# Adaptive comfort assessments in urban neighbourhoods: Simulations of a residential case study from London

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ABSTRACT

A warming climate, increasing frequency and severity of extreme heat events, and the heat island effect are cumulatively expected to exacerbate climate thermal loading on urban buildings. This in turn could lead to increased summertime overheating risk, with any active means for addressing this likely to influence future energy consumption and $CO_2$ emission patterns. This paper examines how the microclimatic loading presented by the heat island (UHI) effect influences summertime adaptive comfort in urban residential buildings. The method for addressing this is the simulation of a residential street canyon within the London heat island. Key findings highlighted adaptive capabilities to achieve summertime 'comfort' in most rooms without the need for energy intensive mechanical cooling. The indiscriminate and widespread adoption of mechanical cooling within the canyon length is estimated to result in a 0.4 K increase in nocturnal canyon temperatures, and an additional 4.4% of $CO_2$ released to the climate. In contrast, a targeted approach to addressing residual risk more than halves the canyon $CO_2$ emission estimate, which in turn highlights the necessity for detailed overheating assessments in estimating energy use in 'difficult to cool' residential neighbourhoods within UHIs.

Keywords: Adaptive comfort; urban heat island effect; space-conditioning; cooling loads; urban energy use.



## 1. Introduction

The influences of climate change and the heat island (UHI) effect are expected to exacerbate environmental thermal loading on urban buildings. This is likely to lead to increased summertime overheating risk with potential for causing adverse effects to the health and wellbeing of building occupants. The use of active means for addressing such heat-related risks are likely to influence future energy consumption and $CO_2$ emissions, particularly in residential areas where cooling has traditionally received less attention in temperate climate cities in Europe and the UK.

The heat island experienced in cities relative to rural contexts results from a net positive thermal balance that arises from surface property changes; including increased morphological roughness that affects the radiative balance and convective cooling efficiency [1–3], high heat storage and low albedo material use [4], reduced evapotranspiration from green and blue-space loss and high surface water runoff [3,4], and increased heat and pollution generated from human activities [1]. The UHI effect that results is an additional environmental thermal load that affects how energy is used within buildings, with potential benefit in winter and increased consumption in summer. Building energy use in turn contributes to and intensifies UHIs by feeding back heat as anthropogenic emissions [4,5]. If high-energy solutions are increasingly adopted to condition buildings in the summer, the net annual influence could generate a positive feedback-loop of ever-worsening energy expenditure, $CO_2$ emissions, and a warming and unhealthy urban environment [6,7].

The purpose of this study is to identify summertime heat island influence and its degree of significance to indoor conditions of urban residential units, and its relevance when considering adaptive comfort assessments. To achieve this in a manner that is not reliant on site-specific measured data and suitable for wider applicability, the study presents the combined approach of using an urban climate framework and a building energy model, as a simplified and computationally efficient simulation pathway to estimate UHI influence on indoor comfort and corresponding building energy use.

### *1.1. Background to domestic overheating*

Dwelling characterisation is a significant determinant of overheating risk [8]. Main characteristics include solar heat gain defences, ventilation rates, thermal capacity, and insulation of the structure; all of which describe how dwellings modify the coupling between outdoor and indoor environments [9]. Reviews of the UK dwelling stock have revealed those built before 1920 (particularly uninsulated loft conversions), 1960s, and post-1990s to be at heightened risk [9]. In contrast to larger detached dwellings, apartment flats and mid-terraced dwellings tend to have increased vulnerability due to their compact arrangements and spatial standards [10,11]. As a concern, most high-density arrangements (e.g. 95% of high-rise flats) tend to be sited in central urban areas, where the risk of overheating is heightened by high occupancy gains and the additional climate load from the UHI effect [11]. In this study, a simplified climate model is utilised to account for this heightened urban risk by simulating a reasonable approximation of the relevant local canyon climate. This is significant given that the weather file used in simulations have been found to present the largest impact on overheating estimation [12].



Previous studies on domestic overheating have consistently identified higher risk for top-floor flats and terraced house attics [13]. This is attributed to relatively higher exposure to solar thermal loading transferring into indoor rooms (pronounced with poorly insulated constructions); as well as by the trapping of buoyancy-driven internal airflow (pronounced with constructions with high airtightness). Single-aspect arrangements (particularly south-facing) exacerbate the issue by preventing cross-ventilation and being adversely affected by heat flow from adjoining units [14]. The management of flats and multiple-occupation units can also place arrangements at risk, as inadequately ventilated communal areas and circulation routes could transfer gains to adjoining dwelling units. Ground floor and basement units in contrast have been found to be relatively cooler, owing to reduced exposure to solar gains and greater heat conduction to the subsurface [15].

Until recently, such overheating risk had been estimated with the use of fixed thresholds. In recent times these have been criticised as attempts to define a phenomenon that is inherently imprecise [16], as well as being insensitive towards adaptive capacities particularly in free-running buildings. Updates to CIBSE guidance have consequently revised assessment practices to utilise Adaptive Comfort theory [17], which suggests a 'dynamic' threshold that is sensitive to external climate variations, as oppose to a fixed one that is either arbitrary or based on limited evidence. The approach allows for the natural adaptation of human physiology to seasonal durations of overheating as well as short-term daily intensities and relative maximum thresholds. This also allows for specific climate considerations such as heat island and heatwave influence to be included in determining overheating risk and prevents periods of discomfort and concomitant energy demand for cooling from being overestimated.

### *1.2. Adaptation and occupant behaviour*

Adaptation may be approached as environmental and behavioural modifications. The environmental adaptation of the built-environment may be approached from macro-scale urban planning to micro-scale detailing of buildings and their constituent rooms. The adaptation of urban parameters is associated with UHI influence, with the central objective to minimise heat storage factors of the urban energy balance [1]. Urban morphology, materiality, and green and blue-space distribution are such parameters that urban planning processes can modify to mitigate UHI intensities [3]. It is critical to incorporate such principles into urban policy, as their implementation will in turn drive building specific adaptations and determine their eventual efficacy. At the building scale, the available adaptation measures are numerous with varying efficiencies. Good ventilation for example is considered a fundamental necessity for moderating a free-running dwelling's indoor climate. Higher rates achieved by opening window vents is associated with efficient dissipation of heat from internal gains and absorbed climate loads. It increases airflow from one space to another to facilitate convective and advective heat dissipation. The existence of a temperature gradient (higher indoor temperature relative to outdoor) will make use of buoyancy forces to achieve natural convection. Convection is also forced by the movement of air by induced currents (pressure differential), with wind loading and turbulent flow on and around a building envelope forcing heat loss to a much greater efficiency, regardless of temperature gradients. Cross-ventilation facilitated by dual-aspect arrangements increases this forced convection benefit, while vent arrangements assist with buoyancy-driven natural convection flow. Vent opening however has limitations in certain conditions. On calm days with low wind flow (anticyclonic conditions typical of heatwaves and high UHI intensity) forced convection is less available for efficient heat dissipation, while conditions with negligible internal-to-external temperature gradient will reduce natural convection dissipation. This is particularly critical for night-purge ventilation strategies, as with a warming climate the diurnal temperature variation may not be enough to purge stored heat [18].

In addition to such behavioural tasks that seek to modify the environment, heat stress and thermal comfort relief is dependent on how occupants modify their own physiological state. The adjustment of activity levels (metabolic rate) and/or application of clothing are key physiological adaptations to consider and are dependent on the description of the occupants concerned. Effective engagement with adaptive strategies is also influenced by occupant rituals (routines and habits) [19]. Some habits are governed by occupant automatic decision-making processes, while others will be rational and reflective. The efficiency of engagement with adaptive measures consequently requires a deeper understanding of occupant descriptions as well as how their rituals might favour or inhibit the use of these measures. Building design must therefore seek to take account of occupant practices, rather than attempting to impose ideal behaviours. Individual occupant control in this regard has significant bearing on how users respond to warmer conditions. Greater control of the indoor climate is believed to increase the perception of comfort and encourage adaptive actions such as vent opening [20]. In domestic circumstances, occupants often have considerable advantage over the ability to control their environment unlike communal settings. This however is dependent on the physical and mental capacity of occupants. If occupants are faced with a vulnerability as with older people, lack of control over their surroundings may render adaptive approaches redundant. The nature of controls and the complexity of their operation are therefore significant aspects to consider in the design of Adaptive Comfort friendly domestic spaces.

## 2. Methodology

To approximate urban climate processes and influences, this study utilises the validated multiscale coupled framework published as the 'Urban Weather Generator' or UWG (V4.1.0) [21,22]. The framework is based on multiscale energy balances and Monin-Obukhov similarity theory and is composed of four coupled sub-models. A summary of principal data exchanges is presented in Gunawardena *et al.* [23], while detailed description of its workings is included in Bueno *et al.* [22,24], with field data validations from Basel, Toulouse, and Singapore included in Bueno *et al.* [22,24] and Nakano *et al.* [25]. The framework is primed with the input of a rural weather file, which is used by the sub-models to calculate temperature and humidity values to compile a modified urban canyon-specific weather file. This output file can then be used by dynamic building thermal modelling software to simulate indoor conditions and energy use of buildings representative of the canyon neighbourhood [23].

In this study, a case study morphology that represents an urban residential district in London (maritime temperate) is considered. To aggregate results, a site within a relatively uniform morphological context was selected, and a mid-terraced canyon section was extracted to represent the increased vulnerability of such compact arrangements [10,14]. This canyon section represents a 100 m extent of Gloucester Terrace in the Bayswater Conservation Area of Westminster. The buildings on either side of this canyon represent Grade II Listed terraces with narrow 4-5 storey townhouses including attics and basements (see Fig. 1). The construction includes stuccoed uninsulated masonry facades typical of the area, thick masonry uninsulated party-walls, timber joisted floors, and uninsulated slate and lead trimmed mansard roofs (see Table A1)[26]. Most units have been internally converted to multi-occupancy arrangements (which makes significant contribution to meeting housing needs of the area) [27], some with energy performance enhancements (disregarded for this study).

a) b)


**Fig. 1.** Gloucester Terrace, typical canyon view (© Google Earth, Street-view 2018) (**a**); and typical section (**b**).

The Gloucester Terrace morphology was normalised by averaging parameters to generate a roughness profile with a 500 m characteristic radius. The rural weather data used for this study was the Typical Meteorological Year (TMY) for London Gatwick (LGW) (~40 km due south of the site). This input weather data represents the rural boundary condition where the influence of the city is assumed negligible, and follows the 'rural' designation advocated by CIBSE [28] in relation to simulating the relative influences of London's climate. The roughness profile, together with the rural weather file were then input to the UWG to generate a new weather file that includes UHI influence on air temperature and humidity values for the canyon.

The resulting UWG profile was then applied to a thermal model of a representative mid-terraced unit of the Gloucester Terrace canyon, created using the dynamic simulation platform IES-VE [29] to estimate indoor environmental conditions and energy use. This simulation unit was considered for two occupancy profiles including small families (FamOcu) and older couples (EldOcu) as detailed in Appendix: Table A1. The overheating assessment firstly considered the now superseded CIBSE [30] and EST [31] fixed threshold criteria as a reference for the second assessment of the current Adaptive Comfort method [12,16,32]. The adaptive actions tested included increasing air change rates by increased window operation and usage of motorised fans. To address overheating concerns, air-conditioning scenarios were simulated for the unit in isolation as well as for the entire canyon neighbourhood (Table 1).

**Table 1**
Scenarios simulated.

| Scenario | Description |
|---|---|
| Base-LGW | Free-running base unit (as existing) simulated with rural LGW weather data |
| LGW+UHI | Free-running base unit simulated with UHI morphed weather data from the UWG |
| …+AC0 | Cooling load applied to Base-LGW unit @ summer profile (see Appendix, Table A2) |
| …+AC1 | Cooling load applied to LGW+UHI |
| …+UAC | Simulated with widespread cooling load in urban canyon (40 units) |

## 3. Results

The following presents firstly, the features of the weather files generated by the UWG with UHI influence included; secondly, indoor overheating assessments for the mid-terraced unit at Gloucester Terrace; and finally results from cooling scenarios.

### *3.1. Generated urban microclimate profile*

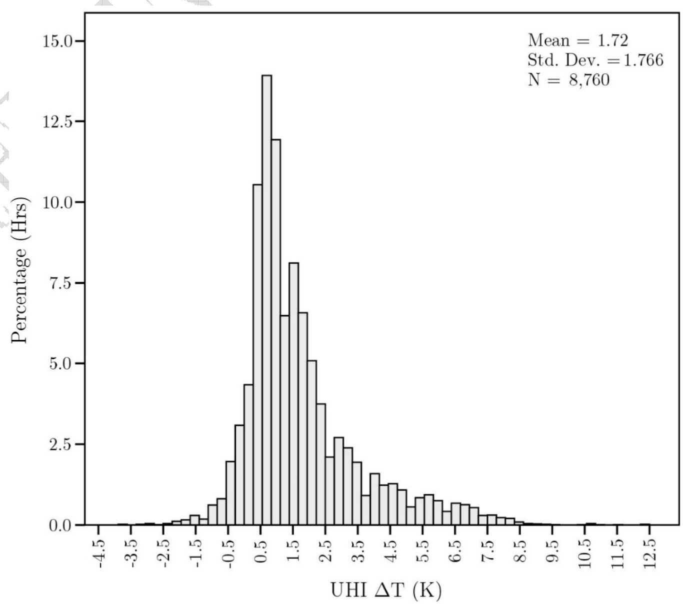



**Fig. 2.** Annual UHI △T (K) frequencies for canyon.

The UWG translation produced a microclimate profile for the Gloucester Terrace canyon with a UHI intensity (△T) annual mean of M = 1.72 K (SD = 1.66) and a summertime mean of M = 1.65 K (SD = 1.57); including summer UHI $\Delta T_{max}$ = 12.2 K and UHI $\Delta T_{min}$ = -2.2 K. While a direct comparison with observed historical data is not straightforward given the changes a city such as London has experienced over the years [32], a few studies can be presented to highlight the relative significance of the descriptive features of this simulation. The summer mean UHI $\triangle T$ for example is similar to the recorded 1.6 K for central London reported by Chandler [33] for data between 1931 and 1960; although is lower than the Watkins *et al.* [34] value of ~2.8 K measured in 1999. The simulated peak is considerably higher than the Watkins *et al.* [34] observed 8.0 K; 9.5 K derived from Bohnenstengel *et al.* [35] modelled data; and Doick *et al.* [36] measurements of 10.0 K for the nocturnal UHI. Reviews of UHI $\triangle T$ frequency distributions highlight these peak values as rare occurrences (<1%) [32]. The singular (hourly) high figure of the UWG translation could therefore be regarded as an extreme value in a frequency distribution that included intensities >9 K representing <0.2% of the annual hours (Fig. 2a).

### *3.2. Overheating estimation with fixed thresholds*

Fixed thresholds for defining overheating vary between sources. As examples, the simulation of the Gloucester Terrace unit was considered for both FamOcu and EldOcu occupation profiles in relation to the criteria defined by CIBSE [30] and EST [31]. Under single-aspect (no cross-ventilation) and free-running conditions with minimal adaptive measures, the simulation results for both profiles demonstrated that nearly all rooms exceeded the CIBSE [30] overheating criterion (Fig. 3a). Both north and south-facing rooms demonstrated positive correlation with building storey level, suggesting that overheating hours of exceedance increase with floor level; e.g. highest risk is at south-facing attic room, which overheats (hrs >26°C) for 8.8% of its occupation (FamOcu profile). However, for higher thresholds of >28°C and >26°C for the EldOcu profile, overheating hours of exceedance at the attic level was slightly lower than for the penultimate floor level. This counterintuitive outcome was caused by a feature of the dwelling, where the attic storey offset that facilitates the mansard-parapet junction detail (Fig. 1b) presents a reduced floor area (~7 m$^2$ less) for the rooms at this level than those below (in addition to a reduced head-height). This resulted in the area-based internal gains profile calculating lesser gains relative to lower rooms; while lower window solar-gain from smaller extents (35-45% less area than floors below) and heat loss from a more exposed surface also contributed.

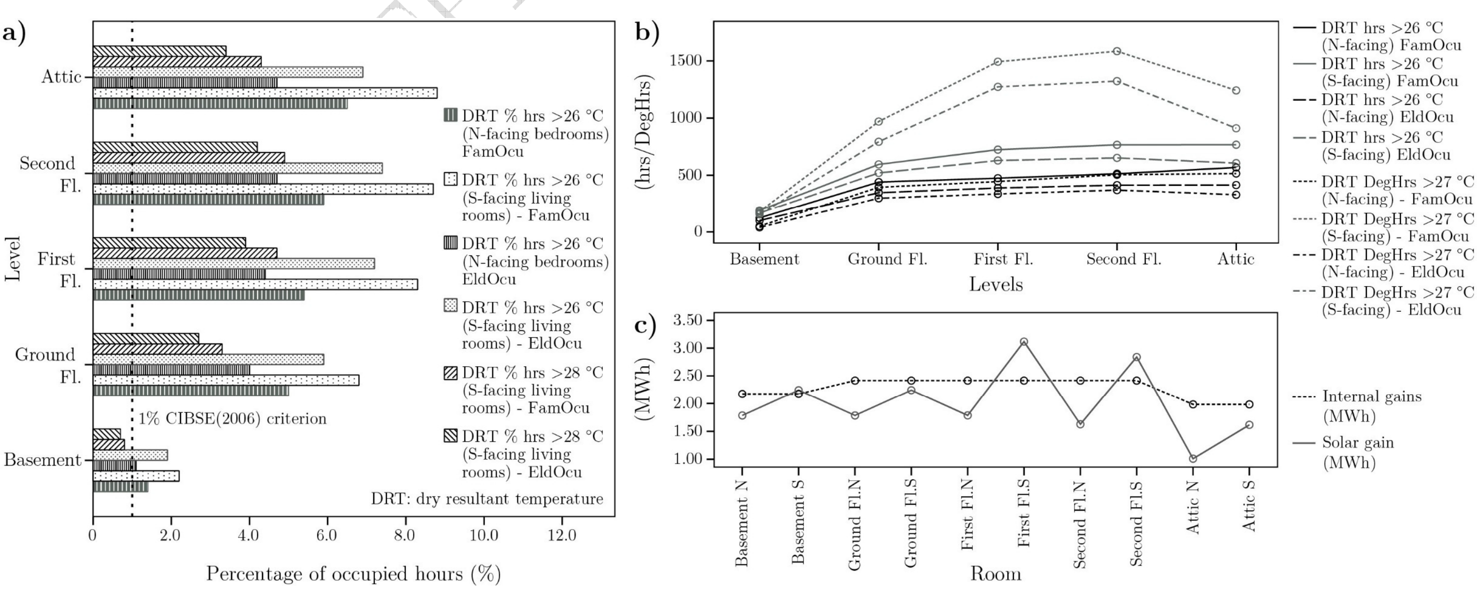



**Fig. 3.** Summertime overheating hours of exceedance by profile, floor level, and room (**a**); CIBSE hrs >26°C and EST degree-hrs >27°C by floor level, room, and profile (**b**); and thermal gains by floor level and room for FamOcu profile (**c**).

The results for the FamOcu profile highlighted a significant higher overheating risk for south-facing rooms (M = 562 hrs, SD = 216) than north (M = 378 hrs, SD = 154) when the CIBSE [30] hrs >26°C criterion was considered. A similar relationship was demonstrated with the EST [31] degree-hrs >27°C assessment for south (Mann-Whitney Mean Rank = 13.9) and north-facing (MR = 7.1) rooms (though the EST threshold is defined as an air temperature, it is considered in this study as a dry-resultant temperature or DRT for comparative assessment). The EST [31] assessment gives a better account of overheating severity, which highlighted first and second floor rooms as experiencing considerably greater severity than attic rooms (Fig. 3b). This again was caused by the above-mentioned mansard roof features of the unit that modify internal and external gains for these floor levels (Fig. 1b). The peak-day gains profiles highlighted that south-facing living rooms peak in the morning hours, while north-facing rooms peak (greater in relative magnitude) in the afternoon, which is not ideal for the higher daytime occupancy of the EldOcu profile. Gains analysis also demonstrated that the cooler temperatures achieved in basement rooms to be caused by a heat flux to the subsurface (through the uninsulated floor). For example, with the FamOcu profile ~3 MWh of thermal energy representing ~70% of summer gains for the rooms were conducted through to the ground.

### *3.3. Adaptive measures and assessment*

The simulation of the unit adopted standard ventilation rates advised by CIBSE [30] for windows left open only during the day and following the assumed summer occupational profile (i.e. 3.0 ach). Night-time ventilation operation was excluded from this simulation due to assumed security and noise concerns given the central urban locality [37,38]. To assess the influence of ventilation rates on overheating hours (>26°C), the model for the FamOcu profile was simulated for the summer period with increasing air-change rates facilitated by increased durations of opened vents.

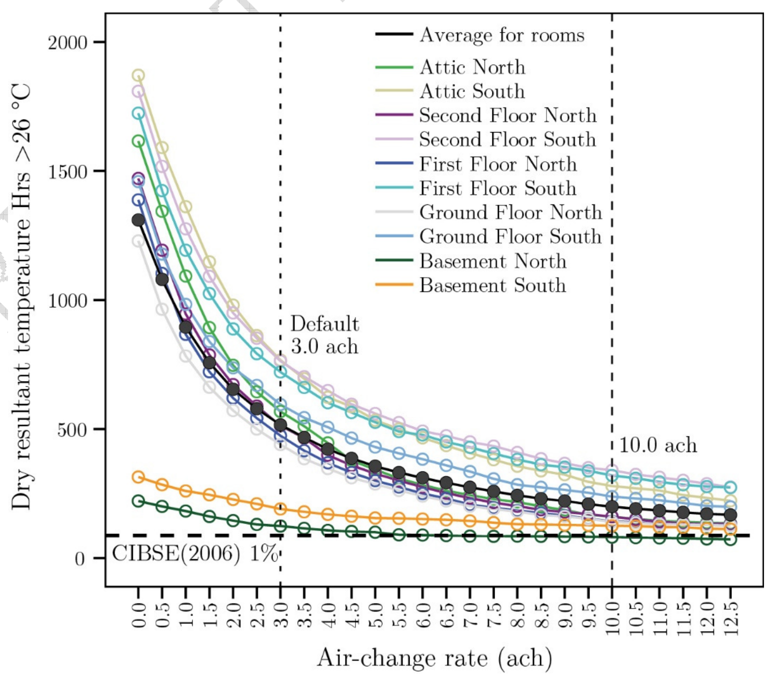



**Fig. 4.** Overheating hours of exceedance (DRT >26°C) variation with increasing air-change rate.

Under single-aspect free-running conditions, the results demonstrated summertime overheating hours predictably decreasing with increasing air-change rates following a polynomial regression (Fig. 4). CIBSE [30] guidance states that if 24-hour ventilation operation is utilised, air-change rates may be increased by up to 10 ach. The results show that beyond 10 ach, the reduction in overheating is minor, while meeting the 1% CIBSE [30] criterion exclusively from an air-change rate increase would require very high rates to be achieved; e.g. for the 'average for rooms' this is likely to be ~13 ach.

The methodology presented by CIBSE [16,32] restricts the Adaptive Comfort assessment to none-heating months from May-to-September (N = 153 days), with rooms requiring compliance with a minimum of two out of the three Criteria. These are defined in terms of the difference (or ΔT) between the actual room operative temperature ($T_{op}$) and the limiting maximum acceptable temperature ($T_{max}$); with Criterion 1 requiring the number of hours ($H_e$) that ΔT is ≥1 K to be ≤3% of occupied hours; Criterion 2 that accounts for overheating severity requiring the weighted exceedance ($W_e$) to be ≤6 on any one day, and Criterion 3 sets the upper limit $T_{op}$ temperature ($T_{upp}$) where ΔT shall not exceed 4 K. For Gloucester Terrace, the FamOcu profile was considered under the Category II $\Delta T_{max}$ threshold, while the EldOcu profile was considered under Category I that defines a more onerous $\Delta T_{max}$ (-1 K) for assessment [16]. The results showed that 'failure-days' (days where two out of the three criteria are not satisfied) for both profiles gradually increased with floor level, with the notable exception of the attic level (Fig. 5). This finding and its explanation is in common with the previous fixed threshold assessment. Comparing both occupant profiles highlights that the EldOcu profile (higher expectation) results in notably higher failure-days mostly due to the onerous $\Delta T_{max}$. In terms of orientation, both profiles demonstrated that maintaining comfort with adaptive strategies as challenging for south-facing rooms than north-facing. For most days and in the most frequented spaces (i.e. north-facing bedrooms) of the FamOcu profile, comfort temperatures were achieved by adaptive practices (Fig. 5a).

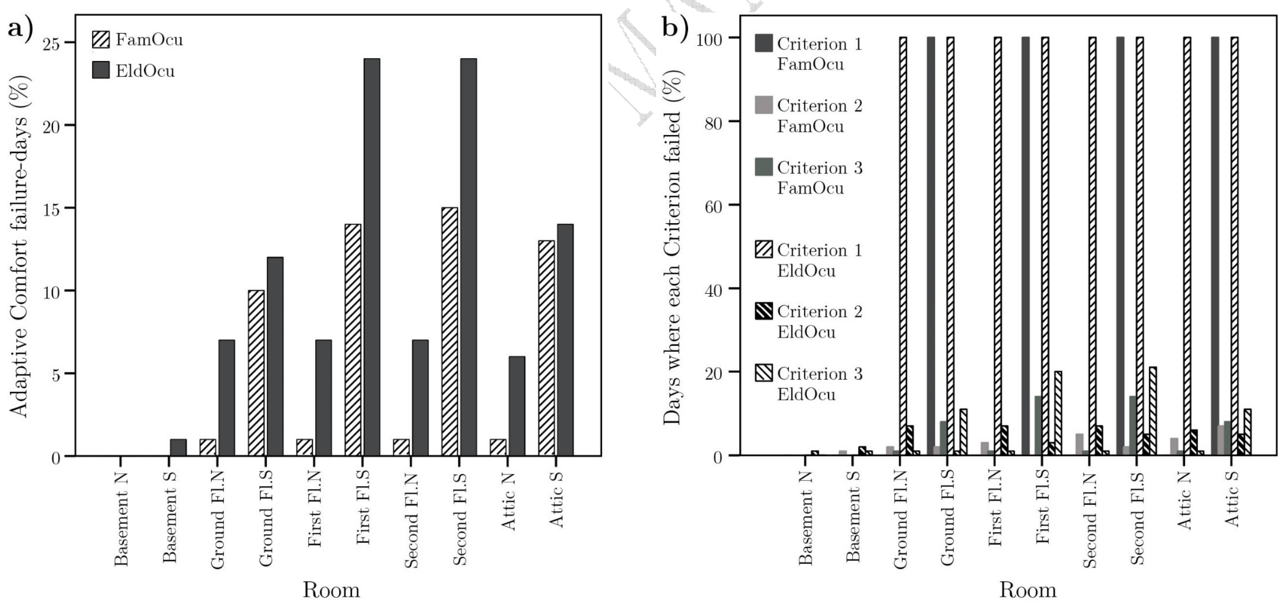



**Fig. 5.** Summertime (May-to-September) Adaptive Comfort [16,32] failure-days (**a**); and Criterion 1-3 failure-day breakdown (**b**).

Failure-days for both profiles demonstrated a strong positive correlation to Criterion 3, moderate correlation to Criterion 1, and a weak correlation to Criterion 2. This suggests that the variance in overheating failure-days is influenced by the failure of Criterion 3, followed by Criterion 1, and the least by Criterion 2 (considering daily severity of overheating). If the room is within the seasonal duration criterion ($H_e$); and does not exceed the $T_{upp}$ threshold (heat stress safeguard); a warm day that exceeds the daily criterion ($W_e$), may fall within the permitted 'comfort range'. This relaxation is significant for anomalous extreme heat events, when for short durations warmer temperatures may be endured provided the $T_{upp}$ limit is not exceeded. Sensitivity of the CIBSE [16,32] Adaptive Comfort assessment in relation to the CIBSE [30] 1% hours of exceedance (>26°C) criterion for the same period highlighted that save for basement rooms, all other floors demonstrated significant reduction in overheating failure-days; notably pronounced for north- rather than south-facing rooms (Table 2).

**Table 2**
Sensitivity of Adaptive Comfort against fixed threshold assessment.

| **Reporting overheating failure-days** | Basement N | Basement S | Ground Floor N | Ground Floor S | First Floor N | First Floor S | Second Floor N | Second Floor S | Attic N | Attic S |
|---|---|---|---|---|---|---|---|---|---|---|
| | % | % | % | % | % | % | % | % | % | % |
| Reduction FamOcu | 0 | 0 | **98** | 78 | **98** | 73 | **98** | 71 | **98** | 73 |
| Reduction EldOcu | 0 | 0 | 74 | 73 | 74 | 51 | 74 | 50 | 77 | 68 |

**Table 3**
UHI influence on overheating assessments.

| | Basement N | Basement S | Ground Floor N | Ground Floor S | First Floor N | First Floor S | Second Floor N | Second Floor S | Attic N | Attic S |
|---|---|---|---|---|---|---|---|---|---|---|
| ***FamOcu Profile*** | | | | | | | | | | |
| **Fixed >26°C exceedance** (% of failure-days) | | | | | | | | | | |
| Base-LGW | 3% | 12% | 18% | 39% | 22% | 47% | 22% | 48% | 22% | 39% |
| LGW+UHI | 10% | 18% | 29% | 44% | 30% | 51% | 30% | 52% | 29% | 48% |
| ***UHI influence*** | **+7%** | **+6%** | **+11%** | **+5%** | **+8%** | **+4%** | **+8%** | **+4%** | **+7%** | **+9%** |
| **Fixed >27°C degree-hrs** (%) | | | | | | | | | | |
| Base-LGW | 0% | 2% | 4% | 15% | 4% | 25% | 5% | 26% | 4% | 17% |
| LGW+UHI | 1% | 5% | 11% | 26% | 12% | 41% | 14% | 43% | 14% | 34% |
| ***UHI influence*** | **+1%** | **+3%** | **+7%** | **+11%** | **+8%** | **+16%** | **+9%** | **+17%** | **+10%** | **+17%** |
| **Adaptive Comfort** (% of failure-days) | | | | | | | | | | |
| Base-LGW | 0% | 0% | 0% | 5% | 0% | 10% | 1% | 10% | 0% | 5% |
| LGW+UHI | 0% | 0% | 1% | 10% | 1% | 14% | 1% | 15% | 1% | 13% |
| ***UHI influence*** | 0% | 0% | **+1%** | **+5%** | **+1%** | **+4%** | 0% | **+5%** | **+1%** | **+8%** |
| ***EldOcu Profile*** | | | | | | | | | | |
| **Fixed >26°C exceedance** (% of failure-days) | | | | | | | | | | |
| Base-LGW | 8% | 16% | 24% | 43% | 27% | 48% | 27% | 48% | 21% | 40% |
| LGW+UHI | 9% | 16% | 25% | 43% | 27% | 48% | 27% | 48% | 25% | 43% |
| ***UHI influence*** | **+1%** | 0% | **+1%** | 0% | 0% | 0% | 0% | 0% | **+4%** | **+3%** |
| **Adaptive Comfort** (% of failure-days) | | | | | | | | | | |
| Base-LGW | 0% | 1% | 7% | 23% | 6% | 11% | 7% | 24% | 1% | 12% |
| LGW+UHI | 0% | 1% | 7% | 24% | 7% | 12% | 7% | 24% | 6% | 14% |
| ***UHI influence*** | 0% | 0% | 0% | **+1%** | **+1%** | **+1%** | 0% | 0% | **+5%** | **+2%** |

The adaptive comfort assessment is influenced by the prevailing air-velocity in a room. The indoor operative temperature ($T_{op}$) may be revised down from its default value (relatively still) to address the cooling effect provided by motorised fan use controlled by occupants. If such fans raised room airflow velocity from 0.1 to 0.6 $ms^{-1}$ for example, $T_{op}$ could be adjusted down by up to 2 K (assuming 1met for sedentary person) [32]. Applying this additional adaptation to the summer peak-day of 30 June (FamOcu profile with default 3.0 ach natural ventilation), resulted in rooms deemed to overheat reduced from eight to three rooms. The overall effect was greatest for south-facing rooms from the first floor and above. As far as the Criteria are concerned, greatest effect was noted for Criterion 3 and 2, although Criterion 2 suggested a marginal (1%) increase in failure at higher-level south-facing rooms (Table 4).

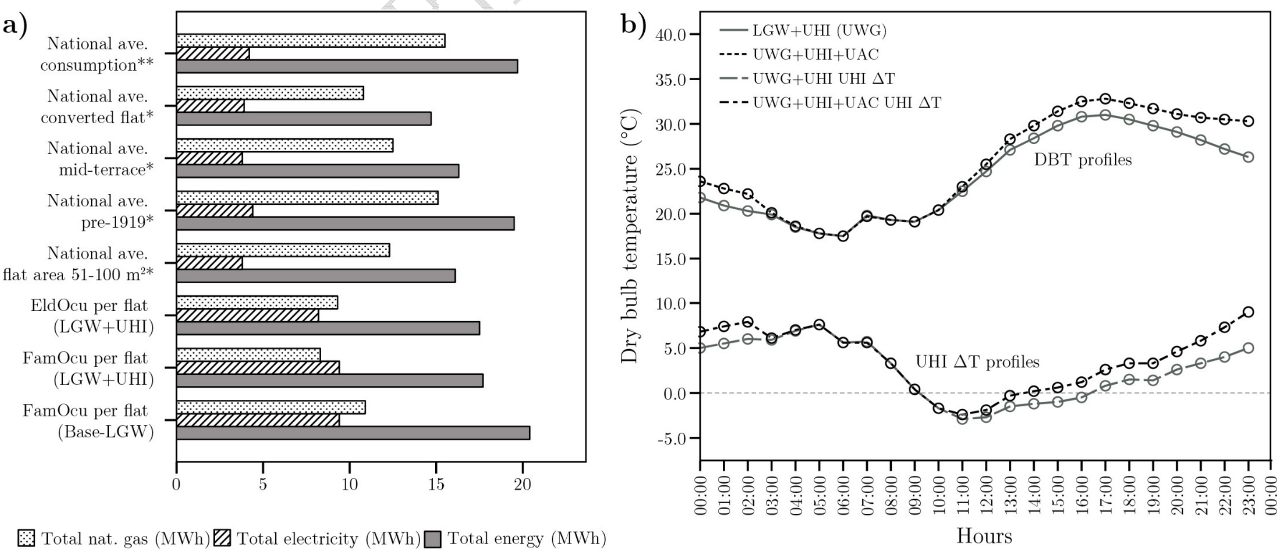
**Table 4**
Impact of fan usage on summertime overheating for FamOcu profile.

| **Fan usage on CIBSE** [16,32] **Reductions:** | Basement N % | Basement S % | Ground Floor N % | Ground Floor S % | First Floor N % | First Floor S % | Second Floor N % | Second Floor S % | Attic N % | Attic S % |
|---|---|---|---|---|---|---|---|---|---|---|
| Criterion 1 | - | - | - | 0 | - | 0 | - | 0 | - | 0 |
| Criterion 2 | - | 0 | 67 | 0 | 80 | 0/**1*** | 86 | 0/**1*** | 83 | 82/**1*** |
| Criterion 3 | - | - | 0 | 75 | 0 | 48 | 0 | 48 | 0 | 75 |
| Overall overheating | - | - | 0 | 0 | 0 | **47** | 0 | **48** | 0 | **95** |

***** Failure of Criterion 2 increased by 1%.

### *3.4. Cooling load applications*

At high floor level south-facing rooms, overheating risk was still estimated following the consideration of adaptive measures to suggest some requirement for alternative cooling measures. As means of addressing this risk, a domestic air-conditioning scenario for the entire unit (scenario AC1, Appendix, Table A2) was first simulated. This indiscriminate (entire unit) application addressed overheating risk (disregarding adaptive contributions) with 3.8% additional annual energy usage (Table 5). The impact of accounting for the UHI effect (comparison between AC0 and AC1 scenarios, Table 1 and Table A2) was highlighted by a 24.6% increase in the chiller load estimate for the unit.




* Period between 2005-11; and ** 2008-13 [39].

**Fig. 6.** Simulated annual energy usage comparison with UK national averages (**a**); and summer peak day (30 June) Gloucester Terrace canyon dry-bulb temperature (DBT) and UHI intensity profile comparison with and without canyon cooling loads (+UAC) (**b**).

The Gloucester Terrace canyon (100 m with 40 mid-terraced units) was subsequently simulated to estimate the impact of widespread and indiscriminate application of air-conditioning on canyon temperatures. Visual inspection of the peak-day UHI $\Delta T$ profiles for LGW+UHI and LGW+UHI+UAC scenarios highlighted that the influence was minimal during the morning-to-midday period, while in the evening and at night a pronounced increase in canyon temperatures was evident (Fig. 6b). The summertime hourly UHI $\Delta T$ comparison for both scenarios indicated a statistically significant difference in estimated canyon temperatures, with UHI $\Delta T$ mean for the free-running canyon (LGW+UHI) elevated from $M = 1.65$ K ($SD = 1.7$, $N = 5064$ hrs) to $M = 1.81$ K ($SD = 2.02$) with the widespread use of domestic air-conditioning (LGW+UHI+UAC). This equated to a summertime hourly average temperature increase of 0.1 K during the day and 0.4 K during the night (8PM-6AM).

As rejected heat from widespread air-conditioning use adds to environmental thermal loading, a modest 1.9% annual energy reduction was estimated relative to the free-running unit with no air-conditioning (LGW+UHI+UAC), attributed to a marginally reduced heating load estimated at the start of the heating period (Table 5). With cooling also employed at the unit (LGW+UHI+AC1+UAC), the influence of widespread air-conditioning contributed to a modest 0.3% increase in energy use (increased chiller load). In terms of aggregated $CO_2$ assessments, this future scenario resulted in an additional ~70 metric tons of $CO_2$ released to the climate. However, when a targeted approach (addressing residual risk in difficult to cool rooms) was simulated, this canyon emission estimate was reduced to ~30 t.

**Table 5**
Summary table of annual energy use* and $CO_2$ emission influence.

| Scenario | Total energy* (MWh) | % | Total electricity* (MWh) | Total nat. gas* (MWh) | Total $CO_2$ emissions ($kgCO_2$) | % | Canyon aggregate $CO_2$ emissions ($kgCO_2$) |
|---|---|---|---|---|---|---|---|
| **Influence of the UHI effect** | | | | | | | |
| Base-LGW | 122 | | 56 | 66 | 43,485 | | |
| LGW+UHI | 106 | | 56 | 50 | 40,093 | | |
| ***Savings*** | 16 | 13.1% | 0 | 16 | 3,392 | 7.8% | 135,680 |
| **Influence of adding summer air-conditioning to unit (to address overheating)** | | | | | | | |
| LGW+UHI | 106 | | 56 | 50 | 40,093 | | |
| LGW+UHI+AC1 | 110 | | 60 | 50 | 42,004 | | |
| ***Savings*** | -4 | **-3.8%** | -4 | 0 | -1,911 | **-4.8%** | **-76,440** |
| **UHI influence on summer air-conditioning of unit (to address overheating)** | | | | | | | |
| Base-LGW+AC0 | 123 | | 59 | 64 | 44,867 | | |
| LGW+UHI+AC1 | 110 | | 60 | 50 | 42,004 | | |
| ***Savings*** | 13 | 10.6% | -1 | 14 | 2,863 | 6.4% | 114,520 |
| **Effect of widespread air-conditioning for entire canyon on free-running unit** | | | | | | | |
| LGW+UHI | 106 | | 56 | 50 | 40,093 | | |
| LGW+UHI+UAC | 104 | | 56 | 48 | 39,739 | | |
| ***Savings*** | 2 | 1.9% | 0 | 2 | 354 | 0.9% | 14,160 |
| **Effect of widespread air-conditioning for entire canyon and unit** | | | | | | | |
| LGW+UHI | 106 | | 56 | 50 | 40,093 | | |
| LGW+UHI+AC1+UAC | 110 | | 68 | 42 | 41,838 | | |
| ***Savings*** | -4 | **-3.8%** | -12 | 8 | -1,745 | **-4.4%** | **-69,800** |
| **Effect of widespread air-conditioning for entire canyon on air-conditioned unit** | | | | | | | |
| LGW+UHI+AC1 | 110.1 | | 60 | 50 | 42,004 | | |
| LGW+UHI+AC1+UAC | 110.4 | | 68 | 42 | 41,838 | | |
| ***Savings*** | -0.3 | **-0.3%** | -8 | 8 | 166 | 0.4% | 6,640 |

* See Fig. 6a for usage comparison with DECC UK national averages. Negative values indicate relative increases.

## 4. Discussion

Previous findings including higher overheating risk in top-floor rooms, single-aspect (particularly south-facing), and multiple occupancy arrangements; and lower risk in ground floor and basement rooms generally agree with Gloucester Terrace simulation results; save for minor deviations explained by the unique features of the unit. It is worth noting that compared to dwellings built around the 1960s, post-1990, and compact purpose-built top-floor flats built in recent times, observations at nineteenth century terraced housing such as at Gloucester Terrace have been found to be less pronounced [11,13,14,40]. Examining diurnal change in overheating is significant for determining occupancy risk. A study of diurnal profiles of English dwellings (n = 224) for example had monitored indoor temperatures to be at their highest during evening and lowest during early morning hours [40]. The Gloucester Terrace simulation for the FamOcu profile agreed, although the EldOcu profile demonstrated the daytime average $T_{op}$ for all bedrooms as marginally higher than evening; possibly explained by higher daytime occupancy resulting in marginally increased gains. The performance of the envelope and its material properties are key determinants of how the lagged temperature response is experienced, with envelopes with higher thermal inertia likely to shift this risk to evening and nocturnal periods [23,41]. In bedrooms this shift could lead to nocturnal discomfort, sleep deprivation, and heat-related health issues. Data from a study of London dwellings (n = 36) monitored during the summer of 2009 highlighted that >40% exceeded the recommended CIBSE [30] night-time overheating threshold [8]. For north-facing bedrooms at Gloucester Terrace with its high thermal mass facades, the nocturnal hours (8 PM to 6 AM) that exceeded the 24°C sleep deprivation threshold [12,32,42] was estimated at 38% and 27% for FamOcu and EldOcu profiles respectively. These high percentages suggest that summertime nocturnal sleep deprivation may already be an issue for occupants. For both profiles however, the CIBSE [12] critical bedroom threshold of temperatures >26°C for not more than 1% (≤33 hrs) of annual nocturnal hours (10 PM to 7 AM) was not exceeded.

The principal adaptation considered in this study was window vent operation by occupants. There are many reasons for why dwelling occupants operate vents. These could relate to ventilation, noise, spatial layout, security and safety, habit, and thermal relief concerns. The Dubrul [19] survey of vent opening practices in temperate climates found the principal reasons to be associated with improving air quality and maintaining the desire to relate to the outdoor environment, rather than seeking thermal relief. It was demonstrated that the vents were closed by occupants to control temperature, mainly to keep warm rather than cool. The survey also found that vents were less likely to be opened in flats, older dwellings with sliding sash windows or with open fireplaces (e.g. at Gloucester Terrace), with central heating; high air-tightness, side-hung windows; and non-south-facing rooms. Habitual practices of occupation were also identified as a key influence [19]. For example, it could be said that some occupants prefer to sleep with a vent open to facilitate the exchange of 'fresh' air, while inner-city dwellers will be discouraged by concerns such as noise, pollution, and security. Such barriers to effective vent operation in dwellings may prove to be particularly disadvantageous during extreme heat events. For example, a sample study of dwellings in London (n = 5) and Manchester (n = 4) during the 2003 pan-European heatwave found indoor spaces to be ~5 K warmer, mainly explained by the lack of occupant engagement [43]. While urban difficulties could be addressed by using technical solutions such as acoustic baffles, insect mesh, and security barriers, dwellings in Conservation Areas such as Gloucester Terrace will be challenged by the need to conserve their historic appearance that often precludes significant modification to vents.

The secondary adaptation considered the localised thermal relief achieved by occupant use of fans. Motorised or otherwise, the device cools by enhancing forced convection. In this study, this adaptive influence reduced overheating risk in most rooms to highlight how a device with low-to-moderate energy consumption could be utilised to adapt to warmer conditions (Table 4 and Table 6). At high floor level south-facing rooms however, residual risk was still estimated to suggest the requirement of additional cooling measures.

**Table 6**
The adaptive measure of occupant fan usage and its influence on overheating risk.

| **Summertime residual overheating** failure-days | Basement N | Basement S | Ground Floor N | Ground Floor S | First Floor N | First Floor S | Second Floor N | Second Floor S | Attic N | Attic S |
|---|---|---|---|---|---|---|---|---|---|---|
| ***<u>FamOcu</u> <u>Profile</u>*** | | | | | | | | | | |
| LGW+UHI+Fan failure-days | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | **7.9%** | 0.0% | **7.9%** | 0.0% | **0.7%** |
| Mortality exceedance* | **1.3%** | **1.3%** | **6.5%** | **8.5%** | **7.8%** | **12.4%** | **7.8%** | **14.4%** | **9.8%** | **15.7%** |
| ***<u>EldOcu Profile</u>*** | | | | | | | | | | |
| LGW+UHI+Fan failure-days | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | **8.6%** | 0.0% | **8.6%** | 0.0% | **3.3%** |
| Mortality exceedance* | **0.7%** | **1.3%** | **5.2%** | **7.2%** | **6.5%** | **8.5%** | **6.5%** | **11.1%** | **6.5%** | **9.8%** |

* Average daily $T_{op}$ that exceeds the London mortality threshold: 24.7°C [44].

The Adaptive Comfort assessment considers overheating risk in terms of comfort expectations, with vulnerabilities of occupants addressed by more onerous criteria (EldOcu profile). This dynamic comfort approach is not explicitly linked to morbidity or mortality thresholds. The Adaptive Comfort principle of associating outdoor temperatures to indoor adaptability suggests that such outdoor mortality thresholds could in turn be associated to the assessment of indoor health risks. However, the relationship is not explicitly associated in available overheating assessments. Table 6 demonstrates that even though thermal comfort is achieved with adaptations, significant percentages of daily averages still exceed the London outdoor mortality threshold (24.7°C) [44]; this is particularly the case at higher floor levels, and for the FamOcu profile. If such regional mortality thresholds are adopted as the limit (region-specific and dynamically associated to its mortality regression) beyond which indoor temperatures may be considered unsafe, all rooms of the unit may still be regarded to overheat despite achieving comfort. Another criticism is that the significance of prolonged exposure to moderately high temperatures (>25°C is acknowledged as detrimental to sleep and health), is not addressed by the criteria. Furthermore, the criterion thresholds offered are still mostly based on studies of office buildings, with limited evidence considered on occupant health and comfort in dwellings, and even fewer examined for nocturnal conditions when adaptive practices are restricted [45].

A climate projection study considering London dwellings had found that although vent opening reduces overheating risk at present, its impact decreased considerably towards the 2030s [46]. This is further complicated by most adaptive measures including vent operation requiring significant occupant engagement, which may not always be available or consistent to alleviate overheating risk. The aforementioned study consequently suggested that the future requirement for alternative active cooling solutions as likely, particularly in urban areas of southern England [46]. Another projection study has estimated that climate change and concomitant heat-related risks as likely to compel 29-42% of households in the south of England acquiring air-conditioning by 2050 [47]. Although currently there is little use of domestic air-conditioning in Europe and the UK (~3%), the reality of increasing heat-related risks will encourage adoption [48], with the Committee on Climate Change (CCC) identifying growing domestic air-conditioning unit sales, and ~5% of conservatories in London as already air-conditioned [49]. For cities like London where high-density living is increasing and a potent UHI is typically observed, this growing air-conditioning use could soon lead to unsustainable residential energy consumption. The way in which this growth is deployed will also influence the magnitude of future consumption increases, particularly if indiscriminate use is utilised as the dominant adaptation as demonstrated by the study's simulations. As an alternative, a targeted approach informed by overheating assessments could provide efficient risk mitigation. For example, the simulated use of air-conditioning only in problem rooms (south-facing, first-to-attic level rooms identified by the Adaptive Comfort assessment, Table 6) resulted in a 3.6% lower energy use estimate for the unit in isolation, while an even lower 4.4% was estimated for the widespread canyon air-conditioning scenario (loads in these rooms were higher as the canyon climate was relatively warmer).

The use of excess energy in abeyance, air-conditioning also has an adverse effect on the urban climate from the heat rejected from such systems [50]. A simulation study of semiarid Phoenix (USA) found their waste heat to have negligible effect near the surface during the day (though a maximum is released), while air temperature increase >1 K was observed at night [51]; an observation concurred by another simulation study of central Paris (temperate climate) [52]. A simulation study considering Toulouse also concluded that under a future scenario with widespread air-conditioning, rejected heat would elevate outdoor summer air temperatures by 0.8 K for residential quarters [53]. In comparison, the simulation of the Gloucester Terrace canyon resulted in a moderate nocturnal increase of 0.4 K. The nocturnal significance of such anthropogenic heat emissions is attributed by climatologists to the contracted canopy-layer, which concentrates emissions nearer to the surface while during the day the greater depth of the boundary-layer encourages rejected heat to rise further up into the atmosphere to minimise the surface effect [52]. Another complicating factor is that some systems use evaporative cooling to exchange heat (latent heat) with the external environment [50]. This means that rejected moisture can increase canopy-layer humidity, thereby affecting nocturnal urban comfort and heightening vulnerability to heat-related health risks [54]. The rejection of waste heat from air-conditioning consequently increases outdoor temperatures and discomfort, from which urban inhabitants must then seek to protect themselves further by increasing energy consumption needed for further cooling. A positive feedback loop of this nature is likely to lead to unhealthy urban surroundings that discourage inhabitants from engaging with the outdoors [2]. The dominant and convenient use of the technology therefore adds to environmental, economic, and social burdens, while diverting attention away from alternative low-impact adaptive measures. Avoiding, or in the very least managing the use of air-conditioning, is a primary objective to reducing urban energy demand, as well as anthropogenic heat emissions.

## 5. Conclusions

In this simulation study of Gloucester Terrace, the influence of the UHI effect on fixed threshold overheating estimation for the representative unit was significant and particularly pronounced for the FamOcu profile (Table 3 and Table 7). However when the Adaptive Comfort assessment was considered, this significance was considerably reduced with residual influence mostly evident at high floor level south-facing rooms. This reduction is predictable, as the method accounts for some occupant adaptation to outdoor climate loads, including that of the UHI. By using further adaptive practices such as fan operation, the study highlighted that conditions that facilitate 'comfort' could be increased in most indoor spaces for both occupancy profiles examined (Table 6). At high floor level south-facing rooms however, residual risk was still evident to suggest the requirement for some mechanical cooling. Addressing this current and probable increased future summertime overheating risk with mechanical cooling is likely to increase energy consumption. The simulation of a hypothetical summertime scenario in which the entire canyon length of 40 units indiscriminately adopts mechanical cooling resulted in a 3.8% increase in energy use relative to a free-running canyon. This translated to a $CO_2$ release increase of ~1.7 t per unit, aggregated to ~70 t for the canyon length.

**Table 7**
Summary of UHI influence on overheating assessments.

| **UHI influence** (%) | Basement N | Basement S | Ground Floor N | Ground Floor S | First Floor N | First Floor S | Second Floor N | Second Floor S | Attic N | Attic S |
|---|---|---|---|---|---|---|---|---|---|---|
| ***FamOcu Profile*** | | | | | | | | | | |
| **Fixed >26°C exceedance** | **+7%** | **+6%** | **+11%** | **+5%** | **+8%** | **+4%** | **+8%** | **+4%** | **+7%** | **+9%** |
| **Fixed >27°C degree-hrs** | **+1%** | **+3%** | **+7%** | **+11%** | **+8%** | **+16%** | **+9%** | **+17%** | **+10%** | **+17%** |
| **Adaptive Comfort** | 0% | 0% | **+1%** | **+5%** | **+1%** | **+4%** | 0% | **+5%** | **+1%** | **+8%** |
| ***EldOcu Profile*** | | | | | | | | | | |
| **Fixed >26°C exceedance** | **+1%** | 0% | **+1%** | 0% | 0% | 0% | 0% | 0% | **+4%** | **+3%** |
| **Adaptive Comfort** | 0% | 0% | 0% | **+1%** | **+1%** | **+1%** | 0% | 0% | **+5%** | **+2%** |

If cooling is inevitable in urban localities with such 'difficult-to-cool' dwellings (older units with limitations on fabric modifications), strategic arrangements such as district chilling and alternative fuel sources would require further attention, while targeted applications considering only high-risk conditions such as south-facing rooms will prevent wasteful provision. The latter simulation of only south-facing rooms air-conditioned, more than halved (to ~30 t) the canyon $CO_2$ emission estimate. This targeted approach however would mean that more detailed overheating assessments of residential neighbourhoods including location specific climate loading would be required. This study addressed this by utilising a novel, computationally efficient pathway to include UHI loads and anthropogenic emissions resulting from cooling loads to present an Adaptive Comfort-based estimation approach. As no standardised categorising of dwelling types and their features are presently in use, meta-analysis and generalised conclusions should be considered with caution. The assessment presented here is therefore dependent on the characteristics of Gloucester Terrace, and is only aggregated to the canyon neighbourhood as the uniform morphological features lends itself suitable.

## Appendix

**Table A1**
Key parameters used for simulation.

| PARAMETER | DESCRIPTION | GLOUCESTER TERRACE UNIT |
|---|---|---|
| ***Unit profile*** | | |
| Conditioned area | Main unit only; mews extension omitted | 366 $m^2$ |
| Each floor | Two equal room volumes, single-aspect (i.e. no cross-ventilation) | Rooms facing north considered as bedrooms<br>Rooms facing south (front elevation) considered as living rooms |
| ***Occupational profile, FamOcu*** | Young (working) couple/small family (two adults + one child) assumed for all six units as typical scenario | |
| Occupation | 61 $m^2$ per flat = two-bed, three persons per flat<br>3 × 6 flats [55] | 18 persons considered for full occupation<br>Density ~20 $m^2$ per person |
| Weekdays | Working week | 6 AM to 6 PM at load factor 0.60<br>6 PM to 11 PM at 1.00<br>11 PM to 6 AM at 0.10 |
| Weekends | Full occupation | 8 AM to 12 AM at 1.00<br>12 AM to 8 AM at 0.10 |
| Holidays | UK profile | 24 hrs at 0.1 |
| Summer profile | Adaptive Comfort assessment [12,16] | May-to-September (N = 153 days) |
| ***Occupational profile, EldOcu*** | Older couple (full-day occupation) assumed for all six units as non-typical scenario | |
| Occupation | Two persons per flat<br>2 × 6 flats | 12 persons for full occupation<br>Density ~30.5 $m^2$ per person |
| Full week | Full occupation | 6 AM to 10 PM at load factor 0.75<br>10 PM to 6 AM at 0.10 |
| ***Thermal*** **performance** | | |
| Heating | Natural gas central heating<br>DHW not served by HVAC boiler | ScoP: 0.80<br>Seasonal efficiency: 0.89<br>Set point: 19°C |
| Relative Humidity | | Max. 70% |
| Ventilation | Natural ventilation requirement<br>61.2 $m^3 h^{-1}$ × 6 (flats) - Part F, Table 5.1b [56] | 0.3 ach |
| Cooling | Natural ventilation for one-sided building (single-aspect rooms) with vents open at day and closed at night. Table 5.21 [32] | 3.0 ach<br>@ summer profile |
| Air leakage | UK average | 0.7 ach; On continuously |
| ***Internal gains*** | As per occupational profile | |
| People | Sensible<br>Latent | 70 $WP^{-1}$<br>45 $WP^{-1}$ |
| Lighting | Sensible | 7 $Wm^{-2}$ |
| Equipment | Sensible | 5 $Wm^{-2}$ |
| Cooking | Sensible<br>Latent | 3 $Wm^{-2}$<br>1 $Wm^{-2}$ |
| ***Default construction*** [26] | | |
| Ave. floor height | Height varies per floor | 3.0 m |
| Window ratio | Main unit only; mews extension omitted | 23% (77 $m^2$) |
| Windows | 6mm single-glazing | U-Value: 5.10 $Wm^{-2} K^{-1}$<br>G-Value: 0.82 |
| Walls | Stuccoed brickwork | 1.33 $Wm^{-2} K^{-1}$ |
| Upper floors | Timber joisted with boards | 0.35 $Wm^{-2} K^{-1}$ |
| Basement floor | Limestone on screed | 2.26 $Wm^{-2} K^{-1}$ |
| Roof | Slate on timber structure | 0.80 $Wm^{-2} K^{-1}$ |

| PARAMETER | DESCRIPTION | GLOUCESTER TERRACE UNIT |
|---|---|---|
| ***Urban site*** | | |
| Ave. building height | For canyon | 17.5 m |
| Coverage ratio | Estimate | 54% |
| Tree/green cover | Estimate | 8% |
| Non-building anthropogenic emissions | Based on Greater London averaged estimate [57] | 5.1 $Wm^{-2}$ |

**Table A2**
Cooling loads for simulation.

| Parameter | Strategy | Description | Values |
|---|---|---|---|
| **Cooling upgrades** | | | |
| Unit cooling (+AC0 & +AC1) | Air-conditioning to address overheating risk | Min EER: 2.4 | Included EER: 3.125<br>CoP: 0.92<br>@ summer profile |
| | | Set point | 23°C |
| | | Cooling capacity | 2600 BTU per flat<br>12.5 $Wm^{-2}$ |
| Urban cooling (+UAC) | Widespread use of domestic air-conditioning in canyon (40 units) | Building heat release Greater London average [57] | 4.6 $Wm^{-2}$ |
| | | UWG emission factor for domestic units | 1.0 |

## Acknowledgment

Funding: this work was partly supported by the Cambridge Trust, University of Cambridge.

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