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Comparative evaluation of Environmental Stress Index and Wet Bulb Globe Temperature for modeling heat stress under climate change scenarios in Iranian cities

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Abstract

Background: This study assessed the applicability of the Environmental Stress Index (ESI) as an alternative to the Wet Bulb Globe Temperature (WBGT) for evaluating outdoor heat stress in Iran's climates.

Methods: Using summertime meteorological data from 1992 to 2021, including relative humidity, temperature extremes, and solar radiation, the research analyzed nine representative cities with varying climates. Data were sourced from the National Meteorological Organization, and projections used the Hadley Coupled Atmosphere-Ocean General Circulation Model (HadCM3) and the Long Ashton Research Station Weather Generator (LARS-WG) models, extending predictions to 2099.

Results: The classification of cities revealed temperature fluctuations (29.91-46.00°C) and relative humidity variations (32.33%-72.15%), emphasizing substantial climatic disparities. An intra-class correlation (ICC) analysis of ESI and WBGT showed strong agreement (ICC > 0.9) in seven cities, validating the reliability of both indices. However, lower ICC values in Ahvaz and Bandar Abbas suggest local climatic factors such as humidity and heat may influence index performance. Both indices peak in July, with Ahvaz projected to have the highest values by 2099, reinforcing future heat stress concerns.

Conclusion: Given these limitations, this study emphasizes the need to incorporate additional environmental parameters, such as wind speed, land surface temperature, and air pollution, to improve heat stress assessments. The findings support ESI as a reliable metric for environmental stress evaluation, offering a practical alternative to WBGT across Iran's climate. Its applicability in future climate projections highlights its potential to shape proactive public health strategies mitigating rising heat-related risks, especially in regions facing extreme conditions.

Keywords: Heat-shock response, Temperature, Weather, Iran

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Introduction

Heat poses a significant workplace risk, especially for outdoor workers during hot months. It can lead to serious health problems (1). These workers face high exposure to heat-related hazards due to the nature of their jobs (2). Prolonged exposure can lead to heat stress and strain, making it difficult for the body to regulate temperature (3). Such conditions may result in physical and cognitive impairments, reduced productivity, increased accident rates, and compromised workplace safety (3,4). Additionally, rising global temperatures driven by climate change contribute to increased mortality and morbidity associated with excessive heat exposure, particularly during summer heatwaves (4). Raising awareness of these risks, alongside proper training, is crucial in mitigating exposure and preventing heat-related illnesses (5). Effective heat health warning systems and meteorological monitoring help improve public safety. These tools are crucial in minimizing heat-related hazards during extreme temperature events (6,7).

Iran's vast geographical diversity results in significant climatic variations. About 82% of its territory falls within arid and semi-arid zones (8). Studies on climate changes in Iran have indicated an expected increase in temperatures, especially in the south and central regions, in the coming decades (8). The country's climate distribution includes 35.5% hyper-arid, 29.2% arid, 20.1% semi-arid, 5% Mediterranean, and 10% wet, primarily cold mountainous regions (9-11). These climatic conditions pose risks for outdoor workers. Most of Iran experiences hot summers due to its desert and semi-desert landscape (12). The number of outdoor workers exceeds that of indoor workers. Jobs such as asphalting, surface mining, brick kilns, petrochemicals, farming, and construction are particularly at risk due to prolonged exposure to direct sunlight and hot environments (13). Both short-term and chronic exposure to extreme heat can cause a range of health issues for outdoor workers (14). Heat-related illnesses, cardiovascular diseases (15), are common risks. Workers may also suffer from decreased physical and mental performance (16), along with kidney disorders (17). These effects can significantly influence workers' performance, safety, and efficiency. Greater awareness and stronger protective measures are necessary to safeguard worker health.

Iran's climate is characterized by significant variability, with regions experiencing extreme heat risks, particularly in the context of climate change. Studies show a rising trend in heat stress in Tehran from 1961 to 2009. Predictions estimate a temperature increase of 1.55°C by 2050 (18). Climate models suggest that surface air temperatures will rise in all months, but precipitation patterns remain unclear (19). Iran's "Hotspot Belt" is identified as particularly vulnerable, with the highest temperature increases expected during peak summer periods (20).

Several methods have been developed to assess heat stress, but only a few, like WBGT and PHS, are widely accepted. However, many require specialized equipment to measure environmental and physiological factors, posing practical challenges and limitations (21-25). For instance, the measurement of global temperature, a key parameter in calculating the WBGT index, is not common at weather stations (26). Field measurements often require costly calibrated devices and significant time for sensor stabilization, making the process challenging. Additionally, the index primarily accounts for general environmental conditions, which may not accurately reflect heat stress for seated individuals or those wearing protective clothing (27). Reliance on approximations can result in inaccuracies, particularly in heterogeneous environments where localized heat sources are not sufficiently considered. This limitation may affect the precision of heat stress assessments and reduce their applicability in complex settings (23). Other heat stress indices, like the Predicted Heat Strain (PHS), encounter similar challenges. Their application is limited due to the need for specialized equipment and complex calculations, making them less practical for widespread use. Moreover, calculating indicators like PHS is complex and time-consuming, often disrupting workplace activities. This challenge makes its application in occupational settings difficult, limiting its practicality for real-time heat stress assessment (28). These indices provide numerical evaluations of environmental impacts on human response, yet concerns remain regarding their precision, applicability across diverse climates, and potential interference with workers' activities.

A notable alternative for assessing environmental stress is the Environmental Stress Index (ESI), which offers a valuable approach for assessing environmental heat stress, utilizing meteorological parameters like ambient temperature, relative humidity, and solar radiation. Unlike indices requiring specialized equipment, ESI provides a practical, data-driven alternative, making it more accessible for large-scale climate and occupational health studies (29,30). Developed by Moran to examine environmental effects on living organisms, ESI presents several advantages over WBGT. Firstly, it is simpler and more accessible, as it utilizes readily available weather data without requiring specialized equipment (29). Additionally, ESI can provide rapid assessments through real-time weather data, enabling timely decision-making in heat stress management (31). Moreover, with lower computational complexity, it is more user-friendly for non-specialists and practical in resource-limited environments (32). While WBGT is widely recognized as a standard for heat stress assessment, ESI offers a practical and efficient alternative, particularly in settings lacking advanced monitoring equipment. By relying on readily available meteorological data, ESI enhances accessibility while maintaining reliability in diverse environmental conditions (32).

Increasing greenhouse gas levels in the atmosphere have driven global warming, resulting in a steady rise in temperatures. Researchers are focused on predicting climate change to assess its global and regional impacts (33-35). However, computational challenges are a significant limitation in climate modeling. Dynamic models like General Circulation Models (GCMs) demand extensive computational resources, often leading to inefficiencies and potential inaccuracies, especially in long-term projections, and struggle to process complex environmental variables in real time (36). Conversely, statistical models are less resource-intensive but can suffer from instability and oversimplification of the underlying physical processes, resulting in less reliable predictions (37). Misusing models reduces their effectiveness. When built on small or unsuitable datasets, they can introduce biases and perform poorly, limiting real-world applicability. This issue is particularly critical in fields like wind energy forecasting, where model accuracy must closely align with observed data for reliable predictions (38,39). Additionally, both modeling approaches face inherent uncertainties due to the complexities of initial conditions and climate system variability. Single-model ensembles often fail to capture the full range of possible outcomes (40).

HadCM3, a comprehensive climate model developed by Valdes et al features high horizontal resolution and strong coordination between atmospheric and oceanic components (41). Although newer models have largely replaced it, HadCM3 remains valuable for regional climate projections (42). However, its low spatial resolution necessitates scaling up outputs for climate impact assessments (34,43). To address this limitation, statistical and dynamic downscaling methods are employed, with the LARS-WG model widely used for predicting future climate changes due to its statistical framework (44).

This study evaluated the ESI as a tool for predicting heat stress among outdoor workers in Iran, considering the effects of climate change. Using the HadCM3 and the LARS-WG, the research analyzed various Iranian climates and compared ESI with the widely used WBGT index. Given Iran's predominantly desert and semi-desert landscapes, extreme summer temperatures, and substantial outdoor workforce, assessing ESI's applicability for future climate projections is essential. Since ESI has been underutilized in Iranian climate studies, its suitability must be thoroughly examined before implementation. This research compared ESI and WBGT across nine distinct climates, offering a broader evaluation than previous studies, which often focus on limited climatic conditions. The study also addressed the gap in the existing literature by investigating ESI's usability compared to WBGT, an index more commonly employed in heat stress assessments. Exploring the effectiveness of ESI could provide new insights into its advantages, limitations, and potential applications. Given the limited research on heat stress indices in Iran, these findings contribute valuable knowledge for a region highly vulnerable to climate change and global warming. Practical implications include occupational health improvements and enhanced emergency planning, as ESI may serve as a viable alternative or complement to WBGT in specific climatic conditions.

Materials and Methods

Climate Categorization and Study Environment

This research was conducted in Iran, a country located in Western Asia, situated between 25° and 40° north latitude and 44° and 63° east longitude. According to the primary objective of the study—assessing the applicability of the Environmental Stress Index (ESI) in Iran's outdoor settings—we selected various climates. These included hot and dry, hot and humid, and temperate regions with varying intensities to ensure comprehensive analysis. Consequently, nine distinct climates were chosen based on the DeMartonne climate classification, with some modifications to suit the Iranian context. The cities were selected based on the prevailing weather conditions during the hottest months of the year (June, July, August, and September), as the aim was to evaluate heat stress using the ESI. This approach was adopted to enable the generalization of the results to all provinces of the country with similar weather patterns. Atmospheric parameters were obtained from the National Meteorological Organization for the period between 1992 and 2021. Table 1 presents details on station locations, climatic characteristics, and meteorological data for the studied cities. It includes key parameters such as minimum and maximum air temperature and relative humidity (RH), offering a comprehensive overview of environmental conditions during the hottest months. Assessing thermal stress indices during peak heat months—June to September—provides critical insights into human health

Table 1. Climate Characteristics of the Study Regions: Trends in Air Temperature (Ta), Relative Humidity (RH), and Regression Aquation

Climate category	Nominal category	Representative sites	Ta (ºC) (Mean ± SD)	RH (%) (Mean ± SD)	R	Regression aquation
1	Arid, cool, and warm to very warm regions	Qom	41.60 ± 3.45	30.73 ± 6.24	0.861	$RH = -1.45581*t_a + 69.383$
2	Semi-arid, moderate, and very warm regions	Ahvaz	46.00 ± 4.98	36.01 ± 9.53	0.927	$RH = -1.5061*t_a + 68.318$
3	Semi-arid, cool, and warm regions	Mashhad	38.00 ± 3.53	45.80 ± 7.95	0.903	$RH = -1.4961*t_a + 67.318$
4	Arid, cool, and warm regions	Kerman	35.30 ± 2.85	35.27 ± 6.97	0.868	$RH = -1.5561*t_a + 65.318$
5	Arid, cool, and very warm regions	Yazd	41.80 ± 3.99	32.33 ± 6.25	0.934	$RH = -1.5047*t_a + 68.441$
6	Arid, moderate, and very warm regions	Bandar abbas	41.00 ± 2.83	61.53 ± 9.91	0.884	$RH = -1.4971*t_a + 69.383$
7	Humid, cool, and warm regions	Sari	31.31 ± 2.95	64.14 ± 9.01	0.910	$RH = -1.2769*t_a + 61.388$
8	Semi-humid, cool, and warm regions	Gorgan	33.85 ± 3.09	62.67 ± 8.49	0.862	$RH = -1.2671*t_a + 61.483$
9	Post-Humid, cool, and warm regions	Rasht	29.91 ± 2.93	72.15 ± 9.11	0.847	$RH = -1.2747*t_a + 61.441$

risks and environmental conditions. Research confirms these indices are most effective in outdoor settings during summer, where stress levels are the highest. A targeted timeframe enhances feasibility and ensures comprehensive data collection, particularly in urban areas facing severe heat stress (45-47). Since this study utilized publicly available meteorological data and did not involve human participants, ethical approval was not required.

Prediction Climate and Data Scaling

The study applied the HadCM3 climate model to project future climate changes, focusing on atmospheric responses to rising greenhouse gas levels in the coming decades. This model enables long-term assessments of temperature trends, precipitation shifts, and heat stress impacts across different regions. HadCM3 is a widely used coupled climate model that enables long-term prediction of climate parameters using scenarios approved by the Intergovernmental Panel on Climate Change (IPCC). The scenarios are based on various assumptions regarding population growth, economic development, technological advancement, living standards, and energy production options. In this study, the researchers focused on the A1B and A2 scenarios, which emphasize the balanced use of different energy sources, low population growth, and rapid technological advancements. A1B envisions rapid economic growth, a peaking global population, and balanced energy use via swift technological advancements, leading to moderate-to-high emissions with technological optimism. In contrast, A2 describes a fragmented world with continuous population growth, slower, diverse economic and technological progress, and higher emissions due to less international cooperation (48). To downscale the output from the HadCM3 climate model, the researchers employed the Long Ashton Research Station Weather Generator (LARS-WG) model. LARS-WG is a stochastic weather generator used to simulate daily precipitation, radiation, and temperature extremes for present and future climate scenarios. It accounts for prevailing climatic conditions, enabling reliable projections for meteorological analysis and climate impact assessments. Modeling of radiation and temperature is accomplished using a semi-empirical probability distribution and a Fourier series, respectively.

Data Quality Assessment

Data quality was carefully evaluated to ensure the accuracy and reliability of the results, particularly in handling missing values and outliers. Missing data reduces statistical power, while outliers may distort estimates, leading to misleading conclusions. To ensure data reliability, the study used imputation techniques to fill missing values and applied statistical methods like Z-scores and Interquartile Range (IQR) tests to detect outliers. These steps helped maintain the integrity of climate data used in modeling (49).

LARS-WG Model Calibration and Validation

The study calibrated the LARS-WG model using statistical metrics like Root Mean Square Error (RMSE) and Coefficient of Determination (R^2) to assess its accuracy in replicating observed climate variables. These measures ensured reliable climate simulations. Previous research has shown that LARS-WG effectively models daily weather patterns, with RMSE values indicating strong accuracy in predicting temperature and precipitation across various locations (50). Model validation involved comparing generated synthetic data with observed records to confirm the model's robustness across varying climatic conditions (51).

The results of applying this model to generate meteorological data (air temperature and precipitation) in Canada and the United Kingdom have demonstrated its high level of accuracy (44,52). The model operates in three stages: calibration, evaluation, and meteorological data generation. The model's inputs consisted of meteorological data from various stations, including their name, locations, altitudes, and daily weather records. Following this, the evaluation phase generated an output file containing simulated monthly averages for the entire study period.

Previous research has shown that extended datasets improve predictive reliability by capturing climate variability and long-term patterns. Studies such as Bloomfield (53) and Massoudi (54) support the effectiveness of multi-decadal data in climate modeling, reinforcing its validity for projecting future environmental stress conditions.

Calculation Index

Human comfort in different climates is primarily influenced by four key parameters: air temperature, relative humidity, air velocity, and radiation. Among these, air temperature and relative humidity are considered the fundamental parameters and are used to determine the primary thermal indicators (9). In this study, thermal stress was measured using two indices: the Environmental Stress Index (ESI) and the Wet Bulb Globe Temperature (WBGT) index. The ESI is derived from the Moran formula, which utilizes the following parameters: ambient temperature (Ta), relative humidity (RH), and solar radiation (SR) (29). The formula for calculating the ESI is as follows:

$$ESI = 0.63 \times Ta - 0.03 \times RH - \frac{-0.073}{(0.1 - SR)} \quad (1)$$

Where Ta is the ambient temperature (°C), RH is the relative humidity (%), and SR is the solar radiation (W/m²). The term $\frac{-0.073}{(0.1-SR)}$ represents an inverse function, adjusts the contribution of solar radiation to reflect its inverse relationship with heat dissipation. When solar radiation is low, the denominator approaches 0.1, leading to a more negative contribution, while high SR reduces this term's magnitude. This formulation ensures that intense sunlight increases the heat stress level, while limited solar radiation has a weaker impact.

(Note: Although the SR term may appear unusual, it is derived empirically to reflect solar radiation's nonlinear impact on thermal stress.)

This index provided a comprehensive assessment of the thermal environment, taking into account the combined effects of temperature, humidity, and solar radiation. In addition to the Environmental Stress Index (ESI), the study also utilized the Wet Bulb Globe Temperature (WBGT) index to measure thermal stress. The WBGT was calculated according to the following formula:

$$WBGT = 0.567 \times t_a + 3.94 + 0.393 \times E \quad (2)$$

$$E = \frac{RH}{100} \times 6.105 \times e^{17.27 \times \frac{tg}{273.7+} t} \quad (3)$$

Where *ta* is the average air temperature (°C), *RH* is the relative humidity (%), and *E* is the vapor pressure of water (hPa).

The WBGT index provided a comprehensive assessment of the thermal environment by considering the combined effects of air temperature, relative humidity, and other environmental factors. This index is widely used to evaluate thermal stress and its impacts on human comfort and well-being.

Statistical Analysis

The data analysis was conducted using SPSS 20 and Microsoft Excel 2013, employing descriptive statistics, Pearson correlation, and Intra-class correlation. The study set a confidence level of p-value < 0.05 for the statistical analysis. The intra-class correlation (ICC) analysis was performed to evaluate the agreement between the ESI and the WBGT across different climatic regions. ICC values range from 0 to 1, with higher values indicating stronger reliability. According to standard classification criteria, ICC values below 0.5 indicate poor reliability, while values between 0.5 and 0.75 reflect moderate reliability. Values between 0.75 and 0.9 are considered good, and those above 0.9 signify excellent reliability in statistical assessments. This framework was applied to assess the robustness of ESI as an alternative to WBGT, particularly in regions experiencing extreme climatic conditions. ICC calculations were conducted using a two-way random effects model, considering absolute agreement to ensure comprehensive reliability assessment (55). Linear regression was applied to examine relationships between meteorological parameters (temperature, relative humidity, and solar radiation) and heat stress indices. These methods rely on key statistical assumptions, including normality, independence, and variance homogeneity, but are sensitive to sample size and model selection. Additionally, while ensuring linearity and consistent residual variance, it may be affected by multicollinearity and outliers, which can distort results and impact interpretation.

Results

Table 1 presents the climatic characteristics of the study regions, including mean air temperature (Ta) and relative humidity (RH) for the hottest months (June–September) for the base period from 1991 to 2021. Due to the fact that the LARS model did not provide the relative humidity parameter, the researchers calculated the correlation coefficient between air temperature and relative humidity in the meteorological data from 1992 to 2021. A linear regression equation was then used to estimate relative humidity values. Notably, Ahvaz recorded the highest mean temperature at 46.00°C, while Rasht had the lowest one at 29.91°C. Rasht also exhibited the highest relative humidity (72.15%), whereas Yazd had the lowest one due to its arid climate.

Table 2 presents the intra-class correlation (ICC) analysis comparing the ESI and WBGT across four months—June through September—in nine Iranian cities. The analysis indicates strong agreement for seven cities (Qom, Rasht, Gorgan, Yazd, Sari, Kerman, and Mashhad). For these cities, the ICC values were notably high (ICC > 0.9), with lower and upper bounds ranging from 0.995 to 0.999. This indicates a robust agreement between the ESI and WBGT, suggesting that both indices consistently reflect similar environmental stress levels. In contrast, the cities of Ahvaz and Bandar Abbas demonstrated lower ICC values of 0.872 and 0.787, respectively.

The highest ICC values were observed in June and August, both reaching an impressive 0.999, indicating a near-perfect correlation between the two indices during these months. In contrast, September exhibited the lowest ICC at 0.966, although this still reflects a strong relationship between ESI and WBGT. The overall ICC between ESI and WBGT was calculated to be 0.993, with lower and upper bounds of 0.992 and 0.999, respectively.

The bar charts in Figures 1A–I illustrate the projected changes in the ESI and WBGT under the A1B and A2 emission scenarios across nine cities from 2025 to 2099. The data reveal a strong correlation between both indices, highlighting their reliability in assessing heat stress across diverse climatic conditions. Figure 1A (Qom) demonstrates a sharp increase in both indices, peaking in July, which aligns with its arid desert climate. High ICC values confirm a strong agreement between ESI and WBGT, reinforcing their predictive accuracy in

Table 2. Intra-Class Correlation (ICC) Analysis of ESI and WBGT Across Nine Cities Over Four Months

City	Month	ESI (Mean ± SD)	WBGT (Mean ± SD)	Intraclass Correlation	0.95 Confidence Interval	
					Lower bound	Upper bound
Qom	Jun	20.20 ± 1.67	21.10 ± 1.78	0.999	0.998	0.999
	Jul	25.86 ± 1.79	26.86 ± 1.81			
	Aug	25.44 ± 1.80	26.64 ± 1.84			
	Sep	24.2 ± 1.66	25.35 ± 2.02			
Ahvaz	Jun	29.87 ± 1.99	30.97 ± 2.01	0.872	0.822	0.908
	Jul	32.98 ± 1.93	32.98 ± 1.78			
	Aug	31.67 ± 1.67	32.86 ± 1.81			
	Sep	31.44 ± 1.86	32.55 ± 2.03			
Mashhad	Jun	22.76 ± 1.79	23.86 ± 2.02	0.999	0.995	0.998
	Jul	26.10 ± 1.66	27.29 ± 2.01			
	Aug	25.37 ± 1.99	26.75 ± 1.78			
	Sep	25.2 ± 1.67	26.48 ± 1.84			
Kerman	Jun	19.01 ± 1.93	19.91 ± 2.03	0.999	0.999	0.999
	Jul	24.54 ± 1.86	25.56 ± 2.01			
	Aug	24.30 ± 1.79	25.31 ± 1.80			
	Sep	24.24 ± 1.80	25.04 ± 1.78			
Yazd	Jun	25.78 ± 1.99	26.58 ± 1.85	0.997	0.995	0.998
	Jul	29.02 ± 1.66	30.04 ± 2.03			
	Aug	28.21 ± 1.80	29.22 ± 1.84			
	Sep	26.60 ± 1.86	27.40 ± 1.80			
Bandar Abbas	Jun	27.28 ± 1.99	28.05 ± 1.78	0.787	0.754	0.821
	Jul	29.64 ± 1.67	30.66 ± 1.81			
	Aug	28.74 ± 1.93	29.75 ± 2.02			
	Sep	28.01 ± 1.66	27.05 ± 2.01			
Sari	Jun	17.69 ± 1.79	18.49 ± 1.85	0.999	0.999	0.999
	Jul	23.66 ± 1.80	24.68 ± 1.80			
	Aug	23.17 ± 1.86	24.18 ± 2.03			
	Sep	22.75 ± 1.99	23.55 ± 1.85			
Gorgan	Jun	21.52 ± 1.66	22.32 ± 2.01	0.998	0.997	0.999
	Jul	26.57 ± 1.67	27.69 ± 1.78			
	Aug	26.28 ± 1.97	27.29 ± 1.84			
	Sep	26.06 ± 1.93	26.86 ± 1.81			
Rasht	Jun	22.13 ± 1.79	22.80 ± 2.02	0.997	0.996	0.998
	Jul	25.91 ± 1.66	26.88 ± 1.78			
	Aug	25.48 ± 1.67	26.44 ± 1.84			
	Sep	25.22 ± 1.80	26.06 ± 1.81			
Intraclass Correlation in June				0.999	0.999	0.999
Intraclass Correlation in July				0.992	0.990	0.994
Intraclass Correlation in August				0.999	0.998	0.999
Intraclass Correlation in September				0.966	0.957	0.973
Intraclass Correlation overall				0.993	0.992	0.999

Implications for Occupational Health Policies.
ICC > 0.9 (High Agreement): Supports standardized heat stress assessment and uniform guidelines for workplace safety measures.
0.8 – 0.9 (Moderate Agreement): Indicates reliable application but suggests minor adjustments for localized conditions.
ICC < 0.8 (Lower Agreement): Requires site-specific adaptations, such as revised exposure thresholds and customized mitigation strategies.
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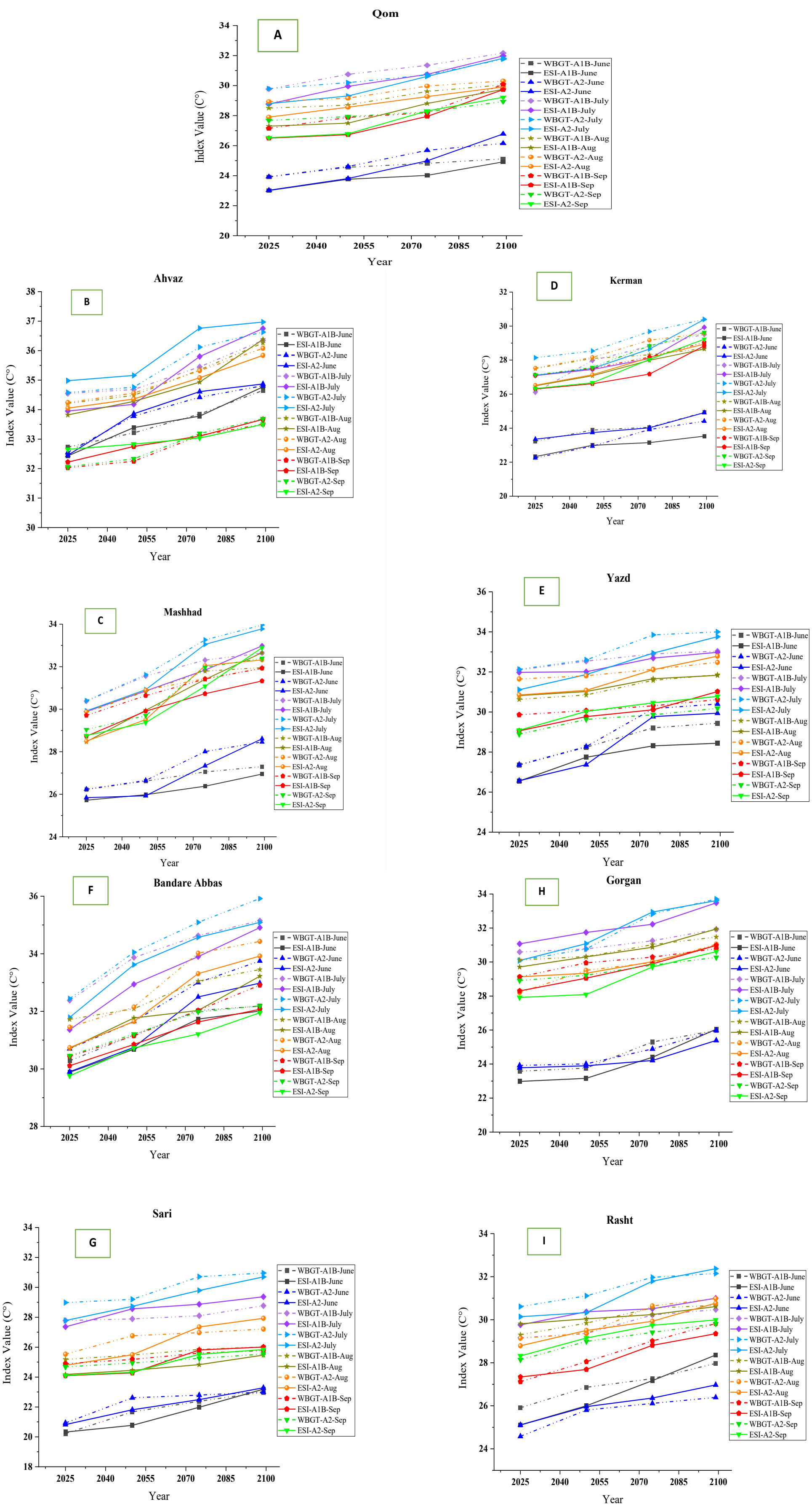

Figure 1. Projected ESI and WBGT from 2025 to 2099 under A1B and A2 climate scenarios during June to September in nine Iranian cities: Qom (A), Ahvaz (B), Mashhad (C), Kerman (D), Yazd (E), Bandar Abbas (F), Sari (G), Gorgan (H), and Rasht (I)

extreme heat conditions. Figure 1B consistently shows elevated ESI and WBGT values, identifying Ahvaz as the most heat-stressed city in the dataset. This highlights its vulnerability to extreme temperatures and underscores the importance of effective heat stress mitigation strategies. Under the A2 scenario, values approach or exceed 36°C by 2099, with July being the peak month. Mashhad presents moderate thermal stress, with WBGT exceeding 27°C in the A2 scenario. The close tracking of ESI, particularly in August and September, supports its validity in semi-arid environments and highlights its potential for integration into early warning systems, as illustrated in Figure 1C. Figure 1D (Kerman) shows a steady increase in heat stress, with strong alignment between ESI and WBGT, particularly under A1B. Yazd, characterized by an arid climate, exhibits substantial increases in both indices, with WBGT nearing 30°C by 2099. The close correlation between ESI and WBGT, as shown in Figure 1E, validates ESI as a reliable heat stress predictor in dry regions. Figure 1F (Bandar Abbas) presents higher WBGT values relative to ESI, particularly in July and August. The relatively low ICC values indicate ESI's limitations in humid climates, necessitating refinements in heat stress assessments for coastal regions. If unmitigated, the projected temperature increases could pose severe public health risks. Sari demonstrates that despite relatively mild temperatures, high humidity significantly raises WBGT levels, particularly in the A2 scenario. As illustrated in Figure 1G, the noticeable divergence between ESI and WBGT in August–September highlights the need for humidity-sensitive stress indices. Gorgan exhibits a gradual increase in both indices, with a strong correlation between ESI and WBGT observed throughout the projection period. As highlighted in Figure 1H, stress levels remain moderate but progressively reach concerning thresholds by 2099. Figure 1I (Rasht) exemplifies the impact of high humidity on WBGT values despite lower ambient temperatures. ESI's underrepresentation of thermal stress in this city, coupled with lower ICC values, underscores its limitations in post-humid zones and the need for multi-index approaches to improve heat stress assessments.

Discussion

Historical data align with previous studies, highlighting significant climatic variations across regions and underscoring the need for localized heat stress mitigation strategies. Ahvaz recorded the highest mean temperature (46.00°C), while Rasht had the lowest one (29.91°C), along with the highest relative humidity (72.15%). In contrast, Yazd exhibited minimal humidity due to its arid climate. These findings reinforce existing research and emphasize the necessity of tailored adaptation measures. As climate change accelerates, resilience-building strategies must address both arid and humid conditions. Keikhosravi et al identified Ahvaz as highly vulnerable to extreme temperatures, necessitating targeted public health interventions (56). Conversely, Hesam et al (2021) highlighted the unique heat stress management challenges faced by humid coastal cities like Rasht, despite their relatively lower temperatures (57). Additionally, Rojanasarot et al estimated global productivity losses due to heat stress at 2.1 trillion USD, emphasizing the economic impact of high temperatures (58).

The findings for Yazd further underscore the implications of arid climates, which often necessitate different adaptation strategies compared to more humid environments. Adaptation strategies differ significantly between arid and humid regions. In arid environments, measures often prioritize water conservation and diversified livelihoods to counter rising temperatures and declining rainfall (59,60). Al-Bouwarthan et al highlighted the significant risks of occupational heat stress in Saudi Arabia, particularly in climates comparable to Yazd. While our study underscores the importance of incorporating additional environmental parameters for more comprehensive heat stress assessments, their research focused on alternative indices such as the Heat Index (HI) and Humidex (HD), demonstrating how local climatic conditions influence the reliability of different metrics. Both studies project an increasing threat of heat stress due to climate change, reinforcing the urgency of implementing proactive public health strategies to protect vulnerable populations in extreme climates (61). As climate change progresses, diversified strategies will be essential to ensure resilience across different climatic contexts. Paramesh et al integrated farming systems (IFS) as an adaptation strategy to climate change in India, and several key insights emerge. While our findings highlight the increasing heat stress risk, particularly in regions like Ahvaz, Paramesh et al reported that 79% of farmers in India have observed rising temperatures and rainfall variability, leading to the adoption of IFS to enhance resilience. This contrast illustrates the diverse approaches to climate adaptation—our study focused on heat stress indices for public health planning, while theirs underscores agricultural diversification as a key adaptation tool. Together, these studies reinforce the need for localized and sector-specific strategies that integrate environmental and socio-economic factors to effectively address climate change challenges (60). Laue et al provide valuable insights into heat stress adaptation in urban informal settlements across several African countries, including Egypt. Their study highlights the challenges faced by poor urban residents exposed to extreme temperatures and emphasizes that heat stress is often overlooked compared to other climate adaptation needs. While their research focuses on qualitative adaptation strategies—such as alternative building designs and greening approaches—our study quantitatively assesses heat stress in Iranian cities using

ESI and WBGT indices. This difference in methodology underscores the need for both environmental metrics and socio-economic adaptation strategies to fully address heat stress impacts. Integrating findings from both studies can enhance understanding of mitigation strategies, emphasizing the importance of urban planning and public health interventions tailored to extreme climates (62). A comparative perspective incorporating Laue et al's insights could strengthen the validity of our conclusions, leading to more effective recommendations for heat stress management in Iran and similar climatic regions.

The analysis reveals a strong agreement between the Environmental Stress Index (ESI) and the Wet Bulb Globe Temperature (WBGT) across seven cities—Qom, Rasht, Gorgan, Yazd, Sari, Kerman, and Mashhad—consistent with previous studies that have established WBGT as a reliable indicator of heat stress. The intra-class correlation (ICC) analysis further supports the robustness of these indices in diverse climatic conditions, with high ICC values (above 0.9) indicating their reliability for occupational heat stress assessments and workplace safety regulations. However, lower ICC values (below 0.8) in Ahvaz and Bandar Abbas suggest that extreme localized climatic factors, such as high humidity and temperature, may influence index performance. These variations underscore the need for site-specific adaptations in occupational health strategies, including customized cooling interventions, modified work-rest schedules, and enhanced protective measures. To improve the applicability of heat stress indices in varying environments, future policy frameworks should account for regional climatic variability, ensuring more precise heat exposure guidelines and improved worker safety in regions experiencing extreme conditions (63,64). With ICC values exceeding 0.9 and extremely narrow confidence intervals ranging from 0.995 to 0.999, the findings indicate excellent reliability between these two heat stress indices. The results of this study are consistent with those of previous studies in IRAN. Zare et al found strong correlations between ESI and WBGT, reinforcing ESI's applicability in occupational heat stress assessments (65). Similarly, Habibi et al validated ESI against WBGT in various indoor work environments in Isfahan, Iran, demonstrating a high correlation and suggesting ESI's applicability in short-term heat stress assessments (66). It is also consistent with research conducted in other countries with similar climatic conditions. Research by Debnath further supports ESI's relevance, particularly in South Asian megacities, where extreme heat significantly affects worker productivity and increases vulnerability (67). The high concordance between ESI and WBGT suggests ESI can reliably serve as a proxy for WBGT, making large-scale heat stress monitoring feasible in scenarios where WBGT measurements are impractical. This robust correlation enhances the credibility of ESI as a tool for public health and occupational safety interventions.

Moreover, the high values of ICC in cities such as Yazd and Kerman underscore the importance of regional context when assessing environmental stress. Much of the existing literature emphasizes the need for localized assessments due to varying climatic and geographical factors. Lapola et al analyzed heat stress vulnerability at a super-local scale in Brazilian cities, emphasizing microclimatic and socio-economic factors (68). Comparatively, Yazd and Kerman's high ICC values suggest that regional climate and geography strongly affect index reliability, indicating that generalized models may overlook crucial local variations—an aspect Lapola et al acknowledge but could be investigated further.

The study highlights near-perfect intra-class correlation (ICC) values for key environmental indices, confirming their reliability and potential for enhancing public health monitoring and predictive modeling. Hess et al propose an evidence-based framework for climate change adaptation, emphasizing the integration of environmental data with surveillance and early warning systems to mitigate heat-related health risks. Their approach aligns with research demonstrating improved accuracy in forecasting heat-related illnesses when multiple environmental indicators are considered (69). This study builds on that foundation, supporting future research efforts to develop comprehensive models for proactive health policies in different climatic contexts. The strong correlation between ESI and WBGT during peak summer months, particularly June and August, highlights critical periods for public health interventions. Targeting these months allows health authorities to allocate resources efficiently and implement preventive measures to protect vulnerable populations from heat-related illnesses (70).

These findings suggest that a single approach to measuring environmental stress may not fully capture climate-health interactions in all locations. Consequently, Ahvaz and Bandar Abbas require region-specific adaptations of environmental indices. While some correlation exists between ESI and WBGT, variations in climatic conditions influence their accuracy. Prior literature confirms that cities with similar temperatures but differing humidity levels exhibit variability in thermal comfort and health outcomes (67). This reinforces the need for customized assessments to account for local environmental influences on heat stress.

Lower ICC values in Ahvaz (0.872) and Bandar Abbas (0.787) raise concerns about the applicability of ESI and WBGT in varying climatic conditions. These discrepancies suggest that factors such as extreme humidity, high temperatures, and urban microclimates can influence the relationship between these two indices. Kong et al analyzed biases in ESI compared to WBGT, finding ESI suitable for average heat stress assessments but less effective in extreme heat scenarios (32). However, Mohammadian et al identified strong correlations between WBGT, ESI, and other indices, reinforcing the relevance of ESI for occupational heat stress assessments, particularly in regions like Jiroft, where high temperatures and humidity prevail (71). Unique climatic challenges, such as extreme humidity, high temperatures, and specific urban microenvironments, can influence the relationship between (72). These findings suggest that a single approach to measuring environmental stress may not fully capture climate-health interactions in all locations. Consequently, Ahvaz and Bandar Abbas require region-specific adaptations of environmental indices. While there are some correlations between ESI and WBGT, variations in climatic conditions influence their accuracy. Prior literature confirms that cities with similar temperatures but differing humidity levels exhibit variability in thermal comfort and health outcomes (72). This reinforces the need for customized assessments to account for local environmental influences on heat stress.

Despite these lower ICC values, both indices still show agreement in Ahvaz and Bandar Abbas, demonstrating their continued relevance for environmental stress evaluations. Multiple studies emphasize the importance of using multiple indices to assess heat-related health risks, thereby strengthening predictive models and guiding effective interventions (30,73). Employing a range of thermal indices improves forecasting and informs more precise public health strategies (63). Therefore, while the lower ICC values may indicate limitations, they should not overshadow the potential for these indices to inform public health strategies tailored to local realities.

Projected changes in ESI and WBGT under the A1B and A2 emission scenarios (2025–2099) provide valuable insights into climate-driven environmental stress across nine Iranian cities. The strong alignment between the indices over the four months underscores ESI's robustness and its reliability as a complementary metric to WBGT. Existing literature supports the use of multiple indices in climate health studies to improve assessments of heat-related risks (74). The demonstrated reliability of both measures reinforces their value in guiding adaptive health strategies to mitigate heat stress. Sharafi and Lorvand further highlight this issue in their detailed assessment of air pollutant emissions and climate projections across Iran, using ESI and WBGT under A1B and A2 scenarios to identify spatial and temporal variations in heat stress risks (75). Similarly, Hosseinpour et al found that under the A1B scenario—characterized by a balanced energy approach—ESI is expected to increase, signaling a rise in heat stress levels. The A2 scenario, reflecting a more fragmented economic trajectory, projects even greater ESI increases, emphasizing severe environmental stress and heightened public health concerns (76).

July consistently exhibits peak values for both ESI and WBGT across all analyzed cities, aligning with seasonal heat stress trends observed in previous studies (77). Brocherie et al documented the intensification of heat stress during summer, particularly in July, when temperatures reach their highest levels (78). Similarly, Hayashida et al found elevated ESI and WBGT values in July, highlighting increased environmental stress and its potential impact on public health, especially for vulnerable populations (79). The findings emphasize the necessity for targeted interventions during this critical period to mitigate heat-related health risks.

The significant differences in absolute values, including projections for Ahvaz reaching 36.19°C by 2099, reveal how local climatic conditions, such as urban heat island effects and geographical factors, can amplify climate change impacts. Brimicombe et al emphasized that the consistent peak in heat stress indices during July reinforces the importance of monitoring and addressing heat stress as a public health priority, particularly in regions prone to extreme summer temperatures (80).

The overall upward trend in ESI and WBGT across all cities highlights the broad implications of climate change on environmental stress, extending beyond traditionally vulnerable regions. Even cities with initially lower stress levels are projected to experience significant increases, indicating climate change as a universal threat to Iran's environmental stability. These projections align with Intergovernmental Panel on Climate Change (IPCC) findings, which stress the widespread impacts of climate variability on urban and rural areas, necessitating preemptive adaptation measures (81).

The contrasting effects of the A1B and A2 scenarios are particularly notable. The A2 scenario, representing a high-emissions pathway, projects more pronounced increases in heat stress indices than A1B, reinforcing the urgent need for comprehensive climate action to reduce greenhouse gas emissions. Data indicates that aggressive climate change scenarios will intensify environmental stress, demanding adaptive strategies tailored to the specific conditions of each city. Given the rising frequency of extreme heat events, public health interventions should prioritize community resilience through infrastructure improvements, public awareness initiatives, and targeted health services to protect vulnerable populations (82,83).

Conclusion

This study highlights the valuable role of both ESI and WBGT indices in assessing climate-induced heat stress across diverse urban climates in Iran. The strong intra-class correlation observed in most cities confirms that ESI can serve as a reliable alternative to WBGT, particularly in national-scale monitoring and long-term climate projections. However, variability in agreement—especially in cities such as Ahvaz and Bandar Abbas—points to the need for localized adaptation of these indices to better account for unique climatic conditions, such as extreme humidity and persistent urban heat.

Beyond academic analysis, these findings carry significant policy implications. First, ESI, given its strong alignment with WBGT in most settings and its relative simplicity, should be incorporated into national and regional heat warning systems to enhance public alertness during extreme temperature events. Second, the projected escalation of heat stress in high-risk cities like Ahvaz and Bandar Abbas suggests a pressing need to revise labor laws governing outdoor work during peak heat hours, especially in summer months. Third, targeted public health education and training programs should be developed for vulnerable populations in high-exposure areas, with a focus on heat illness prevention, hydration, and first aid. Moreover, climate adaptation plans must integrate environmental heat indices into urban planning, emergency preparedness, and infrastructure design, particularly in cities with rapidly growing populations and limited cooling resources. As climate change continues to amplify environmental extremes, localized, evidence-based approaches using tools like ESI will be essential to safeguard public health and enhance societal resilience.

This study confirms a strong correlation between ESI and WBGT, validating their use in assessing environmental stress for public health, particularly when adapted to regional conditions for effective health strategies. This study is constrained by its focus on nine Iranian cities, which may limit the generalizability of the findings to broader climatic regions. Additionally, potential data accuracy concerns and the exclusion of certain local environmental factors could impact the robustness of the analysis. While temperature, relative humidity, and solar radiation serve as key parameters in assessing outdoor heat stress, other influential variables—such as wind speed, vegetation cover, land surface temperature, and air pollution—were not incorporated. These factors significantly affect microclimatic conditions and human thermal exposure, and their omission may influence the precision and applicability of the ESI and WBGT in specific settings. Future research should integrate these elements to enhance the accuracy of heat stress modeling and provide a more comprehensive framework for evaluating environmental stressors under changing climate conditions.

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Competing interests

Authors declare that they have no competing interests.

Ethical issues

We certify that all data collected during the study are presented in this manuscript and no data from the study has been or will be published separately.

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