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Microclimatic performance of greening against urban overheating: a multiseasonal analysis using in-situ monitoring and satellite data

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ABSTRACT

Green-blue infrastructure (GBI) is increasingly promoted as a nature-based solution for mitigating urban overheating and managing heatwave events, highlighting the need for long-term monitoring evidence to support its effective implementation. This study compares cooling contrasts observed at six monitored GBI sites – woodland, lakeside, grassland, pocket park, riverside, and green wall – relative to a selected built-up reference site, using a three-year in-situ sensor network integrated with satellite-derived Land Surface Temperature (LST) data. The largest summer air temperature contrasts relative to the built-up reference during peak hours (12:00–16:00 h) were observed at the woodland, grassland, and lakeside sites, ranging from 2.1 to 2.5 °C. During the same period, air temperature contrasts of 2.1 °C were observed at the pocket park and riverside sites, while the contrast at the green wall was 1.8 °C. Satellite-based mean summer LST provided a complementary surface thermal perspective, revealing pronounced spatial contrasts, with the largest reductions observed at the woodland and lakeside extraction areas. During peak temperature events, cooling benefits declined across all GBI sites. Air temperature contrasts between the monitored GBI sites and the built-up reference varied across regional wind regimes, with contrasts at the woodland, grassland, and lakeside sites generally remaining within 2–3 °C, while greater variability was observed at the smaller monitored GBI sites. Over the three-year study period, the built-up reference recorded the highest heatwave threshold occurrence (19.6% of the summer period), while considerably lower occurrences were recorded across the monitored GBI sites (0.0–8.7%). This study provides long-term microclimatic evidence on the capacity of selected GBI settings to buffer high ambient temperatures. Although no direct epidemiological or individual exposure assessment was conducted, the observed reductions in high ambient temperatures, particularly during daytime heat peaks, provide policy-relevant microclimatic evidence for urban heat-health adaptation.

1. Introduction

Urbanisation has resulted in rapid city expansion, causing elevated temperatures in urban areas that pose significant challenges to urban residents (Kumar et al., 2024). As climate change exacerbates these heat-related issues, the need for effective cooling strategies in urban areas becomes more evident. Heatwaves represent intense episodes of elevated temperatures and humidity, influenced by regional climate variations and triggered by high-pressure systems in summer (Sahani et al., 2023; Kumar, 2021). These extreme weather events are becoming increasingly probable due to climate change and are expected to escalate

with rising greenhouse gas concentrations. In recent years, heat-related impacts have intensified even in temperate climates, highlighting the growing vulnerability of cities traditionally considered thermally moderate. The UK all-time maximum temperature of 40.3 °C was recorded at Coningsby, Lincolnshire, in July 2022 (Met Office, 2025). In this context, a heatwave is characterised as a period during which maximum temperatures surpass a specific threshold for a minimum of three consecutive days. This threshold varies among regions and in the UK is determined based on the climatology of daily maximum temperature from 1991 to 2020, specifically on July 15, which marks the midpoint of the meteorological summer (Met Office, 2025).

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Urban overheating is an important environmental health concern because prolonged exposure to high ambient temperature increases the risks of heat stress, cardiovascular and respiratory strain, heat-related morbidity and mortality, and reduced physiological recovery during warm nights. GBI may therefore provide an indirect public health benefit by reducing local heat exposure and buffering extreme thermal conditions. However, microclimatic cooling evidence should not be interpreted as direct evidence of health-risk reduction unless linked to population exposure, vulnerability and health-outcome data. Understanding the cooling benefits provided by various green and blue infrastructure (GBI) types is critical for creating sustainable and resilient urban development plans (Kumar et al., 2025; Khalili et al., 2026).

Previous studies have evaluated the cooling benefits of various GBIs across different climatic and urban contexts. Ouyang et al. (2021) evaluated the microclimatic cooling contrast of three GBI typologies within a single site, in addition to comparing their thermal irradiance performance across four typical summer days in Hong Kong (Ouyang et al., 2021). Herath et al. (2018) conducted a field assessment and simulation study in tropical Colombo, Sri Lanka, examining the cooling effects of tree curbsides, green roofs, green walls, and a combination of these GBIs. The results revealed that the combination of all options was the most effective strategy for temperature reduction, followed by trees along curbsides and green walls (Herath et al., 2018). Jia and Wang (2021) evaluated cooling strategies in a typical high-density urban area in Hong Kong, highlighting the benefits of street trees in reducing both air temperature and mean radiant temperature compared with other urban cooling strategies, which reduced air temperature but increased mean radiant temperature. Nature-based solutions for urban heat mitigation in historical blocks of Beijing, China, were investigated by simulating five different scenarios, concluding that selecting appropriate GBIs can reduce air temperature by 1.01 °C (Su et al., 2022).

Through assessing different GBI scenarios for Guildford, UK, Tiwari

et al. (2021) concluded that trees are more effective than grasslands in reducing the urban heat island intensity. Ziaul and Pal (2020) examined the implications of GBI for improving microclimatic conditions to evaluate the most suitable mitigation strategy for West Bengal, India. They evaluated the GBI cooling effect in different urban areas, finding that the effect of each GBI type varied across urban settings, and they concluded that the combination of all strategies was the most effective scenario for reducing UHI intensity (Ziaul and Pal, 2020). Marando et al. (2019) carried out a study to assess the cooling capacity and ecosystem services of multiple GBI types in Rome, Italy. The results clarified that the cooling capacity of GBI depended on the GBI element (Marando et al., 2019). Through evaluating the effects of six different GBI interventions on ambient temperatures across Portland, Makido et al. (2019) reported inconsistent cooling outcomes across different landscapes, highlighting the need for site-specific heat mitigation strategies.

Many studies have shown that re-integrating GBIs into urban landscapes is an effective climate mitigation and adaptation strategy (Table 1). However, the influence of GBIs on temperature regulation varies greatly depending on GBI type, species, and urban morphology (Chen et al., 2022; Lau et al., 2012; Morakinyo et al., 2020; Qiu et al., 2017). Imran et al. (2019) evaluated the effectiveness of multiple urban vegetation patches in Melbourne during one of the most severe heat-wave events, concluding that a larger fraction of vegetated patches reduced UHI intensity at night but did not affect near-surface temperature during the hottest time of the day. Wang et al. (2021) found that increasing the green cover by 10% through the addition of street trees and a grove reduced the UHI intensity in Guangzhou, whereas adding a green roof aggravated it. The evaluation of GBIs and urban settings as complex dynamic systems in Sydney, Australia, confirmed the effect of GBI on LST reduction in both summer and winter, while the results showed an increase of nocturnal LST throughout the year (Bartasaghi-Koc et al., 2022). Collectively, these findings demonstrate that the

Table 1

Summary of previous studies examining the cooling benefits of various GBI types across different climatic contexts. The table presents the type of GBI, study location, climate classification, cooling benefit magnitude, and other key findings.

Method	GBI type	Location (climate type*)	Cooling benefit	Reference
Modelling	Park	Ahmedabad, India (BSh)	The presence of a large central park and partial use of reflective pavements reduced peak canopy air temperature by 0.16 to 0.33 °C.	Nagar et al. (2025)
Field measurement	Trees	Roorkee, India (Cwa)	Different tree species showed variation in cooling benefit, with the highest cooling effect of 3 °C occurring during morning hours.	Manavvi and Milosevic (2025)
Remote sensing	Trees, grassland	Zvolen, Slovakia (Dfb)	The large green tree spaces and grasslands provided LST cooling intensity of up to 6 °C and 2 °C, respectively.	Gallay et al. (2023)
Field measurement	Woodland, waterbody, grassland	Guildford, UK (Cfb)	The results showed that woodland, grassland and waterbody provided cooling benefits of up to 5.2 °C, 4.5 °C, and 4.4 °C during the summer period, respectively.	Sahani et al. (2023)
Remote sensing	Urban greenery	Xalapa, Mexico (Cfb, Cfa)	Green spaces larger than 2 ha mitigated the UHI intensity by 2 °C, depending on shape and surrounding tree cover percentage.	Lemoine-Rodríguez et al. (2022)
Remote sensing	Parks	Wuhan, China (Cfa)	The average cooling effect of 54 parks was 3.5 ± 0.2 °C, ranging from 0.5 °C to 6.8 °C.	Chen et al. (2022)
Modelling	Green roof	Berlin, Germany (Cfb)	The green roof lowered daytime air temperature by 0.71 °C and by 0.26 °C during nighttime.	Wang et al. (2022)
Field measurement	Green roof, green wall, tree	Hong Kong (Cwa)	Trees had the highest air temperature reduction (0.21 °C to 0.73 °C), followed by green roof and green wall.	Ouyang et al. (2021)
Field measurement	Urban parks	Beijing, China (Dwa)	Average daytime and nighttime park cool intensity were 1.09 °C and 3.63 °C, respectively.	Li et al. (2021)
Modelling	Green roof, grassland, trees	Guildford, UK (Cfb)	Temperature reductions were up to 1 °C in the presence of GBI at the city scale compared with the no GBI scenario.	Tiwari et al. (2021)
Modelling	Street trees	Erzurum, Turkey (Dsb)	The air temperature of the green street scenario was 1 °C cooler than the existing condition.	Yilmaz et al. (2021)
Remote sensing and modelling	Green roof, green wall	West Bengal, India (Am)	Different GBI strategies reduced the air temperature between 1.3 °C and 2.6 °C.	Ziaul and Pal (2020)
Modelling	Trees and grass, green roof	Portland, Oregon (Csb)	The air temperature decreased up to 2.6 °C while the combination scenario resulted in an average temperature decrease of over 3 °C.	Makido et al. (2019)
Field measurement and modelling	Greenway, green roof, grove	Shenzhen, China (Cwa)	The trees lowered the daily mean air temperature by 0.2 °C, and the maximum reduction can reach up to 2.2 °C during specific hours of the hottest days.	Wang et al. (2019)
Field measurement and modelling	Tree curbsides, green roof, green wall	Colombo, Sri Lankan (Af)	Comparing different GBI scenarios with existing scenarios revealed that GBI scenarios can reduce the temperature up to 1.9 °C.	Herath et al. (2018)
Field measurement	Trees	Hong Kong (Cwa)	The temperature reduction effect generated by the tree was 0.6 °C, reaching a maximum of 2.1 °C.	Cheung and Jim (2018)

cooling performance of GBIs is highly context-dependent, with effectiveness varying across typologies, scales, and implementation strategies.

Other studies further highlight the variability of GBI cooling effectiveness. In Wuhan, China, some GBI types exhibited no cooling effect, whereas others achieved LST reductions of up to 10 °C (Chen et al., 2022). Therefore, although some studies recommend the most effective GBI types for different climates, GBI selection remains highly dependent on local climatic conditions, soil features, and water availability in addition to some social behaviour in terms of community and cultural norms (Bowler et al., 2010; Norton et al., 2015; Pataki et al., 2011). In the absence of robust, context-specific evidence, GBI implementation may result in suboptimal or even counterproductive outcomes for urban heat mitigation.

GBI contributes to enhancing urban environmental conditions; for example, each additional urban tree has been estimated to offset the heat exposure of one heat-sensitive individual (Venter et al., 2020). The cooling effectiveness of GBIs is strongly linked to pre-existing urban surface conditions, GBI type and configuration, and intervention intensity (Abdulateef et al., 2022). Cooling benefits vary across climate types, with the largest reported reductions (up to 12°C) occurring in hot and dry climates (Huang et al., 2022). Nevertheless, nearly 40% of the global urban population does not currently benefit from GBI-induced microclimatic regulation (Marando et al., 2022), emphasising the urgency of evidence-based GBI planning.

Despite the extensive body of research on GBI cooling benefits, several key gaps remain. First, most existing studies focus on single seasons, typologies, short monitoring periods, or isolated heat events, limiting understanding of the temporal robustness of GBI cooling across multiple years. Second, systematic comparisons across multiple GBI typologies within the same urban setting remain scarce, particularly in temperate climates. Third, many studies assess average thermal conditions, while far fewer explicitly examine GBI performance during extreme heat and heatwave events, when cooling is most urgently needed. Finally, the diurnal persistence of cooling – especially the ability of GBIs to mitigate nocturnal heat stress – remains poorly quantified, despite its critical importance for human health and recovery during heatwaves.

This study addresses these gaps through a multi-year assessment of air temperature dynamics at six monitored GBI sites (woodland, lakeside, grassland, pocket park, riverside, and green wall) relative to a selected built-up reference site. Seasonal, diurnal, and heatwave-focused analyses were used to characterise air temperature contrasts and their variation under extreme thermal stress. The study combines in-situ air temperature measurements with Landsat-derived LST data to provide complementary near-surface and surface temperature perspectives. It further examines whether site-level temperature contrasts vary across regional background wind regimes, thereby providing broader meteorological context for the observed patterns. By considering daytime and nighttime cooling, extreme heat events, and regional wind conditions, this work offers a framework for interpreting thermal conditions across the monitored settings in temperate urban environments.

The primary objective of this paper is to quantify and compare site-level microclimatic temperature contrasts between six monitored GBI sites and the selected built-up reference site in Guildford, UK. Specifically, the study aims to: (i) characterise seasonal and diurnal air temperature variations across the GBI monitored sites; (ii) quantify GBI-reference temperature contrasts under typical summer conditions; and (iii) examine how these contrasts vary during heatwave events, including both daytime and nighttime periods.

2. Methodology

2.1. Study design

This study was designed to evaluate and compare microclimatic

temperature differences among selected GBI settings and a built-up reference site in Guildford, a medium-sized town in the UK with a diverse range of GBIs. While Guildford does not represent the full spectrum of UK urban environments, particularly larger high-density metropolitan areas, it is broadly representative of many smaller urban centres in the UK characterised by mixed residential and commercial land uses, moderate building density, and established green-blue infrastructure.

To assess local microclimatic differences under typical and extreme heat conditions, a fixed sensor network was deployed across selected GBI settings and one built-up reference site. This design captures temporal variation in air temperature at the monitored points but does not measure the lateral cooling extent or spatial influence of each GBI beyond the sensor locations. These GBI sites included woodland, grassland, lakeside, green wall, pocket park, riverside, and a built-up area was taken as a reference for comparison (Fig. 1).

The fixed sensor network was designed to provide long-term, high-temporal resolution evidence of local microclimatic conditions at selected GBI and built-up settings in Guildford. Because each GBI typology was represented by one monitored location, the results should be interpreted as site-level comparisons rather than fully replicated typology-level effects. Local factors, including surrounding urban morphology, canopy structure, sky exposure, impervious surface fraction, building materials, traffic exposure, site orientation and ventilation, may also influence the observed temperature differences. Consistent instrumentation, standardised installation procedures, and uniform shielding were employed across all monitoring sites to reduce potential sources of measurement variability and ensure data comparability. Further details on the sites, instrumentation, data collection protocols, and analytical methods are provided in the subsequent sections.

2.2. Site description

This study was conducted in Guildford, a town in southeast England (51.215° N, −0.631° W) in Surrey county. It is characterised by a temperate oceanic climate (Cfb in the Köppen classification; Köppen Earth, 2025). The area experiences mild summers and cool winters, with average monthly air temperatures ranging from 4.7 °C in January to 17.3 °C in July, and average annual rainfall of around 722 mm (ClimateData, 2025). Meteorological seasons are defined by the Met Office as spring (March–May; MAM), summer (June–August; JJA), autumn (September–November; SON), and winter (December–February; DJF) (Met Office, 2025). Guildford had a population of 143,600 in 2021, with moderate levels of urban expansion over the past decade (ONS, 2022).

The selected sites, including six GBI types and a built-up urban area, are shown in Fig. 1. The selected sites were described in terms of dominant land cover, vegetation structure, proximity to water bodies, sky exposure, and the surrounding built environment in Table S1, together with the interpretative limitations arising from their site-specific characteristics. The woodland site was characterised by dense canopy cover and limited sky exposure; the grassland site by open low vegetation and high sky exposure; the lakeside and riverside sites by proximity to water and riparian vegetation; the pocket park by small-scale vegetation embedded within the urban fabric; and the green wall by vegetation attached to a west-facing building façade. The built-up site was selected as a local high-exposure reference because it is characterised by impervious surfaces, limited vegetation, nearby road activity, urban materials with high heat-storage potential and constrained sky exposure. It was used as a consistent within-network reference for calculating temperature contrasts, rather than as a complete representation of all built-up morphologies in Guildford. Elevation changes across sites were minor, with no substantial topographic effects expected.

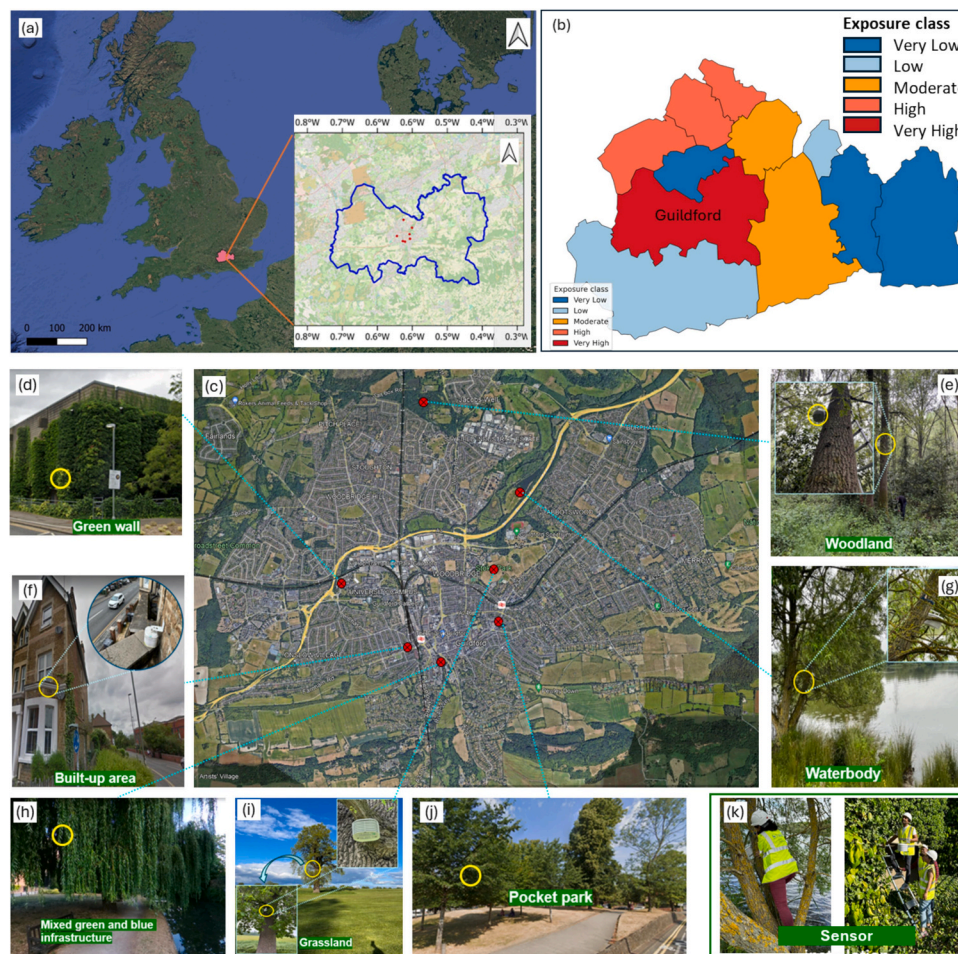


Fig. 1. Location of the study area and network of sensor site locations. (a) Geographical location of Guildford in the UK; (b) cumulative hotspot-based heatwave days (1981–2024, JJA) across Surrey districts derived from ERA5-Land daily maximum 2 m air temperature. Districts classified using quantile-based exposure categories; (c) Location of the fixed data loggers across Guildford, covering (d) green wall (Ivy Arts Centre); (e) woodland; (f) built-up area (Guildford Park Road-Farnham Road junction); (g) lakeside (Guildford nature reserve); (h) riverside – mixed GBI (Millmead lock); (i) grassland (Stoke Park); and (j) pocket park (London Road-Dene Road junction). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Instrumentation and data collection

Air temperature and relative humidity were measured using HOBO MX2301A data loggers installed at fixed locations. Each sensor was placed in a solar radiation shield to minimise the influence of direct sunlight and ensure accurate ambient measurements. The devices recorded data at 1-minute intervals with high precision, suitable for capturing short-term microclimatic variation. The HOBO MX2301A sensors measured air temperature over a range of -40°C to $+70^{\circ}\text{C}$ with a resolution of 0.02°C .

Environmental data were recorded at one-minute intervals continuously from June 2023 till end of August 2025. The green wall sensor was mounted on a west-facing facade. Daytime and nighttime periods were defined as 09:00–21:00 h and 21:00–09:00 h, respectively, following the day-night categorisation framework of [MetOffice \(2025\)](#) to assess temporal variations in air temperature profiles across diurnal and seasonal cycles. Data were retrieved from sensors regularly via Bluetooth to ensure continuous data integrity.

To examine whether air temperature patterns across the monitoring network varied under different regional wind conditions, hourly wind speed and wind direction data for the Wisley station (ID: 00719) were compiled for the period from June 2023 to August 2025. The station is located at 51.310°N , 0.475°W , around 8.6–11.2 km northeast of the monitoring sites ([Table S2](#)). Historical surface observations for 2023 and 2024 were sourced from the Centre for Environmental Data Analysis

MIDAS Open dataset, providing quality-controlled records of air temperature, wind speed, and wind direction (Met Office MIDAS, 2025). To account for the archival lag in official records for 2025 period, this dataset was supplemented with reanalysis data from the Open-Meteo Historical API ([Open-Meteo, 2026](#)). All wind speed measurements were standardised to metres per second (m s^{-1}). These off-site data were used to characterise the regional background wind regime rather than local wind speed and direction at individual monitoring sites. Local airflow may differ from the regional conditions because of building geometry, vegetation structure, surface roughness, wall orientation, and proximity to water bodies.

To complement the in-situ sensor network with a broader perspective on surface thermal dynamics, LST data were retrieved using the Landsat 8 Collection 2 Level-2 Tier 1 dataset via the Google Earth Engine cloud platform. Although the Landsat 8 Thermal Infrared Sensor has a native thermal spatial resolution of approximately 100 m, the Collection 2 Level-2 LST product is distributed on a 30 m grid after resampling to match the reflective bands. This resampling improves spatial alignment with other Landsat products but does not provide additional thermal information below the native sensor resolution. To ensure data integrity, a robust cloud and cloud-shadow masking protocol was implemented using the QA_PIXEL bitmask (bits 3 and 5) to remove pixels affected by atmospheric interference. The thermal infrared band (ST_B10) was converted to surface temperature in Kelvin using the product-specific scaling factor (0.00341802) and offset (149.0) and subsequently

converted to degrees Celsius (°C) for consistency with the ground-level measurements. LST and near-surface air temperature represent distinct physical quantities. The HOBO sensors measured shielded air temperature at fixed near-surface locations, whereas Landsat-derived LST represents radiometric surface temperature across the satellite pixel and extraction polygon. The land-use composition and spatial extent of the LST extraction polygons are presented in Fig. S2.

2.4. Data analysis

Data analysis was conducted using R (v4.2.2), Microsoft Excel, and QGIS (3.44.7). The 1-minute data were aggregated into hourly means and further classified into daytime (09:00–21:00 h) and nighttime (21:00–09:00 h) periods, based on the MetOffice (2025) classification. Descriptive statistics, including means, standard deviations, and 5th and 95th percentiles, were calculated to characterise the thermal conditions at each monitored site.

To contextualise the climatic risk within which the in-situ sensor network operates, a regional scale heatwave exposure analysis was conducted for Surrey County. Daily maximum 2 m air temperature ($T_{\max}$) data were obtained from the ERA5-Land reanalysis product, a global land-surface dataset produced by the European Centre for Medium-Range Weather Forecasts (Copernicus Climate Change Service, 2025), for the period 1981–2024 (~9 km spatial resolution). The analysis was restricted to the meteorological summer season (JJA), and temperature values were converted from Kelvin to °C.

To capture intra-district peak thermal exposure, a hotspot-based metric was implemented. For each Surrey county district and each summer day, the spatial maximum daily temperature across all ERA5 grid cells intersecting the district boundary was extracted. This approach identifies the highest temperature experienced within each district on a given day, thereby capturing localised peak heat exposure conditions that may be masked by spatially averaged values. Heatwaves were defined using a fixed absolute threshold approach based on the Met Office county-specific heatwave threshold for Surrey (28 °C, Fig. S1) (Met Office, 2025). A heatwave event was identified when the daily hotspot maximum temperature reached or exceeded 28 °C for at least three consecutive days, with the event considered terminated when temperatures fell below this threshold. For each district, the cumulative number of heatwave days over the 1981–2024 period was calculated and used as the primary exposure indicator. Districts were subsequently classified into five relative exposure categories (very low, low, moderate, high, and very high) using quantile-based classification of cumulative heatwave days across Surrey county.

To evaluate air temperature variation, a two-way ANOVA was performed with monitoring site category, labelled 'typology' in the statistical model, and season as fixed effects, and the magnitude of these effects was quantified using partial eta squared (η^2). Since each category was represented by one monitored location, the 'typology' term reflects differences among the monitored settings rather than replicated typology-level effects. Post-hoc spatial comparisons were conducted using estimated marginal means (emmeans) with Tukey-adjusted *p*-values to determine significant differences between sites. Site-level temperature contrasts were quantified as $\Delta T = T_{\text{Built-up}} - T_{\text{GBI}}$ °C, where positive ΔT values indicate cooler conditions at the monitored GBI site relative to the built-up reference. Cooling contrasts were calculated relative to the single built-up reference site. Consequently, the absolute magnitude of ΔT values is conditional on the thermal characteristics of this reference location. Linear mixed-effects models (LMMs) were applied to peak summer hours (12:00–16:00 h) to account for daily temporal autocorrelation by treating "Day" as a random effect.

Associations between regional wind conditions and air temperature across the monitoring sites were explored using bivariate polar plots. Concurrent air temperature measurements from each site were paired with wind direction and speed sourced from MIDAS and Open-Meteo records for the Wisley location. Linear regressions were used to

describe statistical associations between site air temperature and regional wind speed. Since wind data were not measured directly at the monitoring sites, these analyses were used to contextualise temperature patterns under different regional wind regimes rather than to infer local airflow, site-specific aerodynamic processes or wind-driven cooling mechanisms.

Finally, local heatwave threshold exposure was assessed using the Met Office county-specific heatwave threshold for Surrey, where a heatwave is defined as a period of at least three consecutive days with daily maximum air temperature reaching or exceeding 28 °C (Met Office, 2025). This threshold was applied consistently across sites to compare local thermal exceedance within the sensor network. It should be interpreted as a microclimatic heat-exposure metric, not as a direct epidemiological or health-outcome threshold. For each monitoring site, daily maximum air temperature was calculated from sensor data, and site-specific threshold exceedance periods were identified when daily maximum air temperature reached or exceeded 28 °C for at least three consecutive days. Heatwave occurrence was quantified as the percentage of summer observations occurring within these threshold exceedance periods. The cumulative duration of threshold exceedance periods and the mean temperature intensity during these periods were then compared among the monitored sites to characterise site-level temperature differences during the identified events. The satellite-derived LST was analysed through spatial mapping and comparative time-series analysis. For the temporal analysis, daily spatial mean LST values were extracted for seven distinct areas of interest polygons corresponding to the six monitored GBI settings: Woodland, lakeside, pocket park, riverside (mixed GBI), green wall, grassland, and the built-up reference area. These daily values were used to plot long-term LST time series, allowing land surface temperature variation to be compared among the monitored areas and the built-up urban fabric over the three-year study period. For each monitored setting, LST was extracted using an area-of-interest polygon, with polygon size and dominant land-cover composition recorded to support interpretation (Fig. S2). Owing to their small spatial extent and integration within the surrounding urban fabric, the pocket park, riverside and green wall polygons were classified within the built-up land-use category and contained mixed land-cover elements, including vegetation, roads, buildings and other impervious surfaces. Consequently, given the native thermal resolution of Landsat 8, the extracted LST values were interpreted as broad spatial and temporal surface temperature patterns rather than precise thermal footprints of these individual small-scale GBI features. Furthermore, the LST analysis was used to characterise broad, polygon-scale surface temperature patterns rather than to validate the monitored sites' air temperature measurements.

3. Results and discussion

3.1. Regional heatwave exposure

Cumulative heatwave days (1981–2024, JJA), calculated using the ERA5-Land reanalysis product, showed pronounced spatial heterogeneity across Surrey districts (Fig. 1b). When peak intra-district temperatures were considered, Guildford ranked within the 'Very High' exposure category, indicating a comparatively greater number of heatwave days over the study period. Northern districts also exhibited elevated exposure, whereas more rural districts showed a lower cumulative heatwave frequency. By accounting for the highest temperature recorded within each district on a given day, this approach captured localised peak thermal stress conditions that may be obscured by area-averaged metrics. Guildford's elevated ranking suggested the presence of spatially concentrated high temperature zones, consistent with urbanised land cover and impervious surface concentration.

3.2. Seasonal variation of air temperature

Seasonal air temperature patterns varied markedly across the study locations (Fig. 2). The built-up area consistently recorded the highest temperatures throughout the three monitoring years, with mean seasonal values ranging from 7.1 °C in winters to 19.2 °C in summers. The woodland and lakeside sites showed the largest seasonal temperature contrasts relative to the built-up reference, with mean temperatures 2 °C lower across most seasons (Table S3). Smaller seasonal contrasts were observed at the grassland and pocket park sites, whereas the green wall site often recorded temperatures similar to or slightly higher than those at the built-up area.

Boxplot distributions (Fig. 2) illustrate these patterns, showing narrower interquartile ranges at the more densely vegetated monitored sites, such as woodland and lakeside, and wider distributions in the built-up area during summer, reflecting more pronounced temperature extremes. Seasonal shifts were evident at all monitored sites: summer temperatures showed higher maximum values and 95th percentiles, while winter minimum were lowest at the grassland and woodland sites.

The two-way ANOVA identified statistically significant variation associated with both season and the categorical monitoring-site factor, labelled 'typology' in the model (Table 2). Seasonal variability accounted for the largest share of variance, while the monitoring-site factor accounted for a statistically significant but small in magnitude ($\eta^2 = 0.027$). The site-season interaction was also statistically significant but very small in magnitude ($\eta^2 = 0.003$). Since each GBI category was represented by one location, these model terms describe differences among the monitored settings and should not be interpreted as replicated typology-level effects.

Post-hoc pairwise comparisons using estimated marginal means (emmeans) further resolved these differences. In spring, woodland and lakeside areas were 1.7 °C cooler than the built-up area, grassland and pocket park areas were 1–1.5 °C cooler, and the green wall area was similar to the built-up area ($p < 0.001$). During summer, the built-up reference was consistently warmer than all monitored GBI sites, with differences ranging from about 0.9 to 1.9 °C. The largest summer contrast was observed at the woodland site (~1.9 °C), followed by the

lakeside, grassland, pocket park, riverside (mixed GBI), and green wall typologies (~0.9–1.5 °C). Autumn showed ~1.3–2.2 °C difference across typologies. In winter, differences were more modest, with woodland remaining around 0.9 °C cooler than the built-up area, while the lakeside and green wall sites showed temperatures similar to or slightly higher than those at the built-up area ($p < 0.001$). Overall, the woodland site maintained the largest contrasts relative to the built-up reference across seasons, whereas the contrast at the lakeside site varied seasonally. The green wall site had higher temperatures than the grassland site in all seasons, including summer maximum temperatures. These comparisons describe the monitored locations and do not establish a general ranking of GBI typologies. The full ANOVA summary, estimated marginal means, and pairwise comparisons for each season are reported in Table S4.

3.3. Diurnal air temperature variations

Diurnal variations in air temperature were analysed across the seven study sites for daytime (09:00–21:00) and nighttime (21:00–09:00) periods over the three years. Both hourly trends and aggregated daytime/nighttime periods were examined to assess thermal dynamics across the monitored GBI and built-up sites.

Daytime temperatures were consistently higher than nighttime temperatures across all typologies, with the largest day–night differences observed in the built-up area during summer (~5.3 °C). The lakeside site exhibited smaller diurnal ranges, which is consistent with the expected thermal inertia and heat storage capacity of the adjacent water body (Theeuwes et al., 2013). The green wall, pocket park, and riverside (mixed GBI) sites displayed intermediate diurnal ranges, suggesting a combination of shading, evapotranspiration, and partial urban heat buffering. Detailed aggregated mean temperatures for daytime and nighttime periods across all monitored sites are presented in Table S5.

Hourly mean air temperatures revealed pronounced diurnal cycles across all typologies (Fig. 3). Daytime temperatures typically peaked between 14:00 and 16:00 h, while nighttime minimum occurred between 03:00 and 06:00 h. The built-up reference and riverside (mixed GBI) sites exhibited the highest daytime temperatures during summers,

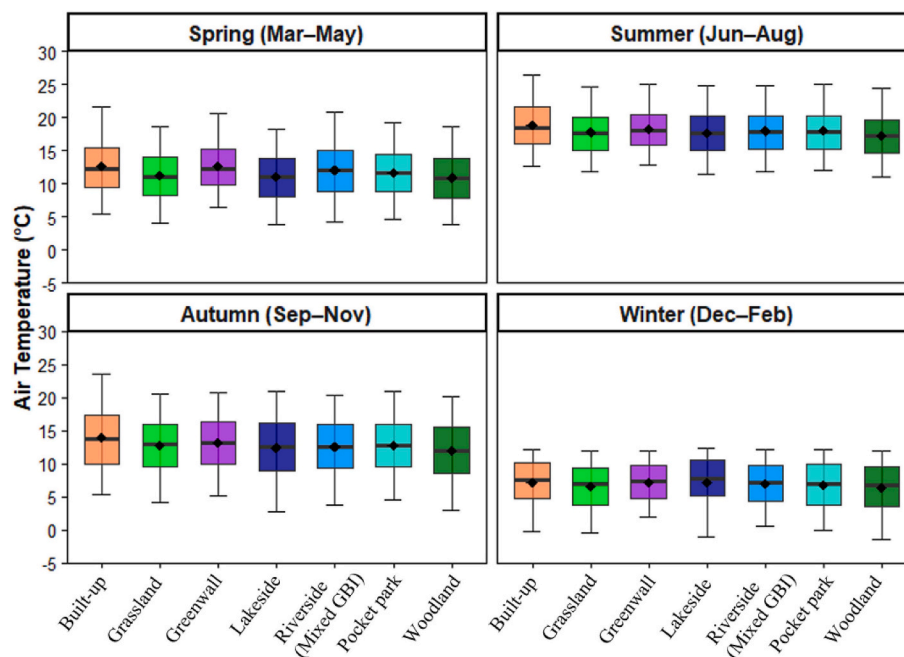


Fig. 2. Seasonal boxplots of air temperature across seven study sites: (a) Spring. (b) Summer. (c) Autumn. (d) Winter. Boxes represent the interquartile range, the median is represented by the bold line, and mean values are shown as black diamonds. Whiskers extend to the 5th and 95th percentiles to highlight the core distribution of seasonal temperatures. Panels are grouped by season (Spring, Summer, Autumn, Winter).

Table 2

Two-way ANOVA results for the monitoring-site factor (labelled 'typology'), season, and their interaction on air temperature. Effect sizes are expressed as partial eta squared (η^2).

Effect	df	Sum Sq	Mean Sq	F value	p-value	Partial η^2
Typology	6	4,069,599	678,266	34,956	<0.001	0.027
Season	3	116,290,237	38,763,412	1,977,773	<0.001	0.442
Typology $\times$ Season	18	436,790	24,266	1,251	<0.001	0.003

* df = degrees of freedom; Sum Sq = sum of squares; Mean Sq = sum of squares divided by df; F value = ratio of effect variance to residual variance; p-value = statistical significance; Partial η^2 = denotes the proportion of variance in air temperature attributable to a given effect, relative to the variance of that effect plus the residual error, with all other fixed effects held constant.

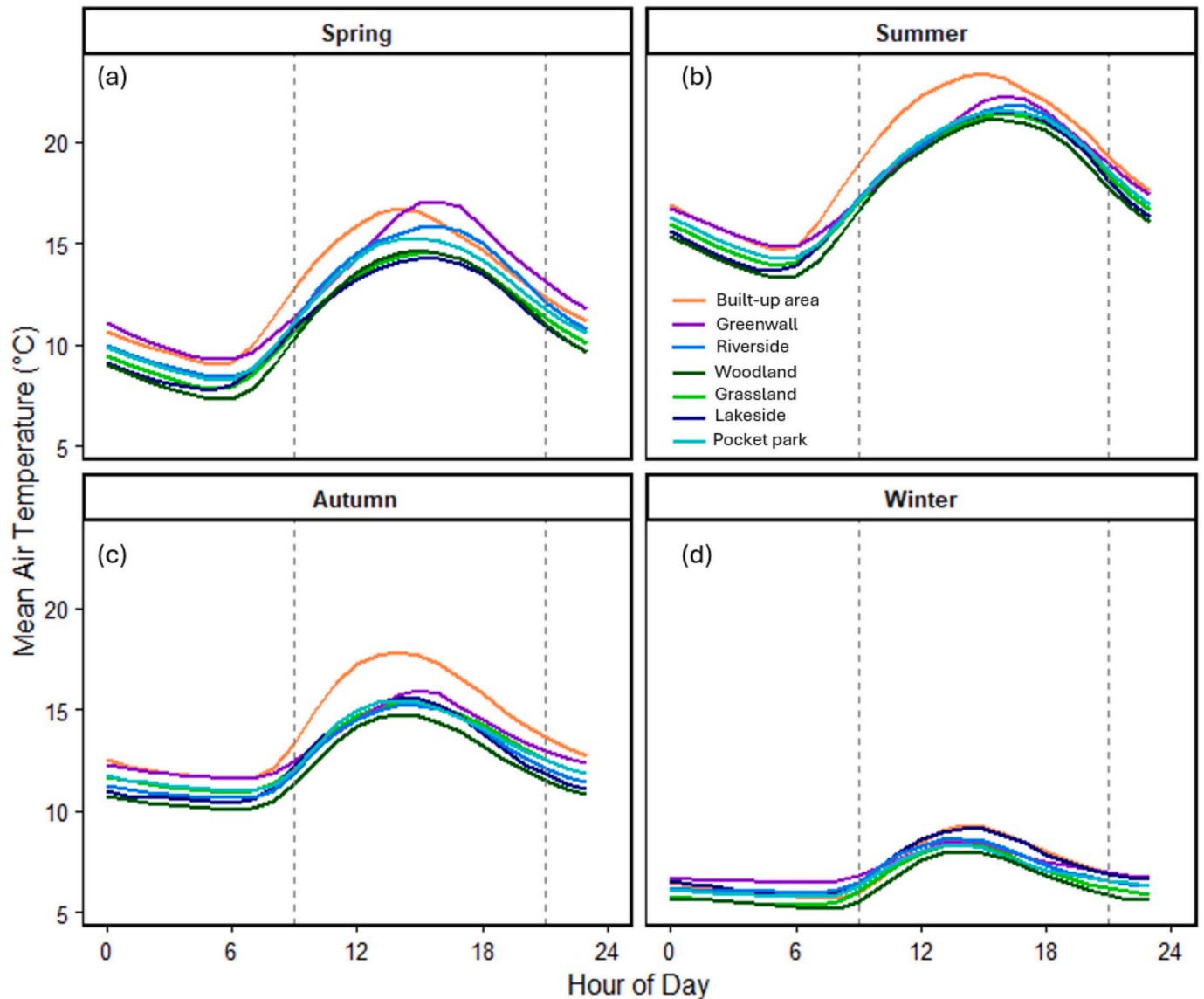


Fig. 3. Hourly diurnal air temperature across the monitored GBI and built-up sites by season: (a) Spring. (b) Summer. (c) Autumn. (d) Winter. Lines represent mean temperatures, and dashed vertical lines indicate transitions between daytime (09:00–21:00 h) and nighttime (21:00–09:00 h).

reaching up to 37.3 °C in the built-up area and 34.7 °C in the riverside area. Conversely, blue infrastructure (lakeside) and green infrastructure sites (grassland, woodland, pocket park) maintained lower diurnal maximum, indicative of evaporative cooling and shading effects. The green wall site showed intermediate temperature peaks and smaller temperature contrasts than the other monitored GBI sites. The thermal conditions observed at the green wall site are highly context-dependent and may vary according to wall orientation, plant species, irrigation, substrate properties, surrounding urban geometry, and local exposure

conditions. In this study, the sensor was installed on a west-facing façade and was therefore exposed to substantial afternoon solar radiation. The thermal properties and heat-storage capacity of the adjoining building may also have contributed to the higher temperatures observed relative to detached green infrastructure sites (Wang et al., 2022; Liu et al., 2025). Further analysis of how the air temperature patterns at the green wall site and other monitoring sites varied across regional wind regimes is presented in Section 3.6. However, since wind conditions were not measured directly at the individual sites, that analysis is interpreted as

regional meteorological context rather than evidence of site-specific aerodynamic mechanisms. Overall, diurnal temperature dynamics demonstrate clear differences in the magnitude and persistence of thermal regulation among the monitored GBI sites. Woodland and lakeside maintained lower and less variable temperatures across the diurnal cycle, consistent with canopy mediated attenuation of daytime radiative loading and the thermal inertia of the adjacent water body. In contrast, smaller and more variable temperature contrasts were observed at the green wall and pocket park sites, indicating a greater dependence on intervention scale, surrounding built form and local exposure conditions.

3.4. Temporal dynamics of site-level temperature contrasts

Site-level air temperature contrasts between the monitored GBI sites and the selected built-up reference were assessed across seasons, diurnal periods, and peak summer hours. Positive ΔT values indicate cooler conditions relative to the built-up reference, whereas negative values indicate warmer conditions. Hourly ΔT dynamics ($\Delta T = T_{\text{Built-up}} - T_{\text{GBI}}$; °C) revealed clear temporal and site-level cooling contrasts (Fig. 4a). During daytime hours, all GBI sites exhibited net cooling relative to the built-up area, with the largest contrasts observed in summer. Mean hourly ΔT during summer afternoons reached up to 2.5 °C at the woodland, grassland, lakeside, pocket park, and riverside (mixed GBI) sites, while the green wall site consistently showed smaller contrasts (~1.5–2 °C). Cooling intensities peaked between early and mid-afternoon, coinciding with maximum solar loading. At night, cooling weakened across all monitored GBI sites, and ΔT values frequently approached zero, particularly at the green wall, site which occasionally exhibited slightly negative ΔT values, indicating marginal nighttime warming relative to the built-up area. The calculated ΔT values represent local temperature differences between each monitored GBI setting and the built-up reference site. They should not be interpreted as estimates of the spatial cooling footprint, cooling distance, or net contribution of each GBI to city-scale outdoor thermal comfort.

3.5. Day–night cooling differences

Day–night contrasts further emphasised the diurnal modulation of cooling effects (Fig. 4b). Across all seasons, daytime cooling exceeded nighttime cooling, with mean daytime ΔT typically ranging between 1 and 3 °C, compared with 0–1.5 °C at night. The woodland, grassland, pocket park, and riverside (mixed GBI) sites maintained positive ΔT during both periods, although with reduced magnitudes at night. In contrast, the lakeside site exhibited seasonally different contrasts: while providing cooling during summer and transitional seasons, it showed near-zero to negative daytime ΔT in winter, consistent with the thermal inertia of water bodies and reduced evaporative cooling under cold-season conditions (Doran et al., 2025). The smallest diurnal contrast among the monitored GBI sites was observed at the green wall site, with limited nighttime benefits.

During peak summer hours (12:00–16:00 h) – a critical period for heat mitigation – all monitored GBI sites demonstrated statistically significant cooling relative to the built-up area. Mean ΔT values ranged from 1.81 °C (green wall) to 2.49 °C (woodland), with grassland (2.28 °C), lakeside (2.12 °C), pocket park (2.06 °C), and riverside (2.05 °C) showing comparable intermediate ΔT values. LMM analysis accounting for day-to-day variability as a random effect (Table 3), with grassland as the reference level, identified significant differences in ΔT among the monitored settings ($p < 0.001$). The temperature contrast at the woodland site was significantly larger than those at most other monitored sites, whereas the temperature contrast at the green wall site was smaller. This comparatively smaller contrast observed at the green wall site should not be interpreted as a general limitation of vertical greening, as green-wall cooling is highly context-dependent and may vary with wall orientation, plant species, irrigation, substrate properties,

surrounding urban geometry, and local exposure conditions. Several contrasts among the lakeside, pocket park, and riverside sites were not statistically significant, indicating partial convergence in performance under peak thermal stress.

The results show that the monitored GBI sites providing substantial daytime cooling did not necessarily maintain an equivalent advantage during nighttime periods. This distinction is important because daytime mitigation is primarily linked to reductions in solar loading and enhanced evapotranspiration, whereas nighttime performance is more strongly influenced by stored heat release and surface thermal properties. Interpretation of the observed GBI contrasts relative to the built-up reference should therefore consider the full diurnal cycle rather than peak daytime conditions alone.

3.6. Variation in site-level temperature contrasts across regional wind regimes

Bivariate polar plots were used to examine air temperature across the network of sensors as a function of regional wind direction and wind speed obtained from the Wisley/Open-Meteo dataset during summer daytime conditions. The resulting plots (Fig. 5), shown as continuous smoothed representations, are interpreted as indicative of dominant temperature regimes associated with regional background wind conditions rather than discrete measurements of local airflow. Since wind was not measured directly at the monitoring sites, the plots do not characterise local wind fields within the monitoring GBI sites.

The analysis showed that air temperature varied systematically across regional wind regimes and that the observed patterns differed among the monitored GBI sites (Fig. 5). At the built-up reference site, the highest mean daytime temperature occurred under northeasterly winds reaching 24.3 °C. GBI temperature contrasts relative to the built-up reference were generally largest under northeasterly and westerly wind regimes, whereas south-easterly winds were associated with weaker temperature contrasts. The mean cooling intensities under these dominant regional wind sectors are summarised in Table S6.

Under northeasterly winds, the largest mean temperature contrasts were observed at the woodland and grassland sites, maintaining mean temperature reductions of 2.9 °C and 2.3 °C, respectively, relative to the built-up site (Table S6). The woodland site showed the weakest negative correlation between air temperature and regional wind speed ($r = -0.13$), while the built-up reference site showed a stronger negative correlation ($r = -0.25$). These coefficients indicate differences in the statistical associations between temperature and regional wind speed but do not demonstrate differences in local ventilation or aerodynamic response. Temperature reductions relative to the built-up reference were also observed at the lakeside, pocket park, and riverside sites under northeasterly winds, with reductions of 2.1 °C, 2.1 °C, and 1.9 °C, respectively. Correlations between air temperature and regional wind speed at these sites ranged from -0.15 to -0.17 , while the green wall site showed a correlation of -0.20 . Although these values varied among sites, the differences should not be interpreted as direct evidence of site-specific aerodynamic sensitivity because local wind conditions were not measured.

In contrast, under southeasterly wind conditions, cooling contrasts across the GBI sites were smaller. During these regimes, built–GBI temperature differences narrowed to 1.1–1.8 °C (Table S5), indicating that the magnitude of the observed temperature contrasts varied across regional wind sectors. However, the analysis cannot determine whether these variations resulted from local ventilation, air-mass characteristics, site exposure, or other meteorological and site-specific factors.

Regression analysis showed negative associations between air temperature and regional wind speed across all monitoring sites (Fig. 5b). The fitted slopes ranged from -0.34 °C per m s^{-1} for woodland site to -0.54 °C per m s^{-1} for the green wall site. Intermediate slopes were observed for riverside (-0.38), lakeside (-0.39), grassland (-0.40), and pocket park (-0.45). These slopes describe the rate of change in site air

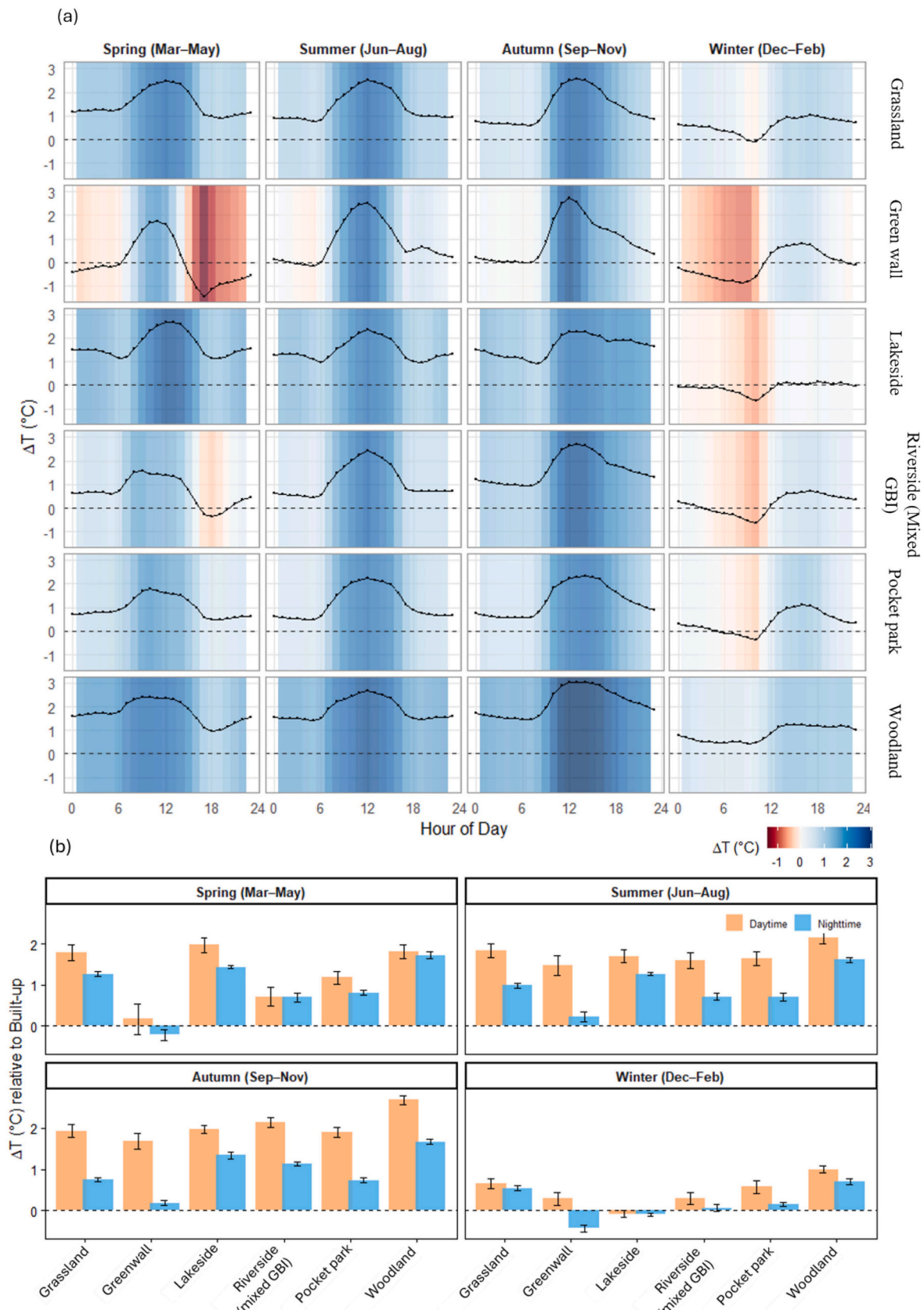


Fig. 4. Site-level air temperature contrasts at the monitored GBI sites relative to built-up reference. (a) Hourly cooling efficiency showing the daily temperature difference (ΔT , °C). The black lines show the hourly change, while the background colours show the intensity: Blue means the site is cooler than the built-up area, and Red means it is warmer. The dashed line at 0 shows where the site and built-up temperatures are equal. (b) Seasonal daytime (09:00–20:59) versus nighttime (21:00–08:59) cooling efficiency of GBI typologies, with error bars representing ± 1 SD. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3

Peak summer site-level temperature contrasts (ΔT) at the monitored GBI sites and corresponding LMM estimates relative to the built-up reference during peak summer hours.

Monitoring site	Peak mean ΔT ($^{\circ}\text{C}$)	SD ΔT ($^{\circ}\text{C}$)	LMM estimate ($^{\circ}\text{C}$)	Std. error	p-value
Grassland (LMM reference level)	2.28	1.80	–	–	–
Woodland	2.49	1.95	+0.21	0.045	<0.001
Lakeside	2.12	1.96	–0.16	0.045	0.0003
Riverside (Mixed GBI)	2.05	1.97	–0.23	0.045	<0.001
Pocket park	2.06	1.90	–0.22	0.045	<0.001
Green wall	1.81	1.95	–0.46	0.045	<0.001

* ΔT = Temperature difference relative to a built-up area (Positive = cooler than built-up).

** LMM estimates describe ΔT differences among the monitored GBI sites during peak summer hours (12:00–16:00), with Day as a random effect, and the grassland site used as the model reference level.

temperature associated with regional wind speed within the fitted models. They should not be interpreted as direct measures of canopy sheltering, convective sensitivity, heat advection, or local aerodynamic performance. Overall, the results indicate that GBI–built-up temperature contrasts varied across regional wind regimes, with the magnitude of the observed differences changing among wind direction sectors and across the range of regional wind speeds. The woodland site maintained among the largest observed air temperature contrasts across the regional wind sectors examined, whereas the pocket park and green wall sites showed smaller or more variable contrasts. These patterns are conceptually relevant to the broader ‘airshed’ framework, which describes the area or volume of air through which environmental effects, such as cooling, may be transported beyond the immediate boundary of a GBI element (Jones et al., 2022). However, the present analysis cannot determine the size or characteristics of site-specific airsheds because local airflow was not measured directly at the monitoring sites.

Consequently, these findings highlight the importance of considering regional wind conditions when interpreting the observed GBI temperature contrasts relative to the built-up reference, while also demonstrating the need for co-located wind measurements when assessing site-level thermal differences in built-up environments.

3.7. Temperature contrasts across the monitored GBI sites during heatwaves

Local heatwave threshold exposure was assessed using the Met Office county specific heatwave threshold for Surrey, whereby daily maximum air temperature reached or exceeded 28°C for at least three consecutive days. Heatwave threshold exposure was analysed across summers 2023–2025 to compare temperature contrasts at the monitored GBI sites relative to the built-up area. The analysis focused on (i) heatwave exposure and intensity across the full summer period, and (ii) event-based temperature contrasts during extreme heat events, providing an assessment of site-level temperature contrasts during the identified heatwave events.

3.7.1. Heatwave exposure frequency and intensity

The built-up area consistently experienced the highest heatwave threshold exposure, with threshold exceedance occurring during 19.6% of summer daytime observations across all summers (Fig. 6a–l). In contrast, all monitored GBI sites recorded lower heatwave threshold occurrence than the built-up reference. The woodland site exhibited the lowest daytime heatwave threshold frequency, with no occurrences, followed by the grassland (2.2%), pocket park (4.3%), lakeside (5.8%), riverside (6.5%), and green wall (8.7%) sites. These results show lower heatwave threshold occurrence at all monitored GBI sites relative to the

built-up reference.

Heatwave intensity metrics further emphasised the mitigation role of GBIs. During daytime heatwave threshold periods, the built-up area exhibited the highest mean heatwave air temperature (30.5°C) and the highest upper-tail intensity (95th percentile = 34.3°C). All monitored GBI sites recorded lower mean and upper-tail temperatures than the built-up reference during the identified heatwave threshold periods. The woodland site showed the lowest mean heatwave temperature (28.7°C) and the lowest 95th percentile (29.5°C), corresponding to a reduction of nearly 5°C at the upper tail relative to the built-up area.

At the lakeside, grassland, riverside, and pocket park sites, mean daytime temperatures during threshold periods ranged from 28.8 to 29.1°C , with 95th percentiles ranging from 30 to 30.7°C . The green wall site recorded the highest mean and upper-tail temperatures among the monitored GBI sites, with a mean heatwave temperature of 29.9°C and a 95th percentile of 32.7°C , yet it remained cooler than the built-up area at both mean and extreme levels.

Heatwave threshold exceedance was primarily a daytime phenomenon, with negligible or zero nighttime exceedance for most monitored GBI sites. The woodland, lakeside, grassland, and riverside sites did not experience nighttime threshold exceedance across the three summers analysed. In contrast, the built-up area exhibited limited but non-negligible nighttime heatwave exposure (0.37%), with a mean nighttime heatwave temperature of 29.8°C and a 95th percentile of 32.6°C , indicating persistent nocturnal heat retention. The green wall and pocket park sites showed rare and marginal nighttime exceedance ($\leq 0.004\%$), with temperatures remaining close to the threshold (≈ 28.0 – 28.1°C), while remaining lower than the corresponding occurrence at the built-up reference. These findings confirm that the monitored GBI settings not only reduced daytime heatwave intensity but also prevented the persistence of nocturnal heat stress.

The analysis of thermal data from 2023 to 2025 identified significant differences in heatwave threshold exceedance and thermal intensity (Fig. 7) across the monitored settings.

Interannual variability was evident across the monitoring network (Fig. 7). The built-up site accumulated 54 threshold exceedance days and recorded both the longest continuous event, lasting nine days from 9 to 17 June 2023, and the highest temperature observed during the study period, reaching 37.3°C in 2024. In contrast, the woodland sites recorded no three-day threshold exceedance event. The remaining GBI sites experienced shorter but year-dependent exceedance periods, with increased exposure at several sites in 2025, indicating greater year-to-year variability at the smaller and mixed GBI sites.

3.7.2. Event-based cooling performance during extreme heat days

Site-level temperature contrasts during heatwave conditions were examined using ten event-based extreme heat days identified between 2023 and 2025 (Fig. 8). These events encompassed moderate to extreme heat conditions, with daytime mean air temperatures in the built-up area frequently exceeding 30°C and reaching maximum values above 37°C during the most severe events.

Across all heatwave events, the largest mean daytime ΔT was observed at the woodland site (4.5°C), frequently exceeding 5 – 6°C during the most severe events. Mean daytime ΔT values of 4.1°C and 4°C were observed at the grassland and lakeside sites, respectively. The pocket park and riverside sites showed moderate but still substantial cooling, with reductions of up to 3.5°C , indicating that even relatively small or heterogeneous monitored GBI sites can remain cooler than the built-up site during heatwave conditions.

In contrast, the green wall site showed the smallest mean daytime ΔT (3°C), alongside the highest upper-tail temperatures among all monitored GBI sites (mean P95 = 30.1°C ; mean maximum = 30.3°C). This indicates that while the green wall site was associated with some daytime cooling, its observed temperature contrast was smaller than those at the other monitored GBI sites.

Across the three summers, nocturnal recovery magnitudes were

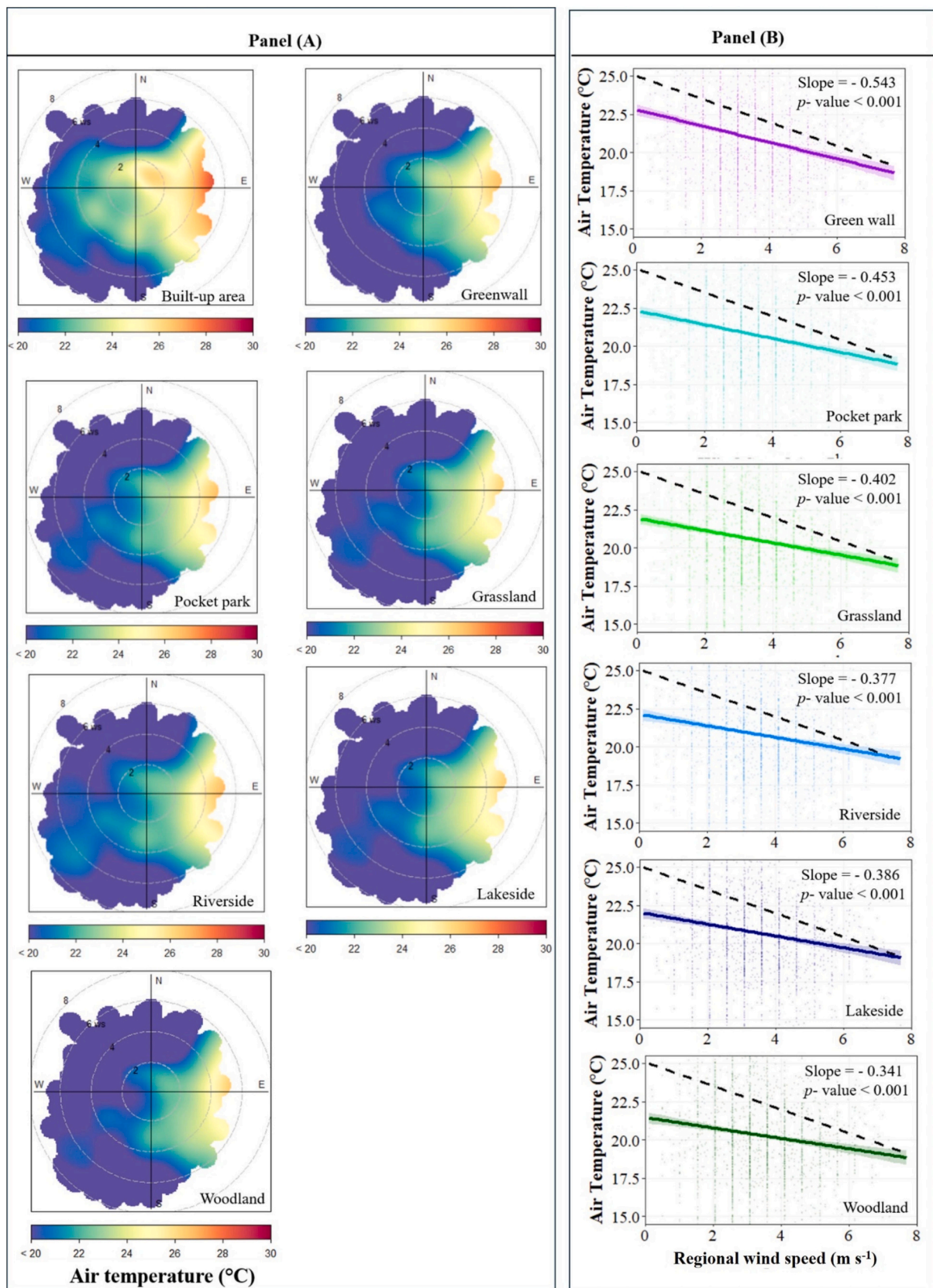


Fig. 5. Variation in summer daytime air temperature across regional wind regimes. (A) Bivariate polar plots showing smoothed air temperature ($^{\circ}\text{C}$) at each monitoring site according to concurrent regional wind direction and wind speed ($\text{m}\cdot\text{s}^{-1}$) during summer daytime conditions (09:00–21:00 h; June–August 2023–2025). Wind data were obtained from the off-site Wisley meteorological station and the Open-Meteo dataset and therefore represent regional background wind conditions rather than local airflow measured directly at the individual monitoring sites. (B) Linear regression relationship between air temperature ($^{\circ}\text{C}$) and regional wind speed ($\text{m}\cdot\text{s}^{-1}$) for each monitored GBI site (solid lines) compared against the built-up reference site (dashed line).

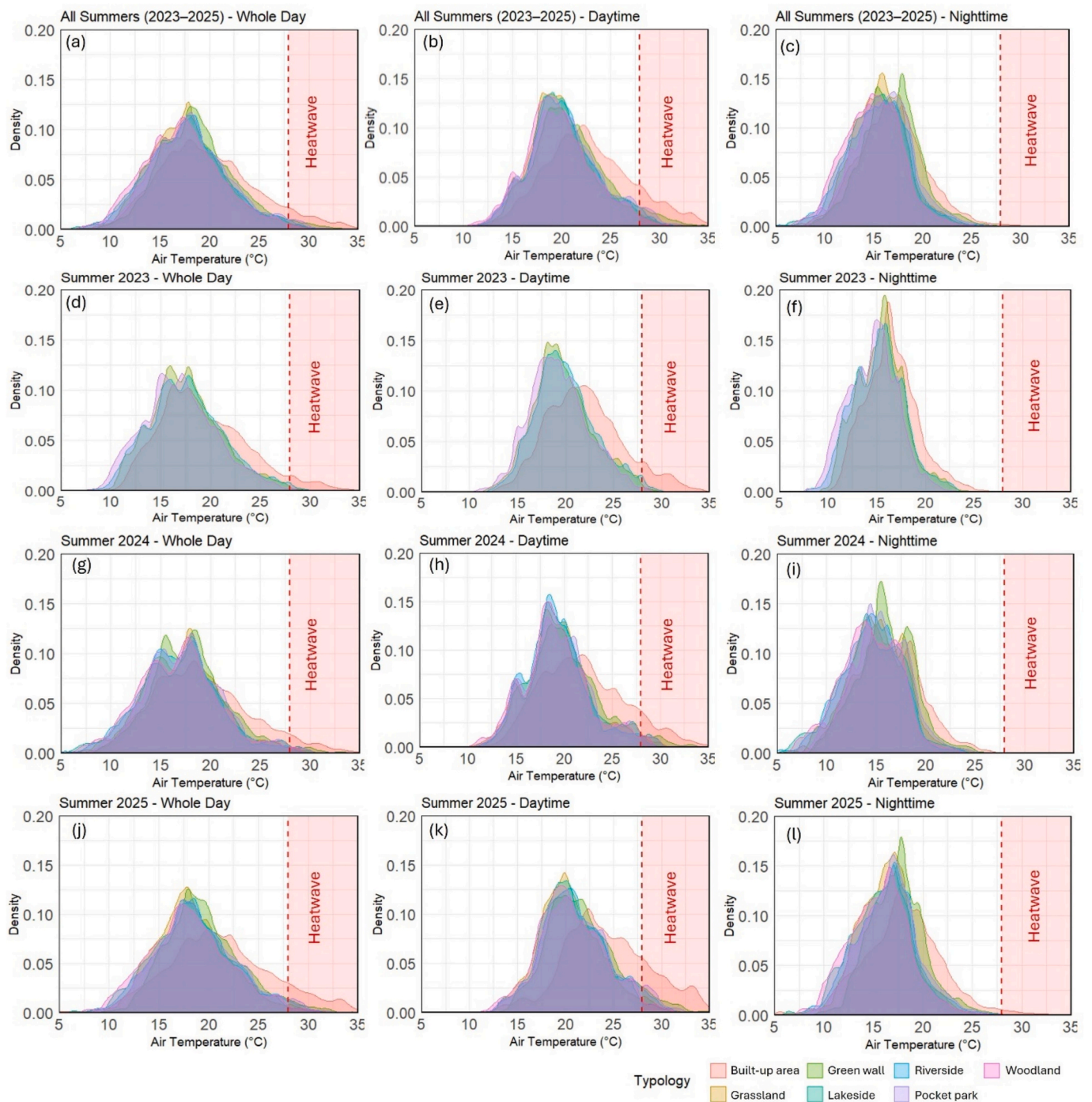


Fig. 6. Summer air temperature density plots (2023–2025). Panels (a–c) show density plots all summers combined: whole day (a), daytime (b), and nighttime (c). Panels (d–f), (g–i), and (j–l) show density plots for summer 2023, 2024, and 2025, respectively, for the whole day, daytime, and nighttime. The red shaded area above 28 °C highlights exceedance of the Met Office county-specific heatwave threshold for Surrey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

generally larger at the woodland and lakeside sites, whereas the riverside, pocket park and green wall sites exhibited greater interannual variability (Fig. 8d). The reduction in riverside recovery during 2025 coincided with longer heatwave exposure, suggesting that prolonged thermal stress may reduce buffering capacity (Joshi et al., 2024). However, this interpretation cannot be confirmed without direct measurements of soil moisture, vegetation condition and local water availability. The analysis of cooling benefits across different monitored sites showed variation in both magnitude and response under extreme conditions. The largest site-level ΔT during the study period was observed at

the woodland site (9.1 °C), followed by the pocket park (8.5 °C) and riverside sites (8.4 °C). The grassland and lakeside sites exhibited slightly lower maximum benefits (8.2 °C and 7.9 °C, respectively), while the green wall site had the lowest (6.7 °C). On the absolute peak day of 30 July 2024, temperature contrasts were reduced across all monitored GBI sites, with decreases of 0.9 °C for the woodland site, 1.3 °C for the grassland site, 1.2 °C for the pocket park site, 0.9 °C for the riverside (mixed GBI) site, and 2.9 °C for the green wall site. The lakeside site showed the smallest reduction (0.6 °C). These results indicate that the magnitude and persistence of the observed temperature contrasts

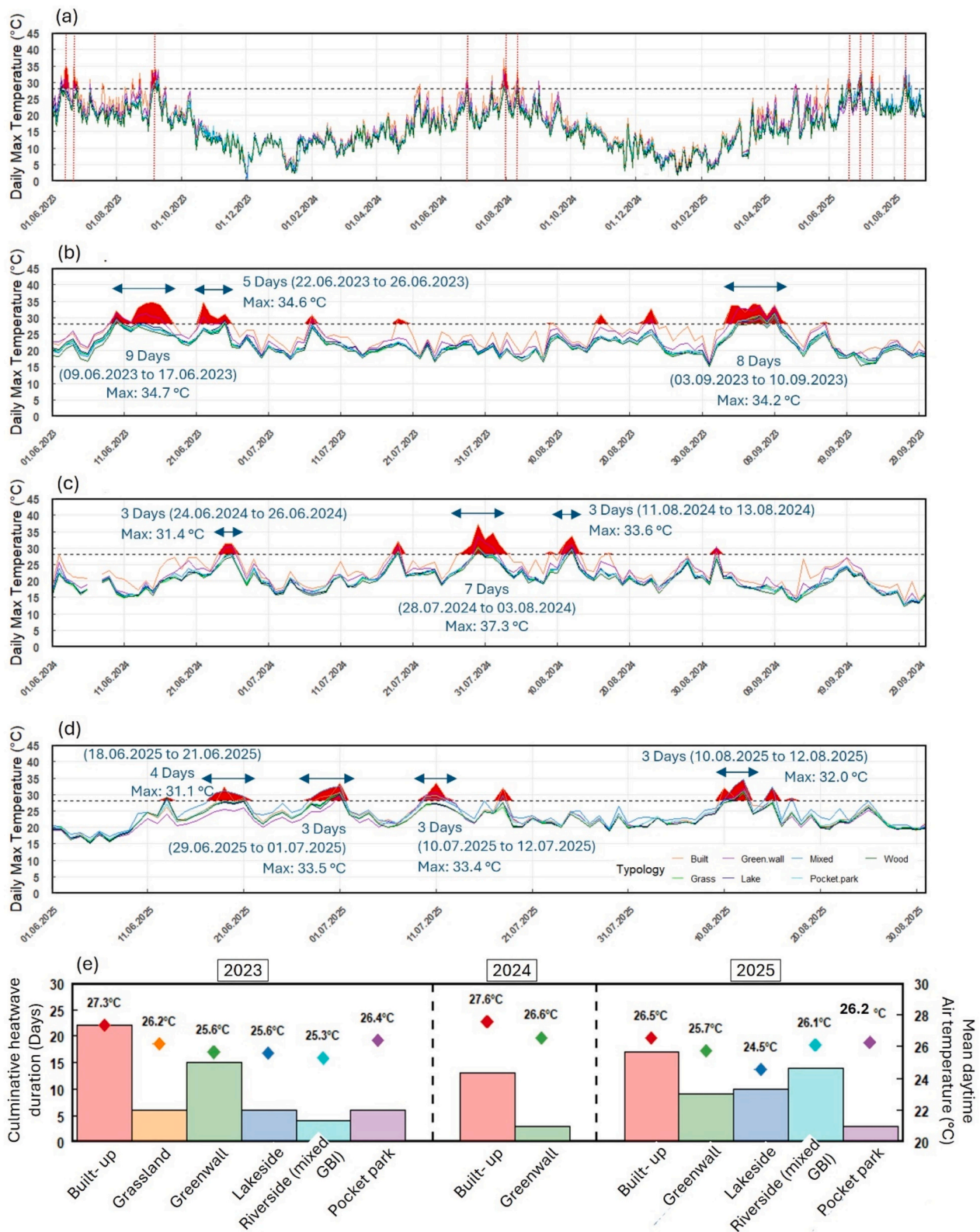


Fig. 7. Heatwave characteristics and diurnal air temperature dynamics across the monitored GBI sites and built-up area during the study period (June 2023–September 2025). (a) Daily maximum air temperature from June 2023 to the end of summer 2025. Red dashed vertical lines indicate periods exceeding the Met Office county-specific heatwave threshold for Surrey (28°C). (b–d) Daily maximum air temperature during summer heatwave periods for (b) 2023, (c) 2024, and (d) 2025. Red shaded areas highlight periods exceeding the heatwave threshold (28°C). Blue arrows denote the duration (number of consecutive days) of each heatwave event, and annotations indicate peak temperatures recorded during each event. (e) Comparative analysis of cumulative heatwave duration and mean daytime temperature intensity (2023–2025). Bars represent total heatwave duration, while diamonds indicate the mean daytime air temperature recorded between 09:00 and 21:00 h during heatwave events. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

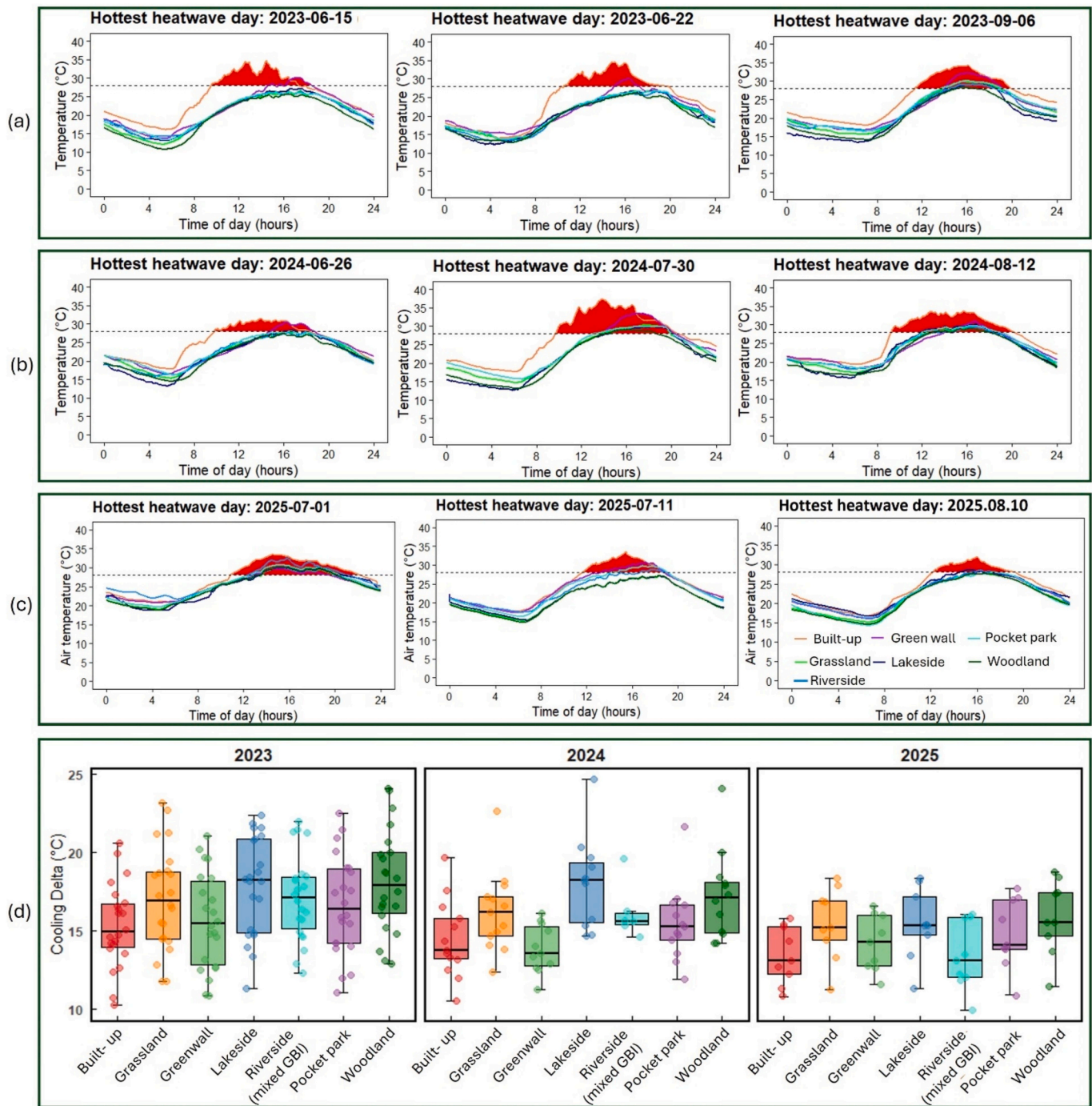


Fig. 8. Diurnal air temperature profiles for the hottest day within each identified heatwave event during the study period. Panels present the hottest heatwave days for (a) 2023 (15 June, 22 June, and 6 September), (b) 2024 (26 June, 30 July, and 12 August), and (c) 2025 (1 July, 11 July, and 10 August). Lines represent diurnal air temperature variation across the monitored GBI and built-up sites. The dashed horizontal line indicates the heatwave threshold (28 °C), and red shaded areas denote periods during which air temperature exceeded this threshold. (d) Nocturnal cooling magnitude (°C) across the monitored GBI sites during heatwave events (2023–2025). Cooling magnitude is defined as the difference between the daytime maximum air temperature and the subsequent nighttime minimum. Boxplots illustrate the distribution of daily cooling magnitude (median, interquartile range, and range). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

differed among the monitored sites during extreme heat events.

Overall, these results indicate that heatwave-related temperature contrasts varied across the monitored GBI settings, with larger and more persistent temperature contrasts generally observed at the woodland, lakeside and grassland sites relative to the built-up reference. While smaller-scale interventions such as the pocket park site were associated with meaningful daytime cooling, their nighttime effectiveness was

more limited. The green wall site showed smaller and more variable contrasts during extreme heat, particularly at night. These findings highlight the importance of integrating GBIs into urban design strategies aimed at reducing both daytime and nocturnal heat stress during future heatwaves.

Nocturnal recovery was also compared among the monitored sites during heatwave events (Fig. 8d). This was quantified by calculating the

decline in air temperature from maximum daytime heat to the subsequent minimum nighttime temperature for each monitored site. This metric captures the capacity of different GBIs to mitigate accumulated heat compared to the built-up area that tends to remain thermally trapped by residual daytime heat.

Analysis of the three-year dataset revealed differences in nocturnal recovery among the monitored GBI sites. The largest median nocturnal recovery magnitudes were observed at the lakeside and woodland sites. In 2023, these sites achieved median cooling magnitudes of 18.2 °C and 17.9 °C, respectively—nearly 3 °C greater than the built-up area. In 2024, median cooling magnitudes were 18.1 °C (lakeside) and 17.1 °C (woodland), compared with 13.8 °C in the built-up area. In 2025, the lakeside and woodland sites recorded median cooling magnitudes of 15.3 °C and 15.5 °C, respectively, while the built-up area reached 13.1 °C.

The riverside site exhibited intermediate but year-dependent recovery magnitudes. In 2023, it achieved a median cooling magnitude of 17.1 °C, approaching the values observed at the grassland and woodland sites and exceeding that of the built-up area. In 2024, the median declined to 15.6 °C, remaining above that of the built-up area but below lakeside and woodland sites. However, in 2025, the riverside site recorded a median cooling magnitude of 13.1 °C, comparable to the built-up area, indicating reduced nocturnal recovery. Notably, this decline coincided with a substantially higher cumulative heatwave duration in 2025 compared with 2023 and 2024 (Fig. 7e), suggesting that prolonged heat exposure was associated with a decline in the nocturnal recovery magnitude of the mixed GBI site.

The green wall and pocket park sites showed greater interannual variability. While they outperformed the built-up area, their nocturnal cooling capacity was lower compared to the larger monitored GBI sites. In 2023, median cooling deltas were 16.4 °C for the pocket park and 15.5 °C for the green wall sites. In 2024, these values declined to 15.3 °C and 13.6 °C, respectively. In 2025, the pocket park and green wall sites recorded median nocturnal recovery magnitudes of 14.1 °C and 14.3 °C, respectively.

The larger nocturnal recovery magnitudes observed at the water-associated and densely canopied sites are consistent with more rapid heat dissipation than at the built-up reference. However, the underlying processes were not measured directly and require further investigation. Moreover, the ability of GBI sites to provide nocturnal thermal relief may reach a point of saturation under severe heatwave conditions, which requires further investigation in future studies.

3.8. Satellite-based analysis of land surface temperature

Analysis of summer LST across the monitored GBI settings revealed pronounced spatial and temporal differences in surface thermal conditions over 2023–2025. Examination of the built-up baseline indicated an interannual increase, with mean summer LST increasing from 28.0 °C in 2023 to 28.5 °C in 2024 and reaching 29.0 °C in 2025, suggesting that 2025 represented the warmest summer within the study period (Fig. 9a–g).

Exceedances of 28 °C were mainly observed in the smaller and mixed extraction areas (Fig. 9h). The woodland site remained below this threshold throughout the study period, whereas the lakeside, grassland, riverside and green wall sites exceeded 28 °C in the hotter summers. In 2025, the pocket park site LST exceeded 28 °C less frequently than the built-up area, although its overall LST values were similar to that of the built-up area, potentially because the extraction polygon included paved surfaces and mixed land-cover materials.

During the summer period (2023–2025), clear differences in LST were observed between the built-up area and the monitored extraction areas (Fig. 9i). The built-up extraction area had a mean summer LST of 29.8 °C. In contrast, the woodland extraction area recorded the lowest mean LST (21.4 °C), corresponding to a surface temperature contrast (ΔT relative to the built-up area) of 8.4 °C. The lakeside extraction area

had a mean LST of 22.9 °C ($\Delta T = 6.9$ °C). Smaller surface temperature contrasts were observed for the green wall (27.3 °C; $\Delta T = 2.5$ °C), grassland (27.9 °C; $\Delta T = 1.9$ °C), and riverside (mixed GBI) extraction areas (28.4 °C; $\Delta T = 1.4$ °C). The smallest observed surface temperature contrast among the extraction areas was recorded for the pocket park, with a mean summer LST of 28.9 °C, representing a 1 °C reduction relative to the built-up area. These results indicate pronounced spatial differentiation in summer surface thermal conditions across the monitored areas. Overall, the LST analysis revealed pronounced spatial differentiation in surface thermal conditions, with the largest contrasts relative to the built-up extraction area observed for the woodland and lakeside areas. By extending the in-situ monitoring to polygon-scale surface patterns, the satellite analysis provides an important complementary perspective on spatial thermal heterogeneity across the study areas. These results are not interpreted as direct confirmation of near-surface air temperature cooling because radiometric LST and shielded air temperature represent distinct physical quantities and spatial sampling scales. Interannual variation in LST, including the increasing built-up baseline, further demonstrates the influence of yearly climatic conditions on surface thermal patterns. The in-situ sensors provide the primary evidence for local near-surface air temperature contrasts, while Landsat-derived LST provides broader surface temperature context. This distinction is particularly important for the pocket park, riverside, and green wall extraction areas, whose small spatial extent and integration with surrounding roads, buildings, and other impervious surfaces produce mixed LST signals. The spatial resolution of Landsat thermal data also cannot resolve narrow vertical features or pedestrian-level micro-climatic conditions.

3.9. Synthesis, limitations and planning implications

Across the seasonal, diurnal, heatwave and satellite-based analyses, the observed temperature contrasts reflected the combined influence of vegetation structure, intervention scale, surface composition and temporal context. The woodland site showed relatively consistent thermal moderation across the analyses, a pattern that is consistent with persistent canopy shading, evapotranspiration and reduced heat storage relative to impervious urban surfaces (Bowler et al., 2010; Gallay et al., 2023). The lakeside site showed comparatively large contrasts during summer and nocturnal recovery, consistent with the high heat capacity and thermal inertia of water (Theeuwes et al., 2013). A relatively large peak-summer contrast was also observed at the grassland site, although its reliance on evapotranspiration may make its cooling benefit more sensitive to soil moisture and vegetation conditions during prolonged dry periods. By contrast, the more variable responses of the pocket park, riverside and green wall sites reflect a greater dependence on intervention size, surrounding impervious cover, wall orientation and local urban geometry, consistent with previous evidence that GBI cooling is strongly context-dependent (Norton et al., 2015; Makido et al., 2019).

These interpretations should be considered in relation to the study design. Each GBI typology was represented by a specific monitoring location; therefore, typology effects cannot be completely separated from the characteristics of the individual sites. Accordingly, the differences observed should not be interpreted as a universal ranking of GBI typologies but as the cooling contrasts recorded at the monitored sites. Replication across multiple examples of each typology, together with measurements of sky view factor, canopy cover, impervious fraction, surrounding building density and local ventilation characteristics, would be required to more clearly isolate typology effects from site-specific controls. The use of a single built-up reference site is also a limitation because built-up areas vary in sky view factor, street geometry, building density, surface materials, traffic exposure and ventilation. The reported temperature differences therefore represent contrasts with the selected high-exposure urban reference rather than with the full range of built-up conditions. Canopy structure, soil moisture, irrigation, vegetation physiological condition and local airflow were not measured

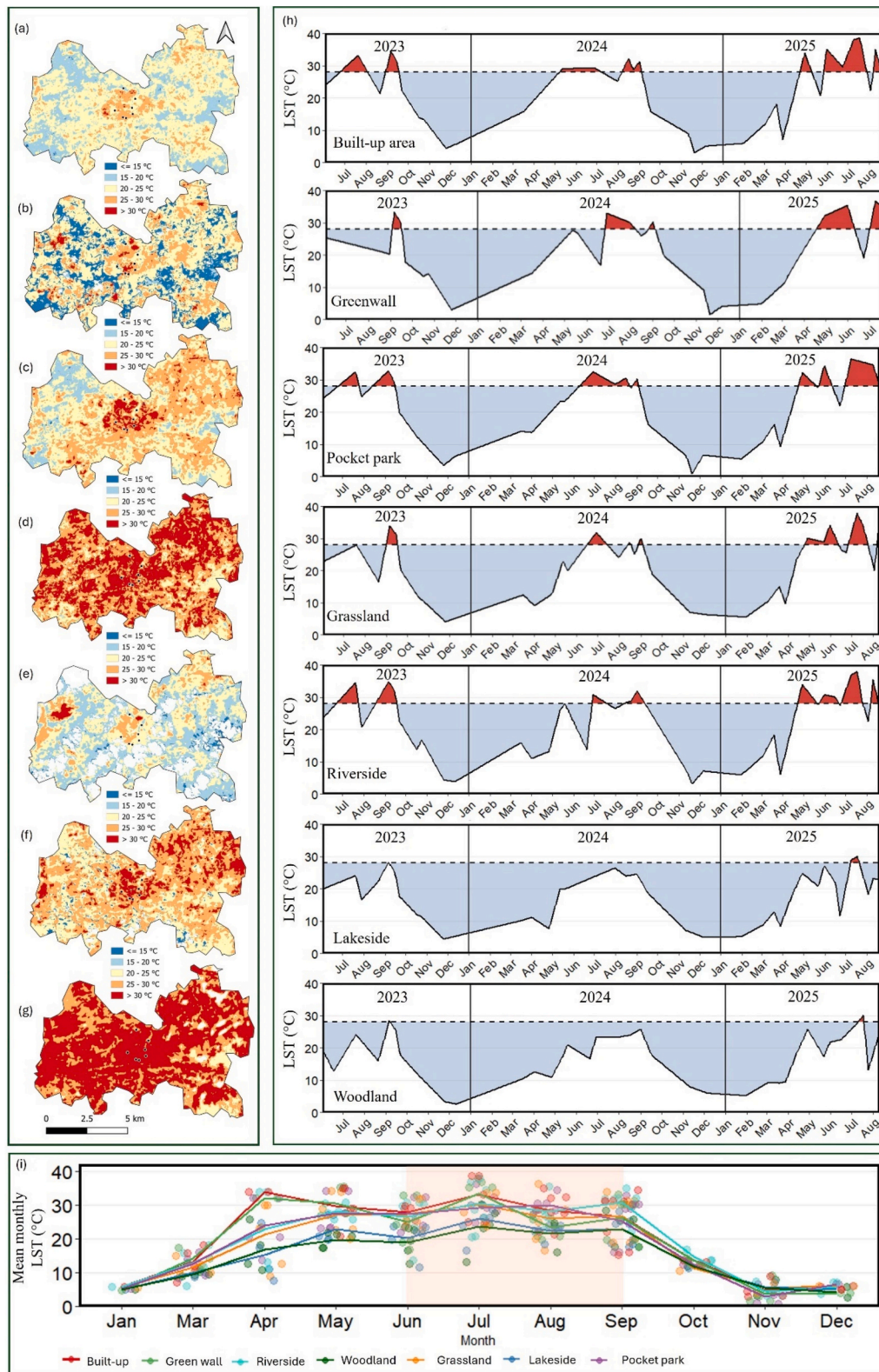


Fig. 9. (a) LST across Guildford for the full study period (June 2023–August 2025). (b–d) Summer LST maps for 2023, 2024, and 2025, respectively. (e–g) LST during peak heatwave events in 2023, 2024, and 2025. (h) LST time series for the built-up area and GBI sites; the dashed line marks the 28°C heatwave threshold and red shading indicates exceedances. (i) Monthly mean LST (2023–2025) for study sites; each point represents the monthly mean aggregated over the study period, and the shaded area indicates the summer season (June–August). LST represents polygon-scale radiometric surface temperature; interpretation of the pocket park, riverside, and green wall sites is constrained by their small spatial extent and mixed land cover composition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in this study. The mechanisms discussed above should consequently be regarded as explanations consistent with the observed thermal patterns and previous literature. In addition, satellite-derived LST and near-surface air temperature represent distinct physical quantities and sampling scales. Accordingly, LST was used to contextualise broad surface temperature patterns rather than to validate the magnitude or ordering of the in-situ air temperature contrasts, particularly for the small and mixed-pixel extraction areas.

The comparatively persistent temperature contrasts observed at the woodland and lakeside sites suggest potential value in further evaluating large, continuous vegetated and water-associated spaces as components of urban thermal-resilience planning. The responses observed at the smaller monitored sites also indicate that surrounding materials, orientation, vegetation condition and the intended period of protection should be considered when assessing such settings. Given the single-site representation of each GBI category, these findings should inform rather than prescribe typology selection. Planning assessments should therefore consider the magnitude and temporal persistence of site-level temperature contrasts, particularly during prolonged periods of extreme heat, rather than relying solely on mean temperature differences.

4. Summary, conclusions and future outlook

A long-term monitoring campaign, integrating both a high-resolution fixed sensor network and satellite-derived LST observations, was conducted over a three-year period in an urban area in the UK. The study compared thermal conditions at six monitored GBI sites—woodland, lakeside, grassland, pocket park, riverside (mixed), and green wall—against a built-up reference area. The objective was to quantify seasonal and extreme-heat temperature contrasts between the monitored GBI settings and the built-up reference, thereby providing multi-year evidence of site-level temperature contrasts under seasonal and extreme heat conditions. The findings provide context-specific evidence relevant to climate-responsive urban design and the strategic deployment of GBIs to mitigate present and future heat risks. This work provides insights for urban planners to strategically incorporate GBIs into the urban fabric to enhance climate resilience and support Sustainable Development Goal 11 (Sustainable Cities and Communities) and 13 (Climate Action).

Based on the analysis, the following conclusions were drawn:

- Seasonal air temperatures varied across GBI monitoring sites, with clear differences in temperature distributions and variability. Two-way ANOVA confirmed that season was the primary predictor of variation ($\eta^2 = 0.442$), while the categorical monitoring-site factor, labelled “typology” in the model, accounted for a significant secondary effect ($\eta^2 = 0.027$), and the interaction was minimal ($\eta^2 = 0.003$), demonstrating that both temporal and spatial factors co-vary with urban thermal conditions.
- Diurnal air temperature patterns varied across the monitored GBI sites, with daytime consistently warmer than nighttime and peak temperatures occurring between 14:00 and 16:00 h. The built-up area showed the largest day–night range ($\sim 5.3^\circ\text{C}$ in summer), reflecting high heat storage, while the lakeside, woodland, and grassland exhibited smaller diurnal fluctuations, indicating greater thermal stability. The green wall, pocket park, and riverside (mixed GBI) typologies displayed intermediate patterns, balancing shading, evapotranspiration, and surface insulation effects. These findings demonstrate that site-level thermal conditions and time of day significantly shape urban thermal dynamics, influencing exposure to heat extremes and the temporal distribution of cooling benefits.
- Site-level temperature contrasts between the monitored GBI sites and the built-up reference exhibited distinct temporal and diurnal dynamics. The largest contrasts were observed during summer afternoons (ΔT up to $\sim 2.5^\circ\text{C}$), while contrasts were smaller at night.

Positive daytime contrasts were observed at the woodland, grassland, lakeside, pocket park, and riverside (mixed GBI) sites, whereas the green wall site showed a smaller daytime contrast and occasional slight nighttime warming relative to the built-up reference.

- Statistical analysis using LMM identified significant differences among the monitored settings during peak summer hours (12:00–16:00 h). The largest ΔT was observed at the woodland site ($\Delta T: 2.5^\circ\text{C}$, $p < 0.001$), while the smallest was observed at the green wall site (1.8°C , $p < 0.001$); the other monitored GBI sites showed intermediate values, with some overlap among the estimated effects.
- During summer daytime conditions, built–GBI air temperature contrasts ranged from 1.1 to 1.8°C under southeasterly winds to 2.0 – 2.9°C under northeasterly and westerly winds. These patterns indicate that the magnitude of GBI–built-up temperature differences varied with regional background wind conditions; however, they should not be interpreted as evidence of local airflow or site-specific aerodynamic mechanisms.
- Heatwave threshold occurrence and temperature intensity differed substantially among the monitored sites. The built-up area experienced the highest daytime heatwave threshold occurrence (19.6%) and the greatest cumulative duration (54 days over 2023–2025), with peak temperatures reaching 37.3°C . All monitored GBI sites recorded lower threshold occurrence than the built-up reference, with the woodland site (0%) showing the lowest daytime occurrence and no recorded heatwave events across the three summers. Mean daytime heatwave temperatures were also lower at the monitored GBI sites (28.7 – 29.9°C) compared with the built-up area (30.5°C), indicating lower mean and upper-end thermal conditions during the identified heatwave periods.
- Event-based analysis of ten extreme heatwave events (2023–2025) showed that the magnitude, persistence and nighttime behaviour of the observed temperature contrasts varied across the monitored GBI settings under severe thermal stress. The largest mean daytime ΔT was observed at the woodland site (mean $\Delta T = 4.5^\circ\text{C}$; maximum up to 9.1°C), followed by the grassland and lakeside sites ($\sim 4.0^\circ\text{C}$) sites. Smaller mean contrasts were recorded at the pocket park, riverside, and green wall sites. At night, comparatively large recovery magnitudes were observed at the woodland and lakeside sites (mean $\Delta T: 3.0^\circ\text{C}$ and 2.6°C), whereas the green wall site exhibited a limited (mean $\Delta T = 0.6^\circ\text{C}$) and more variable contrast. Interannual differences, particularly in 2025, indicated potential saturation of cooling capacity under prolonged heat exposure, especially for mixed and smaller-scale interventions.
- Satellite-based analysis of summer LST (2023–2025) revealed pronounced polygon-scale surface-temperature contrasts across the monitored extraction areas. The largest contrasts relative to the built-up extraction area were observed for the woodland ($\Delta T \approx 8.4^\circ\text{C}$) and lakeside extraction areas ($\Delta T \approx 6.9^\circ\text{C}$), while smaller contrasts were observed at the other extraction areas. These findings extend the fixed-site analysis by providing broader spatial context for surface thermal heterogeneity. However, because LST and shielded near-surface air temperature represent distinct physical quantities and sampling scales, the satellite results were not interpreted as direct confirmation of pedestrian-level air-temperature cooling. Moreover, the interannual warming trends highlight the influence of yearly climatic conditions on temperature contrasts.

These findings provide a multi-year assessment of site-level thermal contrasts across the monitored settings. However, the interpretation of the wind regime results should consider the spatial resolution of the supporting meteorological data. Wind speed and direction were obtained from the off-site Wisley meteorological station and the Open-Meteo dataset rather than measured directly at the monitoring sites. These data are suitable for characterising regional background wind conditions, but local airflow may differ because of vegetation structure, building geometry, surface roughness, wall orientation, and proximity

to water bodies. Therefore, the wind regime results should not be interpreted as evidence of site-specific aerodynamic mechanisms. Future studies incorporating co-located wind measurements would enable a more direct assessment of how local airflow influences the observed GBI temperature contrasts relative to the built-up area reference site.

The study findings indicate that GBI may contribute to public-health protection indirectly by moderating high ambient temperatures during periods of heat stress. Nevertheless, the present study does not quantify health outcomes, individual exposure, morbidity or mortality. Future work should link microclimatic monitoring with population distribution, vulnerable-group exposure, behavioural patterns and health-outcome data to estimate direct public-health benefits.

Overall, the study demonstrates that the monitored GBI settings in Guildford were generally cooler than the selected built-up reference site, but the results should be interpreted within the limits of the single-site-per-typology design. Future research should include multiple monitoring sites for each GBI typology and multiple built-up reference sites representing different urban morphologies, together with sensitivity analyses to assess how site-specific characteristics, such as canopy cover, sky view factor, impervious fraction, surrounding building density, and local ventilation, influence the observed cooling performance and the magnitude of GBI-built-up temperature contrasts. Moreover, future studies should combine long-term fixed monitoring with mobile transects, dense edge-to-centre sensor arrays, or high-resolution urban climate modelling to quantify how cooling extends beyond GBI boundaries into adjacent streets and neighbourhoods. This is particularly important for small interventions such as pocket parks and green walls, where local benefits may extend beyond the sensor point but remain unresolved by the present design.

Future research should prioritise the long-term resilience of these nature-based solutions under escalating climatic stress. The relatively large daytime temperature contrast observed at the grassland site raises critical questions about the persistence of this site-level response under drought and vegetation dormancy. As summer heatwaves intensify, it is essential to investigate how the transition of transpiring grass into dry, dormant vegetation may reduce evapotranspiration and potentially shift these spaces from cooling assets to heat contributors. Furthermore, future efforts should quantify the minimum water availability and soil moisture thresholds required to sustain the cooling contrasts associated with various GBI settings, particularly for smaller-scale interventions that are more sensitive to environmental conditions. Addressing these gaps will provide the evidence-based guidance necessary to ensure that urban greening strategies remain effective in a warming and increasingly water-constrained climate.

CRediT authorship contribution statement

Soheila Khalili: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Laurence Jones:** Writing – review & editing, Supervision, Investigation, Funding acquisition. **Prashant Kumar:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envint.2026.110452>.

Data availability

Data will be made available on request.

References

- Abdulateef, M.F., Al-Alwan, A.S., H., 2022. The effectiveness of urban green infrastructure in reducing surface urban heat island: Baghdad city as a case study. *Ain Shams Eng. J.* 13, 101526.
- Bartesaghi-Koc, C., Osmond, P., Peters, A., 2022. Innovative use of spatial regression models to predict the effects of green infrastructure on land surface temperatures. *Energ. Buildings* 254, 111564.
- Bowler, D.E., Buyung-Ali, L., Knight, T.M., Pullin, A.S., 2010. Urban greening to cool towns and cities: a systematic review of the empirical evidence. *Landsc. Urban Plan.* 97, 147–155.
- Chen, M., Jia, W., Yan, L., Du, C., Wang, K., 2022. Quantification and mapping cooling effect and its accessibility of urban parks in an extreme heat event in a megacity. *J. Clean. Prod.* 334, 130252.
- Cheung, P.K., Jim, C.Y., 2018. Comparing the cooling effects of a tree and a concrete shelter using PET and UTCI. *Build. Environ.* 130, 49–61.
- ClimateData, 2025. Guildford climate. Retrieved July 07, 2025. Available at: <https://en.climate-data.org/europe/united-kingdom/england/guildford-60140/>.
- Copernicus Climate Change Service, 2025. ERA5-Land hourly data from 1950 to present. Copernicus Climate Data Store (CDS). Retrieved March 4, 2026. Available at: <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land?tab=overview>.
- Doran, E., Reichard, W., Boothe, M., Donnell, G., Fan, H., Rowangould, G., Guensler, R., 2025. Mitigating Extreme Heat Exposure Using Advanced and Novel Materials and Improved Pedestrian Infrastructure Design: A Systematic Literature Review and Survey of Agencies.
- Gallay, I., Olah, B., Murtinová, V., Gallayová, Z., 2023. Quantification of the cooling effect and cooling distance of urban green spaces based on their vegetation structure and size as a basis for management tools for mitigating urban climate. *Sustainability* 15 (4), 3705.
- Herath, H.M.P.I.K., Halwatura, R.U., Jayasinghe, G.Y., 2018. Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy. *Urban Forest. Urban Green.* 29, 212–222.
- Huang, J., Hao, T., Wang, Y., Jones, P., 2022. A street-scale simulation model for the cooling performance of urban greenery: evidence from a high-density city. *Sust. Cities Soc.* 82, 103908.
- Imran, H.M., Kala, J., Ng, A.W.M., Muthukumaran, S., 2019. Effectiveness of vegetated patches as Green Infrastructure in mitigating Urban Heat Island effects during a heatwave event in the city of Melbourne. *Weather Clim. Extrem.* 25, 100217.
- Jia, S., Wang, Y., 2021. Effect of heat mitigation strategies on thermal environment, thermal comfort, and walkability: a case study in Hong Kong. *Build. Environ.* 201, 107988.
- Jones, L., Reis, S., Hutchins, M., Miller, J., He, B., Seifert-Dähn, I., Xu, C.-Y., et al., 2022. Airsheds, watersheds and more—the flows that drive intra-extra-urban connections, and their implications for nature-based solutions (NBS). *Nat.-Based Solut.* 2, 100040.
- Joshi, K., Khan, A., Anand, P., Sen, J., 2024. Understanding the synergy between heat waves and the built environment: a three-decade systematic review informing policies for mitigating urban heat island in cities. *Sust. Earth Rev.* 7 (1), 25.
- Khalili, S., Jones, L., Pfautsch, S., Kumar, P., 2026. Quantifying the benefits of parks for mitigating heat, air and noise pollution to inform climate-resilient planning. *City Environ. Interact.* 31, 100407.
- Köppen Earth, 2025. Köppen climate classification map. Retrieved May 21, 2025. Available at: <https://koppen.earth/>.
- Kumar, P., 2021. Climate change and cities: challenges ahead. *Front. Sust. Cities* 3, 645613.
- Kumar, P., Debele, S., Khalili, S., Halios, C.H., Sahani, J., Aghamohammadi, N., Andrade, M.F.A., Athanassiadou, M., Bhui, K., Calvillo, N., Cao, S.J., Coulon, F., Edmondson, J.E., Fletcher, D., Freitas, E.D., Guo, H., Hort, M.C., Katti, M., Kjeldsen, T.R., Lehmann, S., Locosselli, G.M., Malham, S.K., Morawska, L., Parajuli, R., Rogers, C.D.F., Yao, R., Wang, F., Wenk, J., Jones, L., 2024. Urban heat mitigation by green and blue infrastructure: a review of drivers, effectiveness, and future needs. *The Innovation* 5 (2), 100588.
- Kumar, P., Corada Perez, K., Biswal, A., Sun, H., Dwivedi, A.K., Hama, S., Khalili, S., et al., 2025. Overlooked considerations in prescribing green and blue infrastructure solutions for urban environments. *The Innovation*.
- Lau, S.S., Lin, P., Qin, H., 2012. A preliminary study on environmental performances of pocket parks in high-rise and high-density urban context in Hong Kong. *Int. J. Low-Carbon Technol.* 7 (3), 215–225.

- Lemoine-Rodríguez, R., Inostroza, L., Falfán, I., MacGregor-Fors, I., 2022. Too hot to handle? on the cooling capacity of urban green spaces in a Neotropical Mexican city. *Urban Forest. Urban Green.* 74, 127633.
- Li, Y., Fan, S., Li, K., Zhang, Y., Kong, L., Xie, Y., Dong, L., 2021. Large urban parks summertime cool and wet island intensity and its influencing factors in Beijing, China. *Urban Forest. Urban Green.* 65, 127375.
- Liu, L., Wang, S., Dou, J., Chen, G., Hang, J., Yang, X., 2025. Modeling the vertical air temperature rise patterns of densely-built urban canyons under building anthropogenic heat via a scaled outdoor experiment. *Build. Environ.* 290, 114133.
- Makido, Y., Hellman, D., Shandas, V., 2019. Nature-based designs to mitigate urban heat: the efficacy of green infrastructure treatments in Portland, Oregon. *Atmosphere* 10 (5), 282.
- Manavvi, S., Milosevic, D., 2025. Chasing cool: Unveiling the influence of green-blue features on outdoor thermal environment in Roorkee (India). *Build. Environ.* 267, 112238.
- Marando, F., Salvatori, E., Sebastiani, A., Fusaro, L., Manes, F., 2019. Regulating ecosystem services and green infrastructure: assessment of Urban Heat Island effect mitigation in the municipality of Rome, Italy. *Ecol. Model.* 392, 92–102.
- Marando, F., Heris, M.P., Zulian, G., Udías, A., Mentaschi, L., Chrysoulakis, N., Parastatidis, D., Maes, J., 2022. Urban heat island mitigation by green infrastructure in European Functional Urban areas. *Sust. Cities Soc.* 77, 103564.
- Met Office (UKMO) MIDAS Open, 2025. Surrey — 00719 Wisley hourly weather observations, QC version 1. CEDA Archive. Retrieved February 11, 2026, from https://data.ceda.ac.uk/badc/ukmo-midas-open/data/uk-hourly-weather-obs/dataset-version-202507/surrey/00719_wisley/qc-version-1.
- MetOffice, 2025. How is Summer 2025 shaping up so far?. Retrieved August 07, 2025. Available at <https://www.metoffice.gov.uk/blog/2025/how-is-summer-2025-shaping-up-so-far>.
- MetOffice (2025). Summer. Retrieved July 07, 2025. Available at: <https://weather.metoffice.gov.uk/learn-about/weather/seasons/summer>.
- Morakinyo, T.E., Ouyang, W., Lau, K.K.L., Ren, C., Ng, E., 2020. Right tree, right place (urban canyon): tree species selection approach for optimum urban heat mitigation - development and evaluation. *Sci. Total Environ.* 719, 137461.
- Nagar, C., Verma, S.K., Sen, S., 2025. Synergistic deployment of green infrastructure and reflective pavements for mitigation of UHI within urban blocks. *Disc. Cities* 2 (1), 7.
- Norton, B.A., Coutts, A.M., Livesley, S.J., Harris, R.J., Hunter, A.M., Williams, N.S.G., 2015. Planning for cooler cities: a framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landsc. Urban Plan.* 134, 127–138.
- Office for National Statistics (ONS), 2022. How the population changed in Guildford: Census 2021. <https://www.ons.gov.uk/visualisations/censuspopulationchange/E07000209/>.
- Open-Meteo, 2026. Historical weather API documentation. Retrieved February 11, 2026, from https://open-meteo.com/en/docs/historical-forecast-api?latitude=51.31&longitude=-0.47&start_date=2025-01-01&end_date=2025-08-31&hourly=temperature_2m,wind_speed_10m,wind_direction_10m.
- Ouyang, W., Morakinyo, T.E., Ren, C., Liu, S., Ng, E., 2021. Thermal-irradiant performance of green infrastructure typologies: field measurement study in a subtropical climate city. *Sci. Total Environ.* 764, 144635.
- Pataki, D.E., Carreiro, M.M., Cherrier, J., Grulke, N.E., Jennings, V., Pincetl, S., Pouyat, R.V., Whitlow, T.H., Zipperer, W.C., 2011. Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. *Front. Ecol. Environ.* 9 (1), 27–36.
- Qiu, K.B., Jia, B.Q., Cheng, J.F., 2017. Cool island effect of urban parks and its influencing factors within the Fifth Ring in Beijing. *Chin. J. Ecol.* 36, 1984–1992.
- Sahani, J., Kumar, P., Debele, S.E., 2023. Efficacy assessment of green-blue nature-based solutions against environmental heat mitigation. *Environ. Int.* 179, 108187.
- Su, W., Zhang, L., Chang, Q., 2022. Nature-based solutions for urban heat mitigation in historical and cultural block: the case of Beijing Old City. *Build. Environ.* 225, 109600.
- Theeuwes, N.E., Solceroova, A., Steeneveld, G.J., 2013. Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city. *J. Geophys. Res. Atmos.* 118 (16), 8881–8896.
- Tiwari, A., Kumar, P., Kalaiarasan, G., Ottosen, T.B., 2021. The impacts of existing and hypothetical green infrastructure scenarios on urban heat island formation. *Environ. Pollut.* 274, 115898.
- Venter, Z.S., Krog, N.H., Barton, D.N., 2020. Linking green infrastructure to urban heat and human health risk mitigation in Oslo, Norway. *Sci. Total Environ.* 709, 136193.
- Wang, Y., Ni, Z., Chen, S., Xia, B., 2019. Microclimate regulation and energy saving potential from different urban green infrastructures in a subtropical city. *J. Clean. Prod.* 226, 913–927.
- Wang, Y., Ni, Z., Hu, M., Chen, S., Xia, B., 2021. A practical approach of urban green infrastructure planning to mitigate urban overheating: a case study of Guangzhou. *J. Clean. Prod.* 287, 124995.
- Wang, K., Aktas, Y.D., Malki-Epshtein, L., Wu, D., Abdullah, M.F.A.B., 2022a. Mapping the city scale anthropogenic heat emissions from buildings in Kuala Lumpur through a top-down and a bottom-up approach. *Sust. Cities Soc.* 76, 103443.
- Wang, X., Li, H., Sodoudi, S., 2022b. The effectiveness of cool and green roofs in mitigating urban heat island and improving human thermal comfort. *Build. Environ.* 217, 109082.
- Yilmaz, S., Başak, Mutlu, E., Aksu, A., Mutlu, E., Qaid, A., 2021. Street design scenarios using vegetation for sustainable thermal comfort in Erzurum, Turkey. *Environ. Sci. Pollut. Res.* 28, 3672–3693.
- Ziaul, S., Pal, S., 2020. Modeling the effects of green alternative on heat island mitigation of a meso level town, West Bengal, India. *Adv. Space Res.* 65 (7), 1789–1802.