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Comparative Investigation of Outdoor Thermal Comfort in Different Local Climate Zones (LCZ): The Case of Konya

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Abstract

Outdoor thermal comfort is the condition where individuals feel neither too hot nor too cold according to environmental conditions. This comfort is critical for people to be able to continue their physical activities and social interactions in open spaces. Research shows that increasing green spaces, tree cover and urban morphology can increase thermal comfort by lowering temperatures. In this study, it was aimed to determine the effect of outdoor thermal comfort in 6 different local climate zones (LCZ) in Konya city, which has a BSk (cold-semi-arid) climate, in summer and winter. In order to determine the thermal comfort in the outdoor environment, PET (Physiological equivalent temperature) index was found by using ENVI-met software. Summer and winter season data were used for the analyzes. As a result of the study, it was determined which local climate zones are thermally comfortable for summer and winter seasons for cities with BSk climate.

Keywords: *Local climate zone, urban microclimate, urban, morphology, outdoor thermal comfort.*

Farklı Yerel İklim Bölgelerinde (LCZ) Dış Mekan Termal Konforunun Karşılaştırılmalı Olarak İncelenmesi: Konya Örneği

Öz

Dış ortamda termal konfor, bireylerin çevresel koşullara göre ne çok sıcak ne de çok soğuk hissetmeleri durumudur. Bu konfor, insanların açık alanlarda fiziksel aktivitelerini sürdürebilmeleri, sosyal etkileşimde bulunabilmeleri açısından kritik öneme sahiptir. Araştırmalar, yeşil alanların, ağaç örtüsünün artırılmasının ve kentsel morfolojinin sıcaklıkları düşürerek termal konforu artırabileceğini göstermektedir. Çalışmada, BSk (soğuk-yarı kurak) iklimine sahip Konya kentinde 6 farklı yerel iklim bölgesinde (LCZ) yaz ve kış aylarında dış ortamda termal konforun etkisinin tespit edilmesi amaçlanmıştır. Dış ortamda termal konforun tespit edilebilmesi için ENVI-met yazılımından yararlanılarak PET (Fizyolojik eşdeğer sıcaklığı) indisi bulunmuştur. Yapılan analizler için yaz ve kış mevsim verileri kullanılmıştır. Çalışmanın sonucunda BSk iklimine sahip kentler için hangi yerel iklim bölgelerinin yaz ve kış mevsimi için termal açıdan konforlu olduğu tespit edilmiştir.

Anahtar kelimeler: *Yerel iklim bölgesi, kentsel mikroklima, kentsel morfoloji, dış ortamda termal konfor.*

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1. Introduction

The increase in population and the consequent change in the form of urbanization, which has been inadequate, has brought with it some negative environmental impacts. As a result of urbanization, green areas and trees have decreased, the built environment has increased, and accordingly the wind circulating in the city has decreased. At the same time, greenhouse gas emissions have also increased. All these results have led to global warming.

As a result of all this urbanization, the living comfort of urban dwellers has been negatively affected. In particular, the urban heat island effect has led to an increase in temperatures in cities and the emergence of uncomfortable spaces in the summer months. Due to changes in land cover, increase in hard surfaces, decrease in green areas and anthropogenic anthropogenic effects, urban centers are warmer in the air and on the surface than rural areas on the periphery, which is called the "Urban Heat Island Effect" (Oke, 1982; Stone Jr & Rodgers, 2001; Streutker, 2003; Theophilou & Serghides, 2015). With the increase in the urban heat island effect, especially in recent years, the concept of thermal comfort in the outdoor environment has emerged and research on this subject has increased.

The environment and humans have always interacted with each other, with two-way relationships arising (Emekci, 2021). Outdoor thermal comfort, one of the most important environmental factors, also affects people significantly. This topic is a relatively new field of study compared to research on indoor comfort (Spagnolo & de Dear, 2003; Johansson et al., 2014). Today, more than half of the total world population uses urban areas. At the same time, especially in recent years, people have been encouraged to spend more time outdoors. Therefore, in the last few years there has been growing interest in the planning of thermally comfortable outdoor spaces, particularly in urban areas.

Human biometeorology is a discipline that systematically investigates the effects of atmospheric conditions on humans (Höppe, 1997). It gained recognition in the 20th century within the natural sciences thanks to scientific methods such as human energy balance models and quantitative statistical approaches (Höppe, 1997; Błażejczyk, 2011; McGregor, 2012). The evaluation of human thermal comfort has become a significant aspect of biometeorology, driven by the growing impact of global environmental changes (McGregor, 2012), and since the early 2000s, interest in human thermal comfort in outdoor environments has increased markedly (Nikolopoulou et al., 2001; Givoni et al., 2003). Human thermal comfort is defined as an individual's satisfaction with environmental thermal conditions (ASHRAE, 2004), and this definition emphasizes that thermal comfort is a subjective experience that can vary from person to person (Nikolopoulou & Lykoudis, 2006). People's perceptions of thermal comfort may vary significantly depending on both the climate and the cultural background of the city in which they live (Salata et al., 2016). Since each city has its own unique conditions, it is critical to conduct field studies at the local level to create healthy cities.

Urban planning, which is one of the challenges for creating a comfortable and healthy microclimate, needs to take into account physical, environmental, economic, and social variables (Hass-Klau, 1993; Hakim et al., 1998). An optimized outdoor environment design enhances the livability of a city and reduces building energy consumption for heating and air conditioning by encouraging people to spend more time outside. Thus, employing suitable outdoor thermal comfort models is essential for accurately evaluating outdoor thermal conditions.

Challenges in the estimation of outdoor thermal comfort include factors such as behavioral, social, and physiological adaptation and acclimatization (Knez and Thorsson, 2008). Hence, even under identical microclimatic conditions, varying thermal perceptions are observed among residents from regions with different Köppen-Geiger climate classifications (Köppen et al., 2011).

Various indices and models have been developed to estimate how heat exchange between the human body and the environment affects human perception. Most of them were created to assess thermal perceptions in indoor environments and, after some adjustments, were made available for outdoor environments as well (Epstein & Moran, 2006; Blazejczyk et al., 2012; Johansson et al., 2014). These indices include the standard effective temperature (SET) index, predicted mean vote (PMV) index, universal thermal comfort index (UTCI), and physiological equivalent temperature (PET) index. When the literature on outdoor thermal comfort is examined, it is seen that PET values are frequently used.

The parameter of mean radiant temperature (Tmrt) used to calculate PET values is defined as the heat energy emitted from the environment. The radiant heat exchange between the human body and the environment is conducted through shortwave and longwave radiation fluxes (Alkhoudiri et al., 2022). In other words, Tmrt is a critical factor in the calculation of the PET index. It is defined as the uniform temperature of an imaginary environment in which radiant heat exchange from a human body is equal to that in the actual non-uniform environment. Tmrt is a crucial meteorological factor that influences human energy equilibrium (Das et al., 2020). The radiant heat emitted by radiation from heat sources is measured with a globe thermometer (Lau et al., 2019; Banerjee et al., 2020), which consists of a dry thermometer placed in the center of a copper sphere with a diameter of 15 cm and is thin and painted with matte black paint on the outside. Various other methods have also been used to measure Tmrt, such as simulations using Rayman software (Matzarakis et al., 2006; Lee & Mayer, 2016).

In other words, Tmrt represents the heat energy radiated from the environment and numerically reflects how people experience radiation. For individuals in outdoor settings, Tmrt depends on the direct, radiated, and reflected thermal and solar radiation to which they are exposed.

When the previous studies on outdoor thermal comfort are examined; Liu et al. (2022), in their study conducted in Tropical Singapore, found that trees with a wide crown structure significantly reduced PET values and increased comfort levels. Kim et. al. (2022) examined the relationship between the spatial heterogeneity of urban landscape patterns and outdoor thermal comfort in Tokyo, Japan. They found that more integrated, less fragmented and simple forms of green spaces increase the cooling effect. Deevi and Chundeli (2020) examined the physical factors affecting outdoor thermal comfort at Besant Street in Vijayawada, India. The study showed that sky visibility factor (SVF) and mean radiation temperature (MRT) are determinants of thermal comfort.

Abdallah and Mahmoud (2022) aim to improve the thermal comfort of open spaces in urban residential areas located in hot and dry climatic conditions in New Assiut City, Egypt. As a result, the importance of tree density and semi-shading to increase open space utilization was proven. Sun et al. (2023) aims to increase outdoor thermal comfort by optimizing the shape, orientation and location of buildings in the early design phase with a genetic algorithm. In applications in Tianjin and Shanghai climatic conditions, it was shown that optimized building forms reduce outdoor heat stress and solar radiation is more effective on thermal comfort than wind field. Zhou & Dong (2023) examined the effects of wearing masks in outdoor areas on seasonal thermal comfort after the COVID-19 pandemic. In experiments conducted in Xiamen, it was found that individuals wearing masks preferred lower neutral temperatures, especially in summer, and mask use caused more discomfort while walking than sitting and negatively affected thermal comfort.

The subject of the study examines various regions in Konya city center and the thermal conditions experienced by outdoor users in these regions in summer and winter. As Konya has a cold-semi-arid (BSk) climate, urban dwellers who are outdoors in different local climate zones have different experiences in terms of thermal comfort. The problematic of the study is that individuals in different local climate zones in Konya feel different levels of thermal comfort. This is due to the characteristics of the buildings in the city and their effects on outdoor thermal comfort through the urban heat island effect.

In this study, it is aimed to compare the effect of outdoor thermal comfort in six different LCZs in both summer and winter in the Turkish city of Konya, which has a BSk (cold semi-arid) climate, and to determine the most thermally comfortable zones in the city.

2. Materials and Methods

A literature review revealed that the urban heat island effect and outdoor thermal comfort have primarily been analyzed in cities with hot or tropical climates (Salman & Saleem, 2021; Mahmoud & Abdallah, 2022; Nasrollahi et al., 2021; Deng & Wong, 2020; Mirzabeigi & Razkenari, 2022; He et al., 2023; Ma et al., 2023).

The city of Konya, which does not have a hot and tropical climate type, was selected for this study. Konya is categorized as BSk (cold semi-arid) according to the Köppen-Geiger climate classification. Summers are generally dry while winters are harsh and cold. In addition to representing cities that do not have hot and tropical climates, Konya has many different textures within the city, and these were the major reasons for its selection for this study.

Because urban climate is intricately linked to urban spatial structures, geographic surroundings, and climatic factors, findings from a particular urban climate study typically apply only to areas sharing similar climatic and geographic traits. Accordingly, the local climate zone (LCZ) classification system proposed by Stewart and Oke (Stewart, 2011; Stewart & Oke, 2012) is often used to assess the thermal differences of urban areas and their surroundings (Oke et al., 2017). This classification system aims to standardize the observation and identification methods for temperature differences in research on urban heat island effects (Lyu et al., 2019). It takes into consideration both urbanized and natural settings, with a given area distinguished by its unique near-surface temperature patterns (Bassani et al., 2022). The classification system comprises two main groups: the classes of LCZ-1 through LCZ-10 denote built environments, while LCZ-A through LCZ-G denote natural environments (Figure 1). The LCZ classification is being increasingly used in urban heat island density studies based on air temperature or surface temperature for many different cities and climate zones (Dian et al., 2020).

Figure 1. Local Climate Zone (LCZ) classification (Stewart & Oke, 2012)

In this study, evaluations were conducted for the first six LCZ zones, particularly because residential zones were intensively selected. Since this study focuses on residential areas and the built environment in the urban center, these six LCZ zones were selected for analysis. These zones are located in the center of Konya and have different urban textures, such as high-rise/compact (LCZ-1), mid-rise/compact (LCZ-2), low-rise/compact (LCZ-3), high-rise/open (LCZ-4), mid-rise/open (LCZ-5), and low-rise/open (LCZ-6) (Figure 2). The floor areas of the selected zones are all close to each other and encompass approximately 7000-9000 m^2. For the building plan fraction and precedent values of these zones, the table provided by Stewart & Oke (2012) for typical characteristics of LCZs was utilized, and the zones in Konya with building plan fraction and precedent values closest to the values from that table were selected. At the same time, in these selected regions, building islands around the main building island were evaluated to ensure more accurate simulation results.

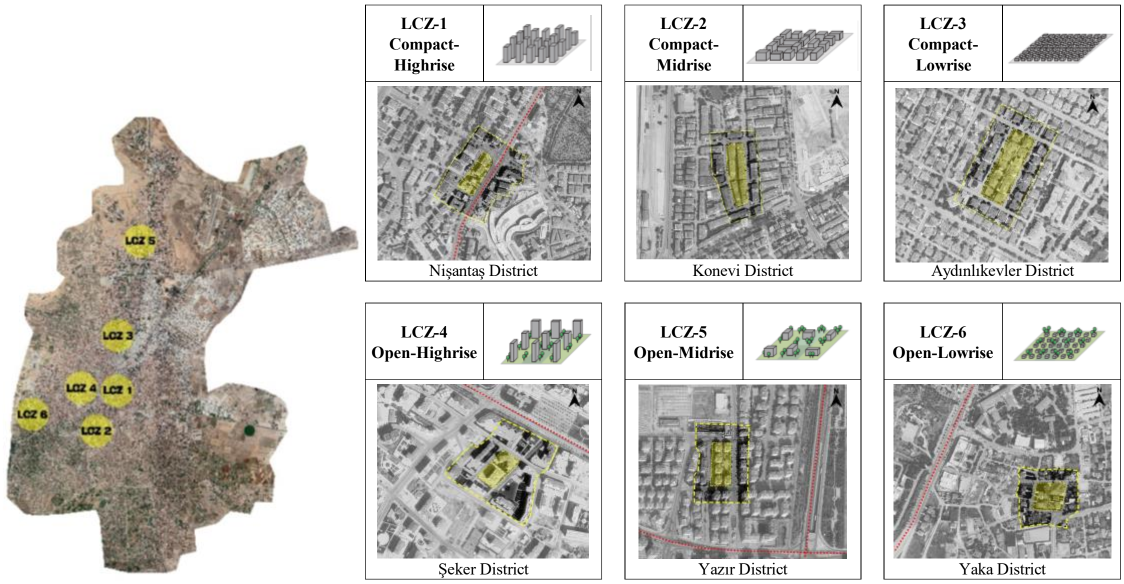

Figure 2. Study areas selected from different local climate zones and their locations within the city of Konya

The ENVI-met simulation program was used in this study. It offers a prognostic, three-dimensional, grid-based microclimate model designed to simulate complex surface-vegetation-air interactions in urban environments, with a typical spatial resolution of 0.5 m to 10 m and temporal resolution of 10 seconds (Ozkeresteci et al., 2003). This software calculates urban climate based on short- and longwave radiation fluxes directly reflected from buildings and vegetation, including the simulation of all physical parameters for plants. The minimum simulation time is usually 6 hours and the best time to start the simulation is at night or sunrise so that the software can give more accurate results while tracking solar radiation.

A key feature of the model is its capability to simulate complex urban geometries and vegetation, as well as accounting for energy inputs like anthropogenic impacts from vehicles. The general preference for using ENVI-met in urban climate studies stems from the balance of the model's lack of complexity and its user-friendliness (Samaali et al., 2007; Lindberg & Grimmond, 2011; Elnabawi et al., 2013) with lower computational costs (Chow & Brazel, 2012; Singh & Laefer, 2015; Roth & Lim, 2017). Another reason is the dynamic interaction between atmospheric processes and vegetation and soil moisture levels. The software also allows the use of spatial resolution of 2 m per cell to accommodate neighborhood size.

After site selection was performed according to the LCZ classification, the study was conducted within six different stages. These included on-site field measurements and determinations, pre-simulation preparation and starting the simulation, visualization and data acquisition after the simulation, obtaining thermal comfort values, making comparisons for different LCZs with the help of statistical data and obtaining some graphs, and making interpretations and developing recommendations according to the obtained findings. The climate parameters of air temperature (Ta), wind speed (Ws), relative humidity (RH), and Tmrt obtained as a result of the simulations were correlated and compared for the summer and winter seasons. With these climatic parameters and user data, PET values were determined and thermal comfort in the outdoor environment was evaluated (Figure 3).

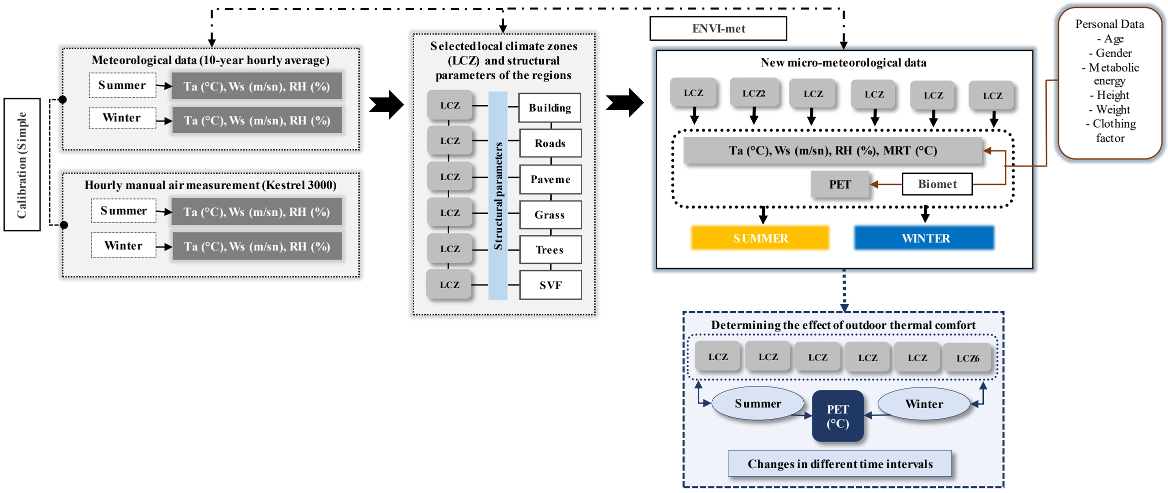

Figure 3. Flow chart of the method used in the study

A Kestrel 3000 air meter was used for on-site field measurements and calibration calculations (Figure 4). On typical days selected for summer and winter months, 15 minutes of manual measurements were carried out during the day in two different LCZs and the accuracy of the software was tested by comparisons with the results obtained from the simulation program.

Simple linear regression model was used in the calibration analysis. This is a statistical method used to examine the relationship between two variables. This method allows to predict the dependent variable using the independent variable when there is a linear relationship between the independent variable and the dependent variable. Thanks to the mathematical equation obtained, y (dependent variable) can be calculated according to the value of x (independent variable). The r^2 value (multiple coefficient of determination) obtained from the analysis shows how much of the changes in the dependent variable can be explained by the independent variable. This value is a measure of fit for linear regression models. r^2 value varies between 0 and 1; as it approaches 1, the significance of the model increases, and as it approaches 0, it decreases. r^2 values above 0.5 can be considered as a significant or appropriate relationship.

Figure 4. Images from meteorological measurements taken on site for calibration (Geyikli, 2022)

The materials and other details of elements in the studied zones were also identified with on-site determinations. General acceptance was established for these material details and they were entered into the program. The heights and types (i.e., broadleaf or coniferous) of the trees in the areas were also determined and entered into the program (Figure 5).

Figure 5. Trees within the studied zones and modelling created with ENVI-met software (Geyikli, 2022)

For use in the simulations, the last 10 years of weather data (2012-2021) for the city of Konya were obtained from the General Directorate of Meteorology. These data belonged to the “Regional” station located in the garden of the 8th Regional Directorate of Meteorology in the Meram district of Konya. These weather data included hourly air temperature, relative humidity, and wind speed and direction. The “Full Forcing” module in the “Forcing” interface of the ENVI-met program was used to produce the most detailed and advanced weather data. This module uses half-hourly air temperature, relative humidity, and wind speed and direction values. However, the data provided by the General Directorate of Meteorology were hourly data. Therefore, while creating the data to be used by the program, an adaptation was made according to half-hourly data. After the materials and trees were created and the meteorological data were organized, all areas were modeled in the Spaces module (Figure 6). Information about the simulation is given below (Table 1).

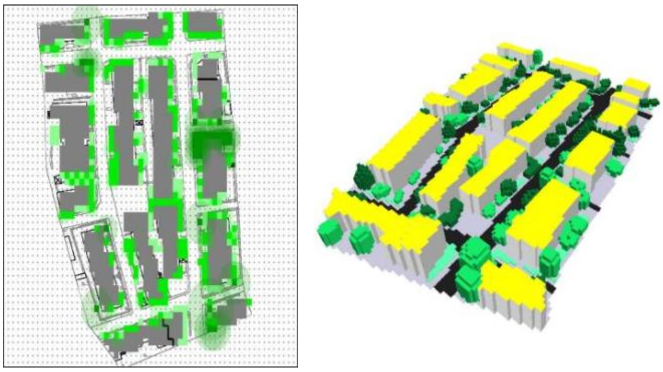

Figure 6. LCZ-2 (Konevi district) modeling created in ENVI-met

To determine thermal comfort levels, PET values were obtained from the “BIO-met” module. For this purpose, some specific arrangements were made in the module. In the first stage, the atmospheric data of the file where PET values would be found were selected for the main file. The time intervals in the selected file were set to find PET values for the whole day. Simultaneously, these PET values were set for a single point in the whole area at a level of 1.50 m. This level was chosen considering the average human standing height.

As stated above, two types of parameters are required to find PET values. First, basic meteorological parameters such as air temperature (Ta), relative humidity (RH), wind speed (Ws), and mean radiant temperature (Tmrt) are required. Additionally, personal data such as age, gender, height, weight, activity, and clothing are needed (Canan et al., 2020). In this study, male individuals aged 35 years, with height of 175 cm and weight of 75 kg, were taken as the reference because most previous studies in the literature have performed analysis for male individuals. The coefficient of clothing thermal resistance was taken as 0.9 clo, and the metabolic rate of the individuals was accepted as approximately 85 W/m^2 considering that they were assumed to be walking.

3. Findings and Discussion

The regression values obtained as a result of the calibration performed to test the accuracy of the simulation program are presented in Table 1. As seen in that table, all of the air temperature regression values were above 0.60 for measurements taken from two different LCZs in summer and winter.

Therefore, it was concluded that the fit of the regression model of the air temperature parameter obtained from the ENVI-met program and the manual measurements made with the air meter was good. When the relative humidity values were analyzed, it was seen that the regression model fit was not good because the values obtained for the summer season were below 0.50. However, since both winter values were above 0.50, it was concluded that the fit of the regression model of the relative humidity parameter taken from the ENVI-met program and the manual measurements made with the measuring device was acceptable (Table 1).

Table 1. Regression values (r^2) for summer and winter obtained as a result of calibration

	Summer		**Winter**	
	LCZ-2	**LCZ-3**	**LCZ-2**	**LCZ-3**
Air temperature (°C)	0.61	0.75	0.67	0.70
Relative humidity (%)	0.33	0.46	0.51	0.85

The PET index calculated with the BIO-met module in the ENVI-met simulation program was used to determine thermal comfort in the outdoor environment. The 10-year average meteorological data (2012-2021) for summer and winter seasons were entered into the simulation program and PET values were found. As explained above, personal data as well as basic climate parameters such as air temperature, wind speed, relative humidity and mean radiant temperature are needed to calculate the PET index. In many studies in the literature, the PET thermal perception categories defined by Matzarakis & Mayer (1996) are taken as a reference. However, it is important to remember that thermal perception categories are unique to each region and climate in order to obtain accurate results (Canan & Geyikli, 2022). The climate and sociocultural structure of every region vary in their own ways, and it has been determined that even in different cities located in the same climate zone, thermal perception categories may differ. Sociocultural factors as well as climatic factors have an impact in creating these differences. This indicates the existence of different thermal perception values for different urban residents living in the same region. In this regard, it was determined in the last decade that thermal perception categories show differences in studies on outdoor thermal comfort conducted in various climate zones (Potchter et al., 2018). In this study, the unique thermal perception categories calculated for the city of Konya by Canan et al. (2020) were used for outdoor thermal comfort analysis (Table 2).

Table 2. Thermal perception categories calculated for West/Central Europe and Konya (Türkiye)

Thermal stress level	**Human sensation**	**West/Central Europe (Mayer and Matzarakis, 1996) PET (°C)**	**Konya/Türkiye (Canan et al., 2020) PET (°C)**
Extreme cold stress	Very cold	< 4	< -5.6
Strong cold stress	Cold	4-8	-5.6-6.2
Moderate cold stress	Cool	8-13	6.2-17.9
Slight cold stress	Slightly cool	13-18	-
No thermal stress	Comfortable	18-23	17.9-29.7
Slight heat stress	Slightly warm	23-29	-
Moderate heat stress	Warm	29-35	29.7-41.5
Strong heat stress	Hot	35-41	41.5-53.3
Extreme heat stress	Very hot	> 41	> 53.3

According to this unique categorization of thermal perception, people living in Konya feel neutral (comfortable) at temperatures between 17.9 and 29.7 °C. At air temperatures below or above those values, they experience thermal stress and feel uncomfortable. Compared to the thermal perception categories established by Matzarakis & Mayer (1996), the categories of "slightly warm" and "slightly cool" are not included in the classification for Konya. Considering the ranges of values for neutral conditions, or the lack of thermal stress, the values found for Europe and Konya are close to each other. However, upon considering the upper limits, differences emerge. People living in Konya are generally more resistant to high air temperatures than people living in Europe. While residents of European cities experience thermal stress at temperatures higher than 23 °C (De Abreu-Harbich et. al., 2015; Cetin, 2020; Lin et. al., 2010), an individual in Konya is likely to feel comfortable between 23 and 29.7 °C. To compare outdoor thermal comfort in different LCZs based on the obtained PET values, 10 different characteristic points from each zone were taken into consideration. Hourly climate parameters and PET values of those points were created and the average values were found and analyzed. Outdoor thermal comfort analysis was performed according to the average climate parameters and PET index for each region.

3.1. Summer Season Findings

As a result of the simulations, climate parameters were obtained for July 10 and January 10, which were selected as typical days in summer and winter for the six different LCZs. The obtained data could be analyzed pointwise in the Leonardo module of the ENVI-met program. For that purpose, several points were identified from all LCZs. While selecting those points, care was taken to select homogeneously spaced points within building islands and to obtain values for each characteristic point. The selected points were diversified as hard ground, soft ground, under trees, in open areas, and between blocks of buildings. At the same time, it was deemed appropriate to select points at equal intervals of approximately 20 m between the selected points. In this way, 10 different points were selected from each region (Figure 7).

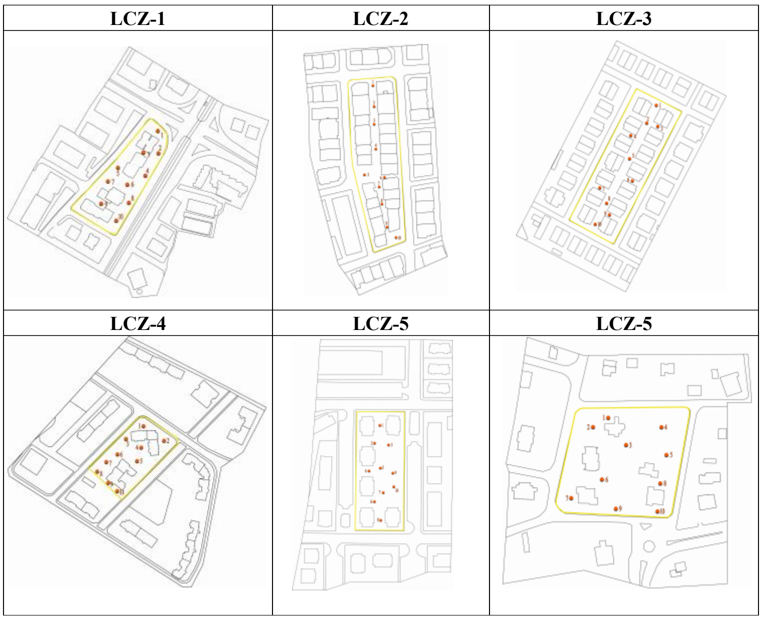

Figure 7. Identified points within all considered local climate zones

In the first stage, the PET values of 10 locations within each LCZ were compared. The hours of thermal stress from sunrise to sunset (daytime) in each region were accordingly determined and those hours were used in the subsequent calculations. When the PET values of LCZ-1 in summer were analyzed, three different thermal perception categories were identified in total during day and night hours in all 10 locations. According to the data obtained, it was seen that the most comfortable hours in all locations during the summer months were between 19:00 and 06:00. Generally, the most comfortable hours were found to occur between 19:00 and 06:00 at all locations. The most stressful hours varied considerably between the considered points, which may be attributed to the built environments in which the points are located. Some of the points are located under trees, on grass, or between two blocks of buildings, while others are located in completely open environments (Figure 8).

The changes in the PET values of different points in LCZ-1 are reflected in the graphs below. Differences were observed between all points in terms of PET values, especially between 08:00 and 14:00. At point N1, a high PET value was detected between 05:00 and 11:00, while a decrease was observed in the following hours (Figure 8).

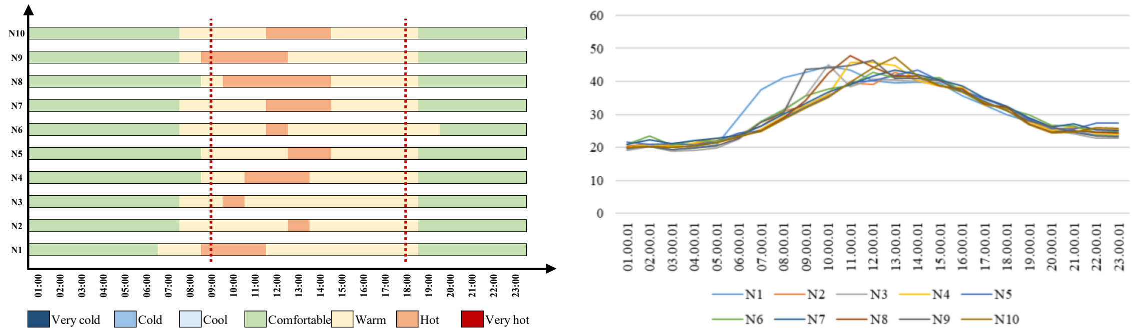

Figure 8. Hourly thermal sensing categories of 10 different locations (left) and hourly PET variations of 10 different points (right) in LCZ-1

When the PET values for LCZ-2 in summer were analyzed, three different thermal perception categories were detected during day and night hours. Considering all points, thermal comfort generally occurs between 19:00 and 07:00. As in LCZ-1, the time intervals in which the most intense thermal stress is felt in the form of heat vary between different points. Point K6 stands out as the only point that does not "feel hot" during the day. Since this point is located between two blocks of buildings, it is in a shaded area, which generates less thermal stress compared to the other points. When the other selected points were analyzed, it was found that most of them "felt hot" between 11:00 and 15:00 (Figure 9).

Changes in PET values across different points in LCZ-2 are shown below. According to these graphs, there are differences in PET values between all considered points, especially between 07:00 and 16:00. In general, high values were detected at point K5 during this time interval (Figure 9).

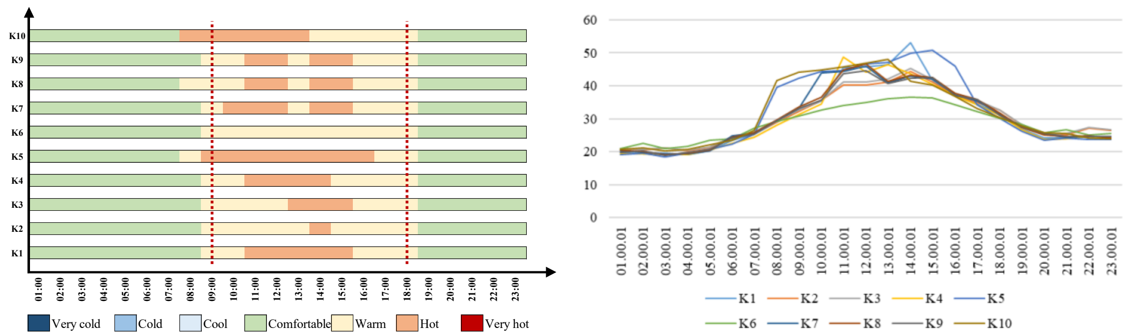

Figure 9. Hourly thermal sensing categories of 10 different locations (left) and hourly PET variations of 10 different points (right) in LCZ-2

The summer PET values of LCZ-3 represent a total of three different thermal perception categories at 10 different locations during day and night hours. Considering all of those points, 19:00-05:00 is the most thermally comfortable range. Unlike other LCZs, the range of hours perceived as comfortable is smaller in this zone. The neutral interval comprises 11 hours in LCZ-1, 12 hours in LCZ-2, and 10 hours in LCZ-3. These intervals are uninterrupted intervals of perceptions of neutral comfort. As in other zones, the time intervals with the most intense thermal stress in the form of heat vary across the 10 different locations. Of these locations, A1 is the only one that does not "feel hot" during the day. A1 is located under a tree, and thanks to the shading and cooling effects of the tree, thermal stress (heat) is not noticeable in comparison to other points. When the other selected locations were analyzed, it was seen that thermal stress (heat) was felt at 14:00 in all of them (Figure 10).

For LCZ-3, the PET value changes of different points are shown below. According to these graphs, there are differences in PET values between all points, especially in the time interval of 05:00-19:00. In general, the lowest values were observed at points A1 and A10 (Figure 10).

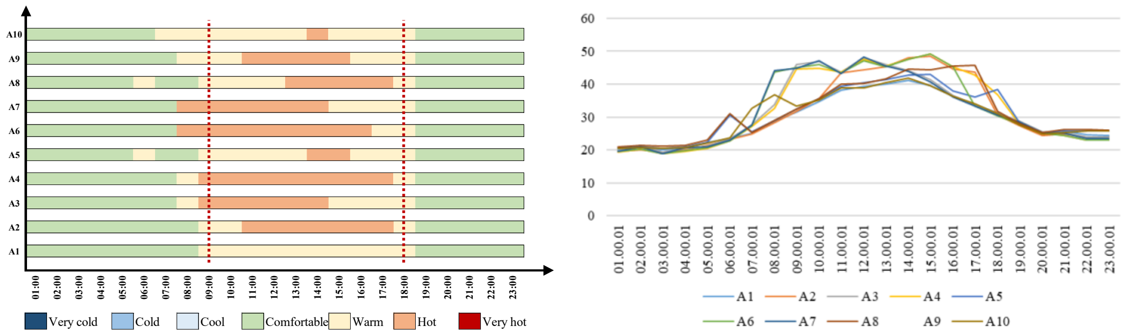

Figure 10. Hourly thermal sensing categories of 10 different locations (left) and hourly PET variations of 10 different points (right) in LCZ-3

When the summer PET values of LCZ-4 were analyzed, three different thermal perception categories were observed in total for all 10 different points during day and night hours. Considering all of the points, the hours between 19:00 and 06:00 constitute the thermally comfortable interval. As in other zones, the time intervals in which the most intense thermal stress (heat) is felt vary across the 10 different points. When all points were analyzed, it was seen that thermal stress (heat) was particularly felt at 14:00 (Figure 11).

PET value changes are shown below for different points of LCZ-4. According to these graphs, there are differences in PET values between all points, especially between 06:00 and 18:00. In general, the lowest values were observed at point S1 during this time interval (Figure 11).

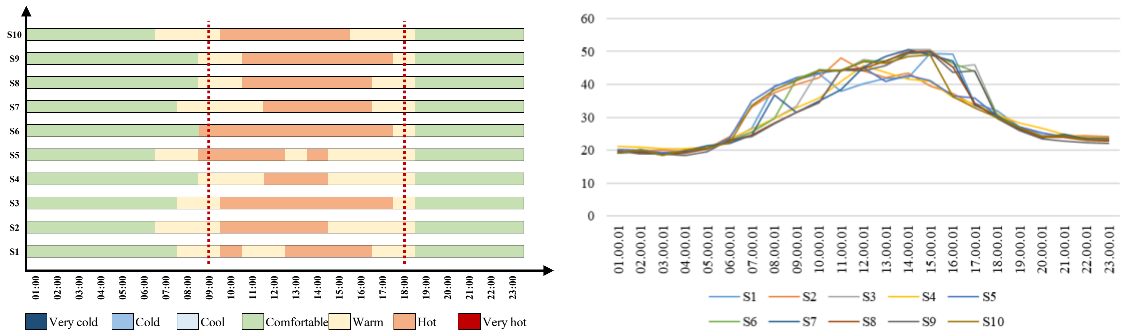

Figure 11. Hourly thermal sensing categories of 10 different locations (left) and hourly PET variations of 10 different points (right) in LCZ-4

When the summer PET values of LCZ-5 were analyzed, three different thermal perception categories were observed in total during day and night hours for all 10 different points. Considering all of the points, the hours between 19:00 and 06:00 constitute the thermally comfortable interval. The time intervals in which the most intense thermal stress (heat) is felt once again vary across the 10 different points. In particular, however, thermal stress (heat) is felt at 11:00 and 12:00 (Figure 12).

The PET value changes of different points in LCZ-5 are shown below. According to these graphs, there are differences in PET values between all points, especially between 05:00 and 17:00. In general, the lowest values were observed at point Z6 during this time interval (Figure 12).

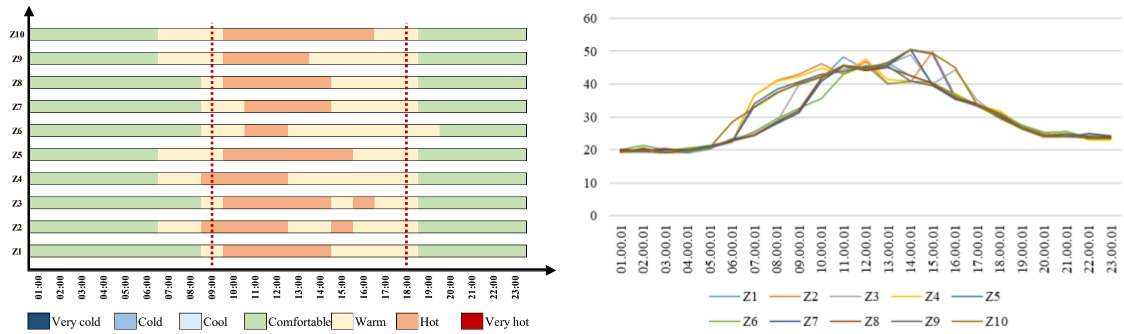

Figure 12. Hourly thermal sensing categories of 10 different locations (left) and hourly PET variations of 10 different points (right) in LCZ-5

When the summer PET values of LCZ-6 were analyzed, three different thermal perception categories emerged in total for day and night hours at all 10 locations. The time interval generally perceived as comfortable was 19:00-06:00 at all points. The most stressful hours were generally found to be between 11:00 and 15:00 when all points were considered. Of all considered locations, Y10 is the only one that does not “feel hot” during the day. This point is located under a tree. Due to the shading and cooling effects of that tree, thermal stress (heat) is minimized compared to other points (Figure 13).

The PET value changes of different points in LCZ-6 are shown below. According to these graphs, there are differences in PET values between all points, especially between 06:00 and 19:00. In general, the lowest values were observed at point Y10 during this time interval (Figure 13).

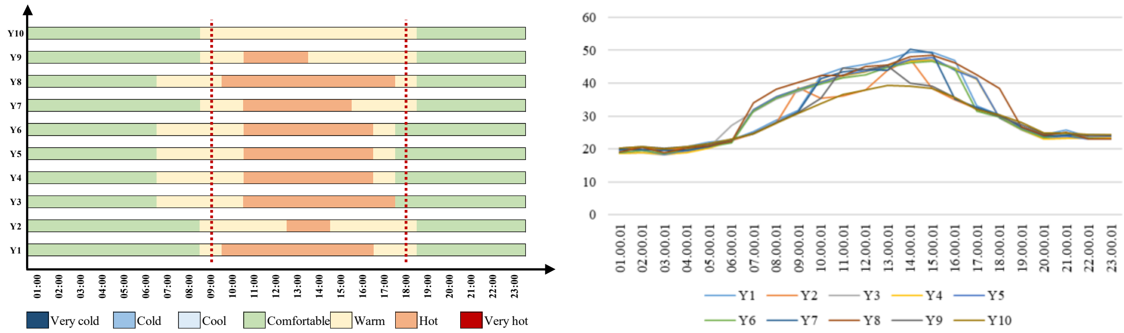

Figure 13. Hourly thermal sensing categories of 10 different locations (left) and hourly PET variations of 10 different points (right) in LCZ-6

General comparisons between LCZs were performed using the thermal perception category graph created according to the average PET values of 10 points for each LCZ (Figure 14). According to that graph, “warm” conditions (thermal stress) are perceived between 07:00 and 18:00 in all LCZs. “Hot” conditions are perceived between 11:00 and 13:00 in LCZ-1; between 11:00 and 15:00 in LCZ-2, LCZ-3, LCZ-5, and LCZ-6; and between 11:00 and 16:00 in LCZ-4. LCZ-1 is the zone with the least intense thermal stress. Therefore, it can be said to be the best zone for thermal comfort in summer. On the contrary, LCZ-4 has the longest duration of intense thermal stress and is the most uncomfortable zone in summer.

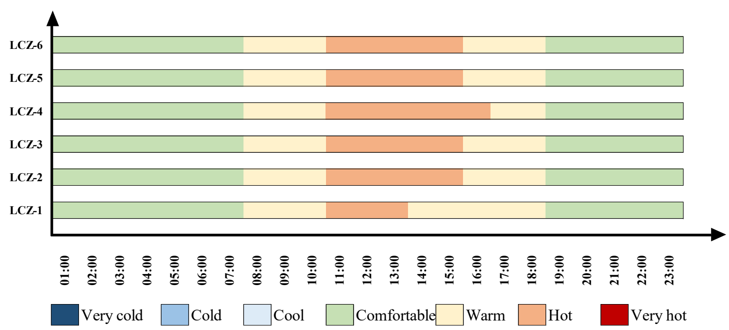

Figure 14. Average hourly thermal perception categories for all local climate zones

The average values for 09:00-18:00 at 10 points from 5 different regions and for 09:00-17:00 at LCZ-6, constituting the time interval from sunrise to sunset, when thermal stress is felt, are shown in Table 3. Based on these results, PET values were analyzed for a comparison of thermal comfort in outdoor environments.

When the PET values of all LCZs were examined, the following sequence was observed: LCZ-1 < LCZ-2 < LCZ-5 < LCZ-3 < LCZ-6 < LCZ-4. When Tmrt values were examined, the sequence of LCZ-1 < LCZ-2 < LCZ-3 < LCZ-5 < LCZ-4 < LCZ-6 was observed (Table 3).

Table 3. Average climate parameters used in outdoor thermal comfort calculations for summer season

	Physiological equivalent temperature (PET, °C)	**Wind speed (m/s)**	**Air temperature (°C)**	**Mean radiant temperature (Tmrt, °C)**	**Relative humidity (%)**
LCZ-1	**38.48**	0.83	31.25	42.58	26.65
LCZ-2	**39.24**	0.56	30.89	43.39	28.38
LCZ-3	**40.62**	0.70	31.13	46.52	30.03
LCZ-4	**41.37**	0.81	30.96	49.70	26.00
LCZ-5	**40.41**	0.73	31.15	46.77	27.38
LCZ-6	**41.35**	0.95	31.34	49.76	29.95

According to these results, the LCZ-1 with a compact and multilayered texture is more comfortable in terms of thermal comfort in the outdoor environment in summer. The most uncomfortable zone was found to be LCZ-4, an open-multistory area. The lower PET and Tmrt values in zones with compact textures may be due to the shading effect of buildings. Although there are multistory buildings in LCZ-4, the PET and Tmrt values were found to be high due to the distances between the buildings and the shadow effect not being sufficiently provided.

When the analyses for the summer season are associated with the built environment parameters; it is determined that especially shading effect and wind have positive effects on thermal comfort in the outdoor environment. According to the evaluation made, lower temperatures were observed in high-rise and compact urban parts due to shade formation in the summer season. At the same time, by determining the prevailing wind direction and providing wind circulation within the city streets, even lower temperatures have emerged. In the LCZ-1 zone, this proved to have positive results in terms of outdoor thermal comfort. Therefore, as a general conclusion for the summer season, multi-storey-compact settlements that contribute to shade formation and urban textures shaped according to the wind direction appear to be favorable regions in terms of outdoor thermal comfort.

3.2. Winter Season Findings

After the analysis for the summer season, PET values for the winter season were calculated and analyzed. According to the results obtained for 10 different points in each zone, the hours of thermal stress from sunrise to sunset (daytime) were determined and these hours were included in the calculations.

When the PET values of LCZ-1 in winter were analyzed, two different thermal perception categories (cool and cold) were observed for all 10 different points during day and night hours. There were no neutral (comfortable) ranges of hours at any of the locations. The hours when the most intense stress is felt are usually night hours and there are differences between the points. This is due to the built environment in which the points are located. Some are located under trees, on grass, or between two blocks of buildings, while others are located in completely open environments (Figure 15).

The PET value changes of different points in LCZ-1 in winter are shown below. According to these graphs, differences in PET values occur between all points throughout the whole day (Figure 15).

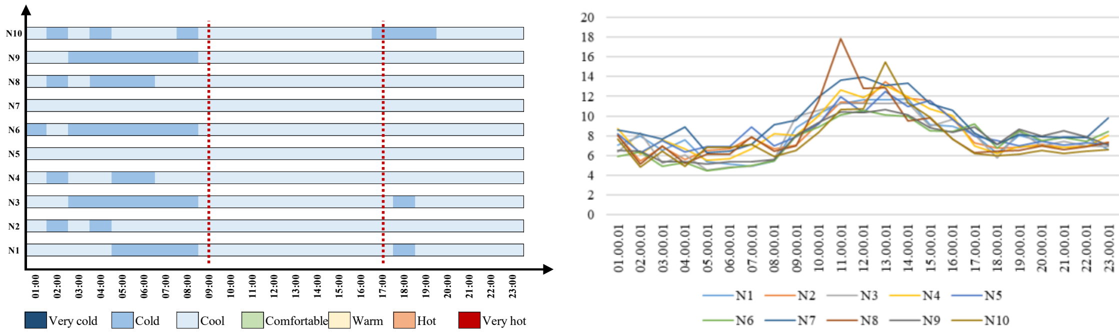

Figure 15. Hourly thermal sensing categories of 10 different locations (left) and hourly PET variations of 10 different points (right) in LCZ-1

When the winter PET values of LCZ-2 were analyzed, three different thermal perception categories (cool, cold, and neutral) were observed in all 10 different locations during day and night hours. Only three of the locations had neutral (comfortable) intervals. These time intervals were generally determined to be 11:00-12:00. The hours when the most intense stress is felt are usually at night, but the exact hours vary between the points. At points K6, K7, and K8, only the “cool” perception category is observed throughout the day and “cold” is not felt. The locations of these points are between blocks of buildings, sheltered from the wind. Since they are protected from the cooling effect of the wind, thermal stress is not felt intensely.

The variations of PET values of different points in LCZ-2 are shown below. According to these graphs, differences in PET values occur between all points throughout the whole day (Figure 16). Instantaneous increases were observed at K1, K2, K4, and K5 at noon. This may have been due to an instantaneous increase in wind speed.

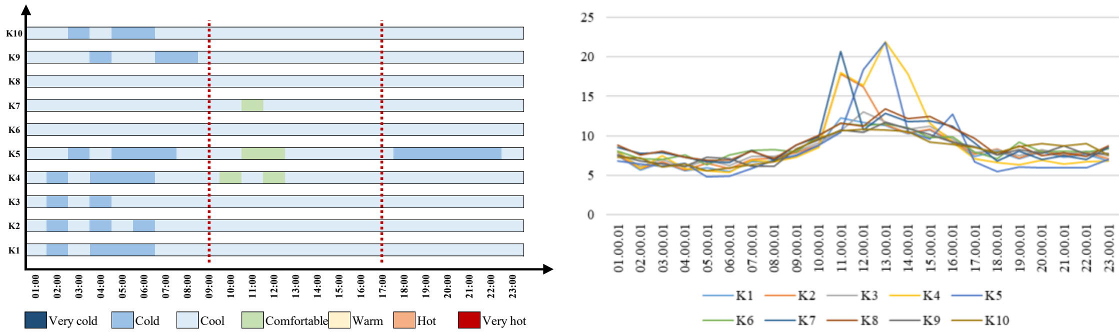

Figure 16. Hourly thermal sensing categories of 10 different locations (left) and hourly PET variations of 10 different points (right) in LCZ-2

When the winter PET values of LCZ-3 were analyzed, three different thermal perception categories (cool, cold, and neutral) were observed in all 10 different locations during day and night hours. Neutral (comfortable) intervals of hours occurred at six different locations. These time intervals were generally determined to fall within 11:00-13:00. The most stressful hours usually occur at night. In many of the locations, intense stress is felt between 03:00 and 08:00 (Figure 17).

The variations of PET values of different points in LCZ-3 are shown below. According to these graphs, differences in PET values occur between all points, especially between 08:00 and 16:00 (Figure 17).

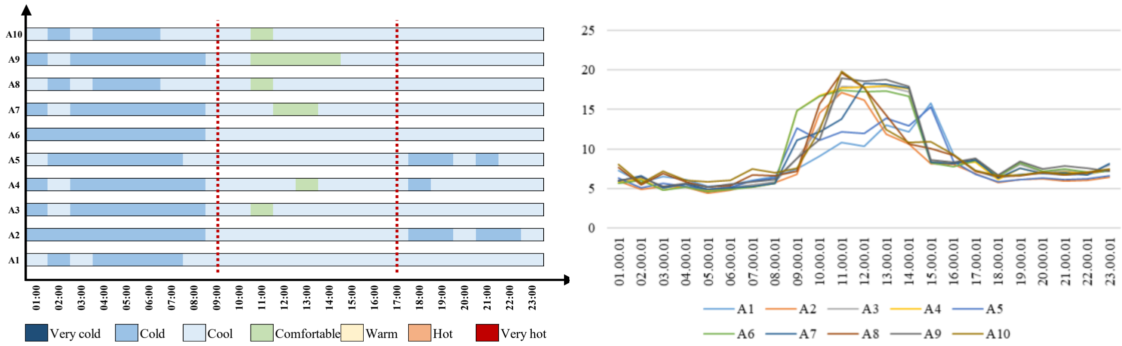

Figure 17. Hourly thermal sensing categories of 10 different locations (left) and hourly PET variations of 10 different points (right) in LCZ-3

When the winter PET values of LCZ-4 were analyzed, three different thermal perception categories (cool, cold, and neutral) were observed in all 10 different locations during day and night hours. A neutral (comfortable) interval occurred at a single point and for a single hour (at 13:00 at point S2). The peak hours of stress occur between 01:00 and 08:00, particularly at night. At some points (S7, S9, and S10), thermal stress is also intense during the evening hours of 18:00-23:00 (Figure 18).

The variations of PET values of different points in LCZ-4 are shown below. According to these graphs, differences in PET values occur between all points between 08:00 and 16:00 (Figure 18).

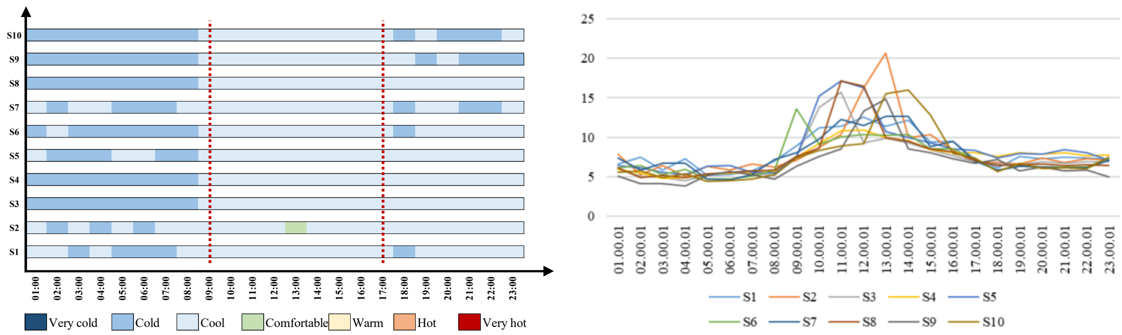

Figure 18. Hourly thermal sensing categories of 10 different locations (left) and hourly PET variations of 10 different points (right) in LCZ-4

When the winter PET values of LCZ-5 were analyzed, three different thermal perception categories (cool, cold, and neutral) were observed in all 10 different locations during day and night hours. At four different points, neutral (comfortable) intervals of hours occurred. These points were generally located in clearings such as squares, away from buildings. Furthermore, these points were generally surrounded by trees and it can be said that the trees minimized the cooling effect of the wind. The peak hours of stress are between 02:00 and 08:00, usually at night. However, at some points (Z2, Z4, Z5, Z9, and Z10), it was observed that intense thermal stress could be felt at 18:00. This may be attributed to the disappearance of the heating effect of the sun with sunset (Figure 19).

The variations of PET values of different points in LCZ-5 are shown below. According to these graphs, differences in PET values were observed between all points between 08:00 and 16:00 (Figure 19).

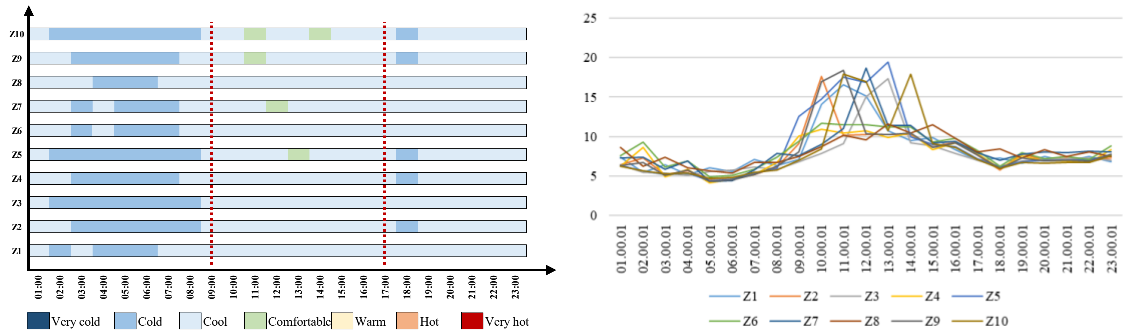

Figure 19. Hourly thermal sensing categories of 10 different locations (left) and hourly PET variations of 10 different points (right) in LCZ-5

When the winter PET values of LCZ-6 were analyzed, three different thermal perception categories (cool, cold, and neutral) were observed in all 10 different locations during day and night hours. Two different points were perceived as neutral (comfortable) at 13:00. Those points were generally located far from buildings but near trees. Therefore, it can be said that the trees minimized the cooling effect of the wind and created thermal comfort. The hours of peak stress were found to vary between 18:00 and 08:00, beginning at sunset and usually occurring at night (Figure 20). Compared to the other points, Y1 had fewer hours of intense thermal stress. That point was located next to a building, surrounded by trees and protected from the cooling effect of the wind.

The variations of PET values of different points in LCZ-6 are shown below. According to these graphs, differences in PET values were observed between all points between 08:00 and 16:00 (Figure 20).

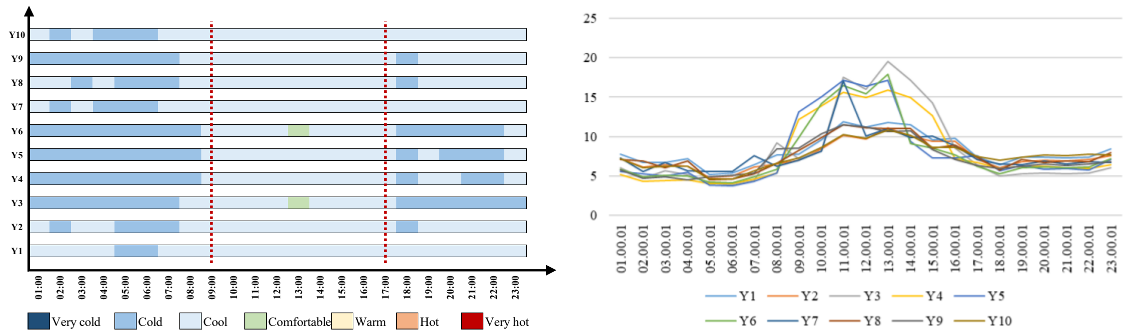

Figure 20. Hourly thermal sensing categories of 10 different locations (left) and hourly PET variations of 10 different points (right) in LCZ-6

General comparisons between LCZs were performed using the thermal perception category graph created according to the average PET values of 10 points for each LCZ in winter (Figure 21). As seen from the obtained graph, for all LCZs, “neutral” (comfortable) conditions were not perceived at any time during the whole day. In contrast to the other zones, only LCZ-2 felt “cool” all day long while “cold” was not perceived. “Cold” was perceived in LCZ-1 between 05:00 and 06:00, in LCZ-5 between 03:00 and 07:00, in LCZ-3 and LCZ-4 between 02:00 and 08:00, and in LCZ-6 between 02:00 and 07:00 and at 18:00. As a result of this comparison of different LCZs, LCZ-2 was found to be the most comfortable zone in winter, while LCZ-3, LCZ-4, and LCZ-6 were found to be the most uncomfortable zones or the zones with the longest durations of intense thermal stress.

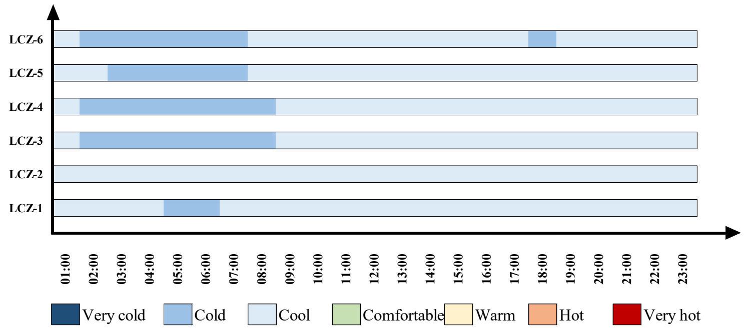

Figure 21. Average hourly thermal perception categories of all local climate zones

When the PET values of all LCZs were analyzed, the following sequence was observed: LCZ-4 < LCZ-1 < LCZ-6 < LCZ-5 < LCZ-2 < LCZ-3. These values were quite close to each other. When Tmrt values were analyzed, the sequence of LCZ-2 < LCZ-1 < LCZ-5 < LCZ-4 < LCZ-6 < LCZ-3 was obtained (Table 4).

Table 4. Average climate parameters used in outdoor thermal comfort calculations for the winter season

	Physiological equivalent temperature (PET, °C)	Wind speed (m/s)	Air temperature (°C)	Mean radiant temperature (Tmrt, °C)	Relative humidity (%)
LCZ-1	**10.24**	0.59	3.19	7.56	66.18
LCZ-2	**10.91**	0.38	2.98	7.00	68.01
LCZ-3	**12.53**	0.46	2.83	14.90	69.86
LCZ-4	**10.16**	0.59	2.64	7.93	68.29
LCZ-5	**10.73**	0.47	3.03	7.70	67.17
LCZ-6	**10.67**	0.49	2.95	7.98	71.12

According to the results obtained, the areas with high-rise buildings are cooler in winter due to the shading effect, creating an undesirable situation. In LCZ-4, where the PET value was found to be lowest, the air temperature decreased due to the shading effect of high-rise buildings and LCZ-4 became the most uncomfortable zone in winter. It was followed by LCZ-1, which also has high-rise buildings.

When analyzes for the winter season are associated with the built environment parameters; unlike the summer season, shading and wind effect appear as an undesirable situation. Especially in the low-rise-compact built environment, the shading effect is less and the wind effect is prevented due to compactness, resulting in a positive situation in terms of thermal comfort in the outdoor environment. LCZ-3 provides quite high temperature values compared to all other zones.

The findings obtained from this study reveal that the effects of urban geometry on thermal comfort and urban heat island effects in outdoor environments are quite important. This has been proven before by many studies conducted in hot and tropical climate conditions (Taleb & Abu Hijeb, 2013; He et al., 2021; Ahmadi et al., 2022). However, it has been studied less often in regions with cold and semi-arid climates (Darbani et al., 2023; Karimimoshaver and Shahrak, 2022). The present study has confirmed that urban geometry is also important in regions with cold and semi-arid climates.

The findings obtained are similar to the findings obtained from most studies conducted for cold climates in the literature (Canan et. al., 2020; Cui et. al., 2023; Karimimoshaver and Shahrak, 2022; Khalili et. al., 2022; Lin et. al., 2022; Mohammadzadeh et. al., 2023).

4. Conclusion and Suggestions

As a result of the analysis carried out to evaluate thermal comfort in the outdoor environment during the summer season, LCZ-1, which is a dense area with high-rise buildings, was found to be the most thermally comfortable zone. This finding may be attributed to the reduction of hot air due to the shading effect created by the buildings in summer. At the same time, since the buildings are close to each other and are high-rise, the sizes of their shadows are also larger, affecting a larger area. In contrast, LCZ-4, a less dense zone with high-rise buildings, was found to be the most uncomfortable zone in summer. In this zone, the high-rise buildings have a shading effect, but that effect does not spread over as large an area as in LCZ-1. Since the buildings are located far apart from each other, the shadows cast by them do not cover a large area. The high proportion of hard ground also affects perceptions of thermal comfort, and wind corridors are not formed due to the irregular layout.

As a result of the analysis conducted to evaluate thermal comfort in the outdoor environment in winter, LCZ-3 was found to be the most comfortable zone. This zone consists of single-story buildings, which causes the air temperature and PET values to be high. Therefore, it is a more preferable area in winter compared to the other LCZs. In contrast, the most uncomfortable zone in winter was found to be LCZ-4, where high-rise buildings are located and where the ratio of hard ground is the highest. The lack of thermal comfort is related to both the high hard ground ratio and the effective shading created by the buildings.

When the most comfortable and least comfortable zones in summer and winter were compared, it was seen that the most comfortable zone differed but the least comfortable zone remained the same (Table 5). LCZ-4 emerged as the most uncomfortable zone in both seasons.

Table 5. Most comfortable and least comfortable zones based on outdoor thermal comfort analysis for summer and winter

	Summer	Winter
Most comfortable	LCZ-1	LCZ-3
Least comfortable	LCZ-4	LCZ-4

It was further found that PET values, as an index used to determine thermal comfort in outdoor environments for the city of Konya, which has a BSk climate, change during the day. To allow for a generalization for summer and winter seasons, the hours in which pedestrians are typically outside during the day were determined and analyses were concluded accordingly. It was concluded that the most thermally comfortable zone in summer in this city with a BSk climate was LCZ-1, a compact and multistory zone comprising an old residential area. The thermal comfort there is generally caused by the decrease in the intense effect of the sun in summer months due to the shading of the multistory buildings. In contrast, the most uncomfortable zone was found to be LCZ-4, a low-density (open) and multistory zone. Although multistory buildings also exert a shading effect in this zone, the sizes of the shadows are limited since there is not a compact texture as seen in LCZ-1. At the same time, since LCZ-4 is an open and less dense zone, wind corridors cannot form. In winter, the most comfortable zone seems to be the compact and low-rise LCZ-3. This is due to the fact that wind corridors do not form during the winter months due to low-rise buildings and the shading effect is not intense. Finally, the most uncomfortable zone in winter was found to be the low-density (open) and multistory LCZ-4, as in the summer season. In this zone, the effect of the sun cannot be felt due to multistory buildings.

The use of a simulation program in this study created some limitations. Although it has been proven in the literature that the closest results to reality can be achieved with the ENVI-met simulation program, not all details were processed in the modeling. For example, buildings were classified by creating an albedo scale according to colors. At the same time, openings in buildings such as windows and doors were not processed. The upper covers of the considered zones were also not included in the modeling. General acceptance was established by taking a mean value of the leaf density of the trees. For this reason, although the results obtained from the simulation program were close to the measured results, they were not exactly the same.

This study can be used as an auxiliary resource for all cities with BSk climates according to the Köppen-Geiger climate classification. LCZs in all cities in this climate class show similarities to the findings obtained in the present study. This study will also provide support for individuals involved in city planning in Konya, especially while considering elements of thermal comfort in outdoor environments and urban heat island effects in the design of new residential areas. Such considerations will aid in making urban residents feel thermally comfortable and minimizing the negative urban heat island effects on both urban residents and the broader environment.

In light of all the findings obtained here, it can be concluded that increasing the number of trees in the city is very important for the summer months in terms of thermal comfort in outdoor environments and urban heat island effects. Although the number of trees does not have as much impact in terms of thermal comfort in winter months, it yields positive results for the urban heat island effect. For this reason, the use of broad-leaved trees that will shed their leaves every winter is recommended for the city of Konya.

The presence of high-rise buildings creates a positive situation in summer in terms of thermal comfort, as the building volume and surface area are large and create shadowed areas. However, the opposite is true in winter. In general, urban heat island effects decrease in zones where construction is not very dense, the ratio of hard ground is low, and green areas and trees are dense.

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This article was produced from a doctoral thesis. This article complies with national and international research and publication ethics. Ethics committee approval was not required for this study.

Author Contributions and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

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