Quantum-Responsive Urban Heat Dynamics and Climate-Adaptive Architectural Strategies for Karbala

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Abstract

Rapid urbanization and vegetation loss have intensified the Urban Heat Island (UHI) effect in Karbala, Iraq, amplifying thermal stress and energy demand. This study integrates multi-year climatological analysis with the emerging paradigm of quantum architecture to examine how micro-scale radiative interactions, material properties, and urban geometry shape localized thermal behaviour. Using meteorological data from 2019–2024 and a reference temperature of 26.6 °C, the analysis reveals a consistent rise in cooling degree-days and a decline in heating degree-days, indicating progressive regional warming. The current 5-year average UHI intensity of 1.51 °C is projected to increase further, particularly during summer. Quantum-informed interpretation highlights how photon-surface interactions, restricted airflow in urban canyons, and low-albedo materials contribute to heat accumulation. The study proposes adaptive architectural strategies—including reflective surfaces, high-performance glazing, night-time ventilation, and expanded vegetation—to mitigate overheating and enhance energy efficiency. Findings demonstrate that quantum-responsive design offers a robust framework for improving thermal comfort and urban resilience in hot-arid environments.

Keywords: Urban Heat Island; Quantum Architecture; Karbala; Albedo; Cooling Degree-Days; Heating Coefficient; Microclimate-Responsive Design

1. Introduction

Karbala has undergone rapid demographic and spatial expansion, driven by economic development and the annual Arba'een pilgrimage, which temporarily increases the population by nearly half a million individuals Karbala(,2018). This growth has reshaped the city's thermal environment, increasing solar absorption and reducing natural cooling capacity. As noted by long-term climatic data are essential for designing ventilation systems, renewable energy solutions, and seasonal energy assessments.

The removal of vegetation to accommodate new construction—particularly in the city centre—has intensified the Urban Heat Island (UHI) effect. Vegetation loss reduces evapotranspiration, a key cooling mechanism Yank and Lu ,(2014),Hatim,(2019), Hasson, and Alaskary(2008), Hasson, (1990) Hasson, and Alaskary,13–5]. Despite recognition of these issues in provincial planning documents, limited coordination between authorities and designers continues to hinder the integration of climate-responsive strategies.

This study aims to provide a comprehensive understanding of the climatic variables shaping Karbala's future and to support the development of adaptive architectural and urban planning strategies.

Materials and Methods

Continuous progress and urbanization are altering the urban landscape and impacting the absorption of solar energy. Consequently, the buildings in Karbala are now more vulnerable to the elements and have a higher capacity to retain heat

The quantities were monitored: daily minimum, maximum, average air temperature were monitored by means of shielded copper–constantan thermocouples. Total solar radiation. Incident and reflected solar hemispherical radiation (0.3 to 3 microns) for the reference point. The instrument was used with an Eppley pyrometer model 4-48, mounted horizontally. Surface albedo was derived from the ratio of daily total reflected to incoming shortwave radiation. The proportion of surface land area over radius (50m) and (100m), (150m), mean building height, ratio, manufactured wall surface area, green land cover area ratio, actual sunshine hours ratio n/N, wind speed WS, relative humidity, and rainfall. Terms for hourly first-differences of current and past weather variables were also included. Though the information contained in the first differences variables is implicit in the current and prior data, providing this information explicitly was found to improve model performance, Table 1.

Kestrel (4200) packet weather monitor, altitude parameter, was used for calculating each measuring point's altitude.

Sensitive anemometers placed to measure wind speed the analogy signals for the Hewlett-Packard Automatic data Acquisition/Control system model. The output data was continuously on hourly basis using a Hewlett Packard model 9845B computers connected on line with the data acquisition system.

The data used for the prediction of air temperature including, reference of minimum, average, maximum air temperatures, total incoming, outgoing solar radiation, wind speed, rainfall and sunshine duration obtained from the local Weather Station, and research centre . The other parameters used in the calculation, Area covered (Ac), Area $_{\text{opened}}$, (Ao). Under the umbrella word "G." is the H / B ratio, which compares the height to the width of the building whole area, W area are simple to obtain. g. Reactive analyses are carried out to learn the temperature dependence of each air parameter $_{\text{are}}$ straightforward to be obtained. Albedo, Latent Heat (LE) and the ratio of real

sunshine hours to estimated sunshine hours (n/N) are calculated. The computing each month's heating coefficient (β) values using the formula β = (1 - p/ρ) [6-8].
According to data collected from two consistent weather stations on a monthly, Karbala has cold winds and winters, extremely hot and dry winds, winds blowing from the north, and dusty summers. The study collected data from February 2019 to April 2024,Hasson,(1990), Hasson, and Kammas,(2013), Sani,(1991).
Establishing a comprehensive database and acquiring precise knowledge are necessary for sustainable building construction, as heat acquisition and daytime usage of solar radiation play a crucial role in creating solar energy in structures Asawa,et.al. (2021)[,Hui, at.el((1997a) Urban Heat (2026). Table 1 displays the average duration of sunlight each day. Using lighter-coloured materials can effectively decrease thermal movements, resulting in lower thermal expansion coefficients than alternative building materials Hasson and Alaskary, (2013), Hatim, 92019).
In order to analyse the air temperature dependency on variations in each parameter, responsive analyses are carried out. Table 1 shows the input on climate predictors based on data at Kerbala Weather Station in were used in this sensitivity analyses based on the conditions on January 2019 to April 2024 [Fig 1].
The data were collected under the guidance of the research department at the Central Karbala Weather Bureau.
Therefore, the radiative effect of the ambient surfaces is at least as important as the air temperature when taking into consideration ordinary comfort conditions in a house.
Rather small differences in average temperature have a much greater effect than similar temperature fluctuations in air Hui et al, (1997b) . This is why the average ambient temperature has to be acknowledged

Results and Discussion

Local climatological parameters

Tables 2 and 3 give the values of references between the minimum, average and maximum air temperatures comparisons. It can observe the view sky reduction due to LAI of space trees varies the behavior of the calculated minimum, average and maximum air temperatures. The increase in greenery density can reduce the minimum air temperature. The green ration covered ($G_{covered}$) and view sky, and Leaf Area Index LAI influence the average temperature. Greenery due to high LAI low sky view provides shading to the environment thus reduces the air temperature. While the reduction in average air temperature of surrounding rural suburbs due to increase in $G_{covered}$ between 0.03-0.20 and LAI more than 4.5 m^2/m^2. The increase in greenery density affects the openness to the sky, which reduces the maximum air temperature through its shading effect Idso,et.al, (1996), Padmanabhamurty. (2019),
Albedo of urban structures in Karbala which depicts notable fluctuations in average albedo values, which are affected by variations in solar altitude angles and/or building materials every month. An analysis was conducted using technique to examine the visibility of buildings and the proportion of ground, sky, and land areas. Oblique angles are visible on light-coloured building facades. Traditional Karbala structures generally have darker surfaces, leading to lower albedo values due to less brightness. The albedo values are higher during the summer months..
The change in building height seems to have relatively influences on minimum, average and maximum air temperature (Table 3). The reduction in heat through its relation with sky view factor. Due to the increasing in LAI.
Estimation of HDD and HCC
Cooling Degree Days (CDD)

$$CDD = \sum \max(T_{mean} - T_{base}, 0)$$

Heating Degree Days (HDD)

$$HDD = \sum \max(T_{base} - T_{mean}, 0)$$

Where:
(T_{mean}): daily mean temperature
(T_{base}): base temperature (usually 18°C or 65°F)
To assess the long-term temperature value difference in the Kerbala region, a degree-day set for the study period has been established, as shown in Figure 3.
Also, it has been found by analyzing the annual heating and cooling degree-days over the study period (2019-2024) by taking into consideration a temperature of 26.6 ºC as reference, that the Karbala region has heated up as specified by the growth of cooling days and a lessening of heating days. This has important implications for urban climate and energy. The degree-day technique is used to estimate heat utilization in the early phase of thermal design .Zou,et,la (2025), Lin(2025).

Urban Heat Island

The Urban Heat Island (UHI) effect generally involves measuring the temperature difference between urban areas and their surrounding rural counterparts.
UHI intensity calculation is by comparing simultaneous temperature readings from a city centre and a nearby rural area.

$$UHI = T_{a,\ urban} - T_{a,\ rural}$$

Heating Coefficient (Β)

Figure 5 illustrates the calculation of each month's heating coefficient (β) values using the formula β = (1 - p/ρ). The results significant variations in monthly heating coefficient values. It is imperative to acknowledge that the heating coefficient applies not only to roofs but to the entirety of the building construction. The heating coefficient measures the steepness of the Rn regression line, which signifies the speed at which net radiation loss occurs due to longwave radiation. The link between Albedo and the heating coefficient is highly correlated, as seen by a considerable correlation coefficient ($R^2 = 0.63$) in the regression equation for monthly averages.

Urban Heat Island

Urban heat islands (UHIs) have become a major challenge for cities and local authorities in their quest for climate resilience. With the intensification of global warming and growing urbanization, the areas impacted by UHIs where temperatures can exceed those of the surrounding areas by several degrees represent an increased risk to the health and quality of life of residents, as well as biodiversity, and can also hinder action to reduce energy consumption.

Despite the challenges caused by UHIs, solutions exist to mitigate their effects and make our cities more liveable. These solutions range from the implementation of urban revegetation policies to the one of innovative infrastructures, driven by cutting-edge tools such as digital twins. These combined approaches pave the way for cooler, greener and more resilient urban environments Joshi, et.al, 2024). Lam (1995).

The parameters influencing UHI are Surface albedo, Vegetation cover (NDVI), Building density and height, Anthropogenic heat emissions and Wind flow and urban geometry.

UHI and CDD/HCC relations

Relationship between the Urban Heat Island (UHI) effect and Heating Degree Days (HDD) and Cooling Degree Days (CDD/HCC) is direct and physically intuitive, because UHI modifies Karbala urban air temperature baseline environment.

UHI and Heating Degree Days (HDD)

HDD represent the demand for heating when outdoor temperatures fall below a base temperature (e.g., 18 °C). Since UHI increases urban temperatures—especially at night and during winter—it reduces HDD values. This means:

Less heating demand in urban cores compared to rural surroundings Lower winter energy consumption in cities affected by strong UHI Conclusion:

UHI → ↑ Temperature → ↓ HDD → ↓ Heating demand

UHI and Cooling Degree Days (CDD / HCC)

Cooling Degree Days (sometimes referred to as HCC in some studies) quantify the need for cooling when temperatures exceed a base level. UHI raises daytime and night-time temperatures, especially during summer, leading to: Higher CDD values, Increased cooling energy demand (air conditioning) and Prolonged cooling season in urban areas

Overall Energy Impact

The increase in cooling demand typically outweighs the reduction in heating demand, especially in hot climates (such as Iraq).

Therefore, UHI generally leads to a net increase in total urban energy consumption.

Key Insight for Research

UHI acts as a temperature bias term in degree-day calculations: [T_{urban} = T_{rural} + \Delta T_{UHI}]

This shift propagates into HDD and CDD calculations, making them essential indicators for quantifying UHI impacts on building energy use.

Karbala's population is experiencing rapid growth amid a barren environment lacking trees and vegetation. Recent industry and urbanisation have significantly altered the city's flat surface and ability to absorb energy. Urbanisation, industrial manufacturing, and growth substantially impact climate patterns. City buildings, especially commercial ones, are typically built using glass, steel, concrete, or stone. These materials have vivid colours that increase their ability to absorb solar energy, affecting the temperature conditions throughout the day and night.

The spread of suburban areas generates vast heat domes that become increasingly intertwined with the city's growth. Engineers must consider these dynamics when designing, as the city's size grows. The intricate interplay of these factors modifies the urban atmosphere, forming the urban heat island (UHI) effect, a phenomenon influenced by artificial surroundings. Fig. 4 shows the effect of this phenomenon

The building template specifications, with façade materials and window properties. Based on the majority of residential buildings were initially categorized into primary façade materials of metal siding, mixed materials approximetly. However, to improve the accuracy of thermal these classifications were refined into eight façade material clusters: asbestos, brick, composite, metal siding, PVC, stucco, Marple and cement. Given the lack of explicit insulation data in the assessor records, a standardized approach was adopted based on the dominant construction practices of the era. As most structures in the neighbourhood were built before 1980, polystyrene insulation was applied uniformly across all templates, reflecting its widespread use in residential buildings of that period. The assumption was necessary to maintain model consistency and prevent excessive variation stemming from unverified retrofit data.

Buildings were further grouped according to their construction properties into templates: for air-conditioned buildings and for naturally ventilated buildings.

Within the framework of quantum urban climatology, the built environment of Karbala can be interpreted as a dynamic system where microscale energy exchanges, surface properties, and spatial geometries collectively influence localized climate behaviour. The city’s buildings, exhibiting diverse geometric forms with expansive horizontal and vertical façades, act as active interfaces for radiative absorption, reflection, and heat storage at multiple scales.

From a quantum-informed perspective, narrow urban canyons (or “valleys”) modify the interaction between solar radiation and material surfaces by altering photon absorption pathways and restricting airflow dynamics. This leads to enhanced heat accumulation due to increased radiative trapping and reduced convective cooling. Consequently, these spatial configurations intensify the Urban Heat Island effect, as the inhibited air circulation limits the natural dissipation of thermal energy.

Material properties further contribute to this phenomenon. Polymer-based coatings on building envelopes can modify surface albedo and emissivity at the micro-level, potentially increasing heat retention when they favour absorption over reflection. In contrast, dense ground coatings with higher reflectivity or shading capacity can reduce direct solar gain, demonstrating how surface engineering—viewed through quantum-scale interactions of light and matter—affects macroscopic thermal outcomes.

The urban fabric of Karbala, composed of heterogeneous distributions of built structures and vegetated areas, reflects a complex thermal mosaic. Vegetation introduces cooling effects through evapotranspiration and altered radiation balance, partially offsetting heat accumulation. However, disparities emerge across socio-economic zones: lower-density suburban areas with moderate vegetation tend to exhibit relatively lower temperatures, whereas districts characterized by dense construction, limited greenery, and intensive economic activity experience amplified thermal stress.

Thus, quantum urban climatology reveals that the interplay between geometry, material science, and socio-spatial organization governs the microclimatic variations observed across Karbala, emphasizing the need for integrative design strategies that operate from the quantum to the urban scale.

Pliability building designs

In the summer, residents of Karbala increasingly express concern over excessive heat in buildings located in suburban and urban zones characterized by the Urban Heat Island (UHI) effect. From a quantum architecture perspective, this overheating is not only a macroscopic climatic issue but also a consequence of energy interactions at micro- and nano-scales within building materials. Raising indoor temperatures becomes particularly problematic when increased insulation disrupts the dynamic balance of heat transfer, potentially trapping thermal energy rather than dissipating it. Consequently, there is growing interest in evaluating the performance of conventional insulation and construction materials through quantum-informed analyses that consider thermal conductivity, radiative exchange, and energy-state transitions within material structures Hala (2025), Wang et.al, 2026).

Reflective window blinds, light-coloured surfaces, and low-polymer materials contribute to reducing solar heat gain by modifying surface reflectivity and emissivity at both macro and quantum levels. These strategies enhance the ability of surfaces to reflect incident solar radiation while minimizing absorption. Installing window shading devices—especially on south-facing façades—further optimizes the control of solar radiation by regulating photon interaction with building envelopes (Figure 4).

Optimal passive solar heating and cooling systems, when viewed through quantum architecture principles, should integrate spatial orientation, thermal mass, and airflow dynamics as part of an energy-field interaction system. South-facing living spaces, high thermal mass materials capable of storing and releasing heat at controlled rates, and aerodynamic building forms that mitigate wind pressure all contribute to stabilizing indoor thermal conditions. Additionally, night-time ventilation plays a critical role in releasing accumulated thermal energy, while enhancing indoor air quality through natural purification processes.

Passive ventilation, in this context, operates as a low-energy mechanism that aligns with quantum efficiency principles by reducing reliance on mechanical systems and maintaining healthier indoor environments compared to fully air-conditioned spaces . In central Karbala, traditional dwellings exemplify this approach, as their design inherently responds to local climatic conditions. These structures enable passive cooling during high humidity periods, unlike contemporary sealed buildings that often lead to thermal discomfort. A significant portion of the population continues to inhabit such free-running buildings, which are well-adapted to regional environmental conditions Ho, (2024).

To mitigate overheating during summer, it is essential to implement design strategies grounded in both classical environmental design and quantum architecture insights. These include harnessing cool evening breezes to facilitate heat dissipation, minimizing exposed external wall surfaces to reduce heat gain, integrating ventilation shafts or solar-responsive systems, and incorporating green spaces that provide shading and regulate microclimates. Vegetation, in particular, contributes to thermal regulation through evapotranspiration and surface cooling Oke, et al (2024), Systematic Review, (2025).

Glass surfaces should be optimized with low U-values and high visible light transmission, while also considering quantum-scale interactions such as spectral selectivity and infrared reflectance. The use of thermally insulated framing systems like wood or PVC enhances overall envelope performance. Adaptive shading systems on eastern and western façades during summer further improve indoor thermal regulation. This approach ensures that windows in bedrooms, living spaces, and façades are equipped with high-performance double glazing, enhancing energy efficiency. Moreover, the use of lightweight insulation materials and double-layered construction systems supports improved thermal resistance while maintaining dynamic heat exchange properties essential for balanced indoor environments.

Observations

Although the monitoring was minimal, the summer conditions were primary controlled by functional windows in three free-running hospital wards and the temperatures reached were consistent with the thermal comfort adaptive model. It ensures that internal temperatures, generally higher at higher atmospheric temperatures, are pouring with the ambient temperature.

Internal temperatures are high, resulting in in satisfaction for the occupant, at nursing stations where the occupant power is not provided for. The uncontrolled electricity power heat leakage from the incorrectly isolated radiant ceiling or windows has probably led to overheating. Unhappiness has been increased as the inhabitants do not have a system to test local temperatures: no operable windows are open and the radiant ceiling thermostats are in poor repair condition…Uncontrolled heat in buildings increases their overheating resistance, in particular when ambient temperatures are high, whether in hot spells such as heat waves or due to sever weather. Good practice in renewable energy the maintenance and repair of existing energy services thus has an important role to play in improving the electricity power. The costs are fairly minimal and will not hinder the operation of the hospital. Due to diligent maintenance, running cost of energy wastage and CO2 emissions can be minimized as well. Therefore, UHI generally leads to a net increase in total urban energy consumption.

Conclusion

This methodology integrates remote sensing and statistical modelling to effectively measure and analysed UHI. It is widely accepted in high-impact research due to its scalability, accuracy, and applicability to urban climate studies. Urban areas in Karbala have experienced substantial growth in size, quality, and spatial distribution, prompting urban designers and engineers to investigate not only their global climatic impacts but also their behavior through the lens of quantum architecture. This emerging paradigm reinterprets built environments as dynamic systems where energy exchange, material performance, and environmental responsiveness operate across multiple scales—from the macroscopic urban fabric to microscopic and quantum-informed interactions.

Studies indicate that these metropolitan areas exhibit higher temperatures than surrounding rural zones, intensifying environmental challenges such as urban heat islands. Within a quantum architectural framework, these temperature variations are not merely physical phenomena but are understood as part of a complex network of energy flows, surface interactions, and adaptive material responses that can be optimized through advanced design strategies. Therefore, UHI generally leads to a net increase in total urban energy consumption.

These findings support the concept of buildings as "quantum-responsive" systems capable of modulating thermal behaviour in real time. Climate change impacts in Karbala—including intensified dust storms, urban heat island effects, condensation phenomena, seasonal droughts, overheating, and elevated humidity—are examined as fluctuating environmental states that require adaptive, multi-scalar design responses. The study concludes that quantum architecture offers a novel approach to urban resilience, enabling the design of buildings and urban systems that dynamically interact with microclimatic variables, thereby improving thermal comfort, environmental quality, and long-term sustainability.

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Table 1: The weekly mean of daily average weather factors data for the project in the study period [2019 - 2024].

Months	Average Ambient Temperature C	Global Solar Radiation MJm^2	Albedo	Relative humidity %	Sunshine hours	Wind speed m/s
Jan	11.4	2.4	0.37	51	6.1	5
Feb	16.1	3.7	0.33	44.1	7	4.7
Marc	17	5.4	0.30	34.9	8.1	3.8
April	20.3	7.3	0.28	31	7.1	0.4
May	21.8	7.7	0.25	27.5	7.3	1
June	35.4	9.4	0.20	25.1	13	2.2
July	41.2	9.7	0.19	23	12.6	1.4
Aug	40.4	8	0.18	22.3	11.3	0.3
Sept	33.4	6.5	016	22.8	11	0.2
Oct	23.5	6.4	0.19	22.1	11.4	2.1
Nov	14.4	4.6	0.27	40	10.5	3
Dec	11.6	3.5	0.32	42	8	2.8

Table 2. Input on climate predictors based on data at local weather station in (10 January 2019).

Climate Factors	Data
Reference Minimum Air Temperature	26.6 C
Reference Average Air Temperature	38.6 C
Reference Maximum Air Temperature	50.5 C
Reference Incoming Total Solar Radiation	33.4 $MJ/m^2/d$

Reference Outgoing Solar Radiation	6.6 $MJ/m^2/d$
Reference Maximum Solar Radiation	3.24 $MJ/m^2/d$
Reference Incident Solar Latitude	80 degrees
Reference Sunshine	14.3 hours
Reference Wind Speed	6.5 m/s

Table 3. Relationships between air temperatures and reference climatic factors at Karbala .

	Inter a	Slope b	A covered %	Q_t	G cover	H/B ratio	W area	N	α	R^2	F	SE
T,min	2.04	0.886	0.007		0.210	0.032	2.0E-5			0.90	1805	0.53
T, avg	5.76	0.746	0.006	2.0E-02	0.03	-0.025	1.0E-02	0.33		0.68	334.5	0.37
T,max	17.17	0.431	0.009	0.13		0.18	5.3E-03	1.333	.98	0.46		

Fig 1. Map of Holy Karbala

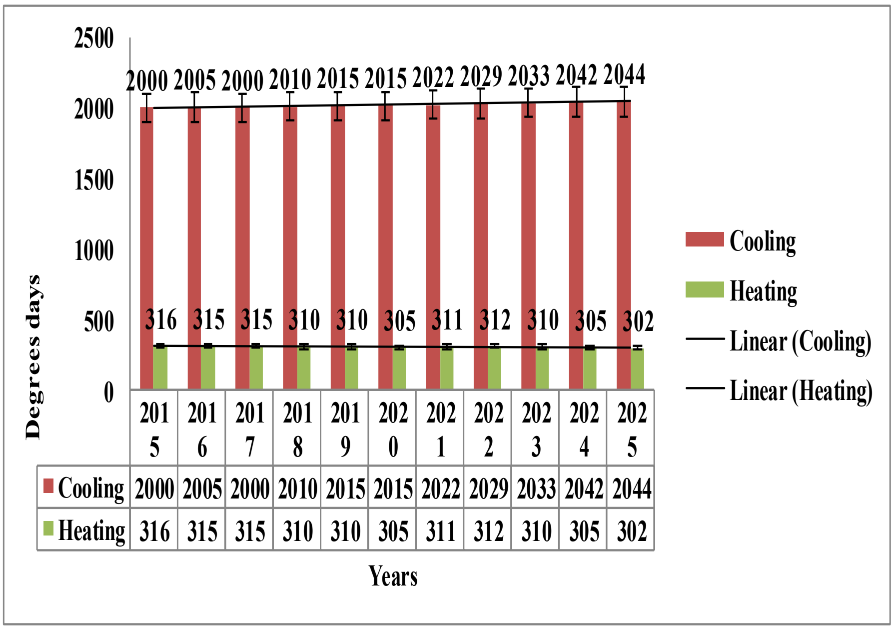

Fig. 2. Annual average of monthly heating and cooling degree-days.

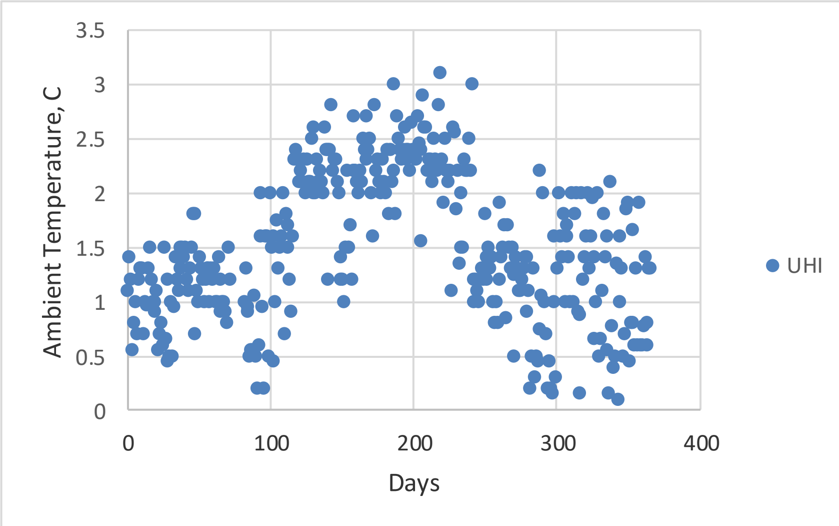

Figure 3. Daily averages of mean daily UHI values were calculated for each day of the recorded period.

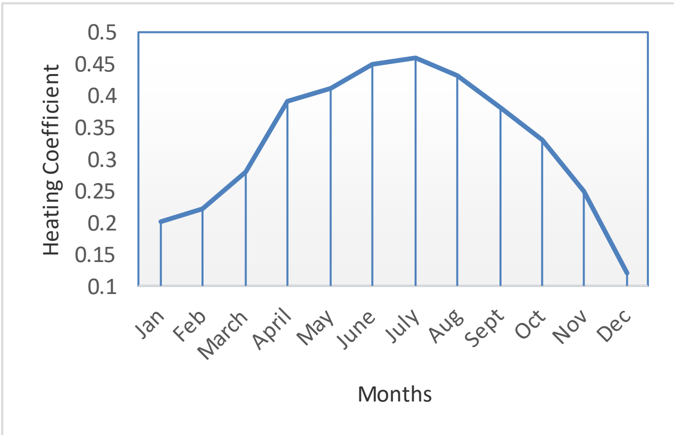

Fig. 4. Annual average of the monthly range of heating coefficients