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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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 ˜ +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.

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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 ($\sim$ -1.2 °C), outperforming green roofs ($\sim$ 0 °C), solar panels ($\sim$ -0.3 °C) and street level vegetation ($\sim$ -0.3 °C). Application of air conditioning across London increase air temperatures by $\sim$ +0.15 °CC 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 (Arbuthnott 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 example, 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 26^{th} and the 27^{th} 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 25^{th} 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 (CR_{100}); 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 (GR_{100}); 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 (PV_{100}); 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); AC_{100}); 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), VG_{100}). 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 ($T2$) 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 ∼1.2 °C going up to ∼2.0 °C in certain locations (Fig. 1 and 2). All cool roofs interventions contribute to a reduction of $T2$ 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 ∼0.15 °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 $T2$ reduction by up to ∼2 °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 ∼1 °C in large industrial areas of east-London. Compared to cool roofs, we find more minor decreases in $T2$ of ∼0.3°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 $T2$ 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 ∼1 °C and of ∼0.15 °C on average for the whole city.

By relating the change in $T2$ of all urban pixels in the GLA area to their relative SEB components we find that the large decrease in $T2$ 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 ∼30 $W{\cdot}m^{-2}$, 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 ∼5 $W{\cdot}m^{-2}$ 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

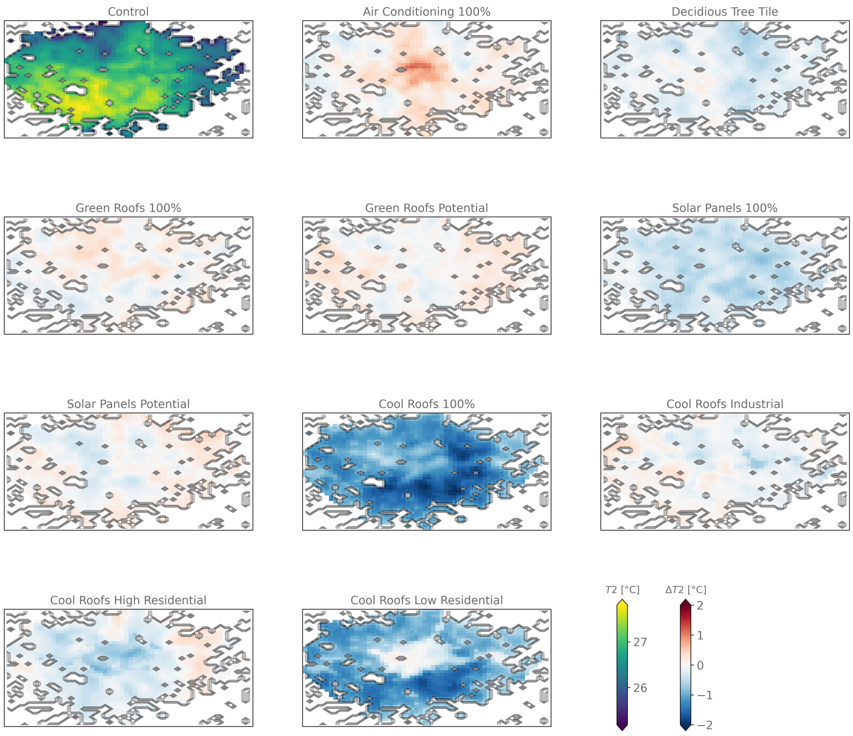

Figure 1. Average 2 m air temperature of the control run (T2; top left panel) and the average difference of each intervention (ΔT2). Grey contours are WRF urban pixels (classified as an urban LCZ).

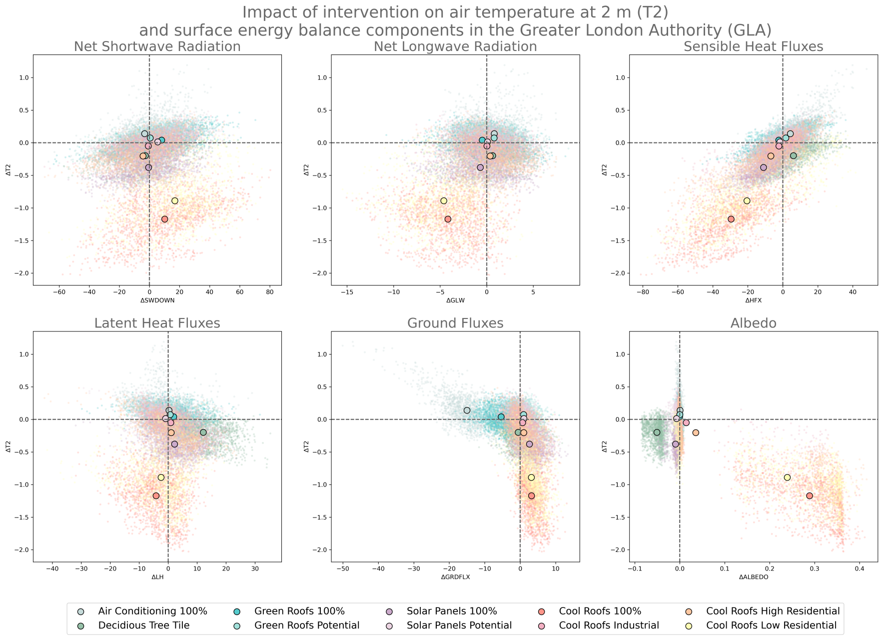

Figure 2. Time-averaged impact of each intervention on each surface energy balance component and the respective change in air temperature at 2 m for all urban pixels (small dots). Average impact is represented by the large dots.

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

Despite an increase of $T2$ induced by green roofs of less than 0.1 °C on average, hourly spatial averages of changes in $T2$ show that if green roofs were implemented across the whole city (GR_{100}), temperatures could be decreased by ∼0.5 to ∼0.8 °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 $T2$ by ∼0.5 °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 °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 °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 ∼0.8 °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}

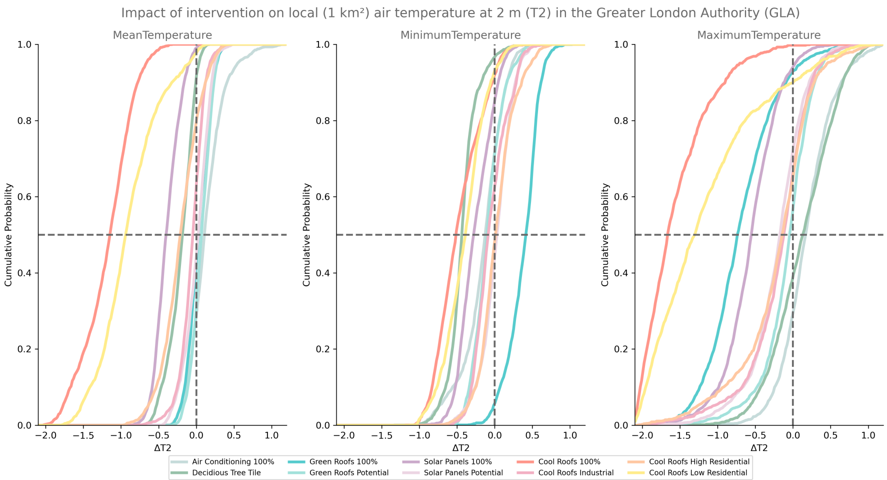

Figure 3. Cumulative distributions of change in air temperature at 2 m for different intervention scenarios. Distributions are of change relative to the reference scenario in average daily mean, daily minimum, and daily maximum 2 m air temperature across grid cells. Distributions are from 200 bin histograms, normalised to unity and based on modelled air temperature on 26^{th} and the 27^{th} 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 (Sinsel 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 $\sim$22.5 MW at time of higher solar incidence (11.00 UTC) and with an average production of $\sim$7 MWh, would cover the energetic consumption induced by AC systems which never goes above $\sim$9 MW during the hottest hours (15.00 UTC to 17.00 UTC), averaging to $\sim$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 $\sim$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 26^{th} and the 27^{th} 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

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References

Arbuthnott, K., Hajat, S., Heaviside, C., & Vardoulakis, S. (2016). Changes in population susceptibility to heat and cold over time: assessing adaptation to climate change. *Environmental Health*, *15*(1), 73–93.

Bassett, R., Janes-Bassett, V., Phillipson, J., Young, P. J., & Blair, G. S. (2021). Climate driven trends in london's urban heat island intensity reconstructed over 70 years using a generalized additive model. *Urban Climate*, *40*, 100990.

Bougeault, P., & Lacarrere, P. (1989). Parameterization of orography-induced turbulence in a mesobeta–scale model. *Monthly weather review*, *117*(8), 1872–1890.

Broadbent, A. M., Krayenhoff, E. S., & Georgescu, M. (2020). Efficacy of cool roofs at reducing pedestrian-level air temperature during projected 21st century heatwaves in atlanta, detroit, and phoenix (usa). *Environmental Research Letters*, *15*(8), 084007.

Brousse, O., Martilli, A., Foley, M., Mills, G., & Bechtel, B. (2016). Wudapt, an efficient land use producing data tool for mesoscale models? integration of urban lcz in wrf over madrid. *Urban Climate*, *17*, 116–134.

Brousse, O., Simpson, C., Kenway, O., Martilli, A., Krayenhoff, E. S., Zonato, A., & Heaviside, C. (2023). Spatially-explicit correction of simulated urban air temperatures using crowd-sourced data. *Journal of Applied Meteorology and Climatology*.

Brousse, O., Simpson, C., Walker, N., Fenner, D., Meier, F., Taylor, J., & Heaviside, C. (2022). Evidence of horizontal urban heat advection in london using six years of data from a citizen weather station network. *Environmental Research Letters*, *17*(4), 044041.

De Munck, C., Lemonsu, A., Bouzouidja, R., Masson, V., & Claverie, R. (2013). The greenroof module (v7. 3) for modelling green roof hydrological and energetic performances within teb. *Geoscientific Model Development*, *6*(6), 1941–1960.

Demuzere, M., Argüeso, D., Zonato, A., & Kittner, J. (2022). W2w: A python package that injects wudapt's local climate zone information in wrf. *Journal of Open Source Software*, *7*(76), 4432.

Fleck, R., Gill, R., Pettit, T., Torpy, F., & Irga, P. (2022). Bio-solar green roofs increase solar energy output: The sunny side of integrating sustainable technologies. *Building and Environment*, *226*, 109703.

Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., ... others (2015). Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *The lancet*, *386*(9991), 369–375.

Grassmann, T., Napoly, A., Meier, F., & Fenner, D. (2018). Quality control for crowdsourced data from cws.

Hammerberg, K., Brousse, O., Martilli, A., & Mahdavi, A. (2018). Implications of employing detailed urban canopy parameters for mesoscale climate modelling: a comparison between wudapt and gis databases over vienna, austria. *International Journal of Climatology*, *38*, e1241–e1257.

Heaviside, C., Vardoulakis, S., & Cai, X.-M. (2016). Attribution of mortality to the urban heat island during heatwaves in the west midlands, uk. *Environmental health*, *15*, 49–59.

Iungman, T., Cirach, M., Marando, F., Barboza, E. P., Khomenko, S., Masselot, P., ... others (2023). Cooling cities through urban green infrastructure: a health impact assessment of european cities. *The Lancet*, *401*(10376), 577–589.

Jones, A., & Underwood, C. (2001). A thermal model for photovoltaic systems. *Solar energy*, *70*(4), 349–359.

Krayenhoff, E. S., Broadbent, A. M., Zhao, L., Georgescu, M., Middel, A., Voogt, J. A., ... Erell, E. (2021). Cooling hot cities: a systematic and critical review of the numerical modelling literature. *Environmental Research Letters*, *16*(5), 053007.

Ma, S., Goldstein, M., Pitman, A., Haghdadi, N., & MacGill, I. (2017). Pricing the urban cooling benefits of solar panel deployment in sydney, australia. *Scientific reports*, *7*(1), 43938.

Macintyre, H., & Heaviside, C. (2019). Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a european city. *Environment international*, *127*, 430–441.

Macintyre, H. L., Heaviside, C., Cai, X., & Phalkey, R. (2021). Comparing temperature-related mortality impacts of cool roofs in winter and summer in a highly urbanized european region for present and future climate. *Environment international*, *154*, 106606.

Martilli, A., Clappier, A., & Rotach, M. W. (2002). An urban surface exchange parameterisation for mesoscale models. *Boundary-layer meteorology*, *104*, 261–304.

Masselot, P., Mistry, M., Vanoli, J., Schneider, R., Iungman, T., Garcia-Leon, D., ... others (2023). Excess mortality attributed to heat and cold: a health impact assessment study in 854 cities in europe. *The Lancet Planetary Health*, *7*(4), e271–e281.

McCarthy, M., Christidis, N., Dunstone, N., Fereday, D., Kay, G., Klein-Tank, A., ... Stott, P. (2019). Drivers of the uk summer heatwave of 2018. *Weather*, *74*(11), 390–396.

Napoly, A., Grassmann, T., Meier, F., & Fenner, D. (2018). Development and application of a statistically-based quality control for crowdsourced air temperature data. *Frontiers in Earth Science*, *6*, 118.

Nazarian, N., Krayenhoff, E., Bechtel, B., Hondula, D., Paolini, R., Vanos, J., ... others (2022). Integrated assessment of urban overheating impacts on human life. *Earth's Future*, *10*(8), e2022EF002682.

Niu, G.-Y., Yang, Z.-L., Mitchell, K. E., Chen, F., Ek, M. B., Barlage, M., ... others (2011). The community noah land surface model with multiparameterization options (noah-mp): 1. model description and evaluation with local-scale measurements. *Journal of Geophysical Research: Atmospheres*, *116*(D12).

Oke, T. R., Mills, G., Christen, A., & Voogt, J. A. (2017). *Urban climates.* Cambridge University Press.

Sailor, D., Anand, J., & King, R. (2021). Photovoltaics in the built environment: A critical review. *Energy and Buildings*, *253*, 111479.

Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., & Martilli, A. (2016). Citywide impacts of cool roof and rooftop solar photovoltaic deployment on near-surface air temperature and cooling energy demand. *Boundary-layer meteorology*, *161*, 203–221.

Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., & Wang, M. (2014). Anthropogenic heating of the urban environment due to air conditioning. *Journal of Geophysical Research: Atmospheres*, *119*(10), 5949–5965.

Salamanca, F., Krpo, A., Martilli, A., & Clappier, A. (2010). A new building energy model coupled with an urban canopy parameterization for urban climate simulations—part i. formulation, verification, and sensitivity analysis of the model. *Theoretical and applied climatology*, *99*, 331–344.

Salamanca, F., & Martilli, A. (2010). A new building energy model coupled with an urban canopy parameterization for urban climate simulations—part ii. validation with one dimension off-line simulations. *Theoretical and Applied Climatology*, *99*, 345–356.

Salamanca, F., Martilli, A., Tewari, M., & Chen, F. (2011). A study of the urban boundary layer using different urban parameterizations and high-resolution urban canopy parameters with wrf. *Journal of Applied Meteorology and Climatology*, *50*(5), 1107–1128.

Salmond, J. A., Tadaki, M., Vardoulakis, S., Arbuthnott, K., Coutts, A., Demuzere, M., ... others (2016). Health and climate related ecosystem services pro-

vided by street trees in the urban environment. *Environmental Health*, *15*(1), 95–111.
Santamouris, M., Ding, L., Fiorito, F., Oldfield, P., Osmond, P., Paolini, R., ... Synnefa, A. (2017). Passive and active cooling for the outdoor built environment–analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. *Solar Energy*, *154*, 14–33.
Scherba, A., Sailor, D. J., Rosenstiel, T. N., & Wamser, C. C. (2011). Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment. *Building and Environment*, *46*(12), 2542–2551.
Schindler, B. Y., Blaustein, L., Lotan, R., Shalom, H., Kadas, G. J., & Seifan, M. (2018). Green roof and photovoltaic panel integration: Effects on plant and arthropod diversity and electricity production. *Journal of environmental management*, *225*, 288–299.
Sharma, A., Conry, P., Fernando, H., Hamlet, A. F., Hellmann, J., & Chen, F. (2016). Green and cool roofs to mitigate urban heat island effects in the chicago metropolitan area: Evaluation with a regional climate model. *Environmental Research Letters*, *11*(6), 064004.
Simpson, C., Brousse, O., & Heaviside, C. (2022). The potential of green roofs in london. In *Egu general assembly conference abstracts* (pp. EGU22–7671).
Simpson, C. H., Brousse, O., Ebi, K. L., & Heaviside, C. (2023). Commonly used indices disagree about the effect of moisture on heat stress. *npj Climate and Atmospheric Science*, *6*(1), 78.
Sinsel, T., Simon, H., Broadbent, A. M., Bruse, M., & Heusinger, J. (2021). Modeling impacts of super cool roofs on air temperature at pedestrian level in mesoscale and microscale climate models. *Urban Climate*, *40*, 101001.
Steadman, P., Evans, S., Liddiard, R., Godoy-Shimizu, D., Ruyssevelt, P., & Humphrey, D. (2020). Building stock energy modelling in the uk: the 3dstock method and the london building stock model. *Buildings and Cities*, *1*(1), 100–119.
Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society*, *93*(12), 1879–1900.
Stone Jr, B., Mallen, E., Rajput, M., Broadbent, A., Krayenhoff, E. S., Augenbroe, G., & Georgescu, M. (2021). Climate change and infrastructure risk: Indoor heat exposure during a concurrent heat wave and blackout event in phoenix, arizona. *Urban Climate*, *36*, 100787.
Sunter, M. (2021). Midas data user guide for uk land observations, v20210705.
Tan, H., Kotamarthi, R., Wang, J., Qian, Y., & Chakraborty, T. (2023). Impact of different roofing mitigation strategies on near-surface temperature and energy consumption over the chicago metropolitan area during a heatwave event. *Science of The Total Environment*, *860*, 160508.
Taylor, J., Symonds, P., Wilkinson, P., Heaviside, C., Macintyre, H., Davies, M., ... Hutchinson, E. (2018). Estimating the influence of housing energy efficiency and overheating adaptations on heat-related mortality in the west midlands, uk. *Atmosphere*, *9*(5), 190.
UKMO. (2021). *Midas open: Uk hourly weather observation data, v202107. centre for environmental data analysis, 08 september 2021.* (data retrieved online, `https://doi.org/10.5285/3bd7221d4844435dad2fa030f26ab5fd`)
Valencia, J. F. M., Henao, J., & Saher, R. (2023). *The effect of removal of all non-functional turf in las vegas: tradeoffs between water conservation, excessive heat, and storminess* (Tech. Rep.). Copernicus Meetings.
Virk, G., Jansz, A., Mavrogianni, A., Mylona, A., Stocker, J., & Davies, M. (2014). The effectiveness of retrofitted green and cool roofs at reducing overheating in a naturally ventilated office in london: Direct and indirect effects in current

and future climates. *Indoor and Built Environment*, *23*(3), 504–520.
Yang, J., & Bou-Zeid, E. (2019). Scale dependence of the benefits and efficiency of green and cool roofs. *Landscape and urban planning*, *185*, 127–140.
Zonato, A., Martilli, A., Gutierrez, E., Chen, F., He, C., Barlage, M., … Giovannini, L. (2021). Exploring the effects of rooftop mitigation strategies on urban temperatures and energy consumption. *Journal of Geophysical Research: Atmospheres*, *126*(21), e2021JD035002.

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 ($\sim$ -1.2 °C), outperforming green roofs ($\sim$ 0 °C), solar panels ($\sim$ -0.3 °C) and street level vegetation ($\sim$ -0.3 °C). Application of air conditioning across London increase air temperatures by $\sim$ +0.15 °CC 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 (Arbuthnott 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 example, 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 26^{th} and the 27^{th} 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 25^{th} 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 (CR_{100}); 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 (GR_{100}); 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 (PV_{100}); 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); AC_{100}); 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), VG_{100}). 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 ($T2$) 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 ~1.2 °C going up to ~2.0 °C in certain locations (Fig. 1 and 2). All cool roofs interventions contribute to a reduction of $T2$ 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 ~0.15 °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 $T2$ reduction by up to ~2 °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 ~1 °C in large industrial areas of east-London. Compared to cool roofs, we find more minor decreases in $T2$ of ~0.3°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 $T2$ 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 ~1 °C and of ~0.15 °C on average for the whole city.

By relating the change in $T2$ of all urban pixels in the GLA area to their relative SEB components we find that the large decrease in $T2$ 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 ~30 $W{\cdot}m^{-2}$, 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 ~5 $W{\cdot}m^{-2}$ 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

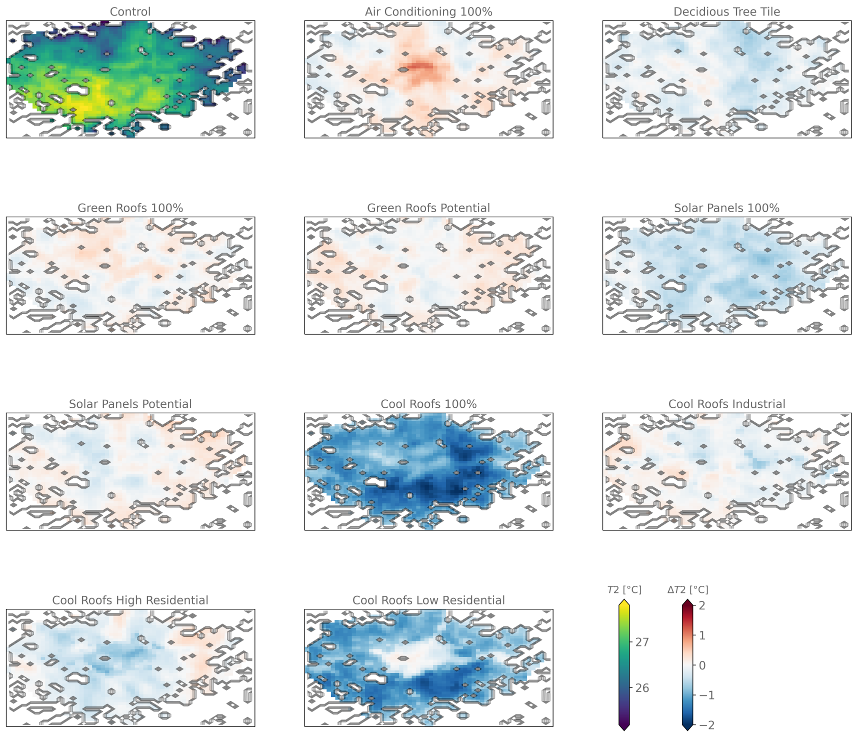

Figure 1. Average 2 m air temperature of the control run (T2; top left panel) and the average difference of each intervention (ΔT2). Grey contours are WRF urban pixels (classified as an urban LCZ).

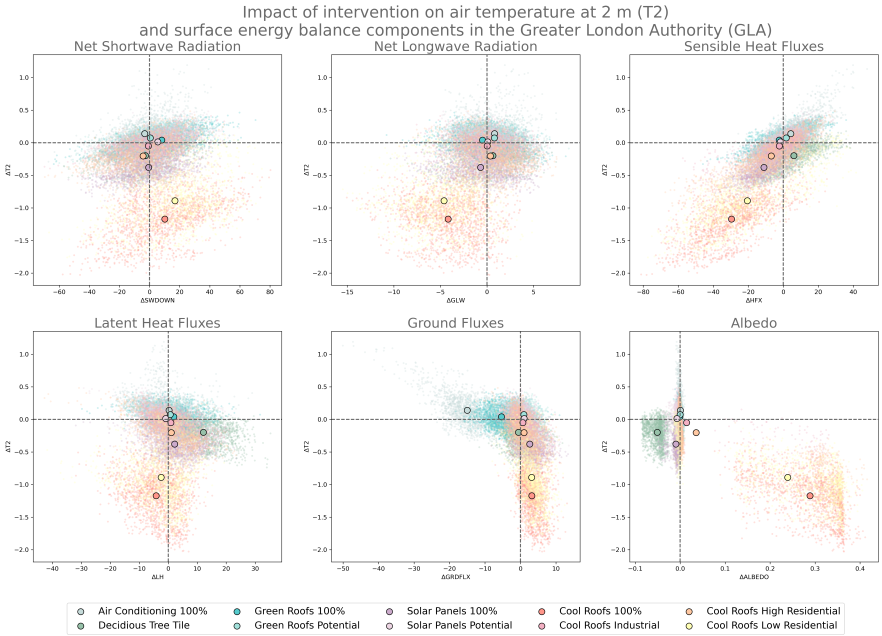

Figure 2. Time-averaged impact of each intervention on each surface energy balance component and the respective change in air temperature at 2 m for all urban pixels (small dots). Average impact is represented by the large dots.

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

Despite an increase of $T2$ induced by green roofs of less than 0.1 °C on average, hourly spatial averages of changes in $T2$ show that if green roofs were implemented across the whole city (GR_{100}), temperatures could be decreased by ∼0.5 to ∼0.8 °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 $T2$ by ∼0.5 °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 °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 °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 ∼0.8 °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}

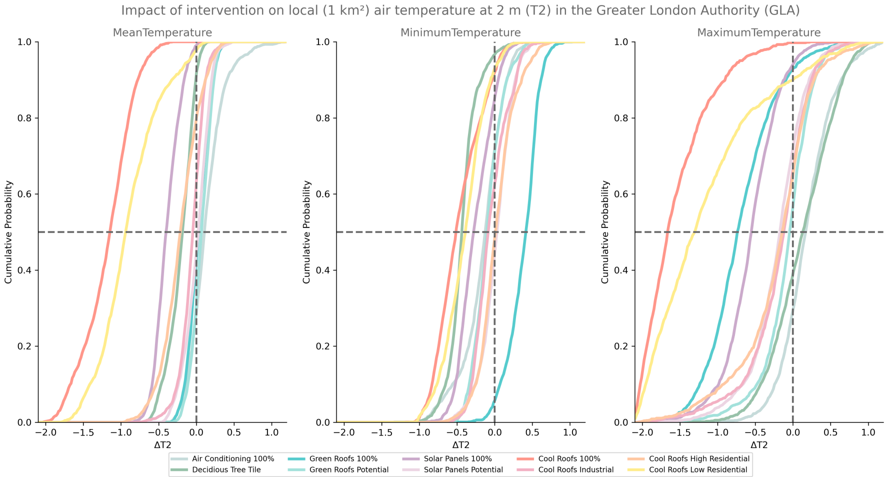

Figure 3. Cumulative distributions of change in air temperature at 2 m for different intervention scenarios. Distributions are of change relative to the reference scenario in average daily mean, daily minimum, and daily maximum 2 m air temperature across grid cells. Distributions are from 200 bin histograms, normalised to unity and based on modelled air temperature on 26^{th} and the 27^{th} 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 (Sinsel 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 26^{th} and the 27^{th} 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

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

References

Arbuthnott, K., Hajat, S., Heaviside, C., & Vardoulakis, S. (2016). Changes in population susceptibility to heat and cold over time: assessing adaptation to climate change. *Environmental Health*, *15*(1), 73–93.

Bassett, R., Janes-Bassett, V., Phillipson, J., Young, P. J., & Blair, G. S. (2021). Climate driven trends in london's urban heat island intensity reconstructed over 70 years using a generalized additive model. *Urban Climate*, *40*, 100990.

Bougeault, P., & Lacarrere, P. (1989). Parameterization of orography-induced turbulence in a mesobeta–scale model. *Monthly weather review*, *117*(8), 1872–1890.

Broadbent, A. M., Krayenhoff, E. S., & Georgescu, M. (2020). Efficacy of cool roofs at reducing pedestrian-level air temperature during projected 21st century heatwaves in atlanta, detroit, and phoenix (usa). *Environmental Research Letters*, *15*(8), 084007.

Brousse, O., Martilli, A., Foley, M., Mills, G., & Bechtel, B. (2016). Wudapt, an efficient land use producing data tool for mesoscale models? integration of urban lcz in wrf over madrid. *Urban Climate*, *17*, 116–134.

Brousse, O., Simpson, C., Kenway, O., Martilli, A., Krayenhoff, E. S., Zonato, A., & Heaviside, C. (2023). Spatially-explicit correction of simulated urban air temperatures using crowd-sourced data. *Journal of Applied Meteorology and Climatology*.

Brousse, O., Simpson, C., Walker, N., Fenner, D., Meier, F., Taylor, J., & Heaviside, C. (2022). Evidence of horizontal urban heat advection in london using six years of data from a citizen weather station network. *Environmental Research Letters*, *17*(4), 044041.

De Munck, C., Lemonsu, A., Bouzouidja, R., Masson, V., & Claverie, R. (2013). The greenroof module (v7. 3) for modelling green roof hydrological and energetic performances within teb. *Geoscientific Model Development*, *6*(6), 1941–1960.

Demuzere, M., Argüeso, D., Zonato, A., & Kittner, J. (2022). W2w: A python package that injects wudapt's local climate zone information in wrf. *Journal of Open Source Software*, *7*(76), 4432.

Fleck, R., Gill, R., Pettit, T., Torpy, F., & Irga, P. (2022). Bio-solar green roofs increase solar energy output: The sunny side of integrating sustainable technologies. *Building and Environment*, *226*, 109703.

Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., ... others (2015). Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *The lancet*, *386*(9991), 369–375.

Grassmann, T., Napoly, A., Meier, F., & Fenner, D. (2018). Quality control for crowdsourced data from cws.

Hammerberg, K., Brousse, O., Martilli, A., & Mahdavi, A. (2018). Implications of employing detailed urban canopy parameters for mesoscale climate modelling: a comparison between wudapt and gis databases over vienna, austria. *International Journal of Climatology*, *38*, e1241–e1257.

Heaviside, C., Vardoulakis, S., & Cai, X.-M. (2016). Attribution of mortality to the urban heat island during heatwaves in the west midlands, uk. *Environmental health*, *15*, 49–59.

Iungman, T., Cirach, M., Marando, F., Barboza, E. P., Khomenko, S., Masselot, P., ... others (2023). Cooling cities through urban green infrastructure: a health impact assessment of european cities. *The Lancet*, *401*(10376), 577–589.

Jones, A., & Underwood, C. (2001). A thermal model for photovoltaic systems. *Solar energy*, *70*(4), 349–359.

Krayenhoff, E. S., Broadbent, A. M., Zhao, L., Georgescu, M., Middel, A., Voogt, J. A., ... Erell, E. (2021). Cooling hot cities: a systematic and critical review of the numerical modelling literature. *Environmental Research Letters*, *16*(5), 053007.

Ma, S., Goldstein, M., Pitman, A., Haghdadi, N., & MacGill, I. (2017). Pricing the urban cooling benefits of solar panel deployment in sydney, australia. *Scientific reports*, *7*(1), 43938.

Macintyre, H., & Heaviside, C. (2019). Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a european city. *Environment international*, *127*, 430–441.

Macintyre, H. L., Heaviside, C., Cai, X., & Phalkey, R. (2021). Comparing temperature-related mortality impacts of cool roofs in winter and summer in a highly urbanized european region for present and future climate. *Environment international*, *154*, 106606.

Martilli, A., Clappier, A., & Rotach, M. W. (2002). An urban surface exchange parameterisation for mesoscale models. *Boundary-layer meteorology*, *104*, 261–304.

Masselot, P., Mistry, M., Vanoli, J., Schneider, R., Iungman, T., Garcia-Leon, D., … others (2023). Excess mortality attributed to heat and cold: a health impact assessment study in 854 cities in europe. *The Lancet Planetary Health*, *7*(4), e271–e281.

McCarthy, M., Christidis, N., Dunstone, N., Fereday, D., Kay, G., Klein-Tank, A., … Stott, P. (2019). Drivers of the uk summer heatwave of 2018. *Weather*, *74*(11), 390–396.

Napoly, A., Grassmann, T., Meier, F., & Fenner, D. (2018). Development and application of a statistically-based quality control for crowdsourced air temperature data. *Frontiers in Earth Science*, *6*, 118.

Nazarian, N., Krayenhoff, E., Bechtel, B., Hondula, D., Paolini, R., Vanos, J., … others (2022). Integrated assessment of urban overheating impacts on human life. *Earth's Future*, *10*(8), e2022EF002682.

Niu, G.-Y., Yang, Z.-L., Mitchell, K. E., Chen, F., Ek, M. B., Barlage, M., … others (2011). The community noah land surface model with multiparameterization options (noah-mp): 1. model description and evaluation with local-scale measurements. *Journal of Geophysical Research: Atmospheres*, *116*(D12).

Oke, T. R., Mills, G., Christen, A., & Voogt, J. A. (2017). *Urban climates*. Cambridge University Press.

Sailor, D., Anand, J., & King, R. (2021). Photovoltaics in the built environment: A critical review. *Energy and Buildings*, *253*, 111479.

Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., & Martilli, A. (2016). Citywide impacts of cool roof and rooftop solar photovoltaic deployment on near-surface air temperature and cooling energy demand. *Boundary-layer meteorology*, *161*, 203–221.

Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., & Wang, M. (2014). Anthropogenic heating of the urban environment due to air conditioning. *Journal of Geophysical Research: Atmospheres*, *119*(10), 5949–5965.

Salamanca, F., Krpo, A., Martilli, A., & Clappier, A. (2010). A new building energy model coupled with an urban canopy parameterization for urban climate simulations—part i. formulation, verification, and sensitivity analysis of the model. *Theoretical and applied climatology*, *99*, 331–344.

Salamanca, F., & Martilli, A. (2010). A new building energy model coupled with an urban canopy parameterization for urban climate simulations—part ii. validation with one dimension off-line simulations. *Theoretical and Applied Climatology*, *99*, 345–356.

Salamanca, F., Martilli, A., Tewari, M., & Chen, F. (2011). A study of the urban boundary layer using different urban parameterizations and high-resolution urban canopy parameters with wrf. *Journal of Applied Meteorology and Climatology*, *50*(5), 1107–1128.

Salmond, J. A., Tadaki, M., Vardoulakis, S., Arbuthnott, K., Coutts, A., Demuzere, M., … others (2016). Health and climate related ecosystem services pro-

vided by street trees in the urban environment. *Environmental Health*, *15*(1), 95–111.
Santamouris, M., Ding, L., Fiorito, F., Oldfield, P., Osmond, P., Paolini, R., ... Synnefa, A. (2017). Passive and active cooling for the outdoor built environment–analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. *Solar Energy*, *154*, 14–33.
Scherba, A., Sailor, D. J., Rosenstiel, T. N., & Wamser, C. C. (2011). Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment. *Building and Environment*, *46*(12), 2542–2551.
Schindler, B. Y., Blaustein, L., Lotan, R., Shalom, H., Kadas, G. J., & Seifan, M. (2018). Green roof and photovoltaic panel integration: Effects on plant and arthropod diversity and electricity production. *Journal of environmental management*, *225*, 288–299.
Sharma, A., Conry, P., Fernando, H., Hamlet, A. F., Hellmann, J., & Chen, F. (2016). Green and cool roofs to mitigate urban heat island effects in the chicago metropolitan area: Evaluation with a regional climate model. *Environmental Research Letters*, *11*(6), 064004.
Simpson, C., Brousse, O., & Heaviside, C. (2022). The potential of green roofs in london. In *Egu general assembly conference abstracts* (pp. EGU22–7671).
Simpson, C. H., Brousse, O., Ebi, K. L., & Heaviside, C. (2023). Commonly used indices disagree about the effect of moisture on heat stress. *npj Climate and Atmospheric Science*, *6*(1), 78.
Sinsel, T., Simon, H., Broadbent, A. M., Bruse, M., & Heusinger, J. (2021). Modeling impacts of super cool roofs on air temperature at pedestrian level in mesoscale and microscale climate models. *Urban Climate*, *40*, 101001.
Steadman, P., Evans, S., Liddiard, R., Godoy-Shimizu, D., Ruyssevelt, P., & Humphrey, D. (2020). Building stock energy modelling in the uk: the 3dstock method and the london building stock model. *Buildings and Cities*, *1*(1), 100–119.
Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society*, *93*(12), 1879–1900.
Stone Jr, B., Mallen, E., Rajput, M., Broadbent, A., Krayenhoff, E. S., Augenbroe, G., & Georgescu, M. (2021). Climate change and infrastructure risk: Indoor heat exposure during a concurrent heat wave and blackout event in phoenix, arizona. *Urban Climate*, *36*, 100787.
Sunter, M. (2021). Midas data user guide for uk land observations, v20210705.
Tan, H., Kotamarthi, R., Wang, J., Qian, Y., & Chakraborty, T. (2023). Impact of different roofing mitigation strategies on near-surface temperature and energy consumption over the chicago metropolitan area during a heatwave event. *Science of The Total Environment*, *860*, 160508.
Taylor, J., Symonds, P., Wilkinson, P., Heaviside, C., Macintyre, H., Davies, M., ... Hutchinson, E. (2018). Estimating the influence of housing energy efficiency and overheating adaptations on heat-related mortality in the west midlands, uk. *Atmosphere*, *9*(5), 190.
UKMO. (2021). *Midas open: Uk hourly weather observation data, v202107. centre for environmental data analysis, 08 september 2021.* (data retrieved online, `https://doi.org/10.5285/3bd7221d4844435dad2fa030f26ab5fd`)
Valencia, J. F. M., Henao, J., & Saher, R. (2023). *The effect of removal of all non-functional turf in las vegas: tradeoffs between water conservation, excessive heat, and storminess* (Tech. Rep.). Copernicus Meetings.
Virk, G., Jansz, A., Mavrogianni, A., Mylona, A., Stocker, J., & Davies, M. (2014). The effectiveness of retrofitted green and cool roofs at reducing overheating in a naturally ventilated office in london: Direct and indirect effects in current

and future climates. *Indoor and Built Environment*, *23*(3), 504–520.
Yang, J., & Bou-Zeid, E. (2019). Scale dependence of the benefits and efficiency of green and cool roofs. *Landscape and urban planning*, *185*, 127–140.
Zonato, A., Martilli, A., Gutierrez, E., Chen, F., He, C., Barlage, M., … Giovannini, L. (2021). Exploring the effects of rooftop mitigation strategies on urban temperatures and energy consumption. *Journal of Geophysical Research: Atmospheres*, *126*(21), e2021JD035002.

Appendix A Model parameterization for interventions

In this study, the model parameterization follows exactly the same as in Brousse et al. (2023). This means that the model is run at a resolution of 1 x 1 km with 210 by 180 horizontal grid points and 71 vertical layers nested in two other domains run at 12 and 3 km, respectively, and forced by ERA5 6-hourly data at 25 km horizontal resolution. We supplement the version 4.3 to the more recent 4.4.1 to benefit for certain bug fixes; these did not relate to the urban scheme. Of importance, sea surface temperatures are updated every 6 hours out of ERA5, no lake models are activated for inland water bodies, and initial land surface conditions are provided by the default MODIS 5-arc-second land use data set. The latter are further interpolated by the Noah-MP land surface model (Niu et al., 2011) in its default parameterization over 4 soil layers. Building effects on the local climate are calculated by activating the BEP-BEM models (Martilli et al., 2002; Salamanca et al., 2010; Salamanca & Martilli, 2010) which calculates energy fluxes within the urban tile of each grid points – given by the urban fraction. Changes in urban vegetation like in VG_100 are therefore only treated by Noah-MP within the natural tile of grid points where the urban fraction is not null. Fluxes are then averaged at the bulk level to estimate prognostic variables at the each grid point (e.g., air temperature). We chose to use the common Bougeault-Lacarrère planetary boundary layer scheme for these simulations (Bougeault & Lacarrere, 1989). More information on the physical parameterization and on the buildings' thermal and radiative properties can be found in Brousse et al. (2023) under the section 2.a.

The impact of the air conditioning in BEP-BEM is estimated by means of a simple Building Energy Module (BEM). This module computes an energy budget of the indoor air by considering the heat generated by people and equipment, the diffusion of heat through walls and roof, the air infiltration/ventilation, and the radiation entering through the windows. When the indoor air temperature reaches maximum value fixed by the user, the internal temperature is kept constant, and all the extra heat (Hsneed) is ejected to the atmosphere. In addition to the atmosphere is added also the heat generated by the A.C. equipments to do the work ($Hsneed/COP$, where COP is the Coefficient of performance of the A.C. system). In the same way the energy consumption due to the A.C: is estimated as $Hsneed/COP$. In our AC_100 simulations, all buildings are equipped with AC systems running with a COP of 3.5 and a target temperature of 294.15 K. More details can be found in Salamanca et al. (2010); Salamanca and Martilli (2010).

The roof mitigation strategies parameterizations are based on the work of Zonato et al. (2021). The land-surface scheme for green roofs has been developed based on De Munck et al. (2013). It calculates energy and water budgets, taking into account incoming net radiation, water input from precipitation and irrigation (the latter considered as irrigation at the green roof surface), evapotranspiration from vegetation, heat exchange with the atmosphere, and diffusion of energy and moisture throughout the soil. A green roof consists of 10 layers with a total depth of 0.3 m, 5 of them represents the vegetation and the soil substrates, while the rest the underlying roof, including the waterproof membrane. The kind of vegetation present in the upper level is parameterized depending on leaf area index and maximum stomatal resistance.

The parameterization taking into account the effects of RPVPs assumes the photovoltaic arrays to be parallel and detached from roofs and composed of a single layer, and it is based on the work of Jones and Underwood (2001). A photovoltaic panel is assumed to be detached from the roof, and to composed of three layers, as in: a monocrystalline silicon PV cell, a polyester trilaminate and a glass face, with a total depth of 6.55 mm. The prognostic equation of its temperature, that is necessary for calculating the incoming/outgoing heat fluxes, considers: 1) The net incoming short- and long-wave radiation at both surfaces of the photovoltaic panel, assuming a view factor for the bottom surface depending on the area covered by the photovoltaic panel and on its distance to the underlying roof; 2) The heat fluxes dependent on wind speed and temperature differences between the panel and the air (Scherba et al., 2011); 3) The energy produced by the PV cell, dependent on its efficiency and on the PV temperature itself.

The standard WRF version 4.4.1 has been appropriately modified in order to consider a grid-specific ratio of green roof or photovoltaic panels independent of the LCZ, thus independent of look-up tables.

Appendix B Observational Data and Model Evaluation

The model evaluation was performed following the strategy described in Brousse et al. (2023) and uses the same data set. Briefly put, personal weather station air temperature measurements from the *Netatmo* company are gathered using an open API. Each personal weather station's data undergoes a statistical quality-check to ensure that the quality of the measurement is sufficient to perform urban climate studies and model evaluation (Napoly et al., 2018). These crowd-sourced measurements complement the official weather stations measurements coming from the UK MetOffice MIDAS network (UKMO, 2021). Hammerberg et al. (2018) and Brousse et al. (2023) indeed demonstrated that crowd-sourced weather data are beneficial for evaluating urban climate simulations and we therefore decided to take advantage of them in this study too. More information on the data gathering and treatment can be found in Brousse et al. (2023) and related codes can be found following `https://github.com/oscarbrousse/JAMC_BiasCorrection_PWS/`.

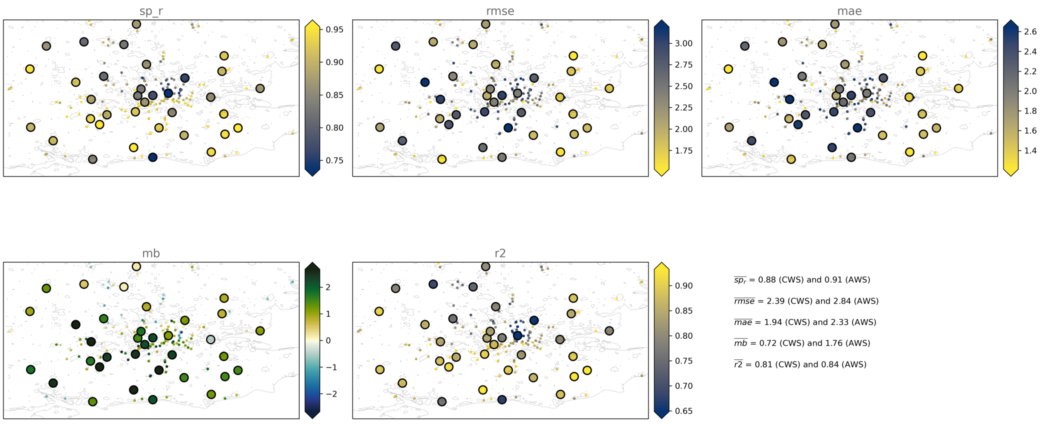

Figure B1. Model evaluation against Netatmo personal citizen weather stations (CWS, small dots) and MIDAS official automatic weather stations (AWS, big dots). Yellow is better. For MB white is the better. Average scores amongst all stations are given in the bottom right.

Appendix C Additional Figures

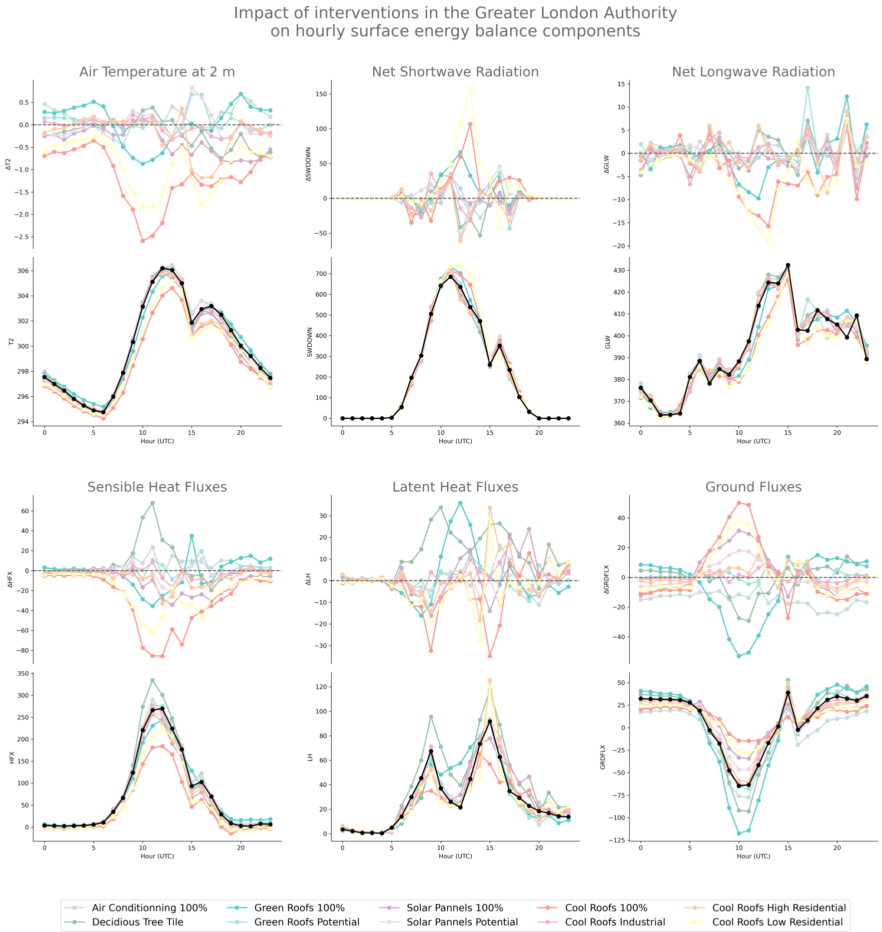

Figure C1. Diurnal cycles of spatially average air temperature at 2 m and of each surface energy balance component (lower panels) and their respective differences (control - intervention; upper panels) over GLA . The black solid line is the control run, the interventions' colors are given in the legend. The dashed grey line represents a null change between the control and the intervention run.

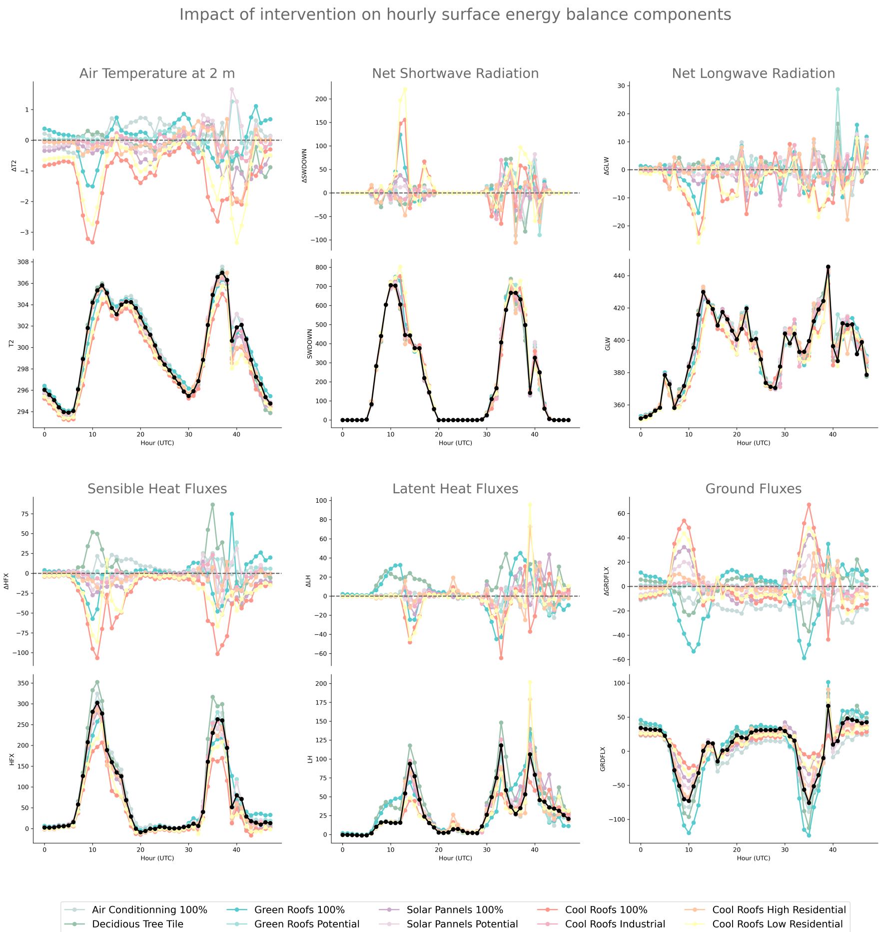

Figure C2. Same as Fig. C1 but without hourly averaging (for the two full days)

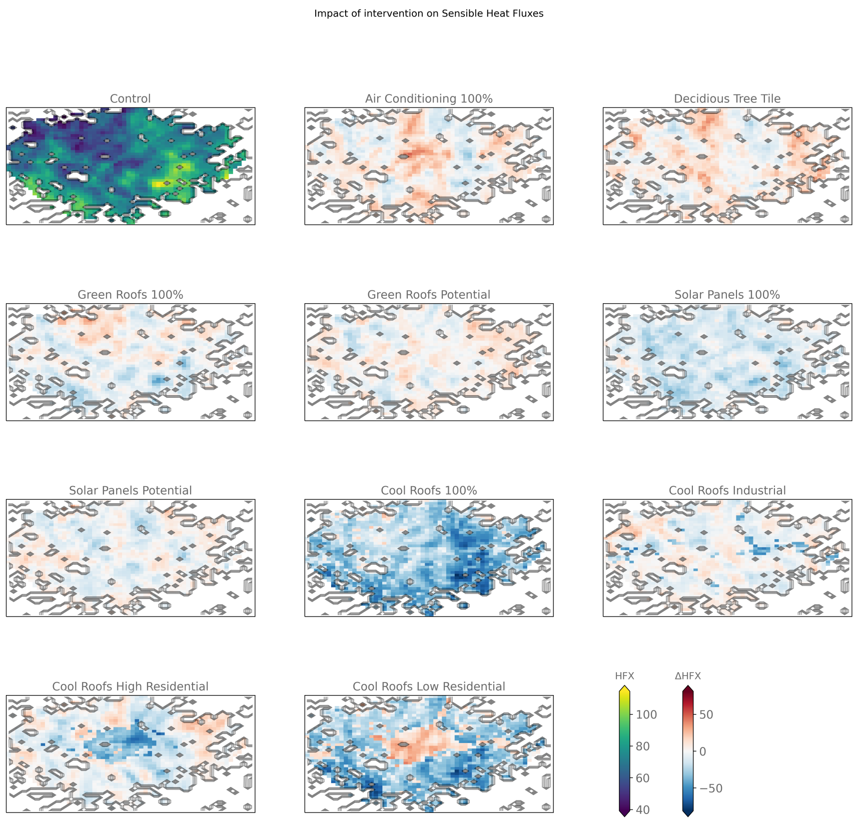

Figure C3. Same as Fig. 1 but for sensible heat fluxes

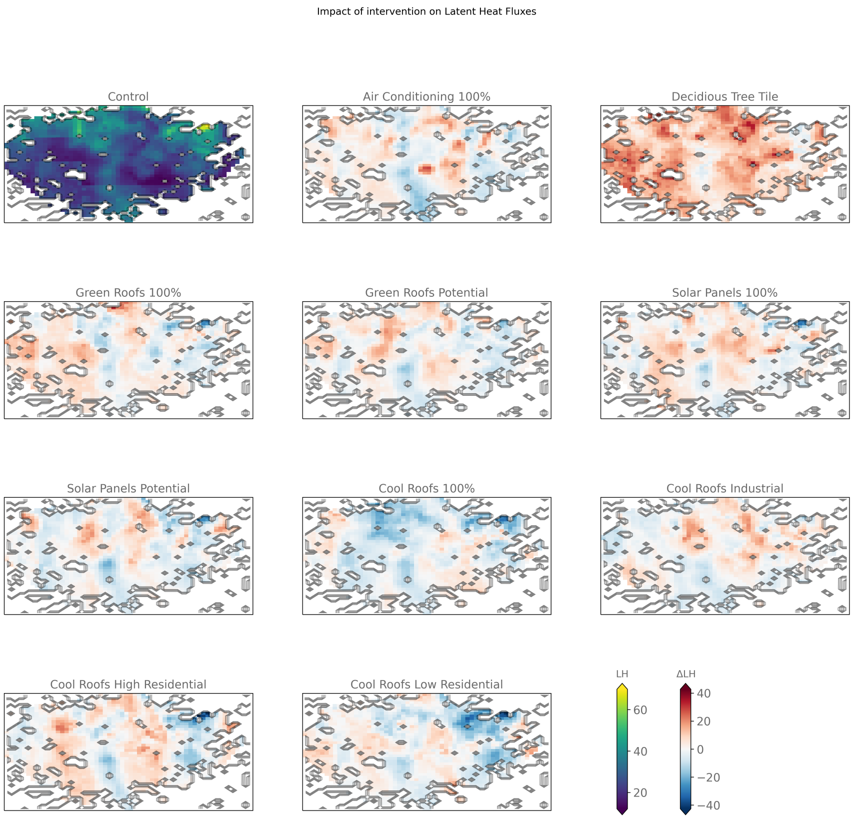

Figure C4. Same as Fig. 1 but for latent heat fluxes

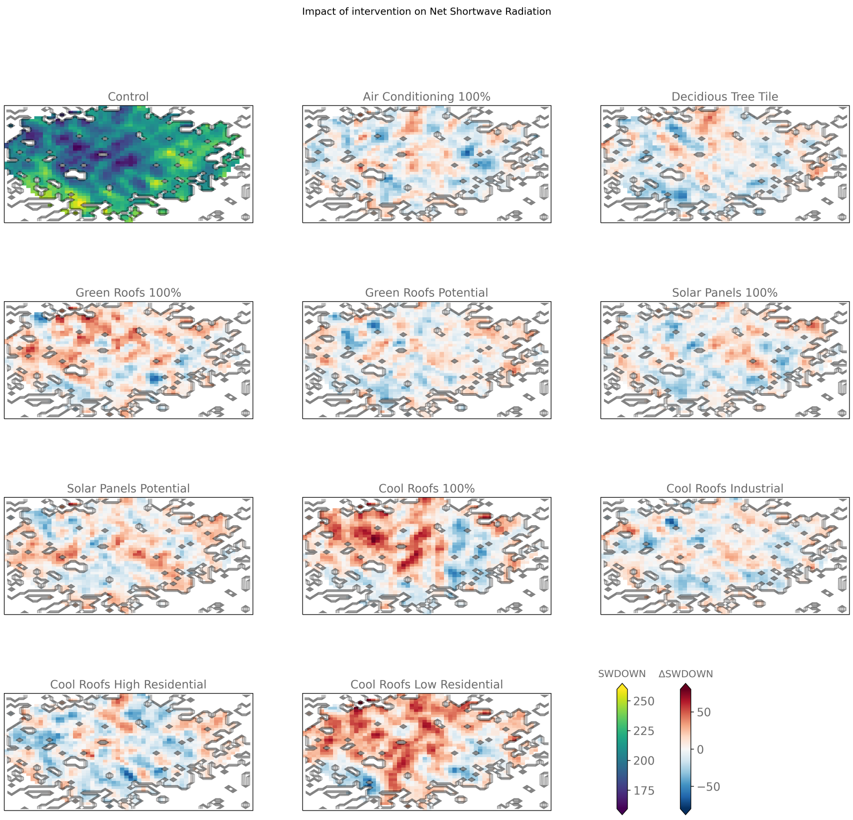

Figure C5. Same as Fig. 1 but for net incoming short-wave solar radiation

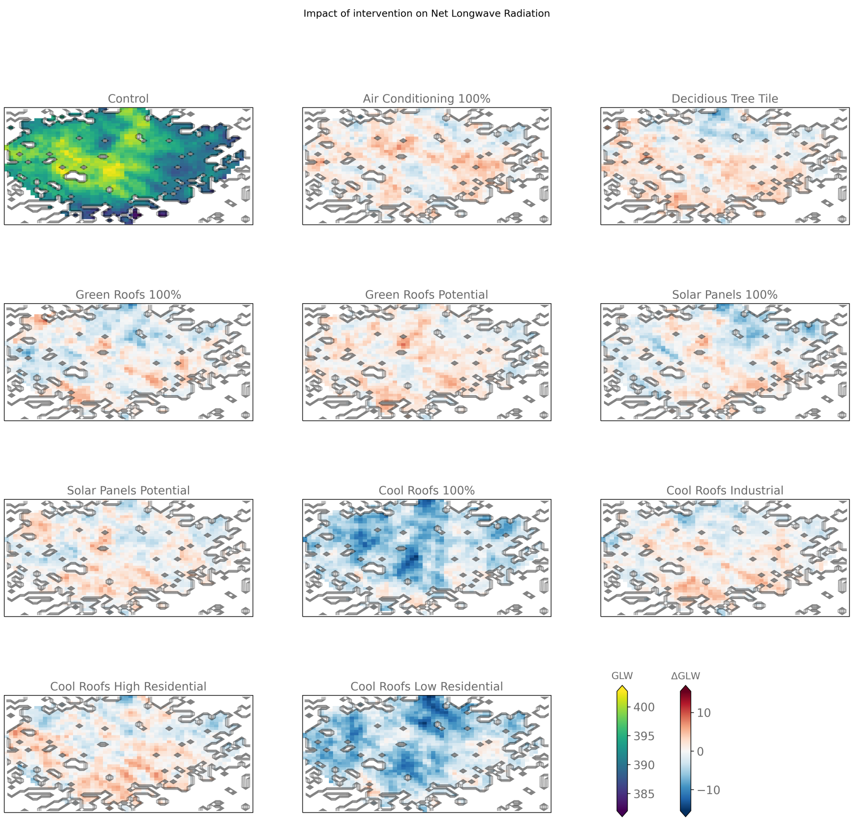

Figure C6. Same as Fig. 1 but for net incoming long-wave radiation

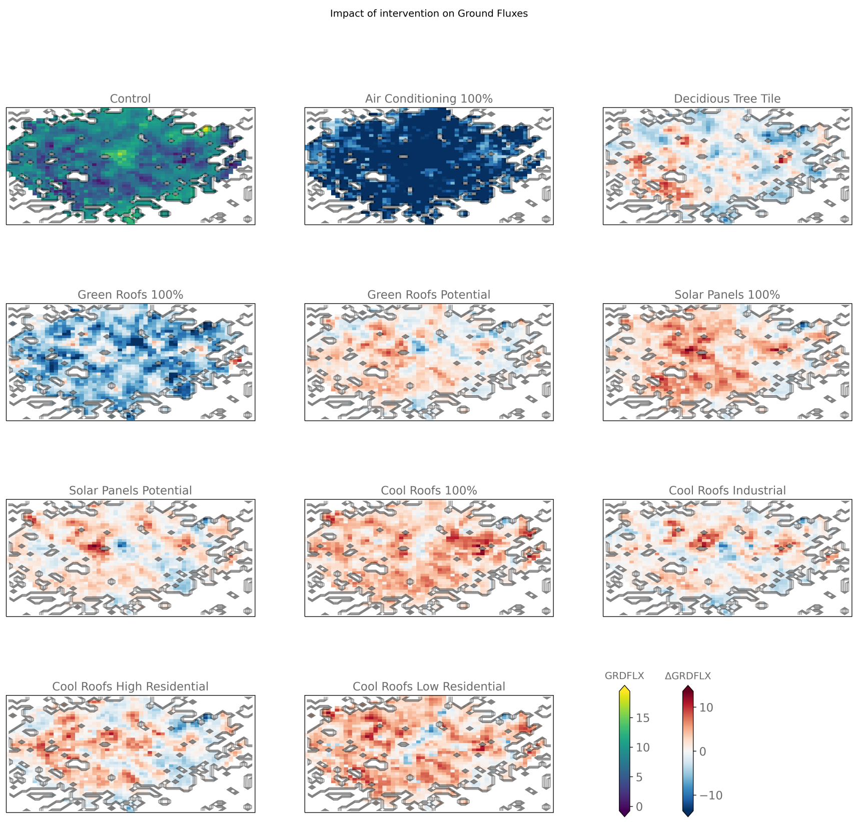

Figure C7. Same as Fig. 1 but for ground fluxes

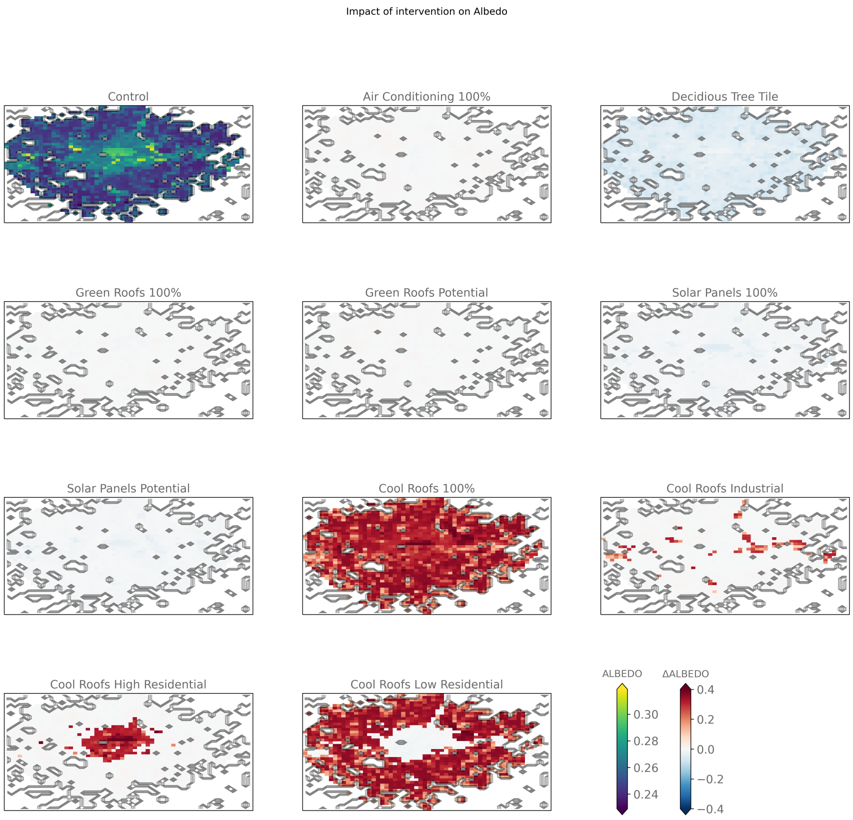

Figure C8. Same as Fig. 1 but for albedo