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Research Article

Developing an integrated framework for measuring and calculating the tourism climate of Duhok province in northern Iraq using bioclimatic indices

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Abstract

Thermal comfort is a crucial factor in determining the temporal and spatial capacity of outdoor tourism, as variations in climatic elements can alter the desirability of tourism activities across different seasons and locations. This study aimed to evaluate thermal comfort conditions and determine the climatic tourism calendar in Duhok Province, northern Iraq, using PET, UTCI, and TCI indices. For this purpose, monthly meteorological data from 2000 to 2025 were obtained from MERRA-2 reanalysis products. After processing, bioclimatic indices were calculated, and their temporal and spatial patterns were examined in a GIS environment. The results showed that thermal comfort in Duhok Province has a distinct seasonal cycle. Winter is characterized by cold stress, and the peak of summer by increased heat stress, while the transitional seasons offer more suitable conditions for outdoor tourism. According to the tourism calendar, April, May, September, and October were identified as the most appropriate times, with May and September exhibiting the strongest alignment between PET and UTCI within the preferred comfort zone. Spatially, the TCI findings revealed considerable variation in the duration of the favorable tourism season. Specifically, the highlands and certain central areas of the province experienced an extended climatic tourism period. This pattern suggests that both altitude and the topographical layout significantly influence the thermal environment and the geographical spread of climatic tourism potential within Duhok. The results suggest that Duhok's climatic tourism capacity varies across different times and locations. Therefore, tourism planning ought to consider the region's thermal calendar and its diverse topography.

Keywords: Thermal comfort, Physiological equivalent temperature, Seasonal desirability, Climatic tourism calendar, Iraq.

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Introduction

Across many countries worldwide, tourism is a crucial economic and social sector, closely tied to the environmental characteristics and weather conditions prevalent in different tourist destinations (Mihăilă et al, 2019). Climate is a crucial factor influencing not only the selection of travel dates and destinations but also the nature of tourism activities and the overall satisfaction of tourists (Kapetanakis et al, 2022; Matthews et al, 2021). The application of bioclimatic indices as scientific instruments to assess the suitability of a climate for tourism has gained considerable interest among researchers in recent years (Enebeli et al, 2026; Durlević et al, 2023). These indices offer a more accurate assessment of thermal comfort and help pinpoint ideal times for tourism by integrating various meteorological factors (Farajzadeh et al, 2016). Duhok Governorate, located in northern Iraq, possesses considerable promise for the growth of its tourism sector, attributed to its varied landscape, mountainous areas, and natural points of interest (Asaad and Balaky, 2021). This study seeks to assess Duhok province's climatic tourism calendar by utilizing various bioclimatic indices. Its objective is to spatially map suitable tourism conditions through the analysis of climatic data. Tourism is an industry significantly affected by the state of natural surroundings and environmental factors. Climatic conditions are recognized as a core element influencing the appeal and practicality of a tourist spot, even though economic, cultural, social, and infrastructural elements also play significant roles in tourism growth (Hidayat et al, 2024). Inclement weather can deter tourists from visiting a destination, shorten their stays, and restrict available activities. Conversely, pleasant weather can stimulate tourism and facilitate a balanced seasonal distribution of travel (Han et al, 2025). Consequently, the notion of "tourism climate" has emerged as a significant subject in the interdisciplinary research between climatology and tourism over recent decades (Mohammadi et al, 2018). In tourism climate research, the primary objective extends beyond merely analyzing average climatic factors to also assessing how concurrent atmospheric conditions impact the human body and influence tourists' thermal comfort levels. Individuals in an outdoor setting constantly exchange energy with their environment. The thermal sensations they experience are a consequence of the interplay among various elements, including air temperature, humidity, wind velocity, solar radiation, and personal attributes (Błażejczyk et al, 2010). Consequently, relying solely on a single factor such as temperature is insufficient for precisely evaluating a region's climatic appeal. This limitation has spurred the creation of comprehensive bioclimatic indices, which aim to quantify the combined impact of diverse atmospheric elements on human thermal well-being (Wu et al, 2022). The Physiological Equivalent Temperature (PET) index, a frequently employed tool in thermal comfort research, quantifies environmental conditions by assessing how the human body physiologically responds to them. The Tourism Climate Index (TCI) evaluates how suitable a particular area is for tourism by integrating several climatic elements (Höppe, 1999). The Wind Chill Index (WCI) also serves to analyze how the perceived temperature decreases due to the combined impact of air movement and cold environments (Osczevski, 1995). The Universal Thermal Climate Index (UTCI) has become widely used in human climate research in recent years. This is because it can be compared across various climatic conditions and accounts for the body's heat exchange mechanisms (Jendritzky et al, 2012). Utilizing multiple indices concurrently offers a more thorough understanding of a region's climatic conditions, given that each index reflects a specific aspect of the intricate connection between climate and human comfort. To assess the effectiveness of the UTCI index in determining biometeorological conditions and heat risks across Europe, Di Napoli et al. (2018) analyzed the UTCI's spatial and temporal changes throughout the summer. Their study utilized 38 years of reanalysis climate data. The UTCI mapping revealed a clear geographical distribution of thermal stress conditions in Europe, along with a notable rise in the severity of heat stress over recent decades. A study investigating the use of the Universal Thermal Climate Index (UTCI) for evaluating bioclimatic conditions focused on the southern Baltic Sea coasts. This research aimed to determine the connection between atmospheric circulation (synoptic) patterns and the presence of extreme thermal stress (both heat and cold), utilizing data from coastal stations and reanalysis climatic information (Kolendowicz et al, 2018). Recent research has focused considerably on how climate change affects bioclimatic conditions and human thermal comfort, particularly through the use of the Universal Thermal Climate Index (UTCI). A key study in this field examined projected shifts in thermal stress within Greece under different greenhouse gas emission scenarios. The findings indicated that Greece is expected to experience a notable rise in the severity of heat stress in the near future. The most substantial increases in thermal stress are anticipated in the country's inland mountainous areas, as well as its northern and western regions (Pantavou et al, 2025). A study in Iraq examined the yearly and seasonal spatial patterns of potential evapotranspiration (PET) from 1981 to 2021, utilizing ERA5-Land reanalysis data. The findings indicated a notable upward trend in PET across the majority of Iraq, with the exception of certain areas within the eastern and southeastern alluvial plains (Al-Hasani and Shahid, 2022). A study in Basra, Iraq, examined the correlation between PET and various meteorological factors, revealing that peak thermal stress indices are recorded in July and August. Conversely, conditions conducive to thermal comfort are more common in March, April, and October (Al-Ramahy, 2024). Similarly, in Baghdad, July and August experience the highest levels of thermal stress, whereas thermal comfort is predominantly found in March, April, and October (Al-Lami et al, 2023). Even with progress in tourism climate research, a significant portion of current studies continues to rely on a small number of weather stations. This reliance can result in lower accuracy, particularly in regions with diverse geographical features like mountains. In regions characterized by diverse elevations, temperature, humidity, wind, and radiation levels fluctuate significantly even over short spans. Consequently, relying on data from a limited number of stations might not accurately capture the actual range of climatic conditions (Körner et al, 2007). Thus, employing reanalyzed data enables a more accurate assessment of thermal comfort trends across a given region. Duhok Governorate, situated in northern Iraq, possesses significant potential for tourism growth thanks to its natural and geographical features (Mohammed, 2015). Nevertheless, the varied topography and geographical expanse of the area mean that data from ground-based weather stations alone are inadequate for creating a comprehensive tourism calendar. In this study, re-analyzed data from Duhok province were utilized to examine its bioclimatic comfort. Although thermal conditions are crucial for tourism planning, evaluating the tourism climate in topographically diverse mountainous regions remains a considerable hurdle (Jendritzky et al, 2012). A solitary index cannot comprehensively capture all facets of thermal and climatic conditions relevant to tourism. Bioclimatic indices such as PET and UTCI function on distinct models of human thermal perception, potentially yielding different intensities or classifications of thermal conditions. Conversely, indices like TCI incorporate a wider array of climatic elements that influence tourism appeal. Consequently, depending on just one index or a single weather station can obscure the actual variability of tourism conditions, particularly in regions marked by substantial changes in altitude and topography (Körner et al, 2007). This problem is particularly pronounced in Duhok province due to its varied altitudes and topography, which cause significant shifts in temperature conditions over short distances. Consequently, a single tourism calendar may not be applicable across the entire province (Mohammed, 2015). From a practical standpoint, the absence of spatial data concerning suitable and unsuitable times for tourism can create difficulties in planning outdoor activities and events, choosing appropriate destinations during hot and cold seasons, and prioritizing areas with greater tourism potential. Therefore, the essential requirement is to pinpoint not just the "best month for tourism," but also to simultaneously identify the optimal time and location for tourism, taking into account thermal and climatic factors. This study aimed to concurrently assess the TCI, PET, and UTCI indices across Duhok province. It sought to analyze shifts in thermal comfort over time and space, subsequently transforming these findings into a climatic tourism calendar. This method not only pinpoints optimal times for tourism but also reveals geographical variations in tourism climate capacity and identifies regions with extended tourist seasons. Therefore, the study's key innovation stems from its integrated approach, which combines multi-indicator assessment with spatial and temporal analysis, rather than solely relying on bioclimatic indices. This allows for the presentation of practical information valuable for tourism planning in diverse mountainous terrains.

Materials and Methods

Study Area

Duhok province, situated in northern Iraq within the Kurdistan Region, possesses a distinctive geographical position in the transitional area between the Mediterranean and arid Middle Eastern climates, leading to a wide array of climatic conditions. The region's terrain is predominantly mountainous, featuring elevations from the Zagros range, which results in significant spatial variations in temperature, precipitation, and other climatic factors over short distances. Generally, Duhok's climate is categorized as semi-arid to mountainous Mediterranean, characterized by hot, dry summers and cold, wet winters. The varying altitudes, from low plains to high mountains, have fostered diverse microclimates throughout the province. These attributes underscore Duhok's considerable importance regarding its natural resources, landscapes, and potential for nature-based tourism (Figure 1). From the standpoint of climate tourism, the pronounced spatial and temporal differences in climatic elements make this province an ideal location for studying thermal comfort and creating a climate tourism calendar.

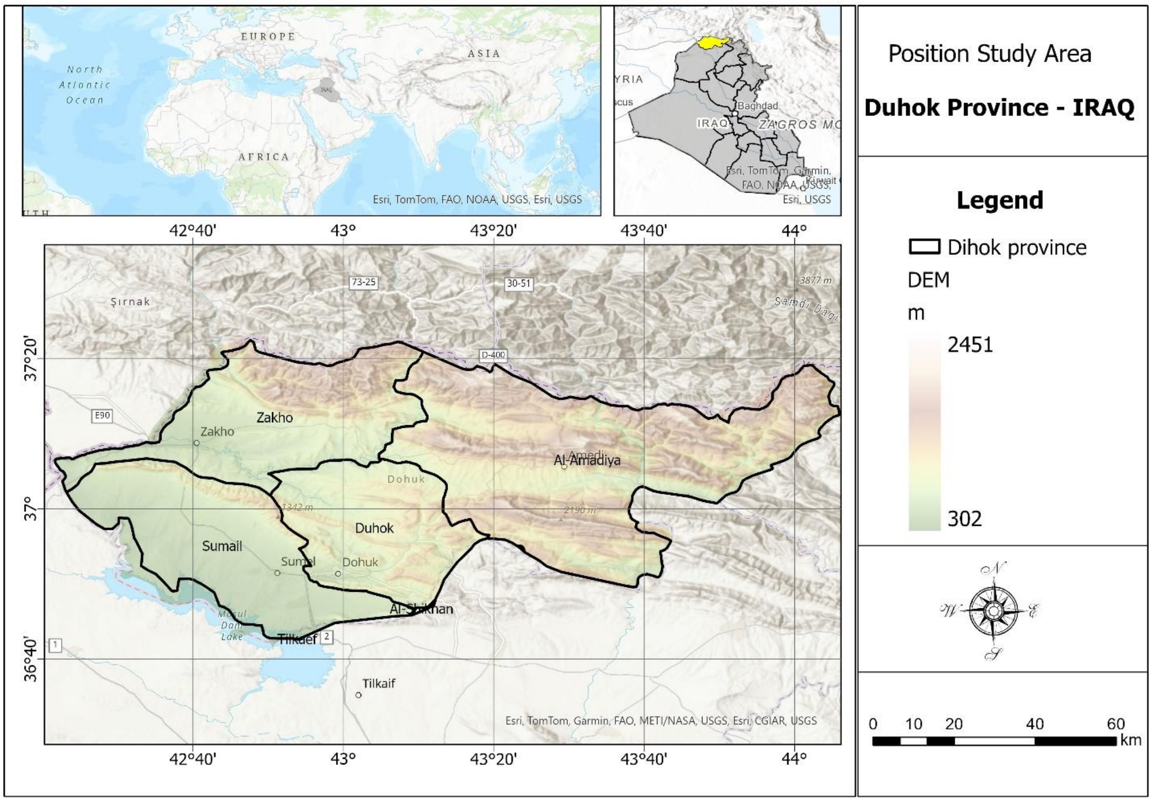

Fig. 1: The area under investigation, Duhok Governorate, situated in northern Iraq.

Research Method

The research employed a multi-stage methodology. Initially, reanalyzed climatic data were gathered, subjected to quality control, and prepared for analysis. Subsequently, these climatic data were used to compute bioclimatic and tourism indices, enabling a monthly assessment of thermal comfort and stress levels. To synthesize the findings from the thermal indices, a composite seasonal tourism suitability index was formulated, which helped ascertain the geographical distribution of climatic tourism suitability across different seasons. The final step involved creating a climatic tourism calendar for Duhok province. This was achieved by spatially averaging monthly Universal Thermal Climate Index (UTCI) values and categorizing thermal conditions, thereby classifying the months of the year into suitable, acceptable, or unsuitable categories for tourism based on their climatic favorability (as illustrated in Figure 2).

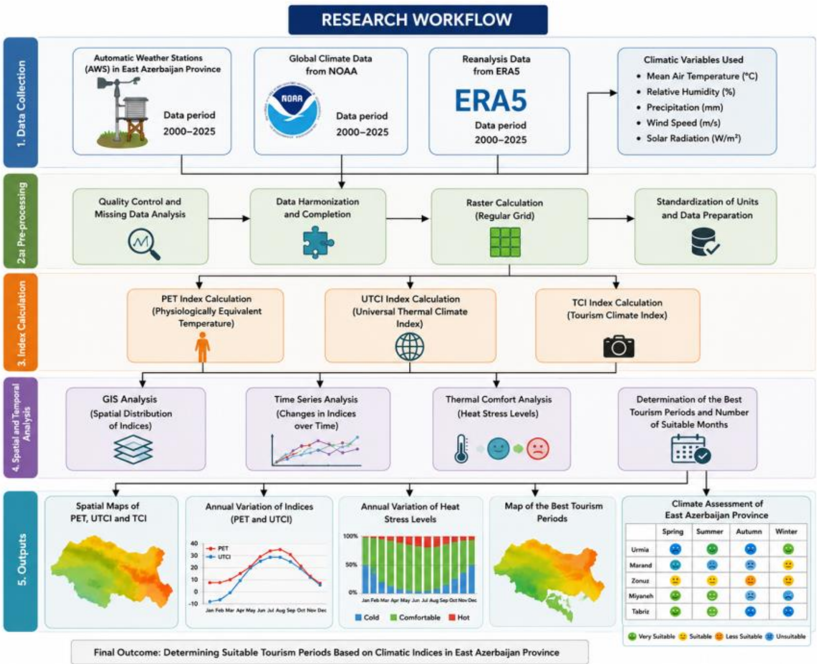

Fig. 2: Methodology for Developing a Tourism Calendar for Duhok Province, Northern Iraq

Climate data and data source

The climate information for this study was sourced from NASA POWER, a global system from NASA that delivers meteorological, climatic, and radiation data. This system offers access to both historical and near real-time data across various timeframes and geographical areas. It gathers and processes its data from a combination of satellite observations, numerical models, and reanalysis products. MERRA-2 reanalysis data is a key component among these products, providing essential meteorological parameters. For this particular research, monthly climate data for Duhok Province from 2000 to 2025 was acquired using MERRA-2 products, which are developed by NASA's Global Modeling and Assimilation Office (GMAO). The data, initially in a gridded format with specific geographical coordinates, was subsequently prepared and processed for use in R and GIS environments. This allowed for the calculation of bioclimatic indices and the generation of spatial maps illustrating tourism climate conditions. To guarantee data consistency across various index calculations, all climatic variables in this study were standardized to a shared timeframe (2000–2025), a monthly interval, and a uniform spatial grid. Data for air temperature, relative humidity, wind speed, and radiation were gathered to compute the PET and UTCI indices. Similarly, temperature, relative humidity, precipitation, radiation, and wind data were collected for TCI calculations (Table 1). These datasets were then transformed into a unified format based on the common geographical coordinates of the grid points. The R environment was utilized for initial data processing, managing missing values, and calculating the indices. The resulting index outputs, which included spatial coordinates, were then transferred to a GIS environment. Subsequently, the layers generated from the different indices were harmonized concerning the study area, coordinate system, and spatial structure. This harmonization facilitated their comparison and spatial integration. For the STSI calculation, the PET and UTCI layers were spatially aligned and normalized to a scale of zero to one, then utilized as a composite index.

Table 1: Characteristics of the NASA POWER (MERRA-2) Meteorological Dataset

Characteristic	Specification
Data source	NASA POWER (MERRA-2 Reanalysis)
Data period	2000–2025
Temporal resolution	Monthly
Spatial resolution	0.5° × 0.625° (~50 km)
Study area	Duhok Governorate, Iraq
Grid	25 points (5 × 5)
Variables	Temperature, RH, wind speed, precipitation, solar radiation

Bioclimatic Indices

This study utilized a range of bioclimatic and tourism climate indices to assess the combined impact of atmospheric conditions on human thermal comfort and to pinpoint optimal times for tourism. By incorporating diverse climatic variables, these indices enable an evaluation of thermal comfort and the attractiveness of the tourism climate across different timeframes and locations.

The Physiological Equivalent Temperature (PET)

The Physiological Equivalent Temperature (PET) index served as a tool to evaluate human thermal comfort in outdoor settings. This index is rooted in the principle of human body energy balance and the Munich Energy Balance Model for Individuals (MEMI) framework, as established by Höppe in 1999. PET quantifies the combined impact of meteorological factors affecting body heat exchange, such as air temperature, relative humidity, wind speed, and mean radiant temperature (MRT), expressing it as an equivalent temperature in degrees Celsius. For this study, PET was computed using a specially developed computational code within the R environment. The pet_steady function from the pythermalcomfort library was utilized to determine the PET value, while the rasterio library facilitated the reading, resampling, spatial alignment, and processing of raster data. These calculations were carried out on a pixel-by-pixel basis for each month throughout the year. Each month, the air temperature raster served as the foundational layer. The rasters representing relative humidity, wind speed, and radiation were then spatially aligned with this temperature raster. To ensure consistency in the input data, these layers were matched to the temperature raster's dimensions, spatial transformation, and coordinate system using the bilinear resampling (Bilinear Resampling) method. Consequently, for every valid pixel, four input variables air temperature, relative humidity, wind speed, and radiation—were positioned on a uniform spatial grid. When calculating PET, the physiological parameters of the reference individual were kept consistent across all months and locations. The metabolic activity rate was fixed at 1.4 met, and clothing insulation was set at 0.5 clo. These values signify light to moderate outdoor activity and a moderate level of clothing insulation, respectively. Maintaining these two parameters constant throughout all months and locations was crucial for facilitating temporal and spatial comparisons of PET values. Mean radiant temperature (MRT), a key input for the PET model, was also derived from a combination of air temperature and radiation data. Within the computational code, MRT was initially determined using the following empirical formula:

Eq. 1)

$$MRT = Ta + 0.05R$$

Here's the paraphrased text: The air temperature (T_a, in degrees Celsius) and the radiation value (R) were used in the computations. To ensure realistic Mean Radiant Temperature (MRT) values, the calculated result was subsequently constrained to a range between (T_a - 5) and (T_a + 30) degrees Celsius. Consequently, the ultimate MRT for each pixel served as an input for the Physiological Equivalent Temperature (PET) calculation. Once the input variables were prepared, the `pet_steady` function was used to calculate the Physiological Equivalent Temperature (PET) for each valid pixel. This function employs the human body energy balance method, considering radiative and convective heat exchange, evaporation, and other factors influencing an individual's thermal state. Consequently, this study utilized the computational implementation of PET available in the `pythermalcomfort` library, rather than manually re-entering the complex equations of the MEMI model. The calculated monthly PET values were then saved as rasters and subsequently used to investigate spatiotemporal changes in thermal comfort within Duhok province. For interpretation, PET values were categorized according to established thermal stress classifications, including cold stress, heat stress, and the thermal comfort zone (Matzarakis et al, 1999). This approach allowed the monthly PET maps to reveal spatial variations in thermal conditions and identify optimal times and locations for outdoor tourism. Following the calculation of the PET index, monthly PET values were combined to create annual and seasonal figures. The trends of these figures within each spatial cell were subsequently analyzed using the Mann–Kendall test and Sen's slope estimator.

Tourism Climate Index (TCI)

The Tourism Climate Index (TCI), developed by Mieczkowski in 1985, evaluates suitable climatic conditions for tourism and identifies the most comfortable times for tourists. This comprehensive index considers the combined impact of several climatic factors affecting tourist comfort, including temperature, relative humidity, precipitation, sunshine duration, and wind speed. The TCI is calculated monthly, with higher values indicating more favorable weather for outdoor tourism. The core formula for the Tourism Climate Index is provided below:

Eq. 2)

$$TCI = 2[(4CID) + CIA + 2(P) + 2(S) + W]$$

The daily thermal comfort index (CID: Daytime Comfort Index) is derived from the day's maximum temperature and lowest relative humidity, reflecting comfort levels during tourists' active hours. The average daily thermal comfort index (CIA: Daily Comfort Index) is calculated by combining the average daily temperature and relative humidity. Precipitation (P: Precipitation Index) is scored according to the total monthly rainfall. The radiation or sunshine hours index (S: Sunshine Index) measures the impact of sky conditions and the length of solar exposure, while the wind index (W) quantifies how wind speed affects tourist comfort. The Climate Index for Daily (CID) is derived from the daily maximum temperature and lowest relative humidity, effectively capturing the thermal environment during the warmer and more active hours of the day. In contrast, the Climate Index for Average (CIA) is established using the daily average temperature and average relative humidity, which reflects the overall thermal conditions of the month. Consequently, the two thermal elements of the Tourism Climate Index (TCI) correspond to daily and average thermal conditions, respectively. The Precipitation (P) component is calculated from monthly precipitation; higher rainfall, particularly during periods that might hinder outdoor tourism, leads to a lower desirability score. The Wind (W) component is also based on monthly wind speed, utilizing the standard TCI scoring system to incorporate the impact of wind on outdoor tourism into the final index. Finally, the Sunshine (S) component illustrates how radiation and sunny weather influence the appeal of a tourism climate. Due to the nature of the climatic data used in this study, the radiation variable in the dataset served as an indicator of radiation conditions. This variable was converted into a score and subsequently incorporated into the TCI calculation. Consequently, all elements of the TCI were derived from the climatic variables present in the dataset and standardized to the index's scoring scale.

The weighting coefficients reflect the comparative significance of each climatic factor. The daily thermal comfort index (CID) holds the highest influence with a coefficient of 4, as thermal conditions are considered the primary determinant of climatic comfort during tourist activities. Furthermore, precipitation and solar radiation each have a coefficient of 2, while daily comfort and wind indices are included in the final calculation with lower coefficients. Once the TCI value is determined, the region's climatic conditions are assessed across various categories. Typically, values exceeding 80 denote highly favorable conditions, whereas values below 40 signify unfavorable conditions for tourism. For Duhok province, the monthly TCI value was computed using monthly meteorological station data—including air temperature, relative humidity, precipitation, sunshine hours, and wind speed—to analyze seasonal fluctuations in tourism climatic comfort.

Universal Thermal Climate Index (UTCI)

The Universal Thermal Climate Index (UTCI) is a tool used to evaluate thermal comfort and identify heat or cold stress experienced by humans. Developed by the International Ergonomics Association and the COST Action 730 group, this index utilizes a human body heat transfer model and the body's physiological responses to atmospheric conditions. UTCI is a bioclimatic metric that quantifies the combined impact of various meteorological factors such as air temperature, humidity, wind speed, and mean radiant temperature (MRT) on human thermal perception. The core principle behind UTCI involves transforming actual environmental conditions into an equivalent temperature. This equivalent temperature signifies that an individual in a reference environment with an air temperature matching the UTCI value would exhibit an identical physiological response. The comprehensive UTCI formula is expressed as an intricate polynomial (Błażejczyk et al, 2010).

Eq. 3)

$$UTCI = T_{\alpha} + \Delta T_{UTCI}$$

Eq. 4)

$$\Delta T_{UTCI} = P(T_a, T_{mrt}, v_{10}, p_u)$$

The Universal Thermal Climate Index (UTCI) is determined by several environmental factors: air temperature (T_a) in degrees Celsius, mean radiant temperature (T_{mrt}) in degrees Celsius, wind speed (v_{10}) measured at 10 meters per second, and relative humidity ($_{pu}$) as a percentage. The classification of UTCI values into thermal stress categories follows the scale established by Bröde et al. (2012). Specifically, UTCI readings exceeding 46 °C signify extreme heat stress. Values ranging from 38 to 46 °C denote very strong heat stress, while 32 to 38 °C indicates strong heat stress. Moderate heat stress is observed between 26 and 32 °C, and no thermal stress occurs from 9 to 26 °C. Moving to cold stress, slight cold stress is indicated by values from 0 to 9 °C, moderate cold stress by -13 to 0 °C, and strong cold stress by -27 to -13 °C. Very strong cold stress is found between -40 and -27 °C, and values below -40 °C represent extreme cold stress (Bröde et al, 2012).

Seasonal Tourism Suitability Index (STSI)

The Seasonal Tourism Suitability Index (STSI) was developed to integrate findings from thermal comfort indicators, offering a comprehensive geographical assessment of optimal tourism environments. This index combines two bioclimatic indicators, Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI), enabling a simultaneous evaluation of physiological thermal comfort and thermal stress caused by atmospheric conditions. For this study, the STSI was calculated for each season (winter, spring, summer, and autumn) across Duhok province. First, seasonal PET and UTCI values were obtained by averaging monthly raster data for each respective season. Subsequently, due to their differing ranges and units of measurement, these PET and UTCI values were normalized to a zero-to-one scale using the min-max normalization technique. After normalization, the STSI was determined by computing a weighted average of the two thermal indices. The resulting STSI values, also ranging from zero to one, indicate that values closer to zero signify less ideal conditions, while those nearer to one suggest more suitable conditions for tourism. This index was geographically computed within a GIS platform and presented as seasonal maps illustrating tourism suitability. STSI values were categorized into five suitability levels for tourism: 0 to 0.2 represented very unfavorable, 0.2 to 0.4 as unfavorable, 0.4 to 0.6 as moderate, 0.6 to 0.8 as favorable, and 0.8 to 1 as very favorable. Ultimately, seasonal STSI maps were generated to identify regions with significant potential for climate tourism and to analyze the spatial variations in thermal comfort within Duhok province. In this study, the STSI was established as an index to assess the relative climatic appeal for tourism, rather than to directly forecast tourism demand or gauge a destination's actual performance. Consequently, STSI classes should be understood as representing comparative degrees of desirable thermal conditions. The index's five classes were determined by dividing the 0 to 1 range into equal 0.2 intervals, which facilitates the interpretation and spatial comparison of the findings. These classes were defined independently of the standard thermal stress categories of PET and UTCI; thus, they do not signify the severity of physiological stress but rather reflect the relative combined desirability of thermal conditions. During the calculation, PET and UTCI data underwent quality checks for outliers, and no significant outliers were found that would substantially impact the normalization range. Due to the differing units and ranges of these two indices, min-max normalization was applied to convert them to a uniform zero-to-one scale. The composite index was then computed by assigning equal weight to PET and UTCI. This equal weighting was chosen to ensure neither index overshadowed the other, thereby achieving a balanced evaluation from two distinct thermal comfort perspectives. Empirical validation of STSI classes using independent tourism data such as tourist numbers, length of stay, thermal satisfaction, or actual visitation patterns was unfeasible in this study. This was because data with spatial and temporal coverage consistent with the climatic grid utilized were unavailable. Therefore, the STSI classification should not be regarded as an empirical classification of tourism performance but rather as a climatic framework for relatively comparing the thermal condition capabilities of various regions. This represents a limitation of the current research, which could be addressed in future studies using actual tourism data and surveys.

Tourism Climate Calendar

A tourism climatic calendar was developed for the Duhok Governorate, converting bioclimatic index findings into actionable data for tourism strategies. This calendar utilized the monthly values of the Universal Thermal Climate Index (UTCI) as the primary metric for assessing thermal comfort. The UTCI was selected due to its capacity to integrate the combined impact of air temperature, relative humidity, wind speed, and radiant conditions on human thermal sensation. Initially, monthly UTCI raster data underwent processing within a GIS platform, where the spatial average of UTCI values across the Duhok Governorate was computed. For each month, cells containing "NoData" were excluded before calculating the UTCI average using the following formula:

Eq. 5)

$$\overline{UTCI_m} = \frac{\sum_{i=0}^{n} UTCI_{i,m}}{n}$$

The variable $\overline{UTCI_m}$ represents the average Universal Thermal Climate Index (UTCI) for a given month 'm'. It is calculated by summing the UTCI values for each pixel 'i' within that month (، $UTCI_{i,m}$) and dividing by 'n', the total number of valid pixels. Once the monthly averages were determined, these UTCI values were categorized according to the established UTCI thermal stress scale. This scale defines no thermal stress between 9 and 26 degrees Celsius. Moderate heat stress is indicated by values from 26 to 32 degrees Celsius, strong heat stress by 32 to 38 degrees Celsius, and very strong heat stress by 38 to 46 degrees Celsius. Values exceeding 46 degrees Celsius signify extremely strong heat stress. Conversely, UTCI values below 9 degrees Celsius are classified under various levels of cold stress (Bröde et al., 2012). For the purpose of creating a practical calendar for tourism planning, these standard UTCI categories were consolidated into more user-friendly, tourism-oriented groups. Consequently, temperatures ranging from 9 to 26 degrees Celsius were deemed ideal for tourism. The range of 26 to 32 degrees Celsius was considered acceptable, albeit with thermal constraints. Temperatures above 32 degrees Celsius were classified as unsuitable for tourism due to heat stress. Similarly, temperatures below 9 degrees Celsius were also grouped into the unsuitable category because of cold stress. This reclassification aimed to transform the physiological UTCI scale into a practical tool for developing a tourism calendar.

Results and Discussion

Regional Weather Maps

An examination of Duhok province's annual climatic data reveals a clear pattern of varied climatic conditions across its topographical features. Maps illustrating temperature, relative humidity, precipitation, and solar radiation demonstrate a noticeable spatial progression from the northwest to the southeast within the province. Specifically, the northwestern areas experience comparatively elevated air temperatures and solar radiation levels, alongside reduced precipitation and relative humidity. This phenomenon is likely attributable to local topographical characteristics, lower altitudes in certain zones, and exposure to warmer air currents, which collectively contribute to greater solar energy absorption and diminished humidity. Conversely, the southeastern area of Duhok province experiences distinct climatic patterns, characterized by lower temperatures, reduced solar radiation, and higher levels of precipitation and relative humidity. This climatic trend is primarily attributed to factors such as elevated altitude, mountainous influences, and the influx of moist air, which collectively temper the heat and boost humidity in the area. Consequently, this climatic variation highlights topography's critical influence on the distribution of climatic factors across Duhok province. Such diverse climatic conditions directly affect human thermal comfort and the region's appeal for tourism (Figure 3).

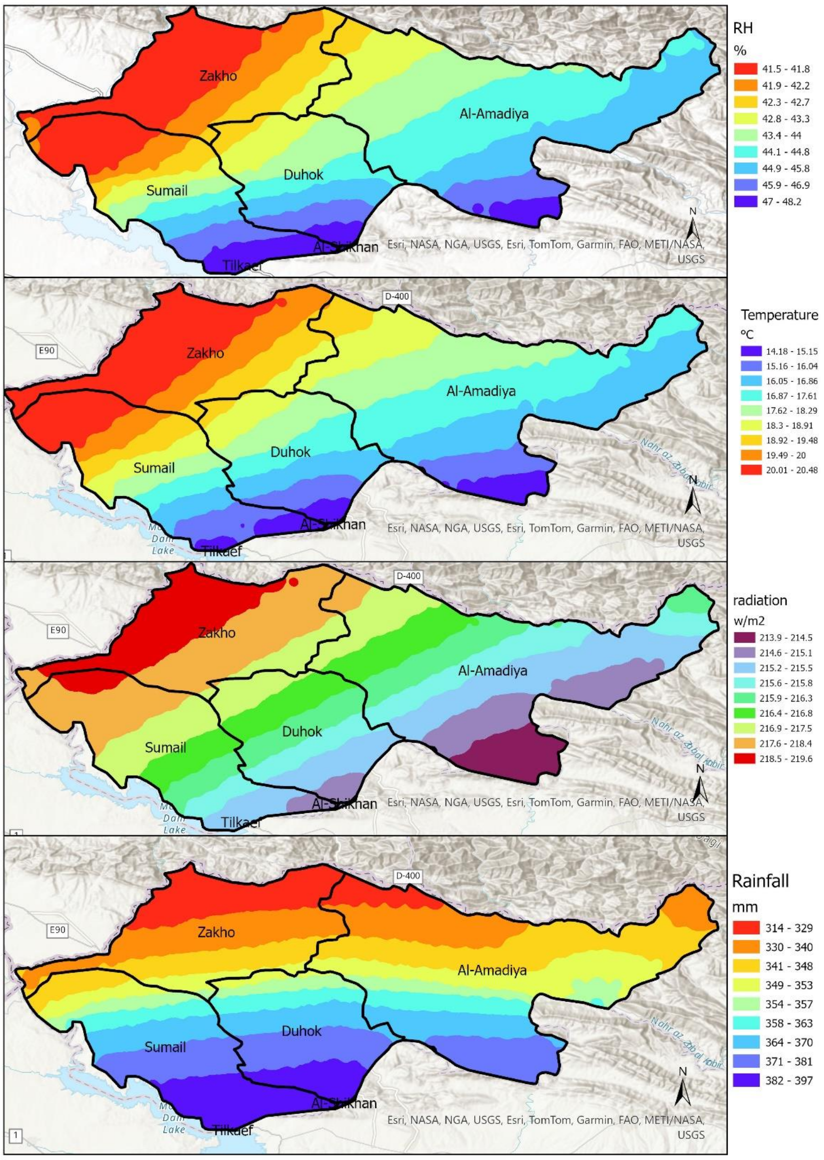

Fig. 3: Spatial distribution of the average climatic parameters of Duhok province from 2000 to 2025

The region experiences annual average minimum, maximum, and mean temperatures of 4.17, 27.8, and 16 degrees Celsius, respectively. Monthly temperature data reveals substantial fluctuations throughout the year. August is the warmest month, averaging 29.96 degrees Celsius, while January is the coldest at 1.65 degrees Celsius, based on mean temperatures. Relative humidity also varies, dropping from 70.3% in January to its lowest point of 22.06% in August. Conversely, both wind speed and solar radiation are higher during warmer periods; July recorded the highest wind speed at 2.22 m/s, and June saw peak solar radiation at 339.92 W/m². Precipitation patterns also display clear seasonal variations. According to monthly and seasonal data presented in the table, the region receives the most rainfall during the colder and transitional months. Summer stands out as the driest season, experiencing a significant reduction in precipitation. The total annual precipitation for the region is approximately 350 mm. Spring records the highest seasonal precipitation with 134 mm, closely followed by winter with 133.5 mm, whereas summer receives a mere 9.3 mm. On a monthly basis, July is the driest with 1.75 mm, and March is the wettest with 55.5 mm. The average surface pressure in the area is reported to be around 89.3 millibars. In summary, the region's climate is characterized by very hot and dry summers with low humidity and high solar radiation, contrasted by cooler and wetter winters and transitional seasons (Table 2).

Table 2: Monthly and Seasonal Mean Climatic Variables in the Duhok Region during 2000–2025

Period	TMIN °C	TMAX °C	TMEAN °C	RH %	Wind speed m/sec	Radiation w/m²	Rainfall mm	Pressure mb
January	-8.7	11.99	1.65	70.36	1.69	95.96	45.45	89.7
February	-8.17	15.12	3.47	69.24	1.74	131.98	41.69	89.57
March	-3.42	20.43	8.5	64.46	1.91	179.04	55.58	89.42
April	1.03	26.32	13.67	58.51	1.87	229.35	50.94	89.35
May	7.36	32.93	20.15	48.29	1.95	284.52	28.13	89.25
June	13.57	38.79	26.18	29.85	2.18	339.92	5.71	88.97
July	17.93	41.67	29.8	23.18	2.22	331.24	1.75	88.73
August	18.8	41.13	29.96	22.06	2.16	300.1	1.86	88.91
September	13.08	37.57	25.33	25.69	1.99	248.89	4.14	89.26
October	6.33	31.19	18.76	40.24	1.81	171.65	26.56	89.66
November	-1.1	21.49	10.19	57.14	1.6	119.65	41.81	89.81
December	-6.63	15.2	4.29	67.25	1.62	88.33	46.38	89.82
Autumn	6.1	30.08	18.09	41.02	1.8	180.06	72.51	89.57
Spring	1.66	26.56	14.11	57.09	1.91	230.97	134.64	89.34
Summer	16.77	40.53	28.65	25.03	2.19	323.75	9.32	88.87
Winter	-7.83	14.1	3.14	68.95	1.68	105.42	133.51	89.7

PET Spatial Interpretation in Duhok Province

The Physiological Equivalent Temperature (PET) index in Duhok province exhibits a clear spatial gradient influenced by topography. Annual mapping reveals that the northwestern areas of the province record higher PET values than other regions, generally ranging from slight heat stress to optimal thermal comfort. This phenomenon is attributed to the lower elevation, greater exposure to solar radiation, and the presence of warmer air masses in these specific locations. Conversely, the province's southeastern sections and elevated terrains exhibit reduced PET readings, predominantly categorized under mild to moderate cold stress. This trend distinctly illustrates how altitude and geographical features influence thermal conditions, leading to enhanced thermal comfort in higher elevations. The central areas of the province also display intermediate conditions, largely ranging from thermal comfort to mild stress (Figure 4).

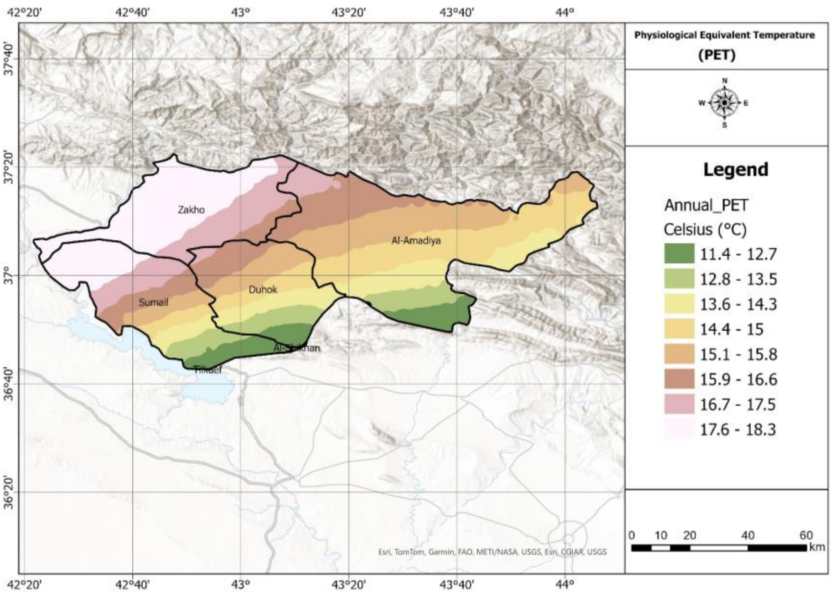

Fig. 4: Spatial distribution of the annual average PET index for Duhok province from 2000 to 2025

An analysis of changes in Potential Evapotranspiration (PET), utilizing the Mann–Kendall test and Sen's slope estimator, revealed a consistent upward trend across all 25 geographical areas, both annually and seasonally. Annually, all 25 cells exhibited an increasing trend, with 23 of these demonstrating statistical significance. The mean Kendall's tau coefficient was 0.412, and the average Sen's slope was 0.0716 °C per year, indicating a general rise in PET throughout the study period. The annual Sen's slope ranged from 0.0377 to 0.107 °C per year. Seasonally, all cells also showed an upward trend in PET, though the intensity and statistical significance varied among seasons. The average Sen's slope for seasonal changes was 0.078 °C per year. Autumn recorded significant trends in 21 cells and displayed the most rapid increase in PET among all seasons, with an average Sen's slope of 0.0964 °C per year. During winter, significant trends were observed in 12 cells, with an average Sen's slope of 0.0684 °C per year. While all 25 cells also demonstrated an increasing trend in spring, none of these trends reached statistical significance at the 0.05 level, and the average Sen's slope for this season was 0.0511 °C per year. In conclusion, the findings highlight a predominant pattern of rising PET across the entire study region, with the most pronounced increases occurring in autumn and the broadest extent of significant trends observed in summer (Table 3).

Table 3: Summary of the Mann–Kendall test and Sen's slope results for PET during 2000–2025

Time scale	Mean τ	Mean Sen's slope (mm day^{-1} year^{-1})	Min Sen's slope	Maxm Sen's slope
Annual	0.412	0.0716	0.0377	0.1070
Spring	0.169	0.0511	0.0167	0.0818
Summer	0.376	0.0788	0.0460	0.1090
Autumn	0.335	0.0964	0.0675	0.1190
Winter	0.258	0.0684	0.0095	0.1720

Analysis of Spatiotemporal Variations in Thermal Comfort

To study thermal comfort trends in Duhok Province, researchers analyzed monthly fluctuations in PET and UTCI indices and the proportion of various thermal comfort zones. Findings revealed a clear seasonal pattern, influenced by shifts in temperature, radiation, and the province's topography. During winter, most of the province experiences cold temperatures. As spring arrives, the area with comfortable conditions expands, peaking in late spring. Throughout summer, increasing temperatures gradually lead to warmer conditions. In autumn, as temperatures drop, comfortable conditions return to a significant portion of the province. The monthly progression of PET and UTCI indices supports this seasonal cycle. Both indices rise from winter into late spring, transition to warmer levels in summer, and then begin to decline in autumn. Consequently, the alignment between the spatial distribution of comfort categories and the temporal behavior of these indices indicates that April, May, September, and October, especially May and September, are the most suitable times for outdoor tourism in Duhok Province. Conversely, winter presents challenges for tourism due to cold stress, and the hotter parts of summer limit activities due to increased heat stress (Figure 5).

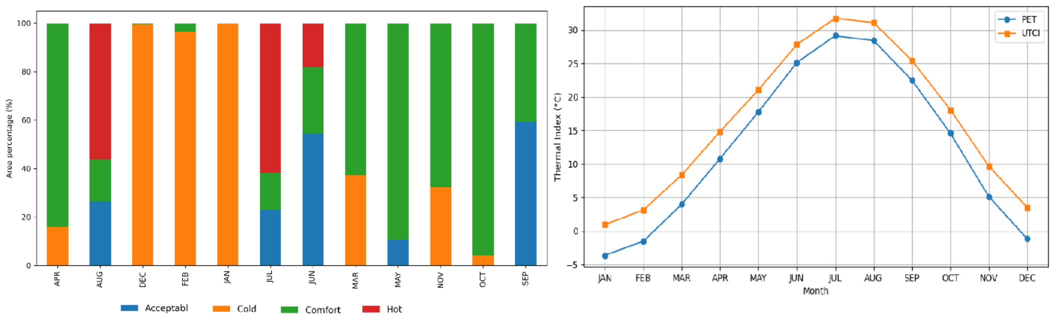

Fig. 5: Monthly average bar chart of PET and UTCI indices for Duhok Governorate from 2000 to 2025

Analysis of Seasonal Tourism Desirability

By synthesizing the outcomes of PET and UTCI, the STSI index offers a comprehensive evaluation of thermal comfort levels, translating them into a more direct indicator of tourism appeal. Consequently, STSI provides insights beyond simply presenting the status of individual bioclimatic indices; it specifies the overall suitability of thermal conditions for tourism across various parts of the province. The findings reveal that the northern and northwestern areas of the province consistently exhibit greater thermal tourism desirability throughout all four seasons, with this appeal diminishing towards the central, southern, and particularly southeastern regions. This geographical distribution is more pronounced during spring and autumn. In the summer, elevated heat stress causes portions of the south and southeast to fall into moderate desirability categories, while in winter, a drop in temperature similarly reduces desirability in certain locales (Figure 6). Thus, the key benefit of STSI in this study lies in its ability to transform data from PET and UTCI into an integrated, spatially-aware assessment of tourism desirability, aiding in the identification of optimal regions and times for tourist activities.

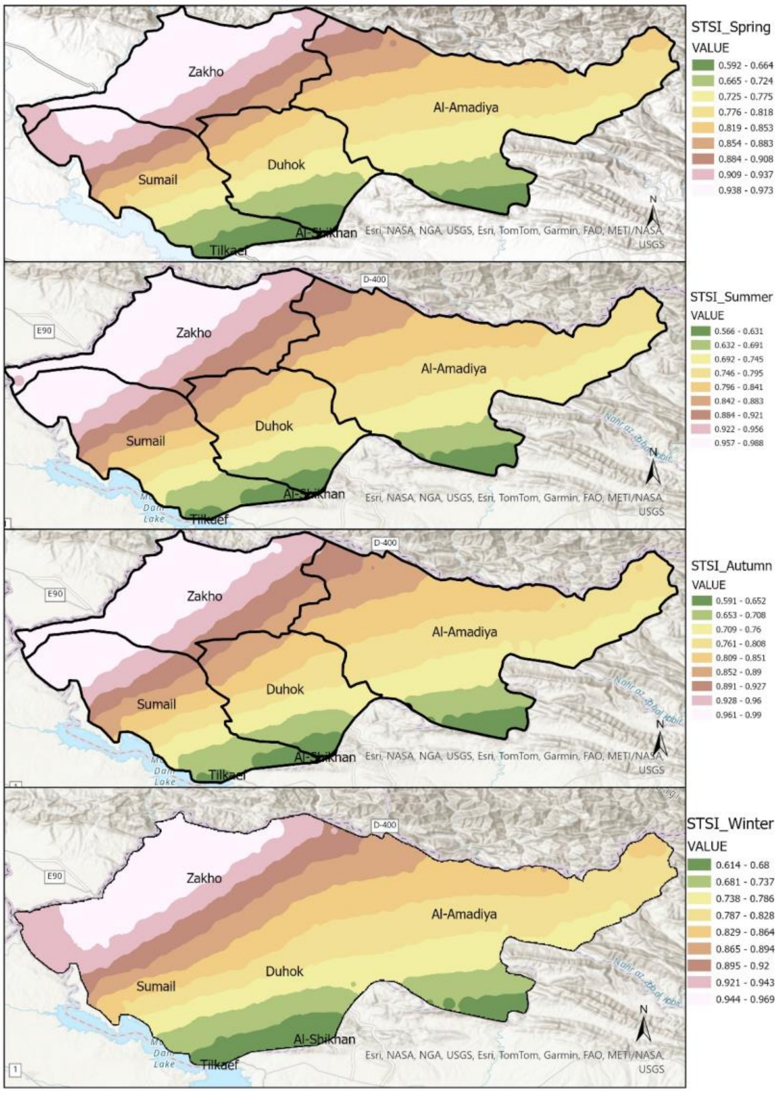

Fig. 6: Spatial distribution of the seasonal average STSI of Duhok province from 2000 to 2025

Spatial Analysis of Tourism Calendar

Research on the Tourism Climate Index (TCI) within Duhok Governorate indicates a favorable temporal and spatial arrangement for tourism activities across the region; however, this distribution is not uniform. Based on climatic data, the optimal times for tourism in Duhok province are spring (April and May) and autumn (September and October). During spring, northern and mountainous regions like Zakho and parts of Amedi experience the most agreeable weather, with April often being exceptionally pleasant in these areas. However, with the onset of summer, only a few northern highland areas maintain tolerable conditions, as the climate in the central and southern parts of the province becomes considerably less comfortable. In autumn, pleasant weather returns to most of the province, especially in the highlands and the vicinities of Duhok and Amedi, though conditions may not be as ideal as in spring for some areas. The map illustrating the duration of climatically suitable months for tourism reveals considerable geographical variation in the consistency of pleasant weather. Specifically, the southern areas of the province, particularly Amedi and Duhok, show the longest periods suitable for tourism, extending up to six months annually in certain locales. These regions' elevated topography contributes to more stable thermal comfort. Conversely, the western and northwestern areas, characterized by lower elevations, including parts of Zakho and the vicinity of Sumail, experience shorter tourism seasons, typically ranging from four to five months. This shorter duration is primarily attributed to rising temperatures during the hot season and a subsequent decline in the Tourism Climate Index (TCI) desirability throughout the summer. The findings generally suggest that Duhok province possesses considerable potential for climate tourism, although this potential is significantly influenced by both altitude and geographical position. The mountainous areas in the eastern and northern parts of the province not only experience a more favorable season for tourism but also provide more consistent and agreeable conditions during the spring and autumn transitional periods than other areas within the province. This observation underscores the critical role of topography in determining the spatial and temporal fluctuations of climatic comfort throughout the region (Figure 7).

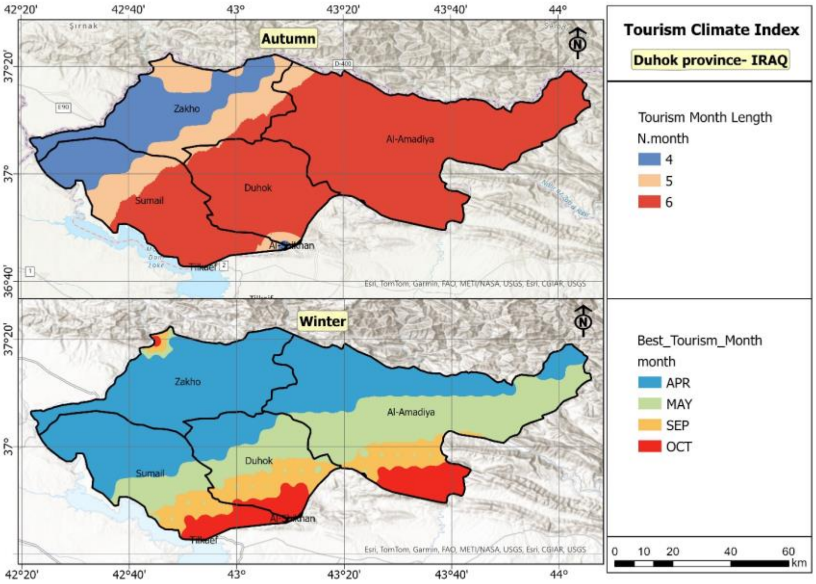

Fig. 7: Spatial distribution of suitable tourism months and the number of suitable tourism months in Duhok province

Tourism Calendar

To identify the optimal period for climatic tourism in Duhok Province, a monthly analysis of the UTCI and PET bioclimate indices was conducted, with the results presented as bar charts in Figure 8. A concurrent review of these indices indicates that although they follow a comparable seasonal pattern in Duhok Province, discrepancies exist in certain months regarding their numerical values and thermal stress categorization. This divergence does not suggest an inconsistency or flaw in either index; rather, it arises from variations in their physiological model structures, reference parameters, and responsiveness to meteorological factors. Both indices utilize air temperature, humidity, wind velocity, and radiation levels to evaluate thermal comfort, but they differ in how these variables are integrated and how the body's thermal response is simulated. Prior comparative research has also demonstrated that PET and UTCI generally exhibit similar patterns, yet their sensitivity to factors like wind speed and mean radiant temperature is not identical (Provençal et al, 2016; Fröhlich et al, 2019). This disparity is particularly noticeable in April. During this month, the UTCI registers 14.9°C and the PET records 10.8°C. Consequently, UTCI suggests an absence of thermal stress, whereas PET indicates conditions of cold stress. This approximate 4.1°C difference can be ascribed to variations in how the models of these two indices react to the specific atmospheric conditions during the transition from winter to spring. In this period, despite an increase in air temperature compared to winter, radiative conditions, wind speed, and humidity can still influence the body's thermal equilibrium. Given that PET is derived from the body's energy balance model and reference physiological states, its reaction might diverge from UTCI under certain radiative and cooling circumstances. Conversely, UTCI models human physiological responses distinctly by employing a multi-node thermoregulation model for the body and a clothing adaptation mechanism. Thus, April's classification into two distinct categories highlights a difference in the sensitivity and underlying structure of the two indices, rather than necessarily implying errors in the climatic data. A comparable difference, though with varying degrees of intensity, can also be observed in other months. For instance, in May, the UTCI registers no thermal stress at 21.1°C, while the PET, at 17.8°C, still indicates mild cold stress. Conversely, throughout the summer, both indices show an escalation in heat stress, leading to a largely similar qualitative interpretation of the region's hot climate in July. Additionally, in September, both indices affirm comfortable thermal conditions. Consequently, the divergence between the two indices is more noticeable during transitional periods, particularly in spring and autumn, while their general trends exhibit greater alignment in the colder and warmer seasons. The findings indicate that combining PET and UTCI offers a more thorough understanding of the thermal comfort calendar for Duhok province. In this research, UTCI was employed to gauge the body's general reaction to atmospheric conditions, while PET was utilized to evaluate the body's energy balance within environmental settings. Consequently, rather than designating one index as superior, the discrepancies between their results were viewed as contributing to the uncertainty and methodological variations in assessing thermal comfort. Given the overall consistency between the two indices, May and September emerge as prime times for climate tourism in Duhok province. April and October, on the other hand, are considered transitional periods, offering reasonably suitable conditions despite some variations between the indices. To establish the climatic tourism calendar, the research adopted a comprehensive approach, rather than relying on a single month or index. The interpretation was based on consistent findings from two indices and seasonal variations in thermal conditions. Consequently, months exhibiting optimal or near-optimal conditions across both indices were prioritized for tourism. Within this framework, May and September emerged as the most appropriate months for climatic tourism in Duhok province, as both indices simultaneously placed them within their optimal ranges. April and October were deemed relatively suitable for tourism, despite minor discrepancies between the two indices. This was attributed to their transitional nature and significantly improved thermal conditions compared to winter. Conversely, the months from December to March present greater restrictions for outdoor tourism due to prevalent cold conditions, while June to August are limited by increased heat stress. Thus, the finalized calendar designates late spring and early autumn, particularly May and September, as the most advantageous times for climatic tourism in Duhok province (Figure 8).

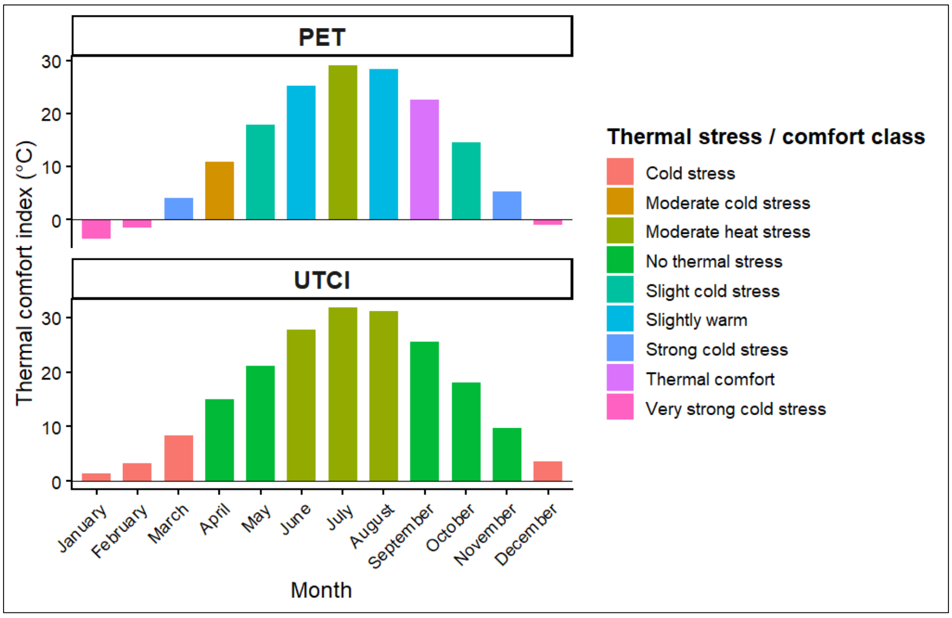

Fig. 8: Duhok Province Tourism Calendar Based on PET and UTCI Indices on a Monthly Scale

Discussion

This study revealed a distinct seasonal and spatial pattern in tourism climate comfort within Duhok province, with optimal conditions predominantly observed during transitional periods, particularly in mid-spring and early autumn. A concurrent examination of TCI, PET, and UTCI indices demonstrated that assessing tourism climate suitability requires more than a single climatic factor like air temperature, as human thermal comfort arises from the interplay of temperature, humidity, wind, and radiation. This finding aligns with the foundational principle of Mieczkowski's (1985) Tourism Climate Index, which aims to provide a holistic evaluation of a destination's suitability for tourism by integrating multiple climatic elements. Furthermore, recent research underscores the importance of employing multi-index methodologies for a more thorough characterization of a tourism destination's climatic potential. For instance, a recent study in the Yangtze River Delta, utilizing a combination of climatic indices, identified spatial variations and a bimodal comfort pattern in spring and autumn—a temporal structure similar to the findings for Duhok province. In Duhok, spring and autumn represent the ideal climatic periods. As winter transitions to spring, temperatures progressively rise, alleviating the harsh cold and creating more comfortable conditions. Conversely, during summer, escalating temperatures and increased environmental heat diminish the overall favorability. With the arrival of autumn, temperatures decline, bringing thermal conditions back into a desirable range (Pantavou et al, 2013). Consequently, Duhok's tourism schedule exhibits a "two-peak season" structure, with spring and autumn offering more agreeable conditions than winter and the height of summer. This observation aligns with recent research on climatic comfort for tourism, such as the study by Han et al. (2025), which identified a similar two-peak comfort pattern in the Yangtze River Delta, designating spring and autumn as optimal times. Comparing the findings of this research with those from other Iraqi regions reveals that a nationwide interpretation of thermal comfort, without accounting for geographical variations, can be inaccurate. While Duhok is part of Iraq's overall climate, its environmental features are distinctly different from many of the drier, lower-altitude areas in central and southern Iraq. Located in northern Iraq, Duhok features considerable variations in altitude and topography, with mountainous terrain contributing to localized temperature and thermal gradients. This means that higher altitudes experience cooler temperatures, which can lessen heat stress during the hot season, but intensify cold conditions in the colder months. This mechanism helps clarify some of the discrepancies between Duhok's thermal comfort patterns and those of Iraq's drier, lower-altitude regions. From this viewpoint, the alignment of these results with studies in mountainous and Mediterranean areas can be attributed to the common influence of topography, altitude, and seasonal temperature fluctuations on thermal comfort. Conversely, differences with drier parts of Iraq are primarily linked to variations in altitude, thermal conditions, humidity, and radiation (Kizilhan et al, 2025). In arid, low-lying regions, a rapid rise in summer temperatures and radiation can extend periods of heat stress, whereas in Duhok, particularly at higher elevations, the moderating effect of altitude can lead to more comfortable thermal conditions (Hamad and Oğuz, 2020). Consequently, this study's results suggest that Iraq's climatic tourism season cannot be viewed as uniform, and tourism strategies should be developed based on the specific climatic and topographical attributes of each region. This geographical variation is crucial for tourism management. In Duhok, higher elevations are ideal for outdoor activities during warmer months, while lower elevations offer more comfortable temperatures in colder periods. Therefore, the diverse distribution of thermal comfort in Duhok is not merely a climatic feature but also an opportunity to organize tourism activities across different times and locations. This insight can be utilized to create a regional tourism schedule and develop complementary travel destinations for various seasons throughout the year. Optimal months in Duhok cannot be determined solely by temperature fluctuations. The agreement between PET and UTCI outcomes in May and September suggests that thermal conditions during these months are quite favorable, according to two distinct thermal evaluation systems. Consequently, the significance of these months for tourism isn't derived from a single factor, but rather from the alignment of multiple thermal indicators that pinpoint a suitable time for outdoor pursuits. This method aligns with recent research advocating for the benefits of employing various climatic indicators to assess tourism potential. Prinsloo and Fitchett (2025) also demonstrated that while different tourism climate indices might show varying levels of desirability and tourism season lengths, their combined application offers a more complete understanding of destination conditions. Conversely, winter weather is predominantly influenced by cold. Lower air temperatures, reduced incoming solar radiation, and shifting wind patterns result in decreased PET and UTCI values during this season. Consequently, the primary constraint on winter tourism in Duhok is thermal, an observation that aligns with expectations for regions characterized by mountainous terrain and transitional climates (Bröde et al, 2012). This is because altitude and varied topography can generate a broad spectrum of thermal conditions within a relatively small area (Krzysztof et al, 2021). In contrast, higher summer temperatures lead to elevated PET and UTCI values, causing thermal conditions to lean towards heat stress. Recent research has also highlighted the significance of UTCI in determining the severity of heat stress at tourist locations. For instance, Hidalgo-García et al. (2025) demonstrated that UTCI can register a considerable rise in thermal stress intensity during heatwaves, and unfavorable thermal conditions can diminish a tourist destination's appeal. Both PET and UTCI exhibit similar seasonal patterns, despite minor classification differences in specific months. This methodological distinction is expected because PET and UTCI are based on different conceptual frameworks for quantifying human thermal comfort. PET utilizes the physiological equivalent temperature and the human body's energy balance, whereas UTCI employs a more sophisticated model of human physiological adaptation to environmental factors. Consequently, discrepancies between these two indices should be attributed to their differing structural and sensitivity characteristics, rather than being considered inconsistencies or computational inaccuracies. Furthermore, research by Jing et al. (2024) indicated that the efficacy and responsiveness of various thermal indices can fluctuate in outdoor settings, influencing the perceived intensity and categorization of thermal conditions depending on the index selected. This distinction is particularly important when considering a tourism calendar. The aim of employing both PET and UTCI in this study is not to standardize their categories but rather to enhance confidence in pinpointing the overarching pattern of thermal comfort. Consequently, May and September exhibit the highest inter-index reliability because both indices indicate more favorable conditions during these months. Conversely, inconsistencies, such as those observed in April, should be understood as conditions bordering the transition between thermal categories, rather than grounds for omitting the month from the tourism calendar. This suggests that a climatic tourism calendar should be interpreted based on the general trend and agreement of various indices, rather than relying solely on the categorization of a single index. A key discovery from the research is the varied distribution of thermal comfort within Duhok province. The differing PET and TCI values throughout the province reveal that the climate's suitability for tourism in this area does not follow a consistent geographical pattern. For a substantial part of the year, elevated and mountainous zones experience distinct thermal conditions compared to lower areas. This is due to cooler air temperatures at higher altitudes, along with variations in radiation and air circulation. Therefore, elevation and the topographical layout can be seen as the main reasons for the spatial differences in the province's tourism season. Similarly, a study by Agakishiyeva et al. (2025) on thermal comfort in Azerbaijan demonstrated that diverse topography, ranging from coastal to mountainous areas, can lead to varied spatial patterns of thermal comfort. This finding holds geographical importance for Duhok, given that both regions share significant topographical diversity and thermal changes influenced by elevation. This variation in spatial distribution holds significant implications for tourism planning. During warmer months, elevated regions offer more pleasant temperatures compared to lower elevations, serving as attractive alternatives or "thermal refuges" for those engaging in outdoor pursuits (Pantavou et al, 2024). Recent research further indicates that a destination's thermal environment, and even variations within it, are heavily shaped by its environmental and topographical characteristics. For instance, a 2025 study examining Turkish tourism destinations using PET revealed substantial spatial differences in thermal comfort, even within the same climatic zone, suggesting these variations can be leveraged for planning tourism activities. The findings from TCI also revealed that climate is not a consistent or uniform element influencing tourism; rather, its appeal varies based on specific times and locations. This highlights the critical need for spatio-temporal calendars, as a single month might present favorable conditions in one area of a province while simultaneously exhibiting unsuitable conditions elsewhere. A 2024 study conducted in Gilgit-Baltistan further demonstrated that TCI can lead to notable variations in the peak tourism season across different destinations, with air temperature being a significant factor in altering climatic desirability. Nonetheless, the study's outcomes suggest that the pattern of desirability is not necessarily uniform across all regions, and the unique climatic and geographical attributes of a destination can shift its peak tourism season. Conversely, the results of this study suggest that the application of climatic indices should align with specific research goals. The Tourism Climate Index (TCI) is designed for a broad evaluation of climatic suitability for tourism, while the Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) focus more on human responses to thermal conditions. Consequently, TCI offers a wider range of information concerning climatic factors influencing tourism, whereas PET and UTCI enable a more in-depth analysis of thermal comfort. This fundamental distinction is the primary justification for employing these indices concurrently in this research. The research findings suggest a practical approach for tourism management in Duhok province: a "time- and place-specific" strategy. Rather than designating a universal tourism season for the entire province, activities could be tailored to the thermal conditions of specific periods and the geographical features of each location. For instance, during warmer months, a larger proportion of outdoor pursuits could be directed towards higher elevation regions. Conversely, during transitional seasons, a broader area of the province could be utilized for natural, cultural, and mountainous tourism. This method would aid in spreading tourism demand across different times and locations, thereby minimizing tourists' exposure to extreme temperatures. The results of this study suggest that the primary benefit of evaluating the tourism climate in Duhok Province extends beyond simply identifying "hot or cold months." Instead, its true value lies in pinpointing specific periods and locations that offer thermal comfort. The consistent findings across TCI, PET, and UTCI indicate that May and September are particularly dependable climatic periods for outdoor pursuits. Generally, spring and autumn demonstrate a greater capacity for climate-based tourism compared to winter and the height of summer. Furthermore, the variations in these indices across different locations imply that tourism development in Duhok should be strategically planned to account for its diverse topography and localized thermal conditions. In this context, climate indices serve not as direct forecasts of tourist numbers, but rather as scientific instruments to identify a destination's climatic strengths and weaknesses. This differentiation is crucial for interpreting the findings, as "climatic favorability" refers to the appropriateness of atmospheric conditions for tourism activities and does not equate to predicting actual tourist demand.

Conclusion

This research aimed to assess thermal comfort and identify the spatial and temporal potential for climate tourism within Duhok Province, utilizing the TCI, PET, and UTCI indices. The findings indicated that the province's climate exhibits clear seasonal and geographical variations in terms of tourism suitability. Spring and autumn, being transitional seasons, offer the greatest potential for outdoor tourism. Conversely, winter and the height of summer present more significant thermal constraints. Geographical analysis demonstrated that the province's topography and elevation significantly influence its thermal conditions. As a result, the capacity for climate tourism varies across the province, with higher-altitude regions offering more agreeable conditions during the warmer months compared to lower-altitude areas. This implies that tourism strategies in Duhok should transition from a province-wide approach to localized, zonal planning that considers specific local conditions.

The PET and UTCI indices revealed a clear seasonal pattern: winter experienced significant cold stress, spring brought improved conditions, summer saw heightened heat stress, and autumn returned to pleasant conditions. For climate tourism, April, May, September, and October are identified as the most appropriate months. However, May and September stand out as the most dependable for scheduling outdoor activities, owing to a stronger agreement between the PET and UTCI results during these months. The ultimate scientific implication of this study is that evaluating climatic tourism capacity in topographically diverse regions necessitates the integration of various indices and the simultaneous analysis of both temporal and spatial dimensions. From a practical standpoint, these findings can provide a foundation for establishing a tourism calendar, determining optimal timings for outdoor events, pinpointing locations for tourism activities, and managing thermal comfort at destinations within Duhok Province. Consequently, rather than establishing a single, fixed tourism season for the entire province, it is recommended that tourism development be structured around a climatic calendar that accounts for spatial variations in thermal comfort.

Consequences for Tourism Strategy and Oversight

The study's results suggest that tourism planning in Duhok province should account for fluctuating thermal comfort levels across different times and locations. Months such as May and September, along with other periods offering pleasant thermal conditions, are ideal for scheduling outdoor tourism activities and events. Conversely, during times of extreme cold or heat, outdoor activities may need to be limited or relocated to more appropriate seasons and areas. The varied thermal conditions across the province also indicate that its elevated and mountainous areas are particularly well-suited for developing activities like ecotourism and mountain tourism, especially during warmer months. In essence, integrating the findings from PET, UTCI, and TCI with a climatic tourism calendar can help pinpoint optimal times and places for tourism activities, serving as a valuable tool for the spatial and temporal organization of Duhok's tourism sector. It is important to note, however, that these findings reflect the climatic capacity for tourism and should not be taken as direct forecasts of tourism demand or visitor numbers. This is because economic, social, accessibility, infrastructure, and destination appeal factors also play a significant role in tourists' decisions.

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