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Thermal comfort atlas of Iran: Insights into comfort and discomfort levels from a 30-year UTCI analysis

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Abstract

Background: This study presents a comprehensive thermal comfort atlas for Iran based on the Universal Thermal Climate Index (UTCI). Utilizing 30 years of meteorological data from 49 stations across the country, the study analyzed seasonal and regional variations in thermal comfort.
Methods: De Martonne's climate classification was used to categorize Iran's climate, and the UTCI was calculated for different seasons. Kriging interpolation was used to create zoning maps, providing spatial representations of thermal comfort conditions.
Results: The results indicate significant regional disparities in thermal comfort. Arid climates experience severe heat stress, particularly in summer, while Mediterranean climates generally offer more favorable conditions. Seasonal variations are also pronounced, with autumn and spring being more comfortable seasons overall.
Conclusion: The study highlights the need for urban planning and building design to address thermal comfort challenges, particularly in areas prone to extreme heat or cold. Future research should consider additional thermal comfort indices and expand the analysis to include more recent data and a wider range of climate zones.
Keywords: Seasons, Extreme heat, City planning, Iran, Spatial analysis
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Introduction

Climate change

One of the influential factors affecting human life, comfort, and health is weather and climatic conditions. Climate, as a geographical phenomenon, has a deep and undeniable connection with humans and their living and working environments. Today, the impact of weather conditions on life, health, comfort, and human behavior is studied within the framework of a scientific discipline known as bioclimatology (1). To achieve human comfort from a climatic perspective, four elements—temperature, humidity, wind, and radiation—play key roles (2). The combination of these factors affects humans and is related to their physical comfort (3).

Climate change is a complex and dynamic process influenced by many unknown external factors (4). Studies indicate that global temperatures are expected to rise between 1.4 and 5.8°C by the end of the 21st century (5). Climatologists predict that in the coming century, weather patterns will change rapidly across different regions, leading to a series of unprecedented events (2). Exposure to extreme heat is becoming an increasing global health concern. It is estimated that by 2070, one-third of the Earth's population will live in areas with a mean annual temperature exceeding 29°C, a condition currently found in less than one percent of the Earth's surface (6). Climate change leads to alterations in climatic parameters and variations in thermal comfort, necessitating immediate action (7).

Heat and Cold Stress

The rise in global temperatures and the occurrence of severe climatic events have jeopardized public health. Weather conditions have combined effects on the human body, potentially leading to increased thermal discomfort and negative health impacts (8). Extreme heat increases the risk of heatstroke, dehydration, cardiovascular diseases, and kidney diseases, leading to higher rates of heat-related mortality and morbidity. Additionally, exposure to extreme heat reduces overall productivity and affects labor efficiency (9).

Cold waves and cold stress, as atmospheric phenomena, cause significant damage to Iran's economy. Atmospheric circulation patterns play a key role in the occurrence of these phenomena (10). Cold and snowy winters are characteristics of the country's mountainous climate. The consequences of severe cold waves include burst pipes, frozen pathways, increased energy consumption, destruction of agricultural products, and the spread of temperature-related diseases (11). Exposure to cold leads to reduced muscle strength and peripheral vascular constriction, which can result in increased metabolic heat production in the body.

Geographical Location and Climate OF IRAN

Due to Iran's unique geographical location, a significant portion of the country is influenced by fluctuations in the tropical high-pressure belt, which spans between 23 and 40 degrees north latitude. This belt, referred to as Arabia, is one of the tropical high-pressure cells that forms over the Arabian Peninsula and shifts in latitude in accordance with the apparent movement of the sun (12). This cell is the dominant atmospheric phenomenon in Iran during the hot season, and its prolonged presence over the country leads to hot and dry summers. Iran experiences a significant variety in weather conditions and climates throughout the year. Considering the increasing trend in temperatures and the rise in mean temperatures observed at most meteorological stations in recent years, along with notable differences in maximum temperature values across various regions of the country, the impacts of climate change and global warming are clearly evident in Iran (13). Therefore, recognizing the existing capacities within the country is essential, as it serves as a fundamental environment for human activities, environmental planning, tourism, and land use. In this context, investigating and evaluating climatic characteristics and their dominant elements in atmospheric changes and the formation of environmental behaviors for human communities play a decisive role (14). On the other hand, to reduce the negative effects of heat and cold waves in the future, it is crucial to identify the mechanisms behind these weather systems, predict their occurrence, and find methods to mitigate their harmful effects on public health. Additionally, identifying areas that are particularly vulnerable to these waves is of great importance (15).

Thermal Comfort

To evaluate the environment in terms of thermal conditions, the perspective of thermal comfort is widely accepted (16). Thermal comfort can be defined as a state that reflects a person's satisfaction with their thermal environment (17). ASHRAE defines thermal comfort as a subjective condition indicating an individual's satisfaction with the thermal conditions of their environment (18). The application of thermal comfort indices yields more reliable results than using air temperature indices for assessing the thermal environment (19).

Various indices and models have been employed by researchers to evaluate human comfort. In most evaluations, efforts have been made to estimate comfort levels utilizing meteorological statistics and information such as temperature, humidity, wind, solar radiation, or a combination of these factors (20). Among existing studies and practical indices, the Universal Thermal Climate Index (UTCI) has gained increasing attention. This index can be applied in various climatic conditions, providing an effective assessment of the effects of climate change on human health (21).

Until now, there is no study in which thermal comfort analysis has been used using meteorological data in different climates of the country, so in the present study, meteorological data recorded over 30 years across different seasons have been analyzed, resulting in the creation of a thermal comfort atlas for Iran based on the mean UTCI. This study aimed to create a reliable thermal comfort atlas for Iran in different seasons, based on the UTCI, which is one of the most accurate indices for assessing thermal comfort. This represents a significant step toward a better understanding of comfort conditions in various regions of the country. The analysis of 30 years of data allows for a broader temporal coverage in the preparation of the thermal comfort atlas.

This study will answer the following questions:

- What is the mean thermal comfort condition based on the UTCI in different regions and climates of Iran across various seasons?
- Which regions and climates of Iran exhibit the highest and lowest levels of thermal comfort according to the UTCI indices in different seasons?
- How is the zoning of Iran zoned regarding thermal comfort levels based on the UTCI across different seasons?

In general, the preparation of the thermal comfort atlas serves as a valuable tool for urban planners, architects, facility engineers, and other stakeholders to optimize thermal comfort conditions in the design and construction of buildings and urban spaces.

Materials and Methods

Study Area

This study was conducted in Iran, which covers an area of 1,648,195 square kilometers, with a latitude range of 25 to 40 degrees north and a longitude range of 44 to 62 degrees east.

Climatic Zoning

In this study, de Martonne's climate classification was utilized to categorize the climate in Iran. This classification is based on the Aridity Index and employs temperature and precipitation data to determine the type of climate. De Martonne identified six climate types within this system, which are as follows:

- Dry climate (AI < 10)
- Semi-arid climate (10 < AI < 20)
- Mediterranean climate (20 < AI < 24)
- Semi-humid climate (24 < AI < 28)
- Humid climate (28 < AI < 35)
- Very humid climate (AI > 35) (21).

Station Characteristics

The characteristics of 49 stations were obtained from the National Meteorological Organization. Their information regarding climate type, latitude, and longitude is presented in Table 1. According to this classification, 21 stations are located in dry climates, 19 in semi-arid climates, 2 represent the Mediterranean climate, 3 are in very humid climates, 3 in humid climates, and 1 is in a semi-humid climate.

In other words, according to this zoning, 43% of the studied stations are located in the dry region, 39% in the semi-arid region, 6% in the humid region, 6% in the very humid region, 2% in the semi-humid region, and 4% in the Mediterranean region. The climatic classification map of the investigated stations, based on de Martonne's method, is presented in Figure 1. Overall, this climate classification map provides a comprehensive overview of the diverse climatic conditions across Iran, and highlights the strong influence of geography, particularly elevation and proximity to the Caspian Sea, on the country's climate.

Meteorological Data Collection

For a 30-year statistical period (1988-2017) in Iran, synoptic meteorological data from 49 stations were obtained from the National Meteorological Organization of Iran. This data included mean parameters such as dry temperature, relative humidity, air flow velocity, and cloudiness for the studied stations. Subsequently, the UTCI was calculated for different seasons. The selected stations had the most complete statistical records compared to other stations in the country, and efforts were made to choose stations

Table 1. Characteristics of the studied Stations

Station	Longitude	Latitude	Type of Climate
Abadan	48.12	30.38	Arid
Ahvaz	48.74	31.34	Arid
Arak	49.76	34.10	Semi-arid
Astara	48.58	38.36	Very humid
Bam	58.35	29.10	Arid
Bandar Abbas	56.37	27.12	Arid
Bandar Anzali	49.72	37.29	Very humid
Bandar Lengeh	54.45	26.33	Arid
Birjand	59.28	32.89	Arid
Bojnurd	57.16	37.28	Semi-arid
Chabahar	65.60	25.28	Arid
Dezful	48.38	32.40	Semi-arid
Fasa	53.71	28.89	Arid
Gorgan	54.41	36.90	Semi-arid
Hamadan	48.55	34.80	Semi-arid
Karaj	58.10	35.33	Arid
Khorramabad	48.17	33.26	Semi-arid
Khoy	74.00	38.50	Semi-arid
Maragheh	46.23	37.38	Semi-arid
Mashhad	59.63	32.26	Arid
Mianeh	47.70	37.40	Semi-arid
Piranshahr	45.13	36.73	Humid
Qaemshahr	52.64	26.27	Semi-humid
Qazvin	55.50	36.25	Semi-arid
Quchan	58.55	37.11	Semi-arid
Ramsar	58.60	36.90	Very humid
Sanandaj	46.26	36.25	Mediterranean
Sanandaj	47.33	35.33	Semi-arid
Semnan	53.55	35.58	Arid
Shahrekord	55.80	32.28	Semi-arid
Shahrood	45.96	36.41	Arid
Shiraz	52.60	29.56	Semi-arid
Tabriz	46.28	38.80	Semi-arid
Tehran	51.31	35.68	Arid
Torbat-e Heydarieh	59.12	35.26	Arid
Yasuj	51.63	3.83	Humid
Yazd	54.40	31.99	Arid
Zahedan	60.90	29.64	Arid
Zanjan	48.48	36.36	Semi-arid
Babolsar	52.65	36.72	Humid
Bushehr	58.10	28.96	Arid
Ilam	46.26	33.38	Mediterranean
Isfahan	51.40	32.37	Arid
Kerman	56.58	30.15	Arid
Kermanshah	47.60	34.31	Semi-arid
Mahabad	45.73	36.76	Semi-arid
Sabzevar	57.71	36.20	Arid
Urmia	58.45	37.55	Semi-arid
Zabol	61.29	31.22	Arid

with 5% or less statistical deficiencies during the period. This index is recognized as an effective tool for evaluating outdoor conditions in various geographical areas and reflects individuals' responses to climatic conditions.

Universal Thermal Climate Index (UTCI)

In 1999, the International Association of Biometeorology established a commission to develop the Universal Thermal Climate Index (UTCI), aiming to create a thermal index based on the most advanced thermophysiological models. Subsequently, in 2005, these efforts were reinforced by the European Organization in Science and Technology (COST) with prominent experts in various fields, including human thermophysiology, physiological modeling, weather, and climatology (22).

This index was developed to establish a standard criterion for suitable thermal conditions in major fields of human biometeorology. Compared to other indices, the UTCI demonstrates greater sensitivity to slight changes in temperature, solar radiation, humidity, and wind speed, providing a better description of various climatic conditions (23). It is capable of showing minor differences in the intensity of these stimuli (16,24).

Outputs of the Model

The outputs of the model also include physiological processes related to heat regulation, which are crucial for understanding human responses to natural, moderate, and severe thermal conditions. Different values of the UTCI are classified based on thermal stress, reflecting the physiological responses of organisms to actual environmental conditions. These responses are established under reference conditions that reduce heat or cold exposure.

The index value depends on temperature, mean radiant temperature, wind speed, relative humidity, and vapor pressure, as expressed in Equation 1 (25). The UTCI categorizes thermal stresses into 10 classes, ranging from extreme cold stress (-40°C) to extreme heat stress (+46°C) (Table 2). This index facilitates the comparison of different locations in terms of climatic comfort and is utilized in various fields, including urban planning, building design, occupational health, sports, and tourism (26,27).

$$UTCI = f\left(Ta;Tmrt;Va;vp\right) = Ta + offset\left(Ta;Tmrt;Va;vp\right) \quad (1)$$

In the above equation, *Ta* represents air temperature (°C), *Tmrt* is the mean radiant temperature (°C), Va is wind speed, and *Vp* is vapor pressure (25).

This index can also be calculated based on the mathematical relationships (Equation 2) (28):

$$UTCI = 3.21 + 0.872 \times t + 0.2459 \times Tmrt - 2.5078 \times v - 0.0176 \times RH \quad (2)$$

Table 2. Thermal Stress Thresholds of the UTCI(°C) (25)

Human Physiological Responses to The Thermal Environment	UTCI values
Extreme Heat Stress;	Above +46
Very Strong Heat Stress	38 to 46
Strong Heat Stress	33 to 38
Moderate Heat Stress	26 to 32
No Thermal Stress	9 to 26
Slight Cold Stress	0 to 9
Moderate Cold Stress	9 to -13
Strong Cold Stress	-27 to -13
Very Strong Cold Stress	-40 to -27
Extreme Cold Stress	Below -40

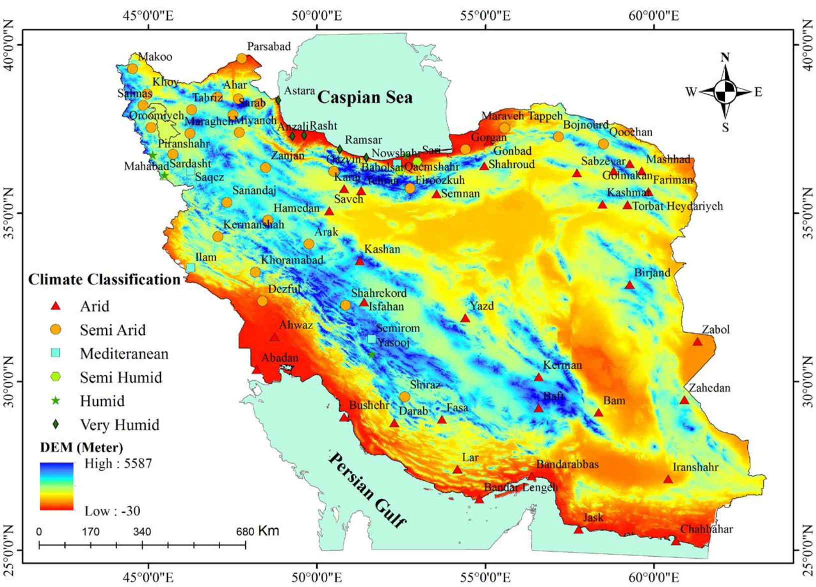

Figure 1. Climatic classification map of the studied stations

In this equation, T is temperature (°C), $Tmrt$ is the mean radiant temperature (°C), V is wind speed (m/s), and RH is relative humidity (%).

Mean Radiant Temperature (Tmrt)

One of the important inputs for calculating the UTCI is the mean radiant temperature. The mean radiant temperature is a crucial variable for evaluating thermal comfort outdoors. Given that the effect of radiant temperature on humans is multifaceted, the mean radiant temperature is the sum of the radiation absorbed by the human body from different radiation levels. The mean radiant temperature cannot be measured directly; however, it can be roughly measured with a spherical thermometer.

The standard spherical thermometer reaches thermal equilibrium with the surrounding heat in about 10 to 12 minutes. The mean radiant temperature is calculated using Equation 3.

$$Tmrt = \left[\left(\left(R' + 0.5La + 0.5La\right) / S_h.s\right)\right]^{0.25} + (-273) \quad (3)$$

In the above equation, R' is solar radiation absorbed by the naked human body, Lg is the Ground radiation, La is reflected radiation, S_h is the emissivity coefficient for the human body, which is equal to 0.95, and S is the Stefan-Boltzmann constant (29) In this study, the mean radiant temperature was calculated using the RayMan Pro model (Version 2.1), and the UTCI was computed using the Bioklima software (Version 2.6). The index values were calculated daily for the studied stations (25).

Preparation of zoning maps

Zoning maps were prepared using the Kriging interpolation method. Kriging is an estimator that considers the values of a variable at unmeasured points as a linear combination of the values of the same variable at surrounding points. This important spatial statistic estimator is named after D.G. Krige, a pioneer of geostatistics and a mining engineer from South Africa. The method was initially proposed to evaluate natural resources. In fact, the Kriging method is a moving weighted mean, recognized as the best unbiased linear estimator. Suppose the value of variable z is measured at n points (Equation 4) (30):

$$Z = (Z(x1);\ Z(x2);\ \ldots Z(Xn \quad (4)$$

The estimation of Z at the point X0 is expressed by the Kriging estimator through Equation 5:

$$Z^*(x0) = \sum z(xi) \quad (5)$$

The most crucial aspect of Kriging is finding the weights (λ_i). For the estimates to be unbiased, these weights must be determined so that their sum equals 1, i.e., $z(xi) = 1\Sigma$. Additionally, to ensure the accuracy of the estimates, the estimation variance should be minimal, as expressed in Equation 6:

$$\mathrm{Var}[z^*(x0)] = E\left[\left(z^*(x0) - z(x0)2\right] = \min \quad (6)$$

Absolute estimation in interpolation is a key feature of the Kriging method. This means that the estimated value of the quantity at sampling points equals the measured value, resulting in a variance of zero for the estimation. This characteristic ensures that the Kriging estimator passes through the maximum number of sampling points when generating isopleths and does not tend to close in or loop back, remaining within the boundaries of the study area. In other words, this model minimizes the variance when estimating the unknown quantity at points with known coordinates (31,32).

Additionally, ArcGIS 10.3 software was used to prepare zoning maps in this study. The exclusion criterion was that if long-term data had not been recorded at the selected stations, or if the data for a station were incomplete, a station in the same climate classification could be replaced.

Statistical Analysis

In this study, the Riemann software was used to calculate the UTCI daily, while SPSS and Excel were used to describe the data.

Results

According to Figure 1, the majority of the country is characterized by Arid and Semi-Arid climates, particularly in the central and eastern regions. In contrast, pockets of Mediterranean, Semi-Humid, and Humid climates are found in the northern and northwestern parts, particularly along the Caspian Sea coast. Very Humid areas are limited and located in the extreme northern regions near the Caspian Sea. Additionally, the highest elevations are found in the Zagros Mountains in the west and the Alborz Mountains in the north. The geographical location of each station and the zoning of Iran based on the mean UTCI over 30 years in different seasons are shown in Figure 2.

- According to Figure 2A , in spring, the majority of the country experiences favorable thermal conditions. However, cities located in the Alborz and Zagros Mountain ranges experience slight cold stress. The cities along the southern coasts exhibit mild heat stress and less severe heat stress.
- According to Figure 2C, in autumn, most of the country maintains favorable thermal conditions. Fewer cities in the Alborz and Zagros Mountain ranges experience slight cold stress compared to spring. Cities on the southern coasts have mild heat stress and less severe heat stress.
- According to Figure 2B, in summer, there is a significant variation in climate. About one-third

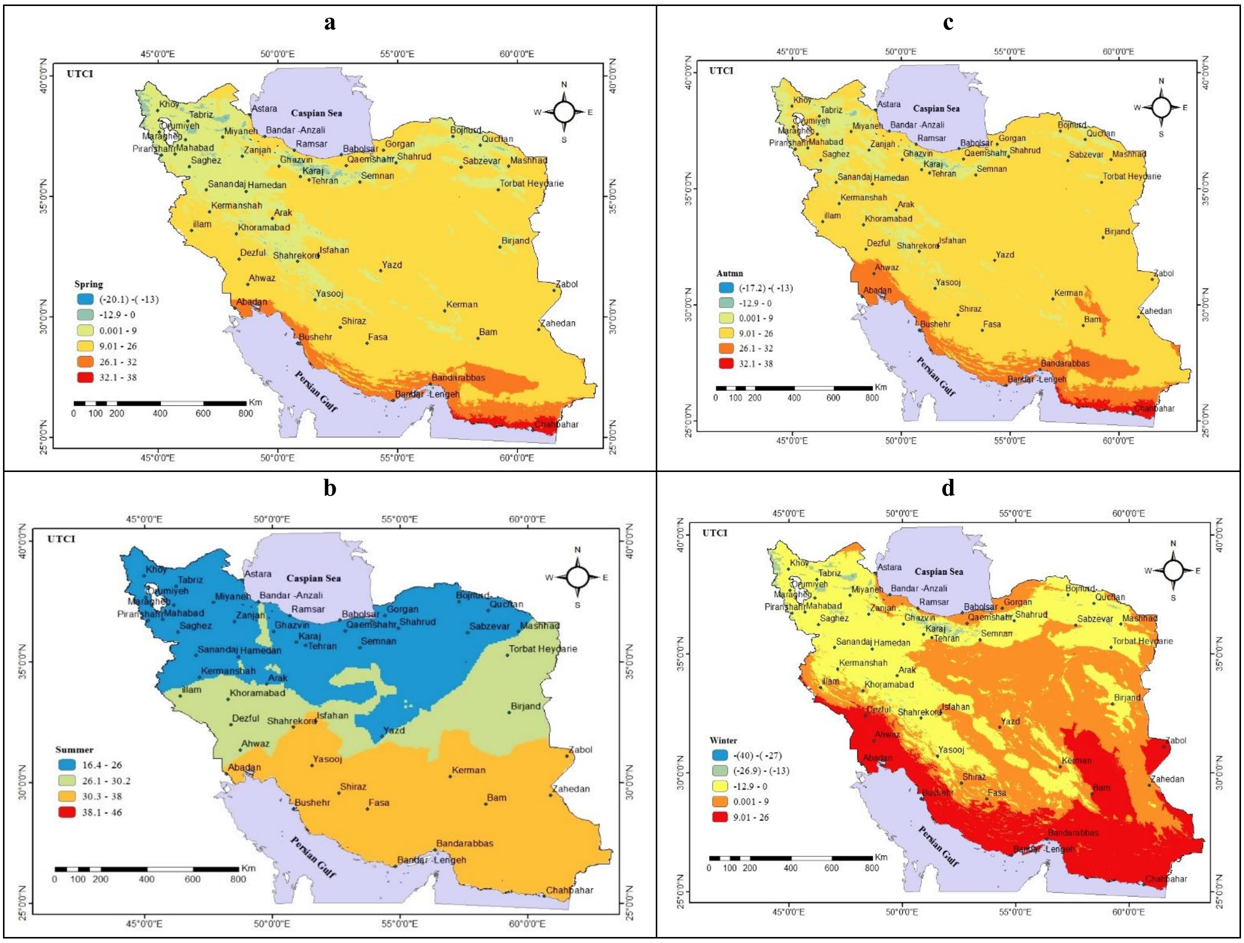

Figure 2. Zoning of Iran based on the mean UTCI(°C) in spring (a), summer (b), autumn (c), and winter (d)

of the upper lands of the country (northern and northwestern regions) have thermal comfort. The eastern, western, and central regions of the country have mild heat stress. The lower one-third of the country (southeastern and southwestern regions) experiences severe heat stress.

– According to Figure 2D, in winter, there is considerable diversity in the weather. Cities in the Alborz and Zagros Mountain ranges experience mild cold stress compared to spring, and very few cities located there have severe cold stress. and very few cities located there have severe cold stress. Cities located in the central regions of the country have slight cold stress, while the southern coasts enjoy thermal comfort.

Additionally, Table 3 presents the mean UTCI at the studied stations over 30 years across different seasons of the country. The maximum and minimum mean UTCI values recorded in spring were 34.73 in Chabahar and -2.1 in Sanandaj; in summer, 42.2 in Bandar Lengeh and 2.39 in Qaem Shahr; in autumn, 35.25 in Bandar Lengeh and 2.1 in Yazd; and in winter, 26.33 in Chabahar and -12.6 in Tabriz.

Based on the mean UTCI at the studied stations in different seasons, the following conditions are observed:

- **Spring:** Bandar Abbas, Bandar Lengeh, and Chabahar experience severe heat stress. The cities of Ahvaz and Bam have mild heat stress, while Bojnurd, Hamadan, Piranshahr, Qazvin, Quchan, and Sanandaj face slight cold stress. Other cities experience thermal comfort.
- **Summer:** Most cities in Iran experience heat stress, highlighting the need for thermal comfort. However, the cities of Abadan, Bandar Lengeh, Ahvaz, Bandar Abbas, and Chabahar face very severe heat stress during the summer. Conversely, several other cities offer favorable weather and thermal comfort.
- **Autumn:** During this season, many cities enjoy thermal comfort. A few cities experience mild cold and heat stress, while Bandar Abbas, Bandar Lengeh, and Chabahar endure severe heat stress, necessitating control measures.
- **Winter:** This season features a variety of climates, with slight and mild cold stress in some cities and thermal comfort in others. None of the cities experiences extreme cold.

Figure 3 illustrates the mean UTCI at the studied stations over 30 years, segmented by different climates in each season. The highest mean index in spring occurs in arid climates with a value of 19.99 (no heat stress), while the lowest is in Mediterranean climates at 7.28 (slight cold stress). In summer, the highest mean index is again in

Table 3. Mean UTCI(°C) at the studied stations over 30 years in different seasons of the country.

Station	Spring	Thermal Comfort Level	Summer	Thermal Comfort Level	Autumn	Thermal Comfort Level	Winter	Thermal Comfort Level
Abadan	24.9	No Thermal Stress	39.14	Very Strong Heat Stress	26.83	Moderate Heat Stress	11.45	No Thermal Stress
Ahvaz	28.47	Moderate Heat Stress	42.1	Very Strong Heat Stress	30.12	Moderate Heat Stress	15.72	No Thermal Stress
Arak	15.5	No Thermal Stress	30.3	Moderate Heat Stress	19	No Thermal Stress	4.7	Slight Cold Stress
Astara	20.1	No Thermal Stress	32.44	Strong Heat Stress	22.4	No Thermal Stress	9.8	No Thermal Stress
Bam	28.25	Moderate Heat Stress	37.85	Strong Heat Stress	27.2	Moderate Heat Stress	16.7	No Thermal Stress
Bandar Abbas	32.9	Strong Heat Stress	41.6	Very Strong Heat Stress	34.15	Strong Heat Stress	22.84	No Thermal Stress
Bandar Anzali	17.1	No Thermal Stress	31	Moderate Heat Stress	19.8	No Thermal Stress	5.15	Slight Cold Stress
Bandar Lengeh	32.3	Strong Heat Stress	42.2	Very Strong Heat Stress	35.25	Strong Heat Stress	23.8	No Thermal Stress
Birjand	17.7	No Thermal Stress	28.1	Moderate Heat Stress	17.86	No Thermal Stress	4.26	Slight Cold Stress
Bojnurd	2.47	Slight Cold Stress	16.4	No Thermal Stress	6.7	Slight Cold Stress	-6.6	Moderate Cold Stress
Chabahar	34.73	Strong Heat Stress	38.35	Very Strong Heat Stress	34.55	Strong Heat Stress	26.33	Moderate Heat Stress
Fasa	12.1	No Thermal Stress	25.3	No Thermal Stress	14.3	No Thermal Stress	3.15	Slight Cold Stress
Gorgan	10.1	No Thermal Stress	24.25	No Thermal Stress	15.3	No Thermal Stress	1.9	Slight Cold Stress
Hamadan	0.52	Slight Cold Stress	17.8	No Thermal Stress	5.93	Slight Cold Stress	-9.55	Moderate Cold Stress
Karaj	13.5	No Thermal Stress	29.15	Moderate Heat Stress	16.9	No Thermal Stress	-1.4	Moderate Cold Stress
Khorramabad	17.88	No Thermal Stress	32.15	Strong Heat Stress	20.25	No Thermal Stress	5.84	Slight Cold Stress
Khoy	16.5	No Thermal Stress	30.45	Moderate Heat Stress	18.95	No Thermal Stress	2	Slight Cold Stress
Maragheh	9.11	No Thermal Stress	24.5	No Thermal Stress	10.77	No Thermal Stress	-5.63	Moderate Cold Stress
Mashhad	15.9	No Thermal Stress	28.9	Moderate Heat Stress	16.4	No Thermal Stress	2.33	Slight Cold Stress
Mianeh	14.8	No Thermal Stress	27.88	Moderate Heat Stress	16.43	No Thermal Stress	0.152	Slight Cold Stress
Piranshahr	1	Slight Cold Stress	19.5	No Thermal Stress	7	Slight Cold Stress	-10.5	Moderate Cold Stress
Qaemshahr	10.4	No Thermal Stress	2.39	Slight Cold Stress	15.77	No Thermal Stress	2.67	Slight Cold Stress
Qazvin	5.7	Slight Cold Stress	20.1	No Thermal Stress	9.4	No Thermal Stress	-4.9	Moderate Cold Stress
Quchan	2.94	Slight Cold Stress	16.6	No Thermal Stress	5.4	Slight Cold Stress	-7.4	Moderate Cold Stress
Ramsar	11.55	No Thermal Stress	24.5	No Thermal Stress	17	No Thermal Stress	5.23	Slight Cold Stress
Sanandaj	-2.1	Moderate Cold Stress	14.17	No Thermal Stress	4.25	Slight Cold Stress	-10.4	Moderate Cold Stress
Sanandaj	3.4	Slight Cold Stress	19.44	No Thermal Stress	8.4	Slight Cold Stress	-6.5	Moderate Cold Stress
Semnan	20.76	No Thermal Stress	34.16	Strong Heat Stress	21.9	No Thermal Stress	8.36	Slight Cold Stress
Shahrekord	12.4	No Thermal Stress	27.5	Moderate Heat Stress	15.85	No Thermal Stress	0.93	Slight Cold Stress
Shahrood	18.3	No Thermal Stress	28.5	Moderate Heat Stress	19.1	No Thermal Stress	5.62	Slight Cold Stress
Shiraz	19.85	No Thermal Stress	33.2	Strong Heat Stress	23.15	No Thermal Stress	10.5	No Thermal Stress
Tabriz	0.81	Slight Cold Stress	16.6	No Thermal Stress	4.66	Slight Cold Stress	-12.6	Moderate Cold Stress
Tehran	6.43	Slight Cold Stress	24.3	No Thermal Stress	11.7	No Thermal Stress	-4.47	Moderate Cold Stress
Torbat-e Heydarieh	14.93	No Thermal Stress	26.3	Moderate Heat Stress	15.75	No Thermal Stress	2.44	Slight Cold Stress
Yasuj	6.4	Slight Cold Stress	19.93	No Thermal Stress	9.94	No Thermal Stress	-2.1	Moderate Cold Stress
Yazd	20.6	No Thermal Stress	34.2	Strong Heat Stress	2.1	Slight Cold Stress	6.1	Slight Cold Stress
Zahedan	19.17	No Thermal Stress	30.5	Moderate Heat Stress	18.86	No Thermal Stress	2.48	Slight Cold Stress
Zanjan	10.1	No Thermal Stress	25.2	No Thermal Stress	12.64	No Thermal Stress	-5.56	Moderate Cold Stress
Babolsar	22.75	No Thermal Stress	34.35	Strong Heat Stress	25.32	No Thermal Stress	13.46	No Thermal Stress
Bushehr	27	Moderate Heat Stress	38.7	Very Strong Heat Stress	31	Moderate Heat Stress	16	No Thermal Stress
Dezful	20	No Thermal Stress	34	Strong Heat Stress	21.8	No Thermal Stress	9.5	No Thermal Stress
Ilam	16.65	No Thermal Stress	31.23	Moderate Heat Stress	20.1	No Thermal Stress	5.85	Slight Cold Stress
Isfahan	7.73	Slight Cold Stress	22.9	No Thermal Stress	11.4	No Thermal Stress	-2.54	Moderate Cold Stress

Table 3. Continued.

Station	Spring	Thermal Comfort Level	Summer	Thermal Comfort Level	Autumn	Thermal Comfort Level	Winter	Thermal Comfort Level
Kerman	5.5	Slight Cold Stress	19.35	No Thermal Stress	8	Slight Cold Stress	-5.8	Moderate Cold Stress
Kermanshah	3.14	Slight Cold Stress	20.7	No Thermal Stress	8.42	Slight Cold Stress	-7.2	Moderate Cold Stress
Mahabad	10.1	No Thermal Stress	28	Moderate Heat Stress	13.6	No Thermal Stress	-5.65	Moderate Cold Stress
Sabzevar	16.56	No Thermal Stress	31	Moderate Heat Stress	16.8	No Thermal Stress	2.2	Slight Cold Stress
Urmia	12.4	No Thermal Stress	26.95	Moderate Heat Stress	14.4	No Thermal Stress	-1.82	Moderate Cold Stress
Zabol	22.16	No Thermal Stress	35.1	Strong Heat Stress	19.17	No Thermal Stress	4.96	Slight Cold Stress

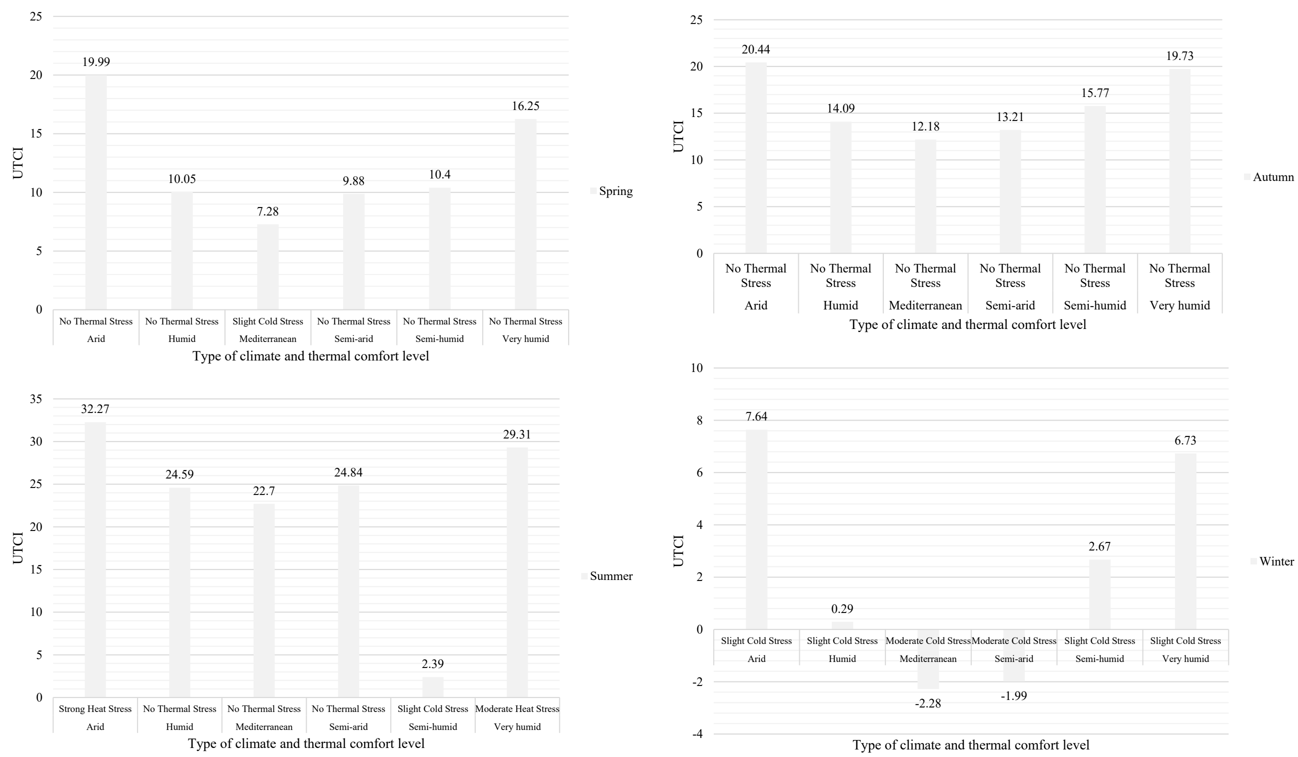

Figure 3. The mean UTCI(°C) at the studied stations over 30 years, categorized by different climates and seasons

arid climates at 32.27 (severe heat stress), and the lowest in Mediterranean climates at 22.07 (no heat stress). In autumn, the highest mean index remains in arid climates at 20.44 (no heat stress), with the lowest in Mediterranean climates at 12.18 (no heat stress). In winter, the highest mean index is in arid climates at 7.64 (slight cold stress), while the lowest is in Mediterranean climates at -2.28 (mild cold stress).

Overall, thermal comfort is present in various climates across the country during autumn. Thermal comfort is also observed in many cities during other seasons, with cold or heat stress occurring only in specific climates during different seasons.

- **Arid Climate:** Severe heat stress in summer, slight cold stress in winter.
- **Humid Climate:** Slight cold stress in winter.
- **Mediterranean Climate:** Slight cold stress in spring and mild cold stress in winter.
- **Semi-Arid Climate:** Only mild cold stress in winter.
- **Semi-Humid Climate:** Slight cold stress in summer and winter.
- **Very Humid Climate:** Mild heat stress in summer and slight cold stress in winter.

Table 4 shows the frequency of physiological stress across various climates and seasons in Iran. In spring, 57.14% of the dry climate, 63.16% of the semi-arid climate, 50% of the Mediterranean climate, 100% of the semi-humid climate, and 100% of the very humid climate experience no heat stress. In contrast, 66.67% of the humid climate experiences slight cold stress.

In summer, 33.33% of the arid climate experiences mild heat stress, while 52.63% of the semi-arid climate, 50% of the Mediterranean climate, 33.34% of the very humid climate, and 66.67% of the humid climate experience no heat stress. Additionally, 50% of the Mediterranean climate experiences mild heat stress, and 100% of the semi-humid climate experiences slight cold stress.

In autumn, 57.14% of the arid climate, 57.14% of the semi-arid climate, 50% of the Mediterranean climate, 100% of the semi-humid climate, 100% of the very humid

Table 4. Percentage of physiological stress in various climates during different seasons in Iran.

Very humid (n=3)	Humid (n=3)	Semi-humid (n=1)	Mediterranean (n=2)	Semi-arid (n=19	Arid (n=21)	Season	Thermal Comfort Level
-	-	-	-	-	-		Extreme Heat Stress
-	-	-	-	-	-		Very Strong Heat Stress
-	-	-	-	-	14.29		Strong Heat Stress
-	-	-	-	-	14.29		Moderate Heat Stress
100	33.33	100	50	63.16	57.14	Spring	No Thermal Stress
-	66.67	-	-	36.84	14.29		Slight Cold Stress
-	-	-	50	-	-		Moderate Cold Stress
-	-	-	-	-	-		Strong Cold Stress
-	-	-	-	-	-		Very Strong Cold Stress
	-				-		Extreme Heat Stress
	-	-	-	-	28.57		Very Strong Heat Stress
33.33	33.33	-	-	15.79	19.05		Strong Heat Stress
33.33	-	-	50	31.58	33.33		Moderate Heat Stress
33.34	66.67	-	50	52.63	19.05	Summer	No Thermal Stress
-	-	100	-	-	-		Slight Cold Stress
-	-	-	-	-	-		Moderate Cold Stress
-	-	-	-	-	-		Strong Cold Stress
-	-	-	-	-	-		Very Strong Cold Stress
-	-	-	-	-	-		Extreme Heat Stress
-	-	-	-	-	-		Very Strong Heat Stress
-	-	-	-	-	14.29		Strong Heat Stress
-	-	-	-	-	19.05		Moderate Heat Stress
100	66.67	100	50	68.42	57.14	Autumn	No Thermal Stress
-	33.33	-	50	31.58	9.52		Slight Cold Stress
-	-	-	-	-	-		Moderate Cold Stress
-	-	-	-	-	-		Strong Cold Stress
-	-	-	-	-	-		Very Strong Cold Stress
-	-	-	-	-	-		Extreme Heat Stress
-	-	-	-	-	-		Very Strong Heat Stress
-	-	-	-	-	-		Strong Heat Stress
-	-	-	-	-	-		Moderate Heat Stress
33.33	33.33	-	-	10.53	28.57	Winter	No Thermal Stress
66.67	-	100	50	31.58	47.62		Slight Cold Stress
-	66.67	-	50	57.89	23.81		Moderate Cold Stress
-	-	-	-	-	-		Strong Cold Stress
-	-	-	-	-	-		Very Strong Cold Stress

climate, and 66.67% of the humid climate have no heat stress, while 50% of the Mediterranean climate experiences slight cold stress.

In winter, 47.62% of arid climates, 100% of semi-humid climates, 66.67% of very humid climates, and 50% of Mediterranean climates experience slight cold stress. Additionally, 57.89% of semi-arid climates, 50% of Mediterranean climates, and 66.67% of humid climates experience mild cold stress.

The mean UTCI at the studied stations over 30 years for different months of the year is presented in Figure 4. The maximum index is recorded in July at 29.4 (indicating mild heat stress), while the minimum is 1.61 in January (indicating slight cold stress).

Discussion

Introduction to Climate Trends in Iran

Iran is one of the largest countries in the Middle East. In recent years, an increasing trend in temperature has been observed in most meteorological stations across the

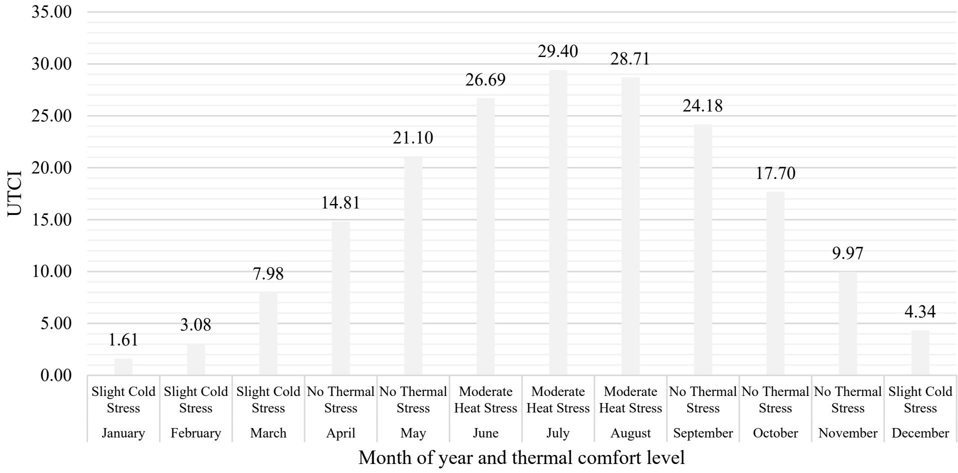

Figure 4. Mean UTCI(°C) in the studied stations over 30 years in different months of the year

country. Additionally, there are significant differences in maximum temperature values in various regions. These factors illustrate the clear effects of climate change and global warming in Iran. In fact, climate change poses one of the major challenges for mankind in the near future; according to various studies in this field, it is predicted that the Earth's temperature will rise by several degrees (33).

Methodology and Data Analysis

In the present study, meteorological data recorded over 30 years in different seasons were analyzed, and an atlas of Iran was prepared based on the mean UTCI. This study aimed to create an atlas of thermal comfort in Iran across different seasons, using the valid UTCI, which is one of the most accurate indices for evaluating thermal comfort. The UTCI has been utilized in various studies in Iran and other countries (34–36). In all these studies, this index is recognized as a practical tool for determining thermal comfort conditions. The present study effectively encompasses Iran's climatic diversity and provides the possibility for accurate comparison of comfort conditions in different regions. Long-term annual or seasonal climate variables, such as temperature, are typically used as indicators to detect climate changes. No place in the world experiences optimal conditions and thermal comfort throughout the year.

Spatial, Temporal, and Seasonal Variations in Thermal Comfort

Based on the mean UTCI over 30 years, the majority of the studied stations are located in arid climates (43%), indicating the predominance of this climate type in the study. This is followed by semi-arid climates at 39%, while humid (6%) and very humid (6%) climates comprise a small percentage of the stations. Semi-humid (2%) and Mediterranean (4%) regions also account for a lesser percentage of the stations. Given the distribution of these areas, urban planning and design should be based on the climatic conditions of each region to optimize thermal comfort and the effective use of resources. More research is needed in regions with lower percentages (humid, very humid, semi-humid, and Mediterranean) to gain a better understanding of the specific needs and challenges of these areas. This information can assist decision-makers and planners in adjusting appropriate strategies for each region and using resources effectively.

Regional Climate Characteristics

According to the results, Chabahar and Bandar Lange, with arid climates, show the highest UTCI values across different seasons, indicating greater challenges in maintaining thermal comfort. In contrast, cities like Tabriz and Sanandaj, with semi-arid and Mediterranean climates, exhibit the lowest values. These findings are consistent with those of another study, which reported that the mean temperature in Sistan, an arid climate city, peaks from May to August. This study also noted that regulating thermal comfort during these months is necessary, with shading suggested as an effective measure to improve thermal comfort in open space (37).

Heat and Cold Waves: A Comparative Analysis

Additionally, another study indicated that UTCI hot spots are primarily located along the southern coasts of Iran, exhibiting minimal seasonal fluctuations (36), which aligns with the results of the present study. Furthermore, another study (38) reported results consistent with the present study, indicating a higher temperature threshold for thermal comfort in southern coastal cities compared to stations in the northwest and northeast of the country. In a study by Roshan et al (39), no cold wave was observed in the southwestern regions of Iran or at the stations along the northern coast of the Persian Gulf. It was found that the most significant cold waves occurred in the northwestern and northeastern regions, as well as in high-altitude areas such as the Zagros Mountains. The results of this research indicated that, compared to cold waves, heat waves can occur throughout the country. Furthermore, these findings confirm that the risk of heat waves in Iran is more serious than that of cold waves, aligning with the present study.

The results of a study showed that the Universal Thermal Climate Index (UTCI) varied from extreme cold stress to extreme heat stress throughout Greece during the 30-year study period from 1991 to 2020, which is consistent with the results of the present study (40). In the present study, a positive trend in mean UTCI (Universal Thermal Climate Index) was observed from January to July, with mild heat stress noted in June, July, and August. Conversely, another study revealed that most cities of Iran experience thermal comfort conditions from June to October, and, generally, UTCI in Iran (except in November) shows a positive and significant trend, particularly from April to September (36). There are no discrepancies between this study and the present research in specific months. Such differences may arise from variations in data type and volume, time periods analyzed, and the methods employed. Additionally, another study recorded the highest monthly mean temperature (27.55 ± 0.57°C) over 15 years for August (41). In another study, it was shown that the highest temperatures in the arid climate of Arak and the hot, dry climate of Bandar Abbas occur in July (42). Furthermore, a study found that moderate and severe heat stress has been recorded in only a few areas along the southern coast from May to November (36), which is consistent with the present study for the months of June to August, while other months exhibited conditions without thermal stress.

Seasonal Variations in Thermal Comfort

From January to March, and in December, slight cold stress was observed, with January showing the least. A study by Mohammadi & Khoorani indicated that most of the country experiences severe, moderate, or mild cold stress from January to May, as well as in November and December (36). Also, in a study, the results showed that the WBGT index had a statistically significant upward trend during the summer months in over 50% of the stations. Additionally, more than 55% of the WBGT measurements were in the high and very high ranges, particularly in the semi-arid regions of Iran (21).

The results of all these studies largely align with the present study, which noted significantly more cold points forming along the Alborz and Zagros mountain ranges, consistent with the findings from another study (36). The present study highlights the diversity of heat and cold waves across different regions of Iran, consistent with previous research (36).

The maximum threshold for heat wave occurrence is found in the coastal areas of the Persian Gulf and the Oman Sea, while the minimum is observed in the northwest and highlands of the northeast. Additionally, the frequency of heat waves was higher than that of cold waves, suggesting that Iranians are more adaptable to higher temperatures than to lower ones. Another study (43) also demonstrated that Iran's bioclimatic conditions are highly diverse throughout the year, with hot and very hot bioclimatic conditions predominantly experienced in the southern regions and lower altitudes. These areas experience heat stress in spring and summer, consistent with the present study. Moreover, a study recorded the lowest mean monthly air temperature over 15 years for January (7.9 ± 0.68°C) (41). Another study found that the lowest temperature in the arid and cold climates of Arak and Bandar Abbas, which has a hot and arid climate, occurs in January (42). Furthermore, research in Isfahan, which experiences a dry winter climate, indicated that people's thermal sensation is primarily influenced by dry temperature and mean radiant temperature; a high level of discomfort was observed in the study's results (44).

In the present study, no regions in Iran experienced severe heat or cold stress, consistent with other studies (36), indicating that severe cold and heat stress are the only bioclimatic conditions that do not exist throughout the year based on UTCI. Additionally, a study found that in April, October, and November, over 70% of Iran experiences comfortable conditions, aligning with the present study's findings (43).

Comparison with International Studies

Similar results have been obtained in studies conducted in various countries. A study in China found that, against the backdrop of global warming, UTCI in the Qinghai Plateau significantly increased from 1979 to 2020 (45). Overall, the results of the present study suggest that climate type alone does not determine thermal comfort levels. Factors such as humidity, temperature, and wind also have significant effects. The combination of these parameters simultaneously determines the level of thermal comfort. Another study in China showed that summer UTCI has an increasing trend, and the analysis of climatic factors revealed that the rise in summer UTCI is due to increasing air temperature, dew point temperature, mean radiant temperature, and decreased wind speed. Among these factors, temperature is the primary contributor to the increase in UTCI. Radiation is the second most important factor in most regions (except for western and southern China), while the contribution of other factors to UTCI primarily relates to regional variations (46). In another study in Hungary, the annual mean PET and UTCI increased over the last three 30-year periods, with spring and summer means of PET and UTCI also rising (47). Additionally, a study in China indicated that pleasant days were concentrated particularly in April, May, September, and October. In contrast, during the winter months of January, February, and December, the cumulative number of pleasant days decreased to its lowest level (48). A study in Europe found that PET was more closely related to temperature, while

UTCI showed greater sensitivity to wind speed and vapor pressure, consistent with the findings of the present study. This research reported an increase in heat stress of up to 1°C in recent decades, underscoring the significance of UTCI as a bioclimatic index that can both depict the thermal bioclimatic diversity of Europe and relate changes to impacts on human health. Thermal bioclimatic charts of European capitals indicate that the frequency of UTCI classes varies from city to city and is dependent on the local climate. The results demonstrate an increase in heat stress, particularly over the last 15 years (49). Another study in Poland revealed that changes in UTCI values were much larger than those in individually analyzed meteorological parameters, further confirming the importance of utilizing biometeorological indicators instead of relying solely on individual meteorological elements. It is also important to note that changes in thermal stress conditions varied seasonally and regionally, likely due to seasonal patterns and the climatic characteristics of specific station regions, which necessitate more detailed studies on this issue in the future (50).

Implications for Urban Planning and Design

Therefore, it is crucial to consider this combination for urban design and planning. To enhance comfort conditions in different regions, more detailed analyses of meteorological data and the identification of local patterns are needed. These results can assist planners and designers in making the necessary optimizations in the design of urban spaces and businesses by considering all relevant factors.

According to the results obtained in Table 4, in the spring season, most climates are without thermal stress, and semi-humid and very humid climates are reported to be completely without thermal stress. Only in the humid climate is there a slight cold stress. This indicates favorable climatic conditions in spring in Iran. In summer, a significant percentage of climates (especially arid and semi-arid) experience mild heat stress. This indicates thermal challenges in these seasons. Semi-humid and very humid climates remain without thermal stress, which may be due to their high humidity.

Similar to spring, most climates in autumn are without thermal stress, especially in semi-humid and very humid climates. This indicates suitable climatic conditions in this season. In winter, a significant percentage of climates face slight and mild cold stress. Particularly, semi-humid and very humid climates are affected in this season. Arid and semi-arid climates also experience mild cold stress, which may indicate thermal challenges in these areas.

According to Figure 4, July, the peak heat month, has a mean UTCI of 29.4, while January, the peak cold month, has a mean UTCI of 1.61. These results show significant fluctuations in the UTCI between hot and cold months, indicating severe climatic changes in these regions. Such fluctuations can have considerable effects on the health and comfort of residents.

Future Research Directions

To provide and maintain the thermal comfort of urban residents across various climates and seasons, the following suggestions can be implemented:

In warm seasons, properly designed shading structures can help reduce heat stress. Using smart irrigation systems and designing green spaces according to the water needs of plants can enhance thermal comfort and lower temperatures. Additionally, creating green and shaded areas in urban regions can further help reduce temperatures and increase comfort. Educating residents about the dangers of heat stress and how to manage it, especially in dry climates, is crucial for improving public health. Furthermore, paying attention to the orientation of buildings concerning sunlight and wind in neighborhood design can enhance thermal comfort.

In cold seasons, utilizing movable shading devices to control solar radiation entering indoor spaces, striving to receive more sunlight, residing on upper floors of buildings compared to ground-level units, having south-facing bedrooms in residential buildings, wearing properly insulated clothing, and using smart heating devices can collectively improve adaptation to reduce individuals' exposure to cold stress.

Conclusion

Overall, the results indicate that, over the past 30 years, the autumn and spring seasons have provided more comfortable thermal conditions in all types of climates. The cities of Zanjan, Maragheh (semi-arid climate), and Ramsar (very humid climate) offer more thermal comfort. It is recommended that the establishment of industries take into account climatic changes, weather conditions, and the workload of individuals. July is the peak heat month, while January is the peak cold month in Iran. To reduce vulnerability to heat stress, protective and control programs and strategies are needed. The results of this evaluation can be utilized in the national macro-management and in planning standards and permissible exposure limits for people in high-risk areas. Conducting more research on climate impacts on human health and well-being, particularly in areas experiencing heat and cold stress, can enhance management measures. This consideration should inform the future design of cities. High-risk areas should modify building materials and design features to prevent hazardous situations and reduce energy consumption. Future climatic changes may significantly impact individuals.

This study, while examining a larger number of stations compared to other studies predicting thermal comfort, primarily focused on the stations located in arid and semi-arid climates. Fewer stations were included for humid, semi-humid, very humid, and Mediterranean climates, suggesting that future research should prioritize these areas. Additionally, since this study is based solely on the UTCI, other indices commonly used in various studies, such as the PET (Physiological Equivalent Temperature) index, could also be applied in future research. Given that the time frame for examining thermal comfort in this study extends to 2017, more recent years should be included in subsequent studies. Also, the limitations of this study could be potential biases in the meteorological data or the representativeness of the selected stations.

In the present study, meteorological data recorded over 30 years in different seasons were analyzed, and an atlas of Iran was prepared based on the mean Universal Thermal Climate Index (UTCI). This study aimed to create a comprehensive atlas of thermal comfort conditions in Iran across different seasons, using the UTCI, which is considered one of the most accurate indices for evaluating thermal comfort. Notably, this research represents the first large-scale case study on the spatial and temporal variations in the UTCI across the entire country, utilizing data collected from 49 meteorological stations that represent the diverse climatic regions of Iran over 30 years.

One notable limitation of De Martonne's climate classification is its reliance on only two primary factors: precipitation and temperature. While this approach facilitates a straightforward categorization of climate types, it may overlook other significant climatic variables such as humidity, wind, and solar radiation, which can profoundly impact thermal comfort and overall climatic conditions. This simplification can lead to an incomplete understanding of the climatic nuances that affect human comfort levels. Furthermore, the assumptions underlying this classification method warrant careful consideration, as they may influence the accuracy of the results. The use of Kriging for interpolating data and creating zoning maps also presents challenges; while Kriging is a powerful geostatistical technique, the validity of the interpolation results depends heavily on the quality and density of the input data. A more comprehensive discussion on these limitations will enhance the robustness of the findings and provide a clearer context for interpreting the results of this study.

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Competing interests

The authors have no competing interests to declare.

Ethical issues

Ethical approval for this study was obtained from Iran University of Medical Sciences (Ethical code: IR.IUMS.REC.1403.144).

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