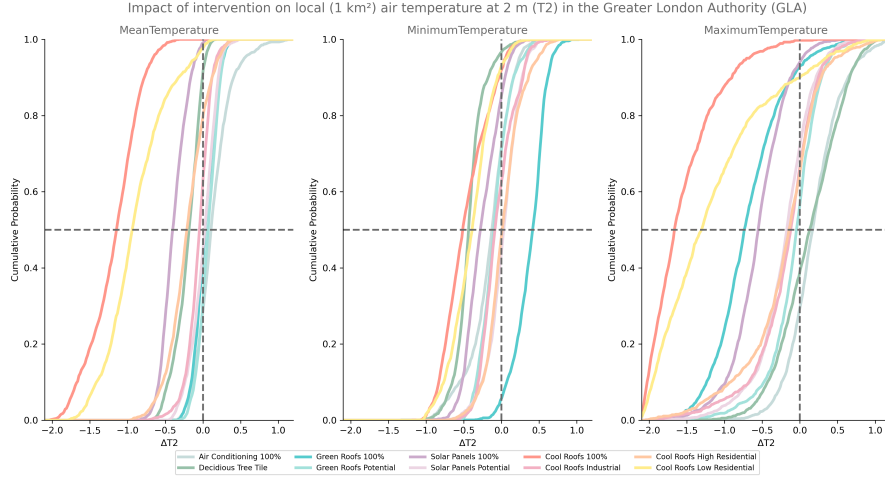


Figure 3. Cumulative distributions of change in air temperature at 2 m for different intervention scenarios. Distributions are of change relative to the reference scenario in average daily mean, daily minimum, and daily maximum 2 m air temperature across grid cells. Distributions are from 200 bin histograms, normalised to unity and based on modelled air temperature on 26th and the 27th of July 2018 in London. The horizontal dashed line indicates the median change. The vertical dashed line indicates zero change.

and PV_{pot}) behave similarly to cool roofs by decreasing the emitted sensible heat fluxes and reducing the intake of fluxes to the ground during daytime hours. The temperature reduction of up to ~ 1.0 °C, for the full-scale deployment, however, only happens during the late afternoon and the evening. At time of daily maximum temperatures, PV_{100} reduces the temperature in similar ways to GR_{100} (3 and Fig. C1 to C2).

4 Discussion

Using the WRF BEP-BEM mesoscale urban climate over the Greater London metropolitan area during the two hottest days of 2018, we performed one of the first comprehensive evaluations of the impact of building and street level interventions tailored at reducing outdoor and indoor heat on the outdoor temperature and the surface energy balance in London.

We find that interventions such as cool roofs, green roofs, rooftop solar PV, and changing natural spaces to deciduous woodland can contribute to a cooling of outdoor temperatures at hyper-local or city scales (also see Fig. C3 to C8, while widespread use of air conditioning could lead to substantial increases in outdoor temperature in the centre of London. On average, cool roofs would be the most effective way of reducing outdoor temperature at the city scale, in line with other modelling studies (Sharma et al., 2016; Yang & Bou-Zeid, 2019; Tan et al., 2023). At the maximum, this temperature reduction is between 3.2 °C and 2.8 °C at times when daily spatial average temperatures reached 33 °C and 37 °C, respectively (Fig. C2), similar to the cooling found in Phoenix and New York (Sinsal et al., 2021). In comparison, if green roofs or rooftop solar PV panels were deployed over all buildings in the Greater London area, the temperature reduction would have never reached more than ~ 1.0 °C for both days; considering that overnight, green roofs would increase the average temperature due to their increased heat-storage capacity that increases heat release at night (Tan et al., 2023). Of note, our green roofs

are modelled with sedum vegetation as they are the most common in London; other designs may lead to other effects as Zonato et al. (2021) found an increased reduction using grass-based green roofs. Conversely, we find that changing the modelled vegetation type of urban natural spaces from grasslands/croplands to deciduous trees would reduce outdoor temperatures only during the night and found mixed effects during the day, possibly due to an increase in the surface albedo which leads to an increased sensible heat emission during the day. Latent heat would also increase as expected from more evapotranspiration and would be equivalent to the increase in latent heat from green roofs deployed at full scale. Although cooling via evapotranspiration reduces air temperature, it increases water vapor in the atmosphere; this could be beneficial for avoiding water stress of vegetation but affect the heat stress from city's inhabitants and should be evaluated using a set of multiple heat stress metrics (C. H. Simpson et al., 2023).

City scale impacts of any intervention are reduced when applied to a smaller area or fewer buildings. For cool roofs, we find that although major impacts are found when applied over low-rises residential areas of London, already applying them over central mid-rises of the city could reduce the temperature in surrounding residential areas. Because of the relatively small area covered by industrial areas in London, applying cool roofs over them would only marginally contribute to a heat reduction of the city, contradictory to results in Birmingham where commercial and industrial areas cover an important part of the city centre (H. Macintyre & Heaviside, 2019). They could also be considered less effective as industrial buildings already observe higher albedo than more residential areas (Brousse et al., 2023). Cool roofs may act to reduce indoor temperatures in summer, but also potentially in winter, thus increasing winter heating demand. Therefore, it is important that they are installed in conjunction with insulation in homes (Taylor et al., 2018). However, in winter, cool roofs have less of a cooling effect outdoor temperatures than they do in summer (H. L. Macintyre et al., 2021). While we find that full application of rooftop solar PV leads to some cooling on average, realistic application, constrained by existing building characteristics, is not enough to have an appreciable effect on the temperature. Similarly, full application of sedum green roofs can reduce daytime temperatures, but the potential for retrofit of existing buildings with sedum green roofs is not enough to produce a substantial cooling effect at the city scale.

Although air conditioning would increase the outdoor temperature, it could still protect vulnerable populations from overheating indoors. Through our modelling experiment, we find that if solar panels were implemented in a realistic manner on the rooftops of existing buildings, the energy production, peaking at ~ 22.5 MW at time of higher solar incidence (11.00 UTC) and with an average production of ~ 7 MWh, would cover the energetic consumption induced by AC systems which never goes above ~ 9 MW during the hottest hours (15.00 UTC to 17.00 UTC), averaging to ~ 4.5 MWh. Under the assumption that deployment of solar panels is not constrained by existing buildings, electric power production is 75 % greater than the realistic retrofit scenario, and outdoor average temperature is reduced by ~ 0.3 °C while temperature reduction is negligible in the realistic case. This temperature reduction should be carefully interpreted as several studies have found that solar panels could heat up the surrounding environment (Sailor et al., 2021). Nonetheless, these local impacts may be dependent on many factors, including the building height and the building plan area fraction (Zonato et al., 2021), or the increase in rooftop albedo. In our case, we argue that the capture of solar radiation by the solar PVs is sufficiently important to lower the expected intake of radiation by the building and that most of it is transformed in the form of electric energy rather than in sensible heat over the roof. In the evening and at night, the low thermal capacity of solar PVs explains the higher cooling capacity of the urban environment. In any case, our results call for more investigation on this specific topic as other studies, like (Tan et al., 2023), found a small night-time increase in temperature over Chicago when implementing solar PV over buildings' roofs. Hence mechanisms explaining solar PV efficiency in our model need to be further explored.

Several limitations apply to this study. First, we used only one UCM, and another UCM may produce different results depending on its dynamics and physics (Krayenhoff et al., 2021). Second, we focused our study only over two hot summer days due to computational limitations. In general, performing such comprehensive analysis with multiple scenarios comes at high computational costs, which often prevents the generalization of the results to expected average seasonal impacts of these interventions or to other cities at similar latitudes. Third, despite the fact that the 26th and the 27th of July were extremely hot days during the summer 2018 in the United Kingdom, full clear-sky condition is absent from our model simulations, which could, for instance, partially explain why solar PV do not lead to a heating of the city during the day. Some of the results observed in this study concerning the surface energy balance may therefore simply be related to the overpass of clouds; although we did not find a particular difference in cloud coverage between our control simulation and our sensitivity tests. Fourth, as discussed above, our study only focuses on outdoor temperatures and does not consider the benefits or the detriments caused by these interventions on other aspects (e.g., biodiversity, indoor temperature, increase in relative humidity, wind circulation, etc.). Lastly, all our estimated impacts should be interpreted cautiously as the average temperature differences resulting from the interventions are smaller than the model MAE with respect to observations (Krayenhoff et al., 2021). Despite these limitations, we expect our results to be at the least indicative of which interventions are capable of producing the greatest cooling effect in London.

Notwithstanding, the outcomes of this study also have to be put in perspective against the costs related to the deployment of each of these interventions which should be weighted according to a cost-benefit analysis.

5 Conclusions

Adaptation to urban heat is of increasing priority. Our modelling study suggests that widespread adoption of cool roofs could be efficient at reducing urban temperatures, and therefore adverse health impacts, during hot spells. Rooftop solar PV may also provide a small amount of cooling as an additional benefit to power production; green roofs appear less effective in reducing temperatures but have other environmental benefits. Furthermore, relying on AC will lead to increased outdoor temperatures, despite improved thermal comfort indoors. It is reasonable to think that there will be a mixture of adaptation measures implemented across the city of London, and their applicability and impact should be further investigated. Our research is a first step towards this and will be of interest to city planners and decision-makers within the built environment sector.

6 Open Research

The simulations done in this research were performed using the WRF model v4.4 (<https://github.com/wrf-model/WRF.git>). The related outputs presented in this research and codes used to plot them are available following this DOI: 10.5281/zenodo.8333363

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OB designed the study and led the conception of the manuscript with the support of CH and CS. OB was responsible for the WRF modelling, the model evaluation and the analysis. CS provided support in the integration of green roofs and solar PV inputs into WRF. AZ implemented a spatially-explicit input of solar PV and green roofs coverages in WRF. AZ and AM offered guidance in the set-up of the WRF model v4.4 and

424 in the analysis of the outputs. JT and MD provided support in the design of the study
425 and in the acquisition of knowledge about building interventions. All authors contributed
426 to the writing of the manuscript.

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