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Effect of wind corridors on thermal comfort in urban and rural settlement areas*

Kentsel ve kırsal yerleşim alanlarında rüzgar koridorlarının termal konfora etkisi

Nursevil YUCA[1 *]

Şevket ALP [2]

Mehmet Akif IRMAK [3]

[1] Van Yüzüncü Yil University, Faculty of Architecture and Design, Department of Landscape Architecture, 65040, Tusba, Van, Türkiye

[2] Van Yüzüncü Yil University, Faculty of Architecture and Design, Department of Landscape Architecture, 65040, Tusba, Van, Türkiye

[3] Atatürk University, Faculty of Architecture and Design, Department of Landscape Architecture, 25240, Centre, Erzurum, Türkiye

* Corresponding author (Sorumlu yazar):

nursevilyuca@yyu.edu.tr

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ABSTRACT

Objective: This study aims to investigate the impact of pedestrian-level wind speed on thermal comfort in urban and rural areas with high elevation and distinct climatic and topographic characteristics.

Materials and Methods: Hourly meteorological data from the districts of Çaldıran, Muradiye, and Erciş in Van Province were used for the period 2018–2023. Physiological Equivalent Temperature (PET) values were calculated using RayMan Pro 2.1 software. Relationships between PET and meteorological variables were evaluated using Multiple Linear Regression and Pearson Correlation analyses, and the results were visualized using maps.

Results: While the average maximum temperature is experienced in Muradiye in July with 37.8ºC, the lowest temperature is experienced in Çaldıran with -9.5ºC, and the monthly average wind values are found to be the highest in Çaldıran with a long-term average of 0.3-0.8 m/s, in Muradiye it is between 0.3-0.6 m/s, and in Erciş it is 0.1 m/s every month.

Conclusion: Thermal comfort dynamics differ between urban and rural areas. Therefore, microclimatic design and wind corridor planning should be adapted to the settlement type.

Keywords: Pedestrian-level wind speed, PET, rural areas, thermal comfort, urban areas

Anahtar sözcükler: Yaya seviyesinde rüzgar hızı, FES, kırsal alanlar, termal konfor, kentsel alanlar

ÖZ

Amaç: Bu çalışma, rakımı yüksek, farklı iklim ve topoğrafya özelliklerine sahip kentsel ve kırsal alanlarda, yaya seviyesindeki rüzgâr hızının termal konfor üzerindeki etkilerini incelemeyi amaçlamaktadır.

Materyal ve Yöntem: Van ilinin Çaldıran, Muradiye ve Erciş ilçelerine ait 2018-2023 dönemi saatlik meteorolojik verileri kullanılarak, RayMan Pro 2.1 programı ile fizyolojik eşdeğer sıcaklık (FES) hesaplanmıştır. FES ile meteorolojik değişkenler arasındaki ilişkiler, Çoklu Doğrusal Regresyon ve Pearson Korelasyon analizleriyle değerlendirilmiş; bulgular haritalar ile görselleştirilmiştir.

Araştırma Bulguları: Ortalama maksimum sıcaklık 37.8ºC ile Temmuz ayında Muradiye'de yaşanırken, en düşük sıcaklığın ise -9.5ºC ile Çaldıran'da yaşandığı, aylık ortalama rüzgar değerlerinde ise Çaldıranın uzun yıllar ortalamasında 0.3-0.8 m/s en yüksek seviyede seyrederken, Muradiye 0.3-0.6 m/s aralığında, Erciş ise her ay 0.1 m/s olduğu ortaya konmuştur.

Sonuç: Kentsel ve kırsal alanlarda farklı termal konfor dinamikleri söz konusudur. Bu nedenle, mikroklimatik tasarım ve rüzgâr koridorlarının planlanması, yerleşim tipine göre şekillendirilmelidir.

INTRODUCTION

With rapid urbanization, urban settlements have expanded significantly (Kurt Konakoğlu & Büyükgüner, 2021), while rural areas have gradually been pushed into the background. In this process, urban living environments have been improved through the development of green and open spaces, increased building density, and enhanced educational opportunities. Indeed, when thermal comfort studies in outdoor environments are reviewed, it is evident that most research focuses on urban areas (Yılmaz et al., 2018). Conversely, rural settlements and their thermal comfort characteristics have been relatively overlooked.

Since the economic, sociological, environmental, and climatic conditions of urban and rural settlements differ considerably, their thermal comfort levels also vary significantly. One significant difference is the impact of wind, which is often reduced in urban settings due to the density of buildings (Özlü et al., 2019). Therefore, findings from urban thermal comfort studies cannot be directly applied to rural areas. Thermal comfort is defined as the climatic range that allows individuals to feel at ease and healthy, based on the average of meteorological parameters such as air temperature (ºC), relative humidity (%), wind speed, and cloudiness (Yılmaz et al., 2021).

There are two primary types of thermal stress: extreme heat and extreme cold, both of which affect human well-being, comfort, and health. Studies have shown that cardiovascular-related mortality rates increase significantly during periods of thermal stress, particularly during the summer months when people spend more time outdoors (Laschewski & Jendritzky, 2002; Urban et al., 2017). Although cold-related mortality is also significant (Hajat et al., 2007), its causes are less understood and underemphasized (Urban et al., 2017). In recent years, global warming has increased the frequency and severity of heatwaves, prompting numerous studies focusing on the impacts of high temperatures (Rahmstorf & Coumou, 2011; Tomczyk et al., 2023). However, despite their influence, cold stress periods have received relatively little attention in the thermal comfort literature.

To better assess outdoor thermal comfort, several bioclimatic indices have been developed. The most widely used of these indices, the PET (Physiological Equivalent Temperature) index, considers both meteorological variables and human thermoregulatory factors, such as clothing and activity level. Most thermal comfort studies are conducted in temperate or hot climates, often focusing on urban heat islands (UHI), thermal zoning, or monthly temperature averages. However, rural areas, which differ significantly in structure and vegetation, present distinct wind environments. These include natural open-air flows, which vary considerably from urban wind dynamics shaped by dense construction (Takebayashi & Moriyama, 2009). In rural settlements, pedestrian-level wind speeds have a direct impact on daily life, especially in winter, when cold stress increases due to wind chill. This makes maintaining thermal comfort more difficult.

Van Province, located in eastern Türkiye, contains significant wind corridors due to its high elevation and mountainous terrain. One of the most prominent is the Gönderme Wind Corridor, which originates in Çaldıran, passes through Muradiye, and continues toward Erciş (Figure 1). Wind speed plays a crucial role in thermal perception, significantly influencing the comfort levels of residents.

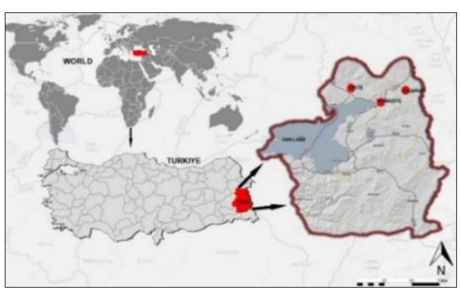

Figure 1. Study area.

Şekil 1. *Çalışma alanı.*

This study aims to assess the thermal comfort levels in Çaldıran and Muradiye, two districts characterized by rural settlement patterns and exposure to wind corridors, and to understand how building density, proximity to Lake Van, and wind dynamics affect thermal comfort. Erciş, a district with urban characteristics and also influenced by the wind corridor, was chosen for comparison. Urban wind environments impact both human comfort and urban ecosystems; yet very few studies have examined the mechanical or thermal effects of pedestrian wind in such contexts (Blocken et al., 2013; Wang et al., 2022).

This study provides novel insights into the interaction between wind corridors, large water bodies, and thermal comfort, particularly in the unique context of Van Province's urban and rural settlements. It is intended to serve as a foundation for future research, especially for studies focusing on thermal planning and comfort strategies around Lake Van, the largest lake in Türkiye.

MATERIALS and METHOD

Materials

The material of this study comprises Van Province and its immediate surroundings, located in the eastern part of Türkiye. Van is situated in the Eastern Anatolia Region and is known for its harsh continental climate, rugged topography, and significant elevation differences. The city has historically served as a settlement area for various civilizations, offering fertile soils and access to freshwater resources such as Lake Van (Kılıç, 2021). The province presents a unique microclimatic structure, shaped by the interaction between Lake Van, a large inland body of water, and the surrounding mountainous terrain. These geographic features contribute to spatial variations in thermal conditions and wind dynamics across the region. Within the scope of this study, three districts were selected as representative sampling areas based on their differing land use, elevation, and settlement typologies:

- Çaldıran, with an average elevation of 2050 meters, represents a rural, high-altitude settlement located in the northern part of the province and is directly influenced by the Gönderme wind corridor.
- Muradiye, with an elevation of approximately 1705 meters, also reflects rural characteristics, featuring a combination of agricultural lands and open plains.
- Erciş, situated at 1750 meters, represents a more urbanized settlement closer to Lake Van, where structural density and built-up areas are higher than in the other two districts.

These elevation differences are not only relevant for characterizing the topographic variation across the study area but also play a critical role in determining local microclimatic conditions, particularly air temperature, wind flow patterns, and thermal comfort levels.

Study area: Çaldıran District

Çaldıran District, located in the northern part of Van Province, is characterized by its high altitude (2050 meters above sea level) and severe continental climate, making it one of the coldest districts in Türkiye during the winter months. The region is directly influenced by the Gönderme Wind Corridor, which channels strong and persistent north-south winds throughout the year. Seasonally, Çaldıran experiences dry and clear summers, whereas winters are extremely cold, snowy, and partially cloudy. Annual temperatures typically range from –11ºC to 26ºC, with occasional extremes ranging from –18ºC to 29ºC. Hydrologically, the Bendimahi Stream, which originates within the district boundaries, traverses the central plain and flows into Lake Van, approximately 35 km to the south (Ministry of National Education, 2024). The district's open topography, minimal built-up areas, and exposure to high winds contribute significantly to its distinct microclimatic conditions, particularly in terms of thermal stress and wind-induced cooling.

Study area: Erciş District

Erciş District is situated approximately 100 kilometers north of Van city center, positioned 5 kilometers inland from Lake Van, at an elevation of 1750 meters above sea level. It encompasses the Erciş Plain, one of the largest and most agriculturally active lowland areas bordering the lake, with a surface area of approximately 2115 km². Climatically, Erciş experiences warm, dry summers and cold, snowy winters. Average annual temperatures range from –10ºC to 28ºC, with rare fluctuations below –17ºC or above 30ºC. July typically marks the warmest period, with sky clarity reaching up to 99%. The southern extension of the Gönderme Wind Corridor also affects the district, albeit to a lesser extent, due to the urban density and modified land surface characteristics. These urban features are thought to moderate wind exposure and contribute to the formation of UHI effects during warmer seasons (Weather Spark, 2024).

Study area: Muradiye District

Muradiye District lies 86 kilometers northeast of Van city center and covers a geographical area of approximately 1100 km². The district exhibits a transitional topography, comprising both mountainous terrain and partial plains, with an average elevation of 1705 meters. Its climatic regime is defined by hot and dry summers and long, cold, and wet winters. Annual air temperatures generally fluctuate between 2ºC and 35ºC, with extremes rarely falling below –3ºC or exceeding 38ºC. Similar to Çaldıran, Muradiye is also traversed by the Gönderme Wind Corridor, which exerts a notable influence on the district's climatic dynamics, particularly through the north-to-south movement of strong cold winds. Despite its proximity to mountainous regions, Muradiye maintains a rural settlement structure, characterized by relatively low building density and extensive open landscapes, which increase its vulnerability to wind-induced thermal stress during the winter months (Weather Spark, 2024).

Method

Analysis of meteorological data

Observation data from meteorological stations located in the districts of Çaldıran, Muradiye, and Erciş were used in this study. To ensure comparability among all stations, the analysis focused on the period between 2018 and 2023, during which consistent and robust data were available. The characteristics of the stations are presented in Table 1.

Table 1. Features of meteorology stations

***Çizelge 1.** Meteoroloji istasyonlarının özellikleri*

Stations	Location	Altitude	Land Usage Features
Çaldıran Station	39° 08' 16"N 43° 55' 28"E	2050 m	Rural settlement area: Generally, there are agricultural lands with little construction (2-4 floors) and abundant planting. It is 35 km away from Lake Van.
Erciş Station	38° 55' 45"N 43° 23' 44"E	1750 m	Urban settlement area: It is a settlement area where the construction and planting are generally at a medium level (5-7 storeys). It is located around Lake Van.
Muradiye Station	38° 59' 45"N 43°45' 39" E	1700 m	Rural settlement area: Generally, there are agricultural lands with little construction (4-5 floors) and abundant planting. It is 12 km away from Lake Van.

A comprehensive literature review was conducted to identify appropriate indices for evaluating outdoor thermal comfort. Based on this review, the Physiological Equivalent Temperature (PET) index was selected, as it is the most widely used indicator for assessing outdoor thermal comfort. The PET index estimates human thermal comfort based on the human energy balance model, accounting for the combined effects of meteorological parameters, including shortwave and longwave solar radiation, air temperature, relative humidity, and wind speed, as well as thermo-physiological factors, such as clothing insulation and activity level (Höppe, 1999). PET was chosen because it transforms the assessment of a complex outdoor climate environment into a simple indoor scenario on a readily understandable, physiologically equivalent basis. Its results are expressed in degrees Celsius, making it easily comprehensible to everyone (Matzarakis et al., 2007; Norouziasas et al., 2022).

In this study, PET values were calculated using the RayMan Pro 2.1 model, which integrates all relevant variables for thermal comfort analysis and provides the most accurate results (Koss, 2006). This program was chosen because it is frequently used to determine outdoor thermal comfort conditions (Krzyżewska et al., 2019; Yılmaz et al., 2021). A standard profile representing a healthy adult male aged 35 years, 175 cm tall, weighing 75 kg, with a clothing insulation value of 0.9 clo, and a metabolic workload of 80 W was used for the calculations. The PET values obtained from Rayman Pro 2.1 were interpreted according to the thermal stress classification ranges proposed by Matzarakis and Mayer in (1999), which are still used as the basis for outdoor thermal comfort ranges in many studies, including international studies (Table 2).

Table 2. Thermal sensation and stress levels of the PET index

***Çizelge 2**. PET indeksinin termal hissi ve stres seviyeleri*

PET° C	Human Temperature Sense	Thermal Stress Level
< 4,0	Extreme Cold	Extreme Cold Stress
4,1–8,0	Cold	Strong Cold Stress
8,1–13,0	Cool	Medium Cold Stress
13,1–18,0	Slightly Cool	Mild Cold Stress
18,1–23,0	**Comfortable**	**No Thermal Stress**
23,1–29,0	Light Warm	Mild Heat Stress
29,1–35,0	Hot	Medium Heat Stress
35,1–41,0	Very hot	Strong Heat Stress
>41,0	Extreme Heat	Extreme Heat Stress

In calculating the Physiological Equivalent Temperature (PET) index, hourly data for air temperature, relative humidity, wind speed, cloudiness, and solar radiation are utilized. The index is based on the human energy balance equation, which considers both environmental and physiological variables.

The PET model uses the following general heat balance equation:

$$M + W + Q^* (Tmrt, v) + QH (Ta, v) + QL (e, v) + QSW (e, v) + QRe (Ta, e) + S=0$$

Where: - M: Metabolic rate (activity level), W: Mechanical work, Q*: Radiation budget, QH: Sensible heat exchange, QL: Latent heat exchange (evaporation), QSW: Latent heat from sweating, QRe: Respiratory heat exchange (sensible and latent), S: Heat storage in the body, Ta: Air temperature, e: Vapor pressure, v: Wind speed, Tmrt: Mean radiant temperature

Wind speed data obtained from meteorological stations are typically measured at a height of 10 meters. However, to reflect pedestrian-level conditions, wind speeds must be adjusted to a reference height of 1.1 meters, which corresponds to the approximate center of gravity of a standing human body (Nastos & Matzarakis, 2019).

This adjustment is made using the following logarithmic wind profile equation:

WS_1.1=WS_h * (1.1 / h)^a

Where: - WS_1.1: Wind speed at 1.1 meters (m/s), WS_h: Wind speed at height h (usually 10 meters) - h: Measurement height (10 m), a: Empirical coefficient based on surface roughness, z0: Surface roughness length (obtained from the European Wind Atlas). The empirical coefficient a is calculated using the equation: a=0.12 * z0 + 0.18 as proposed by Irmak et al. (2020).

Multiple linear regression analysis of PET values

Regression analysis is a statistical tool used to estimate the relationship between the dependent variable and the independent variable. In other words, it focuses on how the dependent variable changes in response to changes in the independent variables (Yilmaz et al., 2018). More than one variable can come together and affect another variable. On the other hand, these variables can also influence one another. In such cases, when more than one variable needs to be used, it is referred to as "multiple regression analysis" (Kılıç, 2013).

In the study, multiple regression analysis was performed to determine how the PET values obtained from numerous variables and other variables affect the meteorological climate data. At this stage, the data were standardized, as the values of the meteorological climate data (temperature (Ta, ºC), humidity (RH—%), wind (m/s), and cloudiness (Octas)) were not in the same category.

Conducting Pearson correlation analysis of PET values

Correlation analysis is a statistical method used to examine the direction and strength of the relationship between two variables (Höppe, 1999). The correlation coefficient (r) ranges from –1 to +1. A negative value indicates an inverse relationship, while a positive value indicates a direct linear relationship. The closer the coefficient is to ±1, the stronger the relationship (Çağlak & Matzarakis, 2024).

In this study, Pearson Correlation analysis was conducted to assess the direction and magnitude of the relationship between the meteorological variables and the PET values derived from them. The interpretation of the Pearson correlation coefficients was based on the classification intervals presented in Table 3 (Çağlak & Matzarakis, 2024).

Table 3. Pearson correlation coefficient ranges

Çizelge 3. *Pearson korelasyon katsayısı aralıkları*

Correlation Coefficient (R2)	Comment
R<0.2	No Relationship
0.2-0.4	Low Relationship
0.4-0.6	Moderate Relationship
0.6-0.8	High Relationship
R >0.8	Very High Relationship

RESEARCH FINDINGS AND DISCUSSION

This study evaluated monthly changes in meteorological parameters and PET values between 2018 and 2023 in the Çaldıran, Muradiye, and Erciş districts. Analysis of monthly average temperatures obtained from hourly climate data between 2018 and 2023 revealed that the highest value was recorded at Muradiye station in August, with 24.2ºC, and the lowest value was recorded at Çaldıran station in January, with 9.5ºC (Table 4). The fact that monthly average temperatures in Erciş were generally higher than those in Çaldıran is consistent with previous findings on temperature differences between urban and rural areas (Özlü et al., 2019; Shi et al., 2015). Interestingly, despite being a rural district, Muradiye recorded higher average temperatures than Erciş in some months. This anomaly is primarily attributed to Muradiye's proximity to large water bodies, which act as thermal buffers, thereby reducing extreme temperatures in surrounding areas (Nakayama & Fujita, 2010).

Table 4. Monthly average temperature data (2018-2023)

Çizelge 4. *Aylık ortalama sıcaklık verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	-9,5	-8,3	-0,2	5,9	11,3	17	20,6	21	16,1	9,2	2,5	-3,4	6,8
Muradiye Station (Rural)	-3,3	-2,1	3,6	9,1	14,1	20,3	24,1	24,2	19,2	13,5	5,6	1,1	10,7
Erciş Station (Urban)	-3,2	-2,1	3,4	8,7	13,5	19,5	23,1	23	18,1	11,3	5,3	1	10,1

An examination of the monthly average maximum temperatures between 2018 and 2023 shows that January values were identical across all three stations. In the remaining months, however, Muradiye and Erciş stations consistently recorded higher maximum temperatures than Çaldıran. Moreover, Muradiye and Erciş displayed similar values throughout the year, except in October, where a noticeable divergence was observed. The most significant temperature difference between Muradiye and Çaldıran was 7.5 ºC in October, followed by 5.1 ºC in December. The smallest difference occurred in September (2.5 ºC) and November (2.7ºC). The greatest urban–rural temperature contrast between Erciş and Çaldıran was noted in December, with Erciş being 5ºC warmer, highlighting the effect of urban warming (Table 5).

Table 5. Monthly average maximum temperature data (2018-2023)

Çizelge 5. *Aylık ortalama maksimum sıcaklık verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	8,4	6,8	15,8	20,6	25,8	31	34,4	33,2	31,2	24,3	16,4	8,8	21,3
Muradiye Station (Rural)	8,4	9,9	19,7	23,6	28,7	34,4	37,8	36,9	33,7	31,8	19,1	13,9	24,8
Erciş Station (Urban)	8,4	10,6	19	23,6	28,4	33,7	37	37,2	32,3	26,8	19	13,8	24,1

Analysis of monthly average minimum temperatures indicates that Erciş station recorded higher values than the other stations in September, reflecting the urban heat retention effect during night hours. In contrast, Çaldıran station consistently exhibited the lowest minimum temperatures throughout the year, a result of its high elevation, continental climate characteristics, and exposure to open wind corridors (Table 6).

Table 6. Monthly average minimum temperature data (2018-2023)

Çizelge 6. *Aylık ortalama minimum sıcaklık verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	-33,8	-32,6	-22,1	-8,9	-2,4	3,2	6,7	5,9	1,8	-7,5	-9,9	-27,2	-10,5
Muradiye Station (Rural)	-20,3	-17,6	-11,1	-3,7	1	6	11,4	10,2	0	0	-6	-16,5	-3,7
Erciş Station (Urban)	-20,6	-19,5	-12,9	-4	-0,2	6,5	10,3	7,8	3,9	-2,5	-6,5	-15,6	-4,4

An evaluation of monthly average relative humidity data reveals that Çaldıran station consistently recorded higher humidity levels compared to the other stations (Table 7). This can be attributed to the district's distinct hydrological and ecological features, including the Bendimahi Stream, which extends approximately 35 km toward Lake Van, the Çaldıran Plain, Kaz Lake, and surrounding reed beds located about 7 km from the district center. Additionally, wetland areas covering 223 km², along with extensive meadow and pasturelands, significantly contribute to the region's elevated atmospheric moisture levels. These natural elements enhance evapotranspiration, which in turn increases local humidity.

Table 7. Monthly average relative humidity data (2018-2023)

Çizelge 7. *Aylık ortalama bağıl nem verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	83	83	78	68	60	48	49	43	42	56	71	80	56,7
Muradiye Station (Rural)	70	73	71	62	59	44	35	33	40	58	72	76	55
Erciş Station (Urban)	67	69	65	57	55	42	35	35	42	59	64	70	55

Wind speed data obtained from The Meteorological Service were adjusted to reflect pedestrian-level conditions by reducing the measurement height from 10 meters to 1.1 meters, which corresponds to the center of gravity of a standing human body. As a result of this adjustment, the wind speed values presented in Table 8 are lower than the original measurements taken at 10 meters.

Table 8. Monthly average wind speed data (2018-2023)

Çizelge 8. *Aylık ortalama rüzgar hızı verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	0,4	0,4	0,7	0,8	0,8	0,7	0,8	0,7	0,7	0,5	0,4	0,3	0,6
Muradiye Station (Rural)	0,4	0,4	0,5	0,5	0,5	0,6	0,6	0,6	0,5	0,4	0,3	0,3	0,4
Erciş Station (Urban)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1

An examination of the monthly wind speed averages shows that Çaldıran station consistently recorded higher wind speeds than Muradiye and Erciş stations between March and November. In contrast, Erciş station exhibited the lowest wind speeds across all months. This difference can be attributed to urban morphology, as narrow streets and densely built structures in urban areas hinder airflow and reduce wind speed (Shui et al., 2018). Additionally, unlike the other districts, Erciş is not positioned between mountain ranges and Lake Van, which limits the formation of a natural wind corridor. These findings are consistent with previous studies comparing urban and rural wind dynamics, which indicate that urban centers with dense building stock tend to have significantly lower wind speeds than high-altitude, open rural areas (Shi et al., 2015; Özlü et al., 2019).

The analysis of monthly average maximum wind speed values indicates that Çaldıran station consistently recorded higher values than both Erciş and Muradiye stations throughout the year (Table 9). The highest monthly average maximum wind speed was observed in May (4.3 m/s), followed by December (4.1 m/s). In contrast, Erciş station exhibited the lowest maximum wind speeds in all months except January, which further supports the finding that urban morphology restricts wind flow, reducing both average and peak wind conditions.

Table 9. Monthly average maximum wind speed data (2018-2023)

Çizelge 9*. Aylık ortalama maksimum rüzgar hızı verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	3,4	3,1	3,8	4	4,3	3,1	2,9	3,2	3,4	3,3	2,8	4,1	3,4
Muradiye Station (Rural)	1,9	1,8	3,7	2,3	3	2,2	1,9	1,7	2,2	1,7	1,7	2,2	2,1
Erciş Station (Urban)	2,5	0,6	0,9	0,7	0,9	0,6	0,7	0,6	0,7	0,7	0,5	0,8	0,8

To better understand the impact of pedestrian-level wind and its relationship with PET values, data on the monthly number of stormy and strong wind days between 2018 and 2023 were obtained from the Turkish State Meteorological Service. Among the stations, Çaldıran recorded the highest number of stormy days, totaling 57 days, with May identified as the stormiest month. Erciş followed with 14 days, while Muradiye experienced the lowest number of stormy days with only 5. In terms of strong wind days, Çaldıran again ranked first, with a total of 629 days over the six years. The peak months were May (88 days), June (101 days), and July (92 days). Erciş station reported 310 strong wind days, with a concentration particularly in April (50 days), May (46 days), and July (41 days). Muradiye had the lowest total, with 221 strong wind days, including April (38 days), May (30 days), and July (36 days).

These findings highlight the climatic intensity and variability of wind conditions in the study area, particularly in Çaldıran, and underscore the importance of integrating wind data into thermal comfort assessments and urban-rural planning strategies.

Interpretation of PET values

Monthly average pet distribution maps

In the PET distribution maps generated for the study areas, red tones indicate heat stress, blue tones represent cold stress, and green areas signify thermal comfort zones with no significant stress. Since the focus of this research is to examine the impact of wind corridors on thermal comfort in residential areas, PET values were interpreted in conjunction with average wind speeds, the number of stormy days per month, and the frequency of strong wind days. Wind data analyses revealed that Çaldıran station had the highest wind speeds from March to November (Table 8). When corresponding PET values were examined, Çaldıran consistently experienced extreme cold stress during these months, while the thermal conditions in Muradiye and Erciş varied more moderately. Notably, in May, Çaldıran exhibited moderate cold stress, whereas the other stations experienced only mild cold stress (Table 10). This can be attributed to the fact that May had both the highest wind speed and the most significant number of stormy days in Çaldıran during the six-year study period.

Furthermore, during July, when Çaldıran recorded its highest number of strong wind days, no thermal stress was observed there, while mild heat stress was detected in Muradiye and Erciş (Table 10, Figure 2). These observations align with previous studies, which have reported that increased wind speed in cold seasons reduces thermal comfort due to the amplified cooling effect of wind, and that open rural settlements are generally cooler than urban areas, particularly due to pedestrian-level wind exposure (Yılmaz et al., 2021). Consistent with the literature, this study confirms that Çaldıran, due to its high wind speeds, frequent stormy days, and strong wind conditions, experiences more pronounced cold stress, highlighting the crucial role of wind in shaping local thermal comfort dynamics.

Table 10. Monthly average PET data (2018-2023)

Çizelge 10. *Aylık ortalama PET verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	-13,2	-11,2	-2,3	4,3	10,8	17	20,5	20,2	14,4	7,1	-0,2	-6,6	5,5
Muradiye Station (Rural)	-4,2	-4,3	2,7	9	15	21,5	25,4	24,9	18,8	12,5	3,7	-1,3	10,3
Erciş Station (Urban)	-5,4	-3	4,1	10,7	16,9	23	26,8	25,8	19,5	11,6	4,3	-0,7	11,1

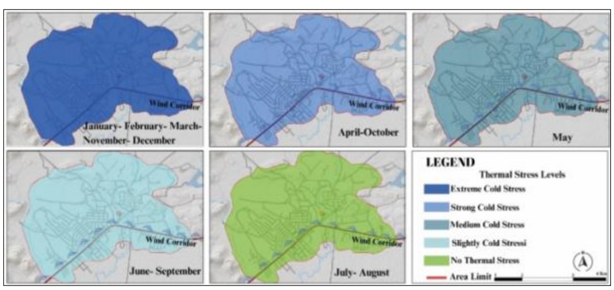

Figure 2. Monthly average PET distribution map of Çaldıran station (2018-2023).

Şekil 2. *Çaldıran istasyonunun aylık ortalama PET dağılım haritası (2018-2023).*

An analysis of Figure 3 reveals that the overall PET averages in Erciş, representing an urban settlement, are generally more favorable in terms of thermal comfort. However, this trend reverses during the summer months, particularly in July and August, where PET values increase significantly, leading to heat stress conditions. This finding is consistent with the results of Irmak et al. (2020), who reported that urban areas exhibited the highest PET values, and Yılmaz et al. (2021), who emphasized that regions with lower elevation and reduced wind exposure tend to experience elevated PET levels. These observations align with the broader literature on UHI, where densely built urban environments are significantly warmer than adjacent rural areas due to factors such as impervious surfaces, reduced vegetation, and limited ventilation (Rizwan et al., 2008; Connors et al., 2013).

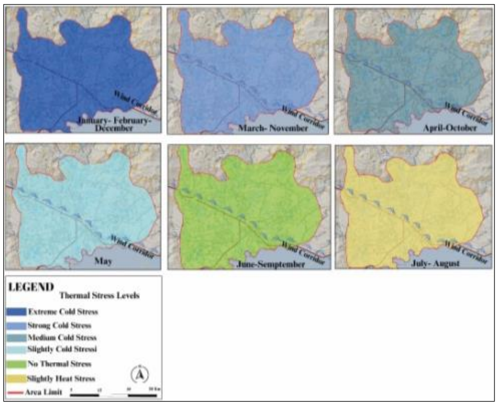

Figure 3. Monthly average PET distribution map of Erciş station (2018-2023).

Şekil 3. *Erciş istasyonunun aylık ortalama PET dağılım haritası (2018-2023).*

Although Muradiye and Erciş stations display similar climatic characteristics, the most notable difference lies in their settlement typologies Muradiye represents a rural environment, while Erciş reflects urban characteristics. Despite this contrast, PET distribution maps indicate comparable patterns between the two, with Muradiye experiencing extreme cold stress for five months and Erciş for only three months (Figures 3, Figures 4). The modifying effects of tree density and land use types may explain this similarity in PET distributions. According to Maniatis et al. (2020), while urban centers in cold climates and areas with dense tree cover may benefit from improved thermal comfort due to wind shielding and radiative trapping, open rural settlements with high proportions of unshaded green areas may exhibit lower PET values in winter due to the cooling and shading effects of vegetation.

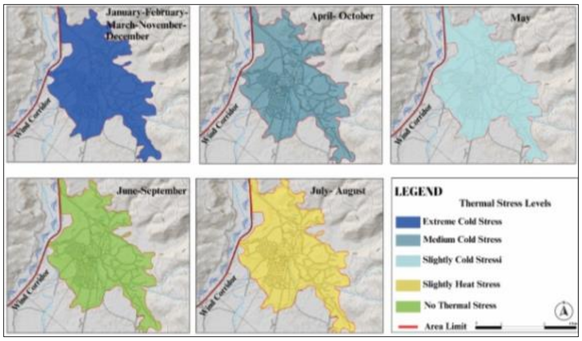

Figure 4. Monthly average PET distribution map of Muradiye station (2018-2023).

Şekil 4*. Muradiye istasyonunun aylık ortalama PET dağılım haritası (2018-2023).*

The monthly average PET values for Çaldıran station are lower than those of Muradiye and Erciş throughout the year. This outcome is expected given that Çaldıran consistently records lower air temperatures, while maintaining higher average humidity and wind speed values. Additionally, Çaldıran's elevation (2050 m) and its location within an active wind corridor contribute to further reductions in PET values by intensifying cold stress conditions. When comparing Erciş and Muradiye, although both stations exhibit similar temperature profiles, the slightly higher wind speeds in Muradiye result in lower PET values relative to Erciş (Table 10). However, in October, Muradiye station records the highest air temperature among all three locations (Table 4), which directly influences its PET value, making it the station with the highest thermal comfort level for that particular month.

Monthly average maximum pet distribution maps

An examination of the monthly maximum PET values reveals that the Erciş station consistently exhibits the highest PET values throughout the year, when compared to the other two stations. The difference between Erciş and Muradiye in terms of maximum PET is relatively small, suggesting similar peak thermal comfort conditions in these two districts. In contrast, Çaldıran station consistently records the lowest maximum PET values, reinforcing the impact of its high altitude, strong wind exposure, and cooler climatic conditions (Table 11).

Table 11. Monthly average maximum PET Data (2018-2023)

Çizelge 11. *Aylık ortalama maksimum PET Verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	14,6	15,5	25,5	28,8	32,7	39	44,8	41,9	39,7	31,7	21,6	13,6	29,1
Muradiye Station (Rural)	10,3	17,3	28	32,4	38,3	44,1	49,2	47,8	41,9	38,5	26,4	18,4	32,7
Erciş Station (Urban)	16,6	21,3	28,2	36,1	42,2	47,8	52	51	47,1	38	30,3	20,7	35,9

As previously emphasized, several topographic and locational factors contribute to Çaldıran station being the site with the lowest heat stress among the three study areas (Figure 5). These include its significantly higher elevation compared to Muradiye and Erciş, its mountain-encircled rural setting, its greater distance from Lake Van, and the fact that a substantial portion of the Gönderme wind corridor traverses this district. These elements collectively enhance wind-driven cooling effects and limit heat accumulation, thereby reducing PET values and associated thermal stress levels.

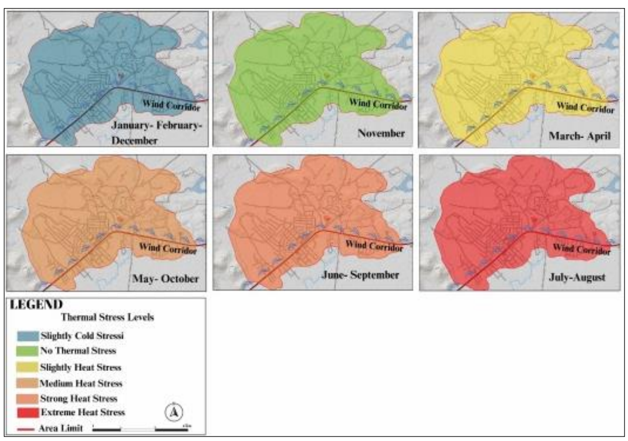

Figure 5. Monthly average maximum PET distribution map of Çaldıran station (2018-2023).

Şekil 5. *Çaldıran istasyonunun aylık ortalama maksimum PET dağılım haritası (2018-2023).*

The occurrence of extreme heat stress in Erciş station during certain months is primarily influenced by its proximity to Lake Van, its relatively low altitude, and its urban settlement character (Figure 6). These factors contribute to reduced ventilation and increased heat retention, particularly during the summer season. Although Muradiye station shares similar geographic conditions, being close to Lake Van and located at a low elevation, it experiences less heat stress than Erciş. This difference can be attributed to Muradiye's rural setting and its position within the Gönderme wind corridor, which enhances natural air circulation and mitigates thermal accumulation (Figure 7).

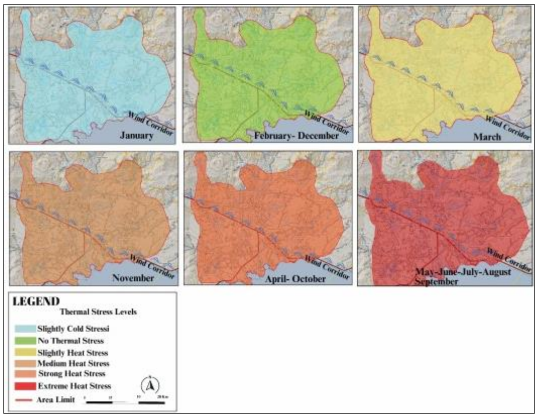

Figure 6. Monthly average maximum PET distribution map of Erciş station (2018-2023).

Şekil 6. *Erciş istasyonunun aylık ortalama maksimum PET dağılım haritası (2018-2023).*

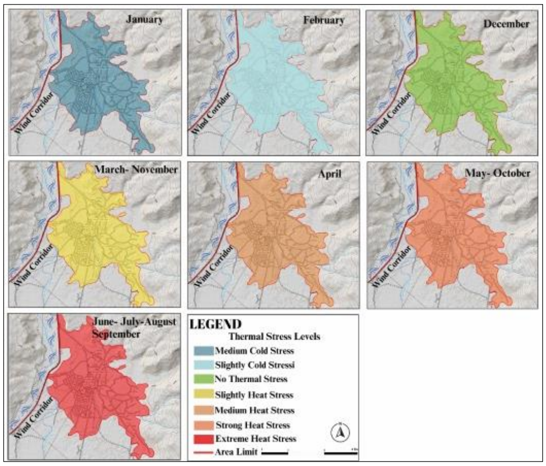

Figure 7. Monthly average maximum PET distribution map of Muradiye station (2018-2023)

Şekil 7. Muradiye istasyonunun aylık ortalama maksimum PET dağılım haritası (2018-2023)

Monthly average minimum pet distribution maps

An analysis of the monthly average minimum PET values at Çaldıran station reveals that the area is subject to extreme cold stress throughout the entire year (Table 12). In Erciş, intense cold stress is observed in July, while extreme cold stress dominates the remaining months. Similarly, Muradiye station experiences strong cold stress in July and August, and extreme cold stress during all other months. These findings reflect the pronounced influence of high elevation, low night-time temperatures, and seasonal wind activity on nocturnal thermal discomfort, particularly in open rural environments such as Çaldıran and Muradiye.

Table 12. Monthly average minimum PET data (2018-2023)

Çizelge 12. *Aylık ortalama minimum PET verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	-40,1	-39,2	-28	-14,9	-8,2	-1,9	0,3	0,3	-4	-14	-16,4	-33,2	-16,6
Muradiye Station (Rural)	-17,5	-24,6	-17,6	-8	-4,1	0,6	4,6	4,2	-1,7	-6,7	-12,6	-22,4	-8,8
Erciş Station (Urban)	-26,6	-26,3	-19,6	-9,6	-5,4	1,5	5	3,1	-1,2	-8,8	-13,1	-21,5	-10,2

Investigation of the relationship between pet values and climate data with statistical analysis

According to the results of the Pearson correlation analysis conducted to assess the relationship between PET values and meteorological parameters at Çaldıran station, a robust positive correlation was found between PET and air temperature (r=0.978), indicating that temperature is the most influential factor affecting thermal perception. A strong negative correlation was observed between PET and relative humidity (r=–0.725), suggesting that increased humidity levels are associated with lower PET values.

In addition, a moderate positive correlation was found between PET and wind speed (r=0.401), while cloudiness showed a weak negative correlation with PET (r=–0.253). All relationships were statistically significant (*p*=0.000) (Table 13). These findings highlight the dominant role of temperature and humidity, followed by wind, in determining PET values in high-altitude rural environments like Çaldıran.

Table 13. Çaldıran Pearson correlation table

Çizelge 13. *Çaldıran Pearson korelasyon tablosu*

Variable	Heat	Humidity	Wind	Cloud	Importance Level (*p*)
Humidity	-0,716	1			0.000
Wind	0,425	-0,358	1		0.000
Cloud	-0,296	0,435	0,014	1	0.000
PET	0,978	-0,725	0,401	-0,253	0.000

The Pearson correlation analysis performed for Erciş station revealed a very strong positive correlation between PET values and air temperature (r=0.908), confirming temperature as the dominant determinant of thermal comfort in this urban area. A weak negative correlation was found between PET and relative humidity (r=–0.220), indicating a limited inverse relationship.

In contrast to rural stations, wind speed showed no significant correlation with PET (r=–0.041), highlighting the diminished effect of wind due to urban morphological features that reduce air circulation. Cloudiness, on the other hand, exhibited a weak positive correlation with PET (r=0.276). All correlation values were statistically significant (*p*=0.000) (Table 14). These findings suggest that in urban contexts like Erciş, thermal comfort is primarily driven by temperature, while wind has little to no influence on PET levels.

The Pearson correlation analysis for Muradiye station revealed a robust positive correlation between PET values and air temperature (r=0.942), indicating that temperature is the primary factor influencing thermal comfort. A strong negative correlation was also found between PET and relative humidity (r=–0.738), indicating that increased humidity significantly reduces perceived thermal comfort.

Table 14. Erciş Pearson correlation table

Çizelge 14. *Erciş Pearson korelasyon tablosu*

Variable	Heat	Humidity	Wind	Cloud	Importance Level (P)
Humidity	-0,182	1			0.000
Wind	0,052	-0,130	1		0.000
Cloud	0,223	0,328	0,124	1	0.000
PET	0,908	-0,220	-0,041	0,276	0.000

In addition, wind speed and cloudiness both exhibited low positive correlations with PET (r=0.364 for each), suggesting that while their effects are more modest compared to temperature and humidity, they still contribute to thermal perception in this rural district. All correlations were statistically significant (*p*=0.000) (Table 15). These results indicate that Muradiye's PET values are shaped by a combination of temperature, humidity, and moderate wind activity, consistent with its position along a wind corridor and rural landscape features.

Table 15. Muradiye Pearson correlation table

Çizelge 15. *Muradiye Pearson korelasyon tablosu*

Variable	Heat	Humidity	Wind	Cloud	Importance Level (*p*)
Humidity	-0,748	1			0.000
Wind	0,403	-0,465	1		0.000
Cloud	-0,348	0,444	-0,113	1	0.000
PET	0,942	-0,738	0,364	0,364	0.000

According to the Pearson correlation analysis, a powerful positive relationship was identified between air temperature and PET values across all three stations, confirming temperature as the primary determinant of thermal comfort. At Çaldıran and Muradiye, a positive correlation was also found between wind speed and PET values, indicating that wind contributes positively to thermal perception in these open rural environments. In contrast, Erciş station exhibited a weak negative correlation with wind speed, suggesting that wind has a negligible influence on PET in urban settings.

When examining relative humidity, Çaldıran and Muradiye both displayed a strong negative correlation with PET values, whereas Erciş showed a weak positive correlation. These findings imply that high humidity levels in rural areas are associated with decreased PET, while in urban areas, the relationship is minimal and inconsistent. Overall, the monthly average PET values in Çaldıran and Muradiye were found to be primarily influenced by temperature, with wind speed being the secondary factor. In Erciş, temperature remained the dominant factor, while wind had no meaningful effect, and humidity had only a minor negative impact. This comparative evaluation underscores the importance of local climatic and morphological contexts in shaping thermal comfort dynamics.

CONCLUSION and RECOMMENDATIONS

This study investigated the impact of meteorological variables on pedestrian-level thermal comfort in three climatically and topographically distinct settlements: Çaldıran, Muradiye, and Erciş. The findings reveal that air temperature, wind speed, relative humidity, and cloudiness significantly influence PET values; however, the nature and strength of these influences vary depending on elevation, topographic structure, proximity to water bodies, and urban-rural settlement characteristics. Çaldıran, with its high elevation, open rural environment, and exposure to a strong wind corridor, consistently exhibited the lowest PET values throughout the year, mainly due to enhanced cold stress. Muradiye, although similarly rural and topographically complex, presented more moderate PET values. In contrast, Erciş, as an urban settlement at a lower elevation, demonstrated higher PET values during summer due to reduced wind movement and UHI effects, while maintaining relatively comfortable conditions in winter.

These results underscore the need for climate-responsive spatial planning that extends beyond temperature-centric approaches, incorporating seasonal wind behavior, landform context, and settlement morphology to ensure thermally livable environments.

Recommendations

Integrated climate-based spatial planning should be adopted. Thermal comfort analyses must guide decisions regarding building orientation, street geometry, vegetation layout, and public space design.

In high-altitude rural areas (e.g., Çaldıran):

Figure 2 shows that Çaldıran's monthly average PET values are cooler than those of other settlements. In this regard: The settlement layout should maximize solar gain in winter through south-facing streets and facades.

- Structural design must minimize wind exposure without entirely blocking natural air circulation.
- Vegetation and building forms should be arranged to reduce wind intensity at the pedestrian level while maintaining visual openness.
- Materials with high thermal mass (e.g., stone, brick) should be prioritized for insulation.

In low-altitude urban settlements near large water bodies (e.g., Erciş):

Figures 3 and 6 show that Erciş station exhibits warmer ranges in terms of thermal stress. Therefore:

- Summer heat stress should be mitigated through shade-providing vegetation, permeable surfaces, and reflective materials.
- Urban morphologies should enable cross-ventilation via strategic street alignment and building gaps.
- Tree canopies, green walls, and water features should be integrated to alleviate the UHI effect.

General principles applicable to all settlements:

- Seasonal variation in thermal comfort should be addressed with distinct summer and winter strategies.
- Wind should be viewed not only as a cooling agent but also as an ecological and health-related factor influencing air quality and ventilation.
- Wind corridors must be preserved and integrated into planning frameworks to balance thermal comfort and environmental ventilation.
- PET and other biometeorological indices should be institutionalized as key indicators in urban and landscape policy-making, especially in areas experiencing climatic extremes.

In conclusion, this study demonstrates that thermal comfort in outdoor environments is not solely governed by air temperature but is also deeply influenced by a combination of topographic features, elevation, wind corridors, settlement morphology, and proximity to large bodies of water. While urban areas like Erciş benefit from higher PET values in colder seasons due to heat retention, they face increased heat stress during summer months due to restricted wind flow and dense structural texture. Conversely, rural areas such as Çaldıran and Muradiye are more vulnerable to cold stress, particularly in winter, due to higher altitudes and exposure to strong winds. These findings underscore the need to develop climate-responsive design strategies tailored to the unique spatial and environmental characteristics of both rural and urban settlements. Integrating PET-based assessments into planning processes can significantly enhance public health, spatial quality, and seasonal livability in climatically diverse regions.

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: NY, ŞA., and MAI; sample collection: NY, ŞA., and MAI; analysis and interpretation of data: NY, ŞA., and MAI; statistical analysis: NY; visualization: NY; writing manuscript: NY, ŞA., and MAI.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that ethical approval was not required for this study.

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