ASSESSING THE IMPACT OF URBAN MORPHOLOGY ON URBAN HEAT ISLAND INTENSITY IN BEIRUT: A TEMPORAL COMPARATIVE APPROACH (2010-2021)

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Résumé

La densification urbaine dans les villes méditerranéennes en croissance rapide soulève des enjeux majeurs en matière de confort thermique et de régulation du microclimat. Cette étude explore l'impact des transformations morphologiques sur les températures de l'air à l'échelle locale, dans le quartier résidentiel de Furn Hayek à Beyrouth, entre 2010 et 2021.

À l'aide du logiciel ENVI-met, il a été possible de simuler les températures à l'échelle microclimatique. Grâce à la cartographie, aux données du facteur de vue du ciel ou Sky View Factor (SVF), aux valeurs de températures modélisées au niveau de cinq points d'étude (R2, R4, R5, R7, R9), il a été possible d'évaluer l'influence de la hauteur des bâtiments, du SVF et de la géométrie des canyons urbains sur les températures horaires de l'air.

Durant la période étudiée, la hauteur moyenne des bâtiments est passée de 19 à 28 mètres, tandis que leur nombre a diminué de 34 % en raison de projets de réaménagement. Ces changements ont eu un effet limité sur la température moyenne diurne (écart < 0,5 °C) mais ont significativement affecté les conditions microclimatiques locales : la baisse de la valeur du SVF dans certaines zones, entre 2010 et 2021, a entraîné des écarts thermiques allant jusqu'à 2,5 °C, notamment autour de midi.

Les résultats mettent en évidence le rôle déterminant de la visibilité du ciel et de l'orientation des rues dans la régulation thermique locale. Il est recommandé que les politiques d'aménagement à Beyrouth intègrent des indicateurs morphologiques sensibles au climat dans les règlements de zonage afin d'optimiser les performances microclimatiques des quartiers densément bâtis.

Mots-clés

Morphologie urbaine – *Îlot de chaleur urbain* – Sky View Factor – *Beyrouth* – ENVI-met – *Microclimat.*

Abstract

Urban densification in rapidly growing Mediterranean cities raises major challenges in terms of thermal comfort and microclimate regulation. This study explores the impact of morphological transformations on local air temperatures in the residential neighborhood of Furn Hayek in Beirut between 2010 and 2021.

Using the ENVI-met software, it was possible to simulate temperatures at the microclimatic scale. Through mapping and data from the Sky View Factor (SVF), as well as modeled temperature values at five study points (R2, R4, R5, R7, R9), the influence of building height, SVF, and urban canyon geometry on hourly air temperatures was assessed.

During the study period, the average building height increased from 19 to 28 meters, while the number of buildings decreased by 34% due to redevelopment projects. These changes had a limited effect on average daytime temperature (variation < 0.5 °C), but significantly impacted local microclimatic conditions: the drop in SVF values in certain areas between 2010 and 2021 led to thermal differences of up to 2.5 °C, especially around midday.

The results highlight the critical role of sky visibility and street orientation in local thermal regulation. It is recommended that urban planning policies in Beirut incorporate climate-sensitive morphological indicators into zoning regulations to optimize the microclimatic performance of densely built neighborhoods.

Keywords

Urban morphology – Urban heat island – Sky View Factor – Beirut – ENVI-met – Microclimate.

Introduction

The speed of urbanization is a major driver of the urban heat island (UHI) because it alters surface materials (e.g., asphalt, concrete) and land-use patterns, increasing heat storage and sensible heat fluxes (Kaplan *et al.*, 2018). Empirical studies also associate the quick development with the variation of thermodynamics, which raises the temperature of the air and surface (Zhao *et al.*, 2020). Landscape-ecological analysis is useful in predicting these effects and providing mitigation, whereas the shape of the city, its urban morphology, is one of the major regulators of local microclimate (Oke, 1981; Emmanuel and Fernando, 2007; Ali-Toudert and Mayer, 2006). Slim, tight street canyons having less sizable sky openings are more likely to trap heat and decrease ventilation; as a result, nocturnal cooling is reduced and localized stress heightens (Oke, 1981; Emmanuel & Fernando, 2007; Ali-Toudert and Mayer, 2006; Stewart and Oke, 2012).

Shading, radiative exchange, and airflows are controlled by urban morphology, including the sky view factor (SVF), building ratios of height to width (H/W), and the orientation of streets (Emmanuel and Fernando, 2007; Oke, 1981). Small values of SVF, which are characteristic of high-rise and congested areas, promote the amplification of long-wave trapping and intensified UHI features, whereas smart geometry can improve shading and cross-ventilation (Fahed *et al.*, 2020; Ali-Toudert and Mayer, 2006; Tuan *et al.*, 2019). On larger scales, a similar perspective may be offered by the Local Climate Zones (LCZ) framework, which allows classifying land cover and urban form on a consistent basis in terms of variability in temperature and heat-retaining capacity (Geletic *et al.*, 2016; Alexander and Mills, 2014). Although increased density usually comes along with reduced vegetation and increased thermal mass, heavily designed compact forms can enhance energy use as well as transport, which compensates in part in combination with green and ventilated designs (Adolphe, 2001; Ali-Toudert and Mayer, 2006).

The vertical development and subtle vegetation coverings in the city of Beirut had acted almost unregulated between 2010 and 2021, with recorded rises in overheating and decreased residential thermal comfort (Kaloustian *et al.*, 2018; Fahed *et al.*, 2020; Jaafar, 2019). Other, more vegetation-limited cities that rapidly urbanize have also exhibited similar UHI amplification, such as those in Dhaka and Colombo (Maheng *et al.*, 2019; Yu *et al.*, 2021). The absence of open space and the existence of small canyons in Beirut leads to daytime heat trapping and the inability to cool down at night, which supports the importance of climate-aware urban design (Asbik *et al.*, 2022). Although the evidence is there, the respective contributions of SVF and canyon geometry at the neighborhood/

receptor scale in Beirut are under-quantified, particularly in the recent decade of morphological change.

This paper fills this gap through analyzing the Furn El-Hayek district in terms of ENVI-met calculated simulations with the incorporation of receptor-based SVF measures. We compare two average days (May 2010 and August 2021), calculate SVF and urban-form indicators in five receptors, and assess near-surface air temperature on an hourly basis to separate morphological-related effects. On the basis of literature related to the compatibility in form-microclimate relationships and mitigation through ventilation corridors and shading (Adolphe, 2001; Ali-Toudert & Mayer, 2006; Tuan *et al.*, 2019), we are asking the following questions:

(i) Until 2021, what was the change in building height and SVF at receptor and district scales as compared to the year 2010?
(ii) What are the effects of SVF differences on the receptor's hourly near-surface air temperature?
(iii) What is the effect of vertical growth (no significant SVF loss) on the mean air temperature of the districts?

1. Study Area and Methodology

1.1. Study Area: Furn El-Hayek, Beirut

The study is located in Furn El-Hayek, a thick neighborhood in the eastern region of Beirut, which has experienced a strong morphological transformation in the past 20 years. Having been defined by mid-rise residential blocks with mixed-use ground floors during the post-conflict phase, the area has undergone such rapid redevelopment due to population growth and economic pressures that it resulted in a rise in the pace of construction and an increase in building heights between 2010 and 2021 (Ferrari, 2022). Those dynamics have resulted in a Furn El-Hayek that can be described as a reflection of the modern Beirut urbanization where vertical development processes and infill develop street canyons and courtyard fabrics. Due to its mix of small street canyons and courtyard planning and an emergence of high-rise buildings that alter shading, ventilation, and radiative exchange at the neighborhood scale, Furn El-Hayek is suitable for conducting microclimatic UHI (Elbardisy *et al.*, 2022). This combination of the fact that older urban tissue still exists and is mingling with more recent interventions involving high density means that comparative analyses can be done to understand how varying form, especially the geometry of canyons, and the openness of the sky can influence near-surface air temperature. Drawing on the high-resolution datasets in 2010 and 2021, which facilitate comparison of the urban form and thermal responses through receptors, the study will draw balanced comparisons of the urban forms across time using the consistency of temporal snapshots. This time series association helps to identify morphology-specific signals successfully in air temperature and removes larger-scale synoptic changes (Adiguzel, 2023).

1.2. Data and Tools

A means of analyzing urban morphology was done through a combination of microclimate simulation and spatial analysis to determine the effects on near-surface air temperature. We used the ENVI-met 3D microclimate model to simulate small-scale urban climate in representative neighborhood blocks and to compare two typical warm-season days in Beirut: 9 May 2010 and 11 August 2021 (Bande *et al.*, 2020; Le & Chan, 2023).

Because stable in-situ meteorological records were unavailable for the study domain, Weather Research and Forecasting (WRF) outputs provided initial and boundary conditions (air temperature, relative humidity, wind speed/direction, and shortwave/longwave radiation). To improve the fidelity of lateral forcing, WRF fields (NetCDF) were pre-processed and formatted for ENVI-met ingestion, following a simple assimilation workflow that localizes the mesoscale signal to the micro-domain (Mahdavinejad *et al.*, 2018).

Urban form inputs were compiled from geospatial databases and field verification: building footprints, land-use categories, and building heights (estimated from floor counts and validated in spot checks). Vegetation type and distribution were documented in field surveys and cross-checked with high-resolution imagery (Google Earth/Maps) and local agronomic knowledge.

Simulations used a 2 m horizontal grid (first vertical layer 0.52 m), domain 400 × 400 m, run time 24 h. This single configuration is used consistently throughout the manuscript and supersedes earlier mentions of 4 × 4 × 4 m. The chosen days exhibit high solar loading and relatively low winds, favourable for expressing UHI contrasts in a Mediterranean climate (Bande *et al.*, 2020; Le & Chan, 2023).

To quantify sky openness and radiative exchange potential, we computed the Sky View Factor (SVF) with the ENVI-met *Leonardo* module and cross-validated patterns against GIS-based tools. SVF modulates short-wave gains by day and long-wave cooling at night; thus, it is a key determinant of local heat accumulation and release (Sui *et al.*, 2023). *(All instances of "Solar View Factor" have been standardized to "Sky View Factor (SVF)".)*

Analyses focus on five fixed receptors, R2, R4, R5, R7, R9, selected to span open intersections, dense canyons, and mid-rise blocks. Example SVF values illustrate contrasts across form types: R2 ≈ 0.8 (open); R5 ≈ 0.1 (highly enclosed); R4 ≈ 0.3 and R9 ≈ 0.3 (narrow canyons with similar SVF but different orientations). *At R2*, higher SVF corresponds to stronger daytime shading/ventilation effects relative to the confined conditions at R5. This five-point design enables receptor-level linkage between geometry and hourly air temperature while avoiding redundancy. Prior receptor-network studies support such spatial sampling for diagnosing UHI mechanisms and mitigation leverage points (Durán *et al.*, 2023; Matias *et al.*, 2023).

1.3. Analytical Methods

Hourly outputs from ENVI-met were used to establish the relationship between urban morphology and near-surface air temperature (Ta) for two representative warm-season days, 9 May 2010 and 11 August 2021, and to compare receptor-level thermal responses across years. For both 2010 and 2021, the morphological description comprised the Sky View Factor (SVF) computed with ENVI-met *Leonardo* and cross-validated in a GIS environment, supplemented by building height (derived from floor counts), street orientation, and canyon height-to-width (H/W) ratios. These variables were selected because they jointly condition short-wave loading, long-wave exchange, and ventilation potential, thereby governing local thermal regimes (Bande *et al.*, 2020; Le & Chan, 2023). Analyses were conducted at five fixed receptors, R2, R4, R5, R7, R9, purposefully sampled to span open intersections, dense urban canyons, and mid-rise blocks; for each receptor, complete hourly Ta series were extracted for both years, and a district-scale reference was computed as the unweighted mean across receptors (Adıgüzel, 2023; Elbardisy *et al.*, 2022).

Temporal aggregation was standardized to two windows that capture the principal diurnal thermal processes: 10:00-15:00 for daytime peak short-wave forcing and 20:00-23:00 for nocturnal release. For each receptor (and for the district mean), we derived mean Ta within each window for 2010 and 2021, the interannual difference ΔTa (2021 − 2010), the daytime peak-hour Ta (arg-max within 10:00-15:00), and a nocturnal cooling rate estimated as the ordinary-least-squares slope of Ta between 20:00 and 23:00. Morphology-temperature linkages were then examined through bivariate associations between SVF and these thermal indicators and by contrasting open versus enclosed canyon types, with attention to potential co-influences from H/W and orientation (Bande *et al.*, 2020; Le & Chan, 2023). Spelling and citation harmonization were enforced (e.g., Bande consistently; Adıgüzel, 2023), and redundant explanatory sentences were removed to preserve analytical coherence.

2. Results and Analysis

2.1. Urban Morphological Change (2010 vs. 2021)

Over the past decade, Furn El-Hayek underwent substantial morphological change. A field-validated survey indicates that mean building height rose from 19 m (2010) to 28 m (2021), while the total number of building units declined by 34% due to plot mergers and redevelopment into larger multi-storey blocks. This trend is consistent with the tendencies reported in the cities with rapid development, where horizontal growth becomes scarce and triggers vertical constructions (Chen *et al.*, 2023; Silva *et al.*, 2018; Qiao *et al.*, 2020).

ENVI-met simulations were carried out with uniform boundary conditions and the inputs of urban forms to assess the thermal implication of this verticalization on 9 May 2010 and 11 August 2021. Fig. 1 (May) and Fig. 2 (August) demonstrate the district-mean hourly air temperature (Ta) of that day and year. Fig. 1 and Fig. 2 show that the 24-h Ta curves of 2010 and 2021 are similar in the day and in the nocturnal.

Across the two typical days (9 May and 11 August), the district-mean air temperature shows no significant interannual change between 2010 and 2021. The 24-h Ta curves overlap (Figs. 1–2), and the 2010→2021 difference in district-mean Ta is < 0.5 °C on both days. Thus, the vertical growth between 2010 and 2021 does not produce a measurable warming at the district scale. This discovery is in line with the previous research where the height of buildings alone has a low impact on the closer surface temperature as long as there is no densification to choke ventilation pathways or intensive vegetation loss and material albedo variations (Qiao *et al.*, 2020; Wang, 2019; Maheng *et al.*, 2019). In Furn El-Hayek, redevelopment had not abandoned courtyard porosity or key flow paths, which probably alleviated warming with additions in height.

In more general terms, urban structure, such as the canyon H/W ratios, orientation, and SVF, and vegetative cover, can appear as a more powerful indicator of thermal variation as compared to bulk size indicators on their own (Shih *et al.*, 2020). In the study region, geometry-related design modifications were not only large-scale in nature, but they also did not translate into localized comfort differences; localized geometry and SVF differences appear where geometry and channel screening have a different response, and this should be supportive of the emphasis on form-sensitive planning that is sensitive to ventilation.

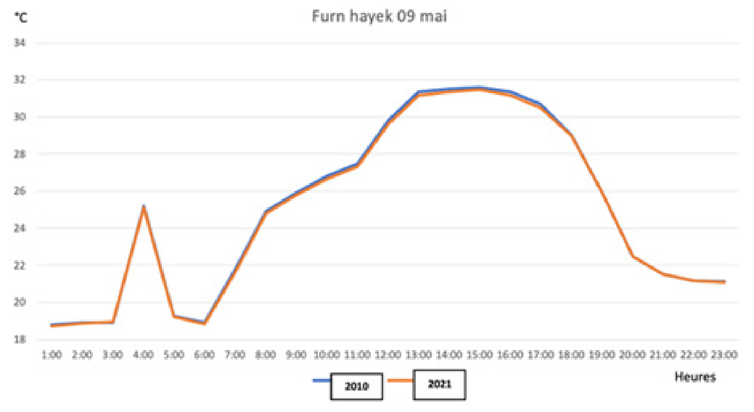

Figure 1. Hourly air temperature variation in Furn Hayek on May 9 for 2010 and 2021 based on ENVI-met simulations.

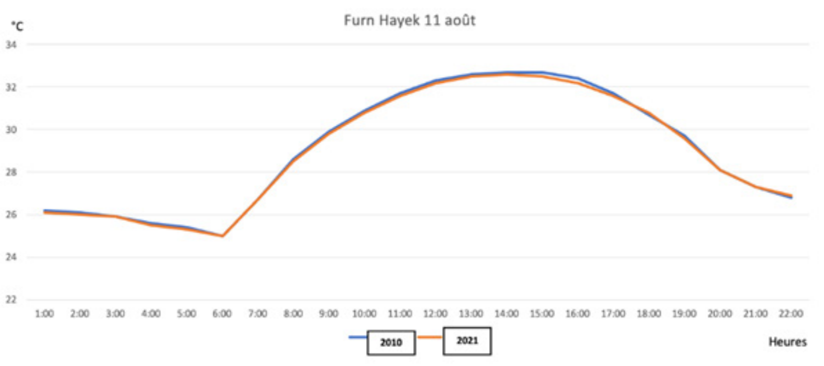

Figure 2. Hourly air temperature variation in Furn Hayek on August 11 for 2010 and 2021 based on ENVI-met simulations.

2.2. Sky View Factor (SVF) and Microclimate Impact

SVF, the fraction of visible sky from ground level, governs daytime short-wave gain and night-time long-wave loss. As such, it is a widely used indicator of heat storage and release in dense urban fabrics (Baghaeipoor & Nasrollahi, 2019). To spatially contextualize the analysis, Fig. 3 maps the study area and the five fixed receptors (R2, R4, R5, R7, R9). To track openness changes through time, we provide SVF maps for both years: Fig. 4.

Five receptor points were selected to span open squares and tight urban canyons and were assigned SVF values using ENVI-met *Leonardo* with GIS validation. R2 represents an open configuration (SVF ≈ 0.8), whereas R5 sits within a deep canyon (SVF ≈ 0.1). Although R4 and R9 exhibit similar SVF (~0.3), their differing orientations and canyon geometries allow controlled comparisons of morphological effects beyond openness alone.

Hourly outputs from ENVI-met for 9 May 2010 and 11 August 2021 indicate clear SVF–temperature linkages. Fig. 5 demonstrates that high-SVF points experience greater daytime heating between 10:00 and 15:00 due to enhanced solar admission, whereas low-SVF canyons (e.g., R5 ~0.1) display muted daytime peaks because of persistent shading, patterns consistent with prior observations in compact districts (Lyu *et al.*, 2019; Meng *et al.*, 2021). At night, receptors with higher SVF cool more rapidly owing to increased exposure to the sky dome and, hence, stronger long-wave radiative loss (Baghaeipoor & Nasrollahi, 2019). At R2, Ta decreased from ~34 °C at 14:00 to ~22 °C at 23:00 in May, illustrating rapid nocturnal cooling under high SVF (~0.8).

SVF alone does not fully explain inter-receptor differences. Despite similar SVF (~0.3), R4 and R9 exhibit distinct thermal curves attributable to height-to-width ratios, surface materials, and solar orientation, underscoring interaction effects between openness, canyon geometry, and fabric properties (Wei *et al.*, 2023; Yildiz *et al.*, 2023). In sum, SVF is an appropriate first-order indicator of thermal response, but microclimatic evaluation benefits from the concurrent consideration of canyon H/W, orientation, and materials, which modulate the magnitude and timing of both daytime heating and nocturnal cooling.

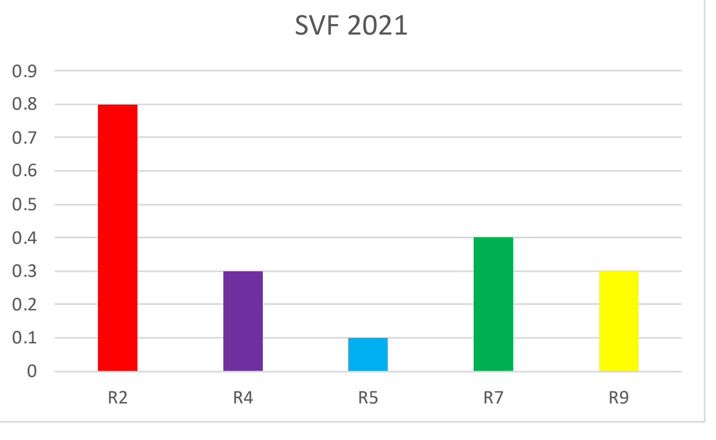

Figure 3. Sky View Factor (SVF) values at receptor points R2, R4, R5, R7, and R9 in Furn Hayek (2021).

Figure 4. Spatial distribution of receptor points R2, R4, R5, and R9 across the urban fabric of Furn Hayek (2021), showing building density and relative sky openness.

2.3. Comparative Sensor Analysis

Several fixed receptor points in Furn El-Hayek enable a detailed examination of how canyon geometry (height-to-width, orientation) and the Sky View Factor (SVF) shape local microclimate. The five receptors, R2, R4, R5, R7, R9, were selected to span conditions from open intersections to highly confined urban canyons within the thermal study zone.

SVF evolution (2010→2021) at the receptors is summarized in Table 1. The open site R2 retained high openness (SVF = 0.8) in both years, whereas R5 and R9 exhibited marked declines (0.3→0.1 and 0.6→0.3, respectively). These trends suggest that accretion and infill between the canyon edges are tighter, thereby reducing the accessibility of the sky, which is likely to alter the ratio of gains during the day and loss of radiation at night. This morphology has a thermal imprint explained by the aggregate perspective between receptors. Figure 5 displays the hourly air temperatures recorded on 9 May (top) and 11 August (bottom) 2021 at five sites, indicating a temperature difference of approximately 2.5°C the low-SVF sites, such as R5 with an approximate value of 0.1, warm less intensely during the day and cool more efficiently at night, while the open site R2 warms more quickly during the day and cools more rapidly at night. Figure 6 illustrates a parallel morphology that records parcel mergers and volumetric expansion from 2010 to 2021, indicating that larger footprints around R4, R5, and R9 reduce airflow and the efficiency of the sky view; it is known that canyon density and height-to-width (H/W) ratios can control access to sunlight and effective ventilation.

Using the composite series of 2010 vs 2021 receptors, interannual contrasts occur. Figure 7 presents comparative results of hourly Ta on 11 August across several receptors, indicating that the observed thermal differences result from a combined effect of SVF and the shape of the canyon. The analysis of R5, R7, and R9 for 9 May (shown in Figure 8) indicates that the thermal paths, even where SVF is similar, are separated by materials and orientation. Indicatively, Figs. 4 and 9 (R4 and R9 are both SVF, approx. 0.3) have different daytime maxima and evening decays that can be explained by H/W, surface features, and orientations of the sun. As in previous studies, SVF is not the only factor affecting the response; at the receptor scale, responses are influenced by canyon height-to-width ratio (H/W), orientation, and material shape.

These interactions are strengthened by nighttime behavior. In May, when the SVF is approximately 0.8, R2 experiences rapid cooling in the evening, with Ta dropping between 14:00 and 23:00; meanwhile, R5, which has an SVF of approximately 0.1, exhibits thermally persistent ventilation after sunset due to the trapping of long waves and inhibited ventilation. These findings align with existing data indicating that the limited sky view in deep canyons raises nighttime temperatures and prolongs heat stress duration. Street-canyon geometry therefore acts as an air-flow regulator in warm climates (Anselm, 2019), and systematic canyon recognition supports climate-responsive planning (Ferreira *et al.*, 2020).

Overall, the receptor analysis confirms that openness (SVF) is a strong first-order indicator of thermal behavior, but microclimatic prediction requires concurrent consideration of H/W, orientation, and materials. This multi-parameter perspective is essential for diagnosing neighborhood-scale heat exposure and for targeting ventilation-aware, shading-oriented interventions in Furn El-Hayek.

Receptor	**(SVF (2010**	**(SVF (2021**
R2	0.8	0.8
R4	0.4	0.3
R5	0.3	0.1
R7	0.5	0.4
R9	0.6	0.3

Table 1: Comparison of Sky View Factor (SVF) values at receptor points in Furn Hayek between 2010 and 2021.

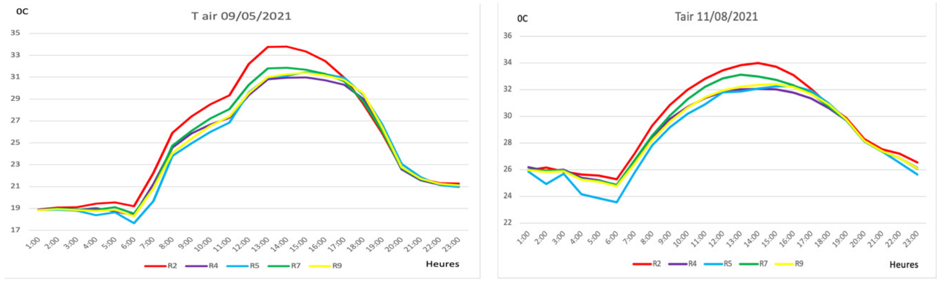

Figure 5. Hourly air temperature variations on May 9 (top) and August 11 (bottom), 2021, at receptors R2, R4, R5, R7, and R9 in Furn Hayek, showing the effect of local SVF values on thermal performance.

Figure 6. Superimposed urban morphology maps of Furn Hayek showing building footprints in 2010 (purple) and 2021 (green), with the location of receptor points (R2, R4, R5, R7, R9) used in SVF analysis.

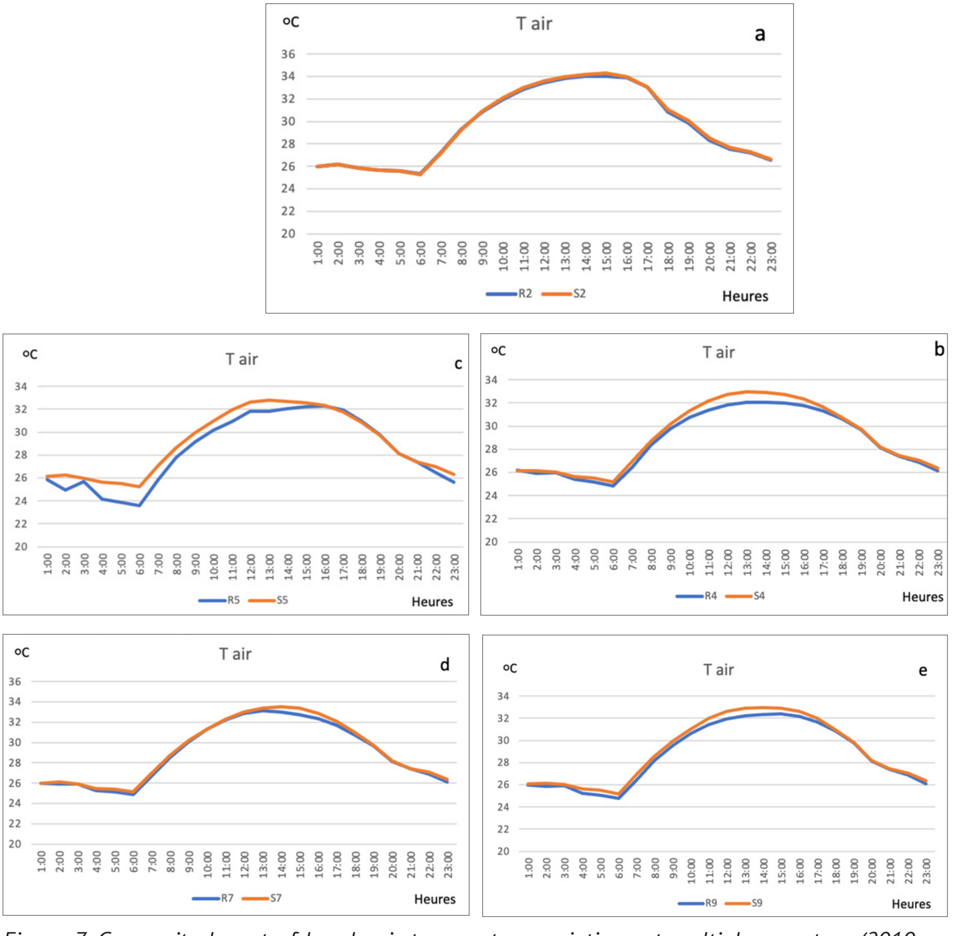

Figure 7. Composite layout of hourly air temperature variations at multiple receptors (2010 vs. 2021), highlighting local microclimatic differences due to SVF and urban geometry in Furn Hayek in 11 august.

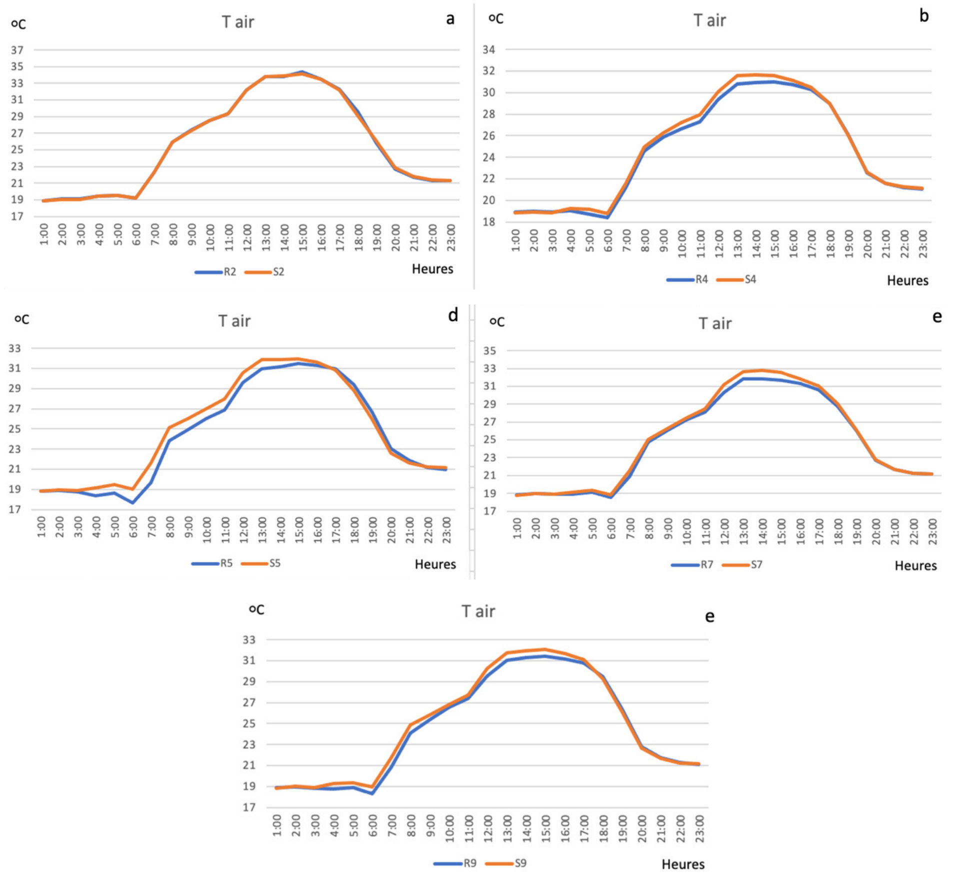

Figure 8. Extended comparison of hourly air temperature at remaining receptors (R5, R7, R9) in Furn Hayek between 2010 and 2021, highlighting morphological effects on local thermal profiles in 09 may.

3. Discussion

The research findings have critical implications for the way thermal properties of the fast-evolving cities like Beirut are influenced by the changes in the building height in addition to the alterations in visibility of skies and street ratios. Height and densification of buildings do not entirely explain the variation in the temperature, as is evident in the analysis, which shows how these two factors interact with the variations in space to influence the local tempos.

Verticalization is a single element that cannot be used to ensure the increased urban heat levels according to the comparisons made by receptors. It has been documented in literature that there is a relationship between the density of building and height on urban heat island effects, but the relationship also has restrictions and limitations. Qiao *et al.*, (2020) reveal the fact that morphological alterations in elevation cause the appearance of temperature variations only under the condition of limited open spaces and limited ventilation. Our case study is supported by the field results because Furn El-Hayek demonstrated a significant vertical expansion but exhibited the same average air temperature results. Such a finding propels the urban densification and its climatic impact as a topic of discussion in the literature (Silva *et al.*, 2018; Chen *et al.*, 2023).

This study establishes the value of Sky View Factor (SVF) as a very vital predictor of microclimate impacts, although it attaches a condition that it cannot perform optimally without other factors. The shape indicators have a "contextual sensitivity" that explains the results of Wei *et al.*, (2023), who observe that dissimilar regions with the same SVF can have varying temperature responses. A receptor of the 0.3 SVF exhibited varying temperature profiles to that of R9 in spite of the similarity in their SVF given the street layout and other dimensional variations. Lyu *et al.*, (2019), as well as Yildiz *et al.*, (2023), in their writing stressed that the opening patterns of the urban canopy in terms of direction and solar accessibility make the same contribution to analysis outcomes as the SVF value.

The study notes that the size of urban canyons in interrelationship with their location and separation serves as a critical decision variable in the process of calculating the heat storage and release mechanisms. The direction of the wind and the sunlight influence the cooling of the canyons when the shape is considered, as Hu *et al.*, (2020) and Ferreira *et al.*, (2020) argue. Narrow shaded canyons such as R5 had receptors whose radiative cooling was restricted by thermal inertia, resulting in them warming down slower during the day. The placement of the canyons also influences the way they obtain the sun's energy and the efficacy of air flowing through them, which validates what Yola and Siong (2018) reported in their study on hot and humid localities.

The research findings are consistent with the conclusions made by Baghaeipoor and Nasrollahi (2019), who discovered that the more the sky is exposed, the more the radiative heat is lost, especially in urban spaces with no significant vegetation. The open spaces in urban neighborhoods are one of the potential design alternatives that can be used to regulate nocturnal heat stress as a result of simulation results indicating that they are more effective during night cooling.

Geometries of the streets at the level of the receptors: the use of simulation models alongside the spatial data analysis indicates that the street geometries should be discussed as a mediator between buildings and ambient environmental temperatures, as Anselm (2019) describes. The micro-scale spatial characteristics with street orientation, intersection distribution, and the size of canyons are the final determinants of the heat behavior of built fabric. Drach *et al*., (2018) conclude that within-urban temperature variability exists due to morphological aberration in combination with atmospheric stability irrespective of homogenous land cover configurations.

The approach to reading urban patterns enhances the developing practice, which promotes climate planning at multiple scales while being mindful of urban forms. This research suggests that appropriate architecture-centered density policies would be better than indiscriminate denigration of densification since excellent building layout strategies can make compact cities thermally manageable. Urban microclimate conditions enhance substantially when designers make deliberate changes to geometric features, according to Wong (2020) in his research on pedestrianized cores.

Between 2010 and 2021, the district underwent marked verticalization: mean building height increased from 19 m to 28 m, while the number of buildings fell by 34% due to plot mergers and redevelopment. At receptor scale, openness changes were heterogeneous: R2 remained high (SVF 0.8→0.8), whereas enclosure increased around R5 (0.3→0.1) and R9 (0.6→0.3), with moderate reductions at R4 (0.4→0.3) and R7 (0.5→0.4). See Table 1 for receptor SVF values, Fig. 3 for locations, and Fig. 4a–b for the 2010/2021 SVF maps.

Hourly ENVI-met outputs show a consistent SVF–temperature relationship. High-SVF sites warm more during 10:00-15:00 but cool faster at night, whereas low-SVF canyons display muted daytime peaks yet elevated nocturnal temperatures due to long-wave trapping and restricted ventilation. Midday contrasts reach ≈2.5 °C across receptors; at R2 (SVF ≈ 0.8) air temperature dropped from ~34 °C at 14:00 to ~22 °C at 23:00 in May, evidencing rapid radiative cooling under open sky (see Fig. 5, Fig. 7–8). In contrast, R5 (SVF ≈ 0.1) remains thermally persistent after sunset.

Despite substantial vertical growth, the district-mean interannual difference on both typical days is small (ΔTa < 0.5 °C). Under the simulated conditions, vertical expansion did not measurably increase mean air temperature at the district scale (see Fig. 1–2). The balance of evidence indicates that openness (SVV), canyon H/W, orientation, and materials dominate receptor-level thermal response and that maintaining courtyard porosity and ventilation paths can offset warming even as building heights rise.

Conclusion

Across Furn El-Hayek (2010–2021), pronounced verticalization did not measurably raise district-mean near-surface air temperature on the two typical days simulated ($\Delta Ta < 0.5$ °C), yet receptor-level conditions varied markedly with morphology: higher SVF sites warmed more by day but cooled faster at night, while low-SVF canyons showed muted daytime peaks and persistent nocturnal heat. These findings indicate that thermal exposure regulations are moderated by openness (SVF) and by canyon H/W and orientation/materials and are not height controlled, and the impact of climate-sensitive form could counteract warming in spite of the rise in building height.

BIBLIOGRAPHY

- Adigüzel, F. (2023). "Effects of green spaces on microclimate in sustainable urban planning". *International Journal of Environment and Geoinformatics*, 10(3), p. 124-131. https://doi.org/10.30897/ijegeo.1342287
- Adolphe, L. (2001). "A simplified model of urban morphology: Application to an analysis of the environmental performance of cities". *Environment and Planning B: Planning and Design*, 28(2), p. 183-200. https://doi.org/10.1068/b27151
- Alexander, P. J. & Mills, G. (2014). "Local climate zone classification and land surface temperature: Case study of Dublin, Ireland". *International Journal of Climatology*, 34(2), p. 258-275. https://doi.org/10.1002/joc.3686
- Ali-Toudert, F. & Mayer, H. (2006). "Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in a hot and dry climate". *Building and Environment*, 41(2), p. 94-108. https://doi.org/10.1016/j.buildenv.2005.01.013
- Anselm, A. (2019). "Effects of street geometry on airflow regimes for natural ventilation in three different street configurations in Enugu City". In *IntechOpen*. https://doi.org/10.5772/intechopen.84786
- Asbik, M., Kettani, M. A. & Bahi, H. (2022). "Microclimate simulation and UHI mitigation strategies for Mediterranean cities: The case of Beirut". *Sustainable Cities and Society*, 77, 103585. https://doi.org/10.1016/j.scs.2021.103585
- Baghaeipoor, G. & Nasrollahi, N. (2019). "The effect of sky view factor on air temperature in high-rise urban residential environments". *Journal of Daylighting*, 6(2), p. 42-51. https://doi.org/10.15627/jd.2019.6
- Bande, L., Manandhar, P., Ghazal, R. & Marpu, P. (2020). "Characterization of local climate zones using ENVI-met and site data in the city of Al-Ain, UAE". *International Journal of Sustainable Development and Planning*, 15(5), p. 751-760. https://doi.org/10.18280/ijsdp.150517
- Chen, Z., Lin, X., Li, M., Chen, Y., Huang, Y., Zhu, Y. & Dong, J. (2023). "Spatio-temporal dynamic characteristics and landscape connectivity of heat islands in Xiamen in the face of rapid urbanization". *Sustainability*, 15(19), 14603. https://doi.org/10.3390/su151914603
- Drach, P., Krüger, E. & Emmanuel, R. (2018). "Effects of atmospheric stability and urban morphology on daytime intra-urban temperature variability for Glasgow, UK". *Science of the Total Environment*, 627, p. 782-791. https://doi.org/10.1016/j.scitotenv.2018.01.285
- Durán, A., Waibel, C. & Schlueter, A. (2023). "A parametric approach to evaluate the impact of BIPV facades on outdoor thermal comfort in different urban contexts". In *Proceedings of the 18th International Conference of the International Building Performance Simulation Association (BS2023)*. https://doi.org/10.26868/25222708.2023.1308
- Elbardisy, W., Salheen, M. & Fahmy, M. (2022). "The impact of street trees on a typical urban canyon in the Eastern Cairo region". *IOP Conference Series: Earth and Environmental Science*, 1056(1), 012025. https://doi.org/10.1088/1755-1315/1056/1/012025

- Emmanuel, R. (2005). *An urban approach to climate-sensitive design: Strategies for the tropics*. London: Spon Press.
- Emmanuel, R. & Fernando, H. J. S. (2007). "Urban heat islands in humid and arid climates: Role of urban form and thermal properties in Colombo, Sri Lanka". *Journal of Environmental Management*, 86(1), p. 1-10.
  https://doi.org/10.1016/j.jenvman.2006.11.025
- Fahed, J., Kinab, E., Ginestet, S. & Adolphe, L. (2020). "Impact of urban heat island mitigation measures on microclimate and pedestrian comfort in a dense urban district of Lebanon". *Sustainable Cities and Society*, 61, 102375.
  https://doi.org/10.1016/j.scs.2020.102375
- Fahed, M., Khalil, A. & Bou Akar, H. (2020). "Urban morphology and thermal comfort: A case study in Beirut". *Urban Climate*, 34, 100671.
  https://doi.org/10.1016/j.uclim.2020.100671
- Ferrari, S. (2022). "Ventilation in a group of courtyard buildings". *EPJ Web of Conferences*, 264, 01014. https://doi.org/10.1051/epjconf/202226401014
- Ferreira, V., Boschi, L. & Souza, G. (2020). "Identification of urban canyons in the city of São Paulo from Landsat 8 images". In *Proceedings of the International Electronic Conference on Geosciences*, p. 17. https://doi.org/10.3390/iecg2020-08911
- Geletić, J., Lehnert, M. & Dobrovolný, P. (2016). "Urban warming in Central Europe: The impact of the urban heat island on temperature trends". *Theoretical and Applied Climatology*, 124(1-2), p. 365-376. https://doi.org/10.1007/s00704-015-1410-1

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