

Modeling and predicting trends of heat stress in the outdoor environment using the CanESM2 model based on RCP scenarios: A case study in Yazd, Iran

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Abstract

Background: This study modeled changes in heat stress in outdoor environments over the coming decades, considering the effects of climate change and global warming.

Methods: We used the Wet Bulb Globe Temperature (WBGT) and Humidex (HD) indices, based on the CanESM2 General Circulation Model (GCM) and the Statistical Downscaling Model (SDSM), to analyze data from the Yazd station, a location with a dry climate. Daily data on minimum and maximum temperatures and relative humidity were collected from the Yazd Meteorological Station for the base period of 1976–2005. Modeling was then performed for three 30-year periods: 2011–2040, 2041–2070, and 2071–2099, using three scenarios: RCP 2.6 (RCP 2.6), RCP 4.5 (RCP 4.5), and RCP 8.5 (RCP 8.5).

Results: The results showed a clear increasing trend in both minimum and maximum temperatures across all periods and scenarios, with the most significant rise projected for 2071–2099. The WBGT and HD indices also followed an upward trend compared to the base period. Specifically, temperature increases were projected at 11.53%, 17.55%, and 29.04%, while WBGT and HD indices showed increases of 9.71%, 14.72%, and 24.84%, and 16.33%, 24.84%, and 41.95%, respectively.

Conclusion: Overall, the modeling period from 2011 to 2099 indicated a consistent increase in temperature, humidity, WBGT, and HD across all months. This persistent trend highlights a growing challenge of heat stress due to climate change, underscoring the critical need for increased awareness and strategic planning for risk management in both communities and ecosystems.

Keywords: Temperature, Climate change, Global warming, Strategic planning, Risk management

Citation: Asghari M, Safari Palangi H, Fallah Ghalhari G, Akhlaghi Pirposhteh E, Abbasinia M, Shakeri F, et al. Modeling and predicting trends of heat stress in the outdoor environment using the CanESM2 model based on RCP scenarios: A case study in Yazd, Iran. *Environmental Health Engineering and Management Journal*. 2025;12:1512. doi: 10.34172/EHEM.1512

Article History:

Received: 2 January 2025

Revised: 8 April 2025

Accepted: 16 April 2025

ePublished: 21 October 2025

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Introduction

Climate change is defined as a significant statistical change in average temperature, precipitation, weather patterns, wind, and other climate variables over a long period, typically decades or more (1). As one of the most critical environmental challenges of the future,

long-term forecasting of climate variables is essential for understanding the extent of these changes and for developing necessary measures to mitigate their adverse effects (2). Iran, with its arid climate, is particularly vulnerable. Predictions indicate that changes in temperature, precipitation, soil moisture, and river runoff



will be among the most significant impacts of climate change in the country (3). Given the high vulnerability of Iran's central regions, including Yazd Province, to dry climatic conditions, studying the effects of climate change on temperature and humidity in these areas is especially important (4).

The primary tool developed by the Intergovernmental Panel on Climate Change (IPCC) to study the effects of climate change on global temperature and precipitation is General Circulation Models (GCMs). Specifically, models like CanESM2 are used to model global climate change (5). However, because GCMs have low spatial resolution, their outputs cannot be directly applied at the station scale. To overcome this limitation, a method called downscaling is used (6). Downscaling creates a link between large-scale atmospheric variables (predictors) and local-scale climate variables (predictands) (7). The Statistical Downscaling Model (SDSM) is a widely used, regression-based tool and is considered a highly effective conditional data generator (8).

Studies have shown that future heat stress resulting from climate change will significantly impact the health of the Iranian population through rising air temperatures (9). While most climate change studies focus on general parameters like temperature and precipitation, assessing heat stress in occupational and outdoor environments requires a more comprehensive approach. Relying on a single meteorological parameter is insufficient; instead, it is necessary to use reliable heat indices such as the Wet Bulb Globe Temperature (WBGT) and Humidex (HD) (10). These indices are favored for their low cost and lack of a need for advanced measurement equipment, making them effective screening tools for assessing heat stress. The WBGT index, in particular, is well-suited for modeling global warming and climate change using weather station data (11).

Climate change and its impact on heat stress in outdoor environments are critical bio-environmental issues that have recently attracted considerable research interest. This study focuses on the Yazd region, a city located in an arid area that has experienced significant climatic anomalies in recent years, partly due to increased industrialization and air pollution. Therefore, this study aims to investigate the projected changes in temperature, WBGT, and HD indices for the period of 1967–2099 at the Yazd station. By combining global and downscaling climate models, this research seeks to provide more accurate and practical forecasts of future trends. The specific objective is to model and forecast the trend of exposure to heat stress in outdoor environments over the coming decades using the CanESM2 GCM and the SDSM, considering three climate change scenarios, and utilizing the WBGT and HD indices.

Materials and Methods

Study Area

This study was conducted in Yazd Province, Iran, an area spanning 76,469 square kilometers. Yazd city itself is located between 31° 40' and 31° 56' N latitude and 54° 18' and 54° 24' E longitude. The city has an average elevation of 1,230 meters above sea level and is characterized by a desert and arid climate.

Data Collection

To ensure data reliability, we used meteorological data from Iran's National Meteorological Organization. Daily data for minimum and maximum temperatures (°C) and relative humidity (%) for all 12 months were sourced from the Yazd Synoptic Meteorological Station for the base period of 1976–2005. These data were then used to model and forecast future trends for air temperature, relative humidity, the Wet Bulb Globe Temperature (WBGT) index, and the Humidex (HD) index using the CanESM2 General Circulation Model (GCM) and the Statistical Downscaling Model (SDSM).

General Circulation Model (CanESM2)

The Canadian Earth System Model 2 (CanESM2) is a GCM developed by the Canadian Climate Centre. It's a complex system that simulates interactions between the atmosphere, oceans, ice, and land. CanESM2 is used to model and predict climate change on a global and long-term scale, making it an essential tool for climate change, global warming, and long-term forecasting studies (12). However, GCMs have a coarse resolution of several hundred kilometers, which means their outputs cannot be used directly for local or regional-scale studies. This limitation necessitates the use of a downscaling model.

Statistical Downscaling Model (SDSM)

The Statistical Downscaling Model (SDSM) is a widely used statistical tool that bridges the gap between the coarse outputs of GCMs and local-scale climate data. SDSM was developed by Wilby and Dawson and first became publicly available in 2001 (8).

Downscaling methods are generally divided into two categories: dynamical and statistical. Dynamic downscaling methods, such as those using Regional Climate Models (RCMs), rely on the numerical simulation of atmospheric and oceanic physical processes (13,14). SDSM, a statistical method, follows a four-step process:

1. Selection of predictor variables.
2. Model calibration.
3. Model validation.
4. Generation of future scenarios (8).

SDSM offers several advantages

- It preserves the correlation between climate variables, which is vital for studies on the hydrological impacts of climate change.

- It reduces the uncertainty of climate fluctuations by producing long-term data series.
- It requires less computational time and cost compared to dynamic methods.
- Previous studies have demonstrated that SDSM has very low error, particularly for simulating temperature, making it a reliable and robust tool for climate change impact assessment (15).

Scenarios Used in the Study

For this research, the CanESM2 GCM and the SDSM downscaling model were used to project changes in minimum and maximum temperatures and relative humidity for three future periods: 2011–2040, 2041–2070, and 2071–2099. These projections were based on three Representative Concentration Pathway (RCP) scenarios: RCP 2.6, RCP 4.5, and RCP 8.5. These scenarios represent different levels of radiative forcing, which is the imbalance between incoming solar radiation and outgoing energy from Earth's atmosphere.

WBGT Index

The WBGT index is one of the most reliable indices for assessing heat stress. This study used the WBGT index as a measure of thermal discomfort, following the simplified model presented by the Australian Bureau of Meteorology (ABM) (11). This model is practical for screening heat stress because it's low-cost and doesn't require advanced equipment. It's also suitable for modeling climate change and global warming.

The ABM's simplified WBGT calculation uses a formula that requires only air temperature (T_a) and water vapor pressure (p). Water vapor pressure is derived from air temperature and relative humidity (RH) as follows:

$$(Eq. 1) 4WBGT(^{\circ}C) = 0.567T_a + 0.393p + 3.94$$

$$(Eq. 2) p(hPa) = (RH/100) \times 6.105e(237.7 + Ta/17.27Ta)$$

Where:

- T_a : Mean air temperature ($^{\circ}C$)
- RH: Relative humidity (%)
- p : Water vapor pressure (hPa)⁵

Humidex (HD) Index

The Humidex (HD) index is another heat stress index, developed by Masterton and Richardson in 1979, that links thermal comfort to air temperature and relative humidity (16). While it was originally developed for specific climatic conditions in Canada's temperate regions, its simplicity and ease of use (even more so than the WBGT) have led to its adoption for assessing heat stress in various outdoor and indoor environments (17,18).

The HD index was calculated using the following equations:

$$(Eq. 3) HD = T_a + 0.5555 \times (p - 10.0)$$

$$(Eq. 4) p = (RH/100) \times 6.112e(237.7 + Ta/17.27Ta)$$

Where:

- HD: Humidex ($^{\circ}C$)
- T_a : Dry air temperature ($^{\circ}C$)
- RH: Relative humidity (%)
- p : Water vapor pressure (hPa)

Results

Base Period Measurements

The minimum temperature, maximum temperature, and relative humidity at the study station were measured for the base period from 1976 to 2005, as presented in Table 1.

Key observations include

- Minimum temperature: Observed in January.
- Maximum temperature: Observed in July.
- Minimum relative humidity: Observed in August.

Average Values

Minimum temperature: 12.04 $^{\circ}C$

Maximum temperature: 26.76 $^{\circ}C$

Relative humidity: 30.91%

Future Projections (2011–2099)

Modeling the parameters of minimum temperature, maximum temperature, and relative humidity for Yazd station over the next three decades (2011–2040, 2041–2070, and 2071–2099) was conducted using the CANESM2 and SDSM models. Three climate scenarios were considered: RCP 2.6, RCP 4.5, and RCP 8.5. The results, shown in Table 2, indicate that both minimum and maximum temperatures in Yazd are expected to rise across all scenarios, with the most significant increases projected for 2071–2099 under the RCP 8.5 scenario.

Table 1. Minimum and maximum temperature values, and relative humidity at the study station for the base period (1976–2005)

Month	Relative humidity (%)	Maximum temperature ($^{\circ}C$)	Minimum temperature ($^{\circ}C$)
January	54.53 $\pm$ 17.60	12.62 $\pm$ 4.90	-0.6 $\pm$ 8.00
February	43.33 $\pm$ 16.20	15.65 $\pm$ 4.76	2.00 $\pm$ 4.00
March	37.73 $\pm$ 17.30	20.15 $\pm$ 4.90	6.75 $\pm$ 4.30
April	30.52 $\pm$ 13.54	27.04 $\pm$ 4.33	12.9 $\pm$ 6.30
May	23.93 $\pm$ 10.43	32.30 $\pm$ 3.56	17.67 $\pm$ 2.30
June	17.12 $\pm$ 6.00	37.90 $\pm$ 2.62	22.16 $\pm$ 35.20
July	16.90 $\pm$ 5.74	39.56 $\pm$ 2.57	24.63 $\pm$ 2.94
August	16.60 $\pm$ 5.90	3.38 $\pm$ 2.35	22.15 $\pm$ 4.95
September	17.60 $\pm$ 9.50	34.63 $\pm$ 5.10	17.90 $\pm$ 3.10
October	26.66 $\pm$ 11.60	27.75 $\pm$ 3.90	12.00 $\pm$ 3.25
November	37.30 $\pm$ 14.00	20.40 $\pm$ 4.40	5.56 $\pm$ 3.86
December	48.70 $\pm$ 17.7	14.92 $\pm$ 5.00	1.37 $\pm$ 3.90

Table 2. Results from the model output for minimum temperature, maximum temperature, and relative humidity parameters over the coming decades until 2099, using climate models and the three mentioned scenarios for the studied station (Yazd)

Scenario	Minimum temperature (°C)			Maximum temperature (°C)			Relative humidity (%)		
	2011–2040	2041–2070	2071–2099	2011–2040	2041–2070	2071–2099	2011–2040	2041–2070	2071–2099
January									
RCP 2.6	2.8±2	3.1±2.1	2.7±1.72	17.37±2.3	17.47±2.1	17.13±1.93	54.1±5.1	54.3±5.1	54.22±5.1
RCP 4.5	2.25±2	3.5±2.1	4±1.9	16.9±2.2	18.2±2.2	18.8±2	54.44±4.5	54.7±4.72	54.23±4.7
RCP 8.5	2.6±2.1	4±2	5.55±2	17.12±2.3	19.03±2.23	1.07±2	54.44±4.8	54.6±4.83	54.33±5
February									
RCP 2.6	5±2.4	4.9±2.2	5.15±2	19.3±2.54	19±2.43	19.4±2.1	45.6±4.4	45.46±4.1	45.6±4.4
RCP 4.5	4.2±2.3	5.5±2.5	5.8±2.2	18.4±2.45	19.92±2.7	20.1±2.5	45.5±4.1	45.53±4.4	45.67±4.4
RCP 8.5	4.95±2.44	5.95±2.4	7±2.34	19.45±2.53	20.4±2.22	15.95±2.4	45.32±4.2	45.5±4.3	45.4±4.6
March									
RCP 2.6	8.4±2.56	8.75±2.6	9.2±2.6	22.9±2.83	22.9±2.65	23.6±2.9	38.5±4.5	38.53±4.7	38.85±4.6
RCP 4.5	8.4±2.5	9.13±2.57	9.9±2.5	22.8±2.66	23.71±2.56	24.4±2.8	38.5±4.5	38.7±4.46	38.6±4.46
RCP 8.5	8.65±24.5	10.12±2.63	11.43±2.6	23.2±2.8	24.8±2.7	26.4±2.7	38.6±2.42	38.34±4.3	38.56±4.6
April									
RCP 2.6	12.9±2.6	13.4±2.26	13.9±2.4	27.92±2.8	28.15±2.6	28.8±2.64	30.95±3.7	30.93±3.7	31.37±3.7
RCP 4.5	12.8±2.25	14.24±2.65	16±2.57	27.6±2.5	29.4±2.9	29.5±3.1	30.9±3.4	31.1±3.44	31.3±3.63
RCP 8.5	12.5±2.5	14.64±2.5	9±2.3	27.45±2.45	29.8±2.6	31.55±2.85	30.9±34.4	31.1±3.5	31.3±3.6
May									
RCP 2.6	18.2±3.1	18.4±2.85	17.9±2.4	33.6±3.2	33.92±3.3	33.4±2.63	24.9±3	25±2.8	25.2±2.9
RCP 4.5	17.1±2.8	18.83±2.5	18.9±2.8	33.03±3.1	34.2±2.75	34.72±2.9	25±3.6	25±3.65	24.93±3.7
RCP 8.5	17.1±2.8	19.44±2.66	20.9±2.8	32.35±3	35.1±3	36.6±2.9	24.9±2.7	24.9±2.72	25.1±2.8
June									
RCP 2.6	23.16±1.5	23.25±1.7	23.3±1.7	39.25±1.8	39.25±2	39.5±1.9	17.83±1.95	17.85±1.9	17.85±1.85
RCP 4.5	22.73±1.75	23.75±1.7	24.5±1.74	38.9±2.1	40.1±1.94	40.7±1.9	17.9±2.11	17.9±2.1	17.8±2.1
RCP 8.5	22.65±1.9	24.42±1.9	26.05±2	38.5±2.3	40.9±2.3	42.62±2.1	17.85±1.8	17.92±1.8	17.9±1.74
July									
RCP 2.6	24.44±1.53	24.25±1.52	24.42±1.6	40.9±1.17	40.7±1.7	40.9±1.72	16.8±1.8	16.8±1.83	16.77±1.8
RCP 4.5	25.44±1.2	24.9±1.5	23.6±1.7	40±1.27	41.6±4.2	42.6±1.5	16.47±1.53	16.8±1.54	16.8±1.52
RCP 8.5	28.05±1.5	25.3±1.7	23.8±1.6	40.3±1.72	42.44±1.8	45.1±1.73	16.7±1.85	16.7±1.85	16.8±1.85
August									
RCP 2.6	22.67±2	22.95±1.8	23±2.1	39.4±2.3	39.6±2.15	39.6±2.2	16.7±1.6	16.57±1.62	16.73±1.64
RCP 4.5	22.1±2.05	23.26±1.8	24.22±1.9	38.54±2.1	40.1±2	41.4±2	16.7±1.62	16.56±1.6	16.75±1.6
RCP 8.5	22.56±2	24.42±2	27.2±1.83	39.32±2	41.24±2.2	44.1±2.1	16.66±1.44	16.73	16.72±1.5
September									
RCP 2.6	19.05±2	20.1±2.2	19.63±2.3	35.55±2.1	36.6±2.33	35.95±2.42	17.3±1.7	17.26±1.73	17.4±1.7
RCP 4.5	19.13±2.1	20.43±2.1	20.7±2.4	35.4±2.4	37±2	37.32±2.6	17.3±1.9	17.3±1.95	17.44±1.9
RCP 8.5	19.3±2.4	21.46±2.11	24.15±2.3	35.9±2.5	38.4±2.4	41.1±2.4	17.23±2.15	17.3±2.1	17.4±2
October									
RCP 2.6	14.76±2.35	15.25±2.6	15.25±2.5	31.1±2.72	31.6±2.7	31.3±2.6	25.66±4	25.45±4.1	26±4.32
RCP 4.5	15.13±2.75	16±2.63	16.15±3.1	31.3±2.17	32.36±2.3	32.63±3.1	25.54±3.5	25.5±4.8	25.72±3.4
RCP 8.5	15.2±2.6	17.05±3.1	18.29±2.8	31.5±2.63	33.55±3	36±2.92	25.65±4.7	25.66±4	25.95
November									
RCP 2.6	8.88±3	9.44±3.2	8.88±3	24.53±3.3	25.3±3.2	24.6±3.5	35.8±4	36±4	36±4
RCP 4.5	8.6±3.22	10±3.1	10.2±3.3	24.32±3.6	25.84±3.1	26.13±3.3	36.94±4.1	35.9±4.4	35.9±4.4
RCP 8.5	8.4±3.5	10.85±2.7	12.77±3.2	24.2±3.65	26.92±3.1	28.8±3.4	35.9±4.2	35.72±4	35.72±4

Table 2. Continued.

Scenario	Minimum temperature (°C)			Maximum temperature (°C)			Relative humidity (%)		
	2011–2040	2041–2070	2071–2099	2011–2040	2041–2070	2071–2099	2011–2040	2041–2070	2071–2099
December									
RCP 2.6	3.95±2	4.3±2.3	3.85±2.3	18.92±2.2	19.43±2.5	18.8±2.5	47.2±4.7	47.3±4.55	47.72±4.54
RCP 4.5	37±2.2	4.6±2.55	5.22±2.5	18.85±2.4	19.48±2.8	20.35±2.64	47.3±4.5	47±4.64	47.64±4.55
RCP 8.5	4.25±2.26	5.75±2.8	7.42±2.46	19.1±2.65	21.45±2.9	23±2.57	47.15±4.6	47.25±4.6	47.7±4.7

RCP 2.6 Scenario: Minimum temperature is expected to increase by 13.62% in the period 2011–2040. The highest minimum temperature occurs in July, while the lowest is in January. Maximum temperature is projected to rise under all scenarios, with the highest values in January and the lowest in July. Relative humidity is also anticipated to increase slightly.

Maximum Temperature Results

RCP 2.6 Scenario

2011–2040: 19.9% increase

2041–2070: 10.2% increase

2071–2099: 9.94% increase

RCP 4.5 Scenario

2011–2040: 7.73% increase

2041–2070: 12.66% increase

2071–2099: 14.79% increase

RCP 8.5 Scenario

2011–2040: 8.55% increase

2041–2070: 19.58% increase

2071–2099: 19.02% increase

Relative Humidity Results

RCP 2.6 Scenario

2011–2040: 0.1% increase

2041–2070: 0.1% increase

2071–2099: 0.71% increase

RCP 4.5 Scenario

2011–2040: 0.1% increase

2041–2070: 0.25% increase

2071–2099: 0.25% increase

RCP 8.5 Scenario

2011–2040: 0.06% increase

2041–2070: 0.1% increase

2071–2099: 0.6% increase

Heat Index Categories (WBGT)

Table 3 presents the frequency and percentage of heat index categories based on the WBGT index for different scenarios.

Key findings include

Comfort: No-Risk Days

- First 30 years: Decreases of 1.83%, 1.79%, and 16.34% for RCP 2.6, RCP 4.5, and RCP 8.5 scenarios, respectively.
- Second 30 years: Decreases of 19.97%, 42.97%, and 34.97%.

- Third 30 years: Decreases of 25.84%, 35.76%, and 71.01%.

Hot Days

- First 30 years: Increases of 1.72%, 8.02%, and 5.01%.
- Second 30 years: Decreases of 2.17%, 0.23%, and 11.69%.
- Third 30 years: Increases of 1.37%, 9.23%, and a decrease of 18.84%.

Extremely Hot Days

- First 30 years: Increases of 30.21%, 21.69%, and 26.60%.
 - Second 30 years: Increases of 42.56%, 52.08%, and 66.26%.
 - Third 30 years: Increases of 28.82%, 54%, and 47.04%.
- A very hot (dangerous) heat index category was added from the 2011–2040 decade. The number of very hot (dangerous) days increased significantly across all scenarios.

Humidex Index Categories

Table 4 presents the frequency and percentage of heat index categories based on the Humidex for different scenarios.

Key findings include

Cold Stress Days: Decrease over time, most rapidly under the RCP 8.5 scenario.

- First 30 years: Decreases of 12.67%, 11.09%, and 10.01%.

Comfortable Days

- First 30 years: Increases of 0.18%, 10.08%, and 2.82%.
- Second 30 years: Decreases of 1.8%, 5.82%, and a slight increase of 0.02%.
- Third 30 years: Increases of 3.42% under RCP 2.6, with decreases under other scenarios.

Discomfort Days

- First 30 years: Increases of 28.13%, 16.34%, and 41.67%.
- Second 30 years: Increases of 50.09%, 68.24%, and 98.81%.
- Third 30 years: Increases of 40.11%, 85.04%, and

Table 3. Frequency and percentage of heat stress index based on the WBGT for three different scenarios over different time periods

Time periods	Thermal feeling	Scenario					
		Optimistic (RCP 2.6)		Pessimistic (RCP 8.5)		Pessimistic (RCP 8.5)	
		N	%	N	%	N	%
1975-2005	Comfort-no risk	5580	51.2	5580	51.2	5580	51.2
	Hot-caution	3078	27.9	3078	27.9	3078	27.9
	Hot-extreme caution	2300	20.9	2300	20.9	2300	20.9
2011-2040	Comfort-no risk	4817	44	4819	44	4796	43.8
	Hot-caution	3131	28.5	3325	30.4	3235	29.5
	Hot-extreme caution	2995	27.5	2799	25.6	2912	26.6
	Very hot - dangerous	7	0.1	7	0.1	7	0.1
2041-2070	Comfort-no risk	4651	42.5	4345	39.7	4134	37.8
	Hot-caution	3011	27.5	3068	28	2718	24.8
	Hot-extreme caution	3279	29.9	3498	31.9	3824	34.9
	Very hot - dangerous	9	0.1	39	0.4	274	2.5
2071-2099	Comfort-no risk	4434	41.9	4110	38.8	3261	30.8
	Hot-caution	3151	29.8	2791	26.4	2498	23.6
	Hot-extreme caution	2963	28	3542	33.5	3382	32
	Very hot - dangerous	37	0.3	142	1.3	1444	13.6

Table 4. Frequency and percentage of heat stress index based on the HD for three different scenarios over different time periods

Time periods	Thermal feeling	Scenario					
		Optimistic (RCP 2.6)		Pessimistic (RCP 8.5)		Pessimistic (RCP 8.5)	
		N	%	N	%	N	%
1975-2005	Cold stress	6019	55	6019	55	6019	55
	Comfort	3331	30.4	3331	30.4	3331	30.4
	Some discomfort	1603	14.6	1603	14.6	1603	14.6
2011-2040	Cold stress	5342	48.8	5418	49.5	5471	50
	Comfort	3337	30.5	3667	33.5	3425	31.3
	Some discomfort	2271	20.7	1865	17	2054	18.8
2041-2070	Cold stress	5260	48	4888	44.6	4626	42.2
	Comfort	3271	29.9	3365	30.7	3137	28.6
	Some discomfort	2419	22.1	2697	24.6	3187	29.2
2071-2099	Cold stress	4894	46.2	4630	43.7	3792	35.8
	Comfort	3445	32.5	2983	28.2	2658	25.1
	Some discomfort	2246	21.2	2972	28.1	3945	37.3
	Severe discomfort, avoid activity	-	-	-	-	190	1.8

146%.

Temperature Changes Over Time

Figure 1. Projected average temperature changes under three Representative Concentration Pathway (RCP) scenarios for the period 2071–2099 relative to the baseline (1976–2005): (a) RCP 2.6 scenario shows the lowest temperatures in January during the baseline period and the highest in July toward the end of the century, with an average temperature increase of 11.53% (2.24 °C); (b)

RCP 4.5 scenario exhibits similar seasonal patterns and an average increase of 17.55% (3.41 °C); (c) RCP 8.5 scenario follows consistent trends with the most pronounced warming, reflecting an average increase of 29.04% (5.71 °C).

WBGT Index Changes

Figure 2. Projected changes in the Wet Bulb Globe Temperature (WBGT) index by the end of the century (2071–2099) relative to the baseline period (1976–2005)

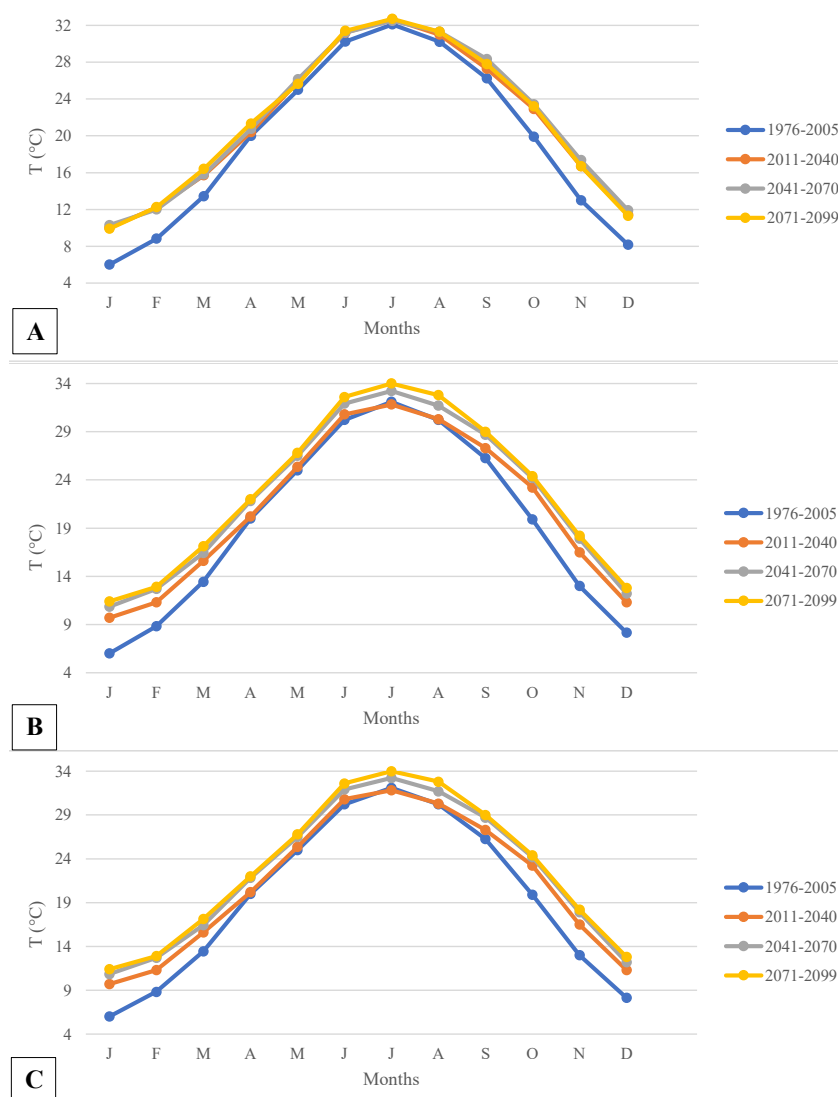


Figure 1. Average temperature changes in Yazd city (RCP 2.6, RCP 4.5, and RCP 8.5 scenarios)

under three Representative Concentration Pathway (RCP) scenarios: (a) RCP 2.6 scenario shows an average increase of 9.71% (1.69 °C); (b) RCP 4.5 scenario shows an average increase of 14.72% (2.56 °C); (c) RCP 8.5 scenario shows the highest increase, with an average rise of 24.84% (4.32 °C).

Humidex Index Changes

Figure 3. Projected changes in the Humidex index by the end of the century (2071–2099) relative to the baseline period (1976–2005) under two Representative Concentration Pathway (RCP) scenarios: (a) RCP 2.6 scenario shows an average increase of 16.33% (2.84 °C); (b) RCP 4.5 scenario exhibits similar trends, with a notable rise in thermal discomfort levels.

Discussion

In this study, which models heat stress exposure trends in outdoor environments over the next three decades (2011–2099), climate change and global warming are taken into

consideration. It utilizes the Wet Bulb Globe Temperature (WBGT) and Humidex (HD) indices, alongside the Canadian Earth System Model (CanESM2) and the Statistical Downscaling Model (SDSM) for Yazd Province, Iran. The results indicate that the lowest minimum temperatures and highest relative humidity occur in January, while the highest maximum temperatures are observed in July. The study also highlights the significant role of general atmospheric circulation in influencing these climatic phenomena (19).

The modeling results indicate that the lowest minimum temperature over the next three decades is expected to occur in January during the RCP 2.6 scenario (2011–2040). Interestingly, in the RCP 4.5 and RCP 8.5 scenarios for this same period, a slight decrease in minimum temperature is observed compared to the baseline. However, subsequent periods consistently show an increase in minimum temperature across all scenarios. This finding contrasts with a study by Ranjbar et al who found severe cold stress in Tehran during the winter months (20). In Yazd, an

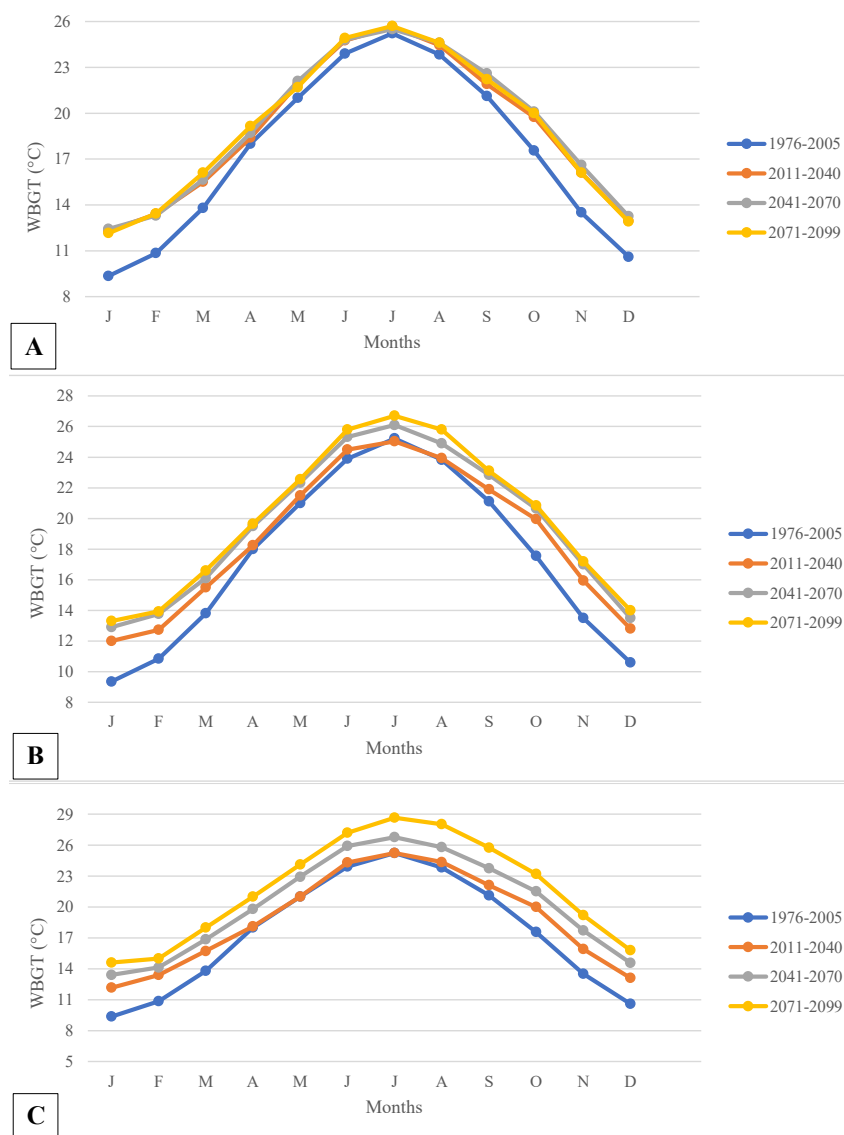


Figure 2. Average WBGT changes in Yazd city (RCP 2.6, RCP 4.5, and RCP 8.5 scenarios)

increasing temperature trend is observed even in the cold seasons, along with a decrease in relative humidity. This global rise in temperatures leads to significant changes in Earth's climate and the timing of climatic events, which aligns with the findings from Akbary et al regarding global warming and atmospheric changes in Iran (21).

The modeling results further indicate that the highest maximum temperature over the next three decades will occur in July during the RCP 8.5 scenario (2071–2099), with increases in maximum temperatures observed across all scenarios compared to the baseline. A study by Zareian et al found that climate change will lead to rising annual temperatures and decreasing precipitation in Yazd Province, noting that the general circulation model effectively simulates these changes (22). Fallah Ghalhari et al also reported a general increase in the heat stress index in Iran, particularly in semi-arid regions, classifying many meteorological stations as high-risk for health impacts during the summer (23). Poorkarim et al highlighted

that climate change not only affects average temperature and precipitation but also increases the frequency of extreme weather events (24). Additionally, Barzegari and Malekinezhad, using the CanESM2 model, predicted a temperature rise of 0.2 to 8.1 degrees Celsius by 2100 at Yazd Synoptic Station (25). These findings are in strong alignment with the current study's results.

A study by Asghari et al also forecasted an increasing trend in minimum and maximum temperatures for the coming decades in Kerman, with more pronounced increases expected from 2071 to 2099 (26). This projected temperature rise will lead to greater thermal discomfort across all seasons. Yazd Province, characterized by its dry and hot desert climate, receives an average rainfall of only 95 mm, making it one of the driest areas in Iran. Given these conditions, understanding climate changes and their impacts is crucial for effective risk management and the development of adaptation strategies to mitigate the adverse effects of climate change on communities,

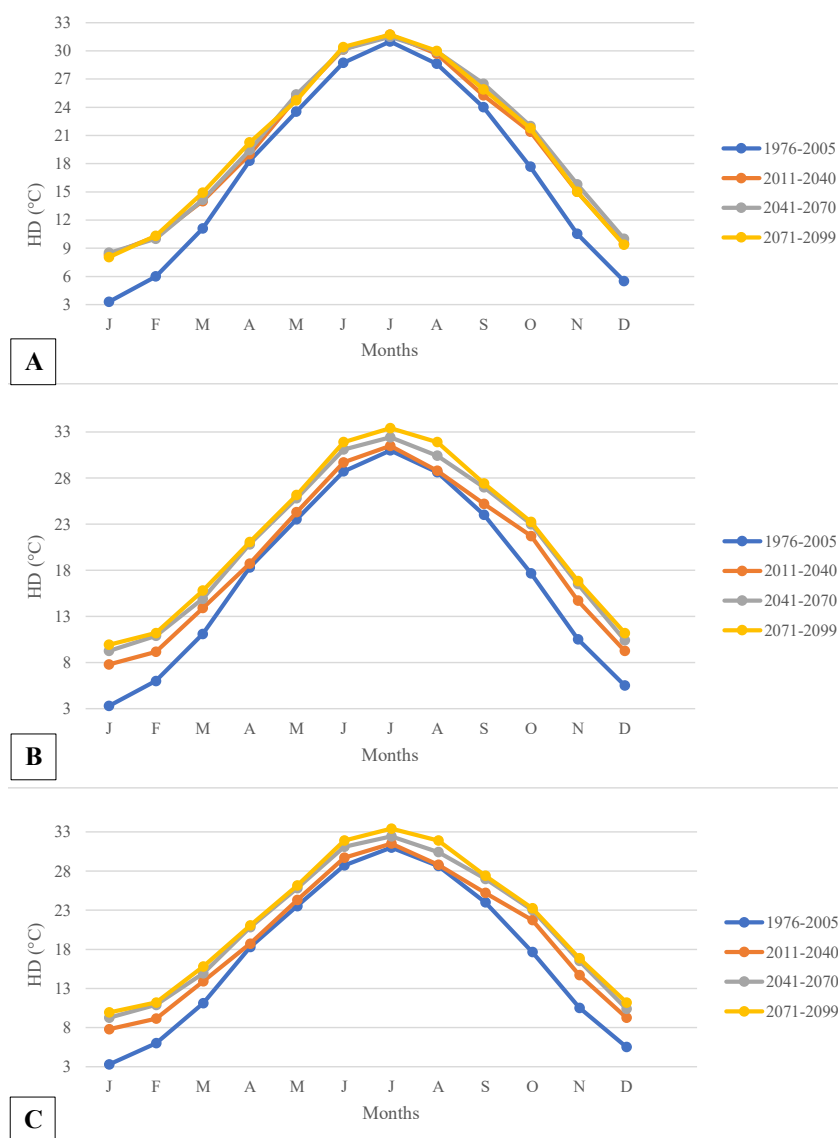


Figure 3. Average HD changes in Yazd city (RCP 2.6, RCP 4.5, and RCP 8.5 scenarios)

ecosystems, and infrastructure (5).

The highest relative humidity over the next three decades is expected in January during the RCP 8.5 scenario for the period 2041–2070, with only a slight increase in relative humidity across all scenarios compared to the baseline. A study by Tabari et al found a general downward trend in humidity indices in Iran from 1966 to 2005, with significant trends at only eight of 41 stations (27). Water vapor plays a key role in Earth's temperature balance, influencing both heat and cold stress occurrences (28). High temperatures combined with elevated humidity can have severe effects, which vary by region and population sensitivity (29). Ataei et al reported that Yazd Province has been experiencing increasing drought since 1997, which complicates urban planning. This trend necessitates the development of strategies to manage risks associated with drought and its impacts (30).

The modeling predicts a decrease in the frequency of "comfortable" (safe) thermal sensations based on

the WBGT index over the coming decades, with a notable increase in "hot" and "warm" conditions. This is particularly severe in the RCP 8.5 scenario and the third 30-year period. A significant finding is the emergence and rapid rise of a "very hot" (dangerous) thermal sensation, with its frequency increasing from 7 to 1444 in the RCP 8.5 scenario across all periods, indicating a heightened risk. Fallah Ghalhari et al found the highest heat stress index values in dry climates (18), while Asghari et al reported similar trends in thermal comfort across various climates in Iran, which aligns with these findings (2). Modeling for the Humidex index shows a decrease in cold stress conditions, particularly in the RCP 8.5 scenario, with an initial increase in comfortable days followed by a subsequent decline. Over time, an increase in "somewhat uncomfortable" conditions is expected across all scenarios (31). Understanding thermal comfort is crucial for human activities, and this study specifically focuses on changes in heat stress in Iran using the temperature-humidity

index to assess the combined effects of temperature and humidity.

Alizadeh-Choobari et al analyzed meteorological data from 15 regions in Iran (1951–2013) and found that average daily temperatures are rising in most areas, while precipitation is declining (32). This indicates that Iran has become drier over recent decades. The warm climate of arid and semi-arid regions near the tropics leads to prolonged saturation of the atmosphere with water vapor, which affects precipitation patterns by transferring moisture to higher latitudes. The increasing heat stress resulting from human activities and global warming poses significant challenges to water, air, and soil ecosystems. The modeling and forecasting results indicate that the severity of these impacts will increase in the coming decades. Selecting appropriate climate models and error correction methods remains a key challenge, as highlighted by Dehghani et al who evaluated the uncertainty in regional climate change models using the CanESM2 model (33). They noted that errors in climate models are inevitable, particularly at smaller scales and in mountainous regions, which underscores the importance of using downscaling models to correct these errors.

The rise in temperature and heat stress significantly impacts public health and safety, leading to both human and financial losses, particularly in high-humidity conditions (34). Jahangir et al highlighted that climate change poses significant challenges for agriculture and water resources, using the CanESM2 model and statistical downscaling with SDSM under various RCP scenarios to predict temperature parameters (35). Their findings indicate that the SDSM model effectively predicts temperature changes at synoptic stations. In Yazd Province, characterized by a dry climate, any fluctuations in temperature and precipitation will adversely affect water resources. Projections suggest an increase in temperature in Yazd until 2099, even under RCP 2.6 emission scenarios. Heidari et al noted that heat stress may intensify in central and southern Iran, necessitating the implementation of control policies (29). Modarres et al found that future heat indices could exceed safe thresholds for human adaptation in Iran, emphasizing the need for early warning systems and strategic healthcare, economic, and social planning (36). Many countries already utilize weather service sensors to issue warnings and implement pre-defined measures during heat waves (37).

While this study provides valuable insights into the increasing trend of heat stress in Yazd Province, it is important to acknowledge its limitations. The study primarily relied on modeling data, which may not fully capture the complexities of real-world climate systems. Additionally, the focus on Yazd Province limits the generalizability of the findings to other regions with varying climatic conditions. Furthermore, this research

did not account for the potential impacts of adaptation strategies, such as urban greening or improved building design, which could mitigate the effects of heat stress.

Future research can address limitations by:

- Combining modeling with ground-based observations to improve projection accuracy and local climate understanding.
- Expanding studies to other regions in Iran and neighboring countries for a broader view of regional climate change patterns and heat stress impacts.
- Investigating the combined effects of temperature, humidity, and other climate variables like wind speed and solar radiation on heat stress for a more comprehensive risk assessment.
- Incorporating probabilistic approaches and uncertainty analysis to better quantify potential future climate scenarios and their impacts.

Conclusion

Yazd Province faces an arid climate and water scarcity, leading to efforts to model heat risk for people exposed to heat stress. Modeling predicts that the lowest minimum temperatures and highest relative humidity will occur in January (2011–2040), while the highest maximum temperatures will be in July (2071–2099) under RCP 8.5 scenarios. Overall, from 2011 to 2099, temperature, relative humidity, and heat indices will increase across all scenarios. As time progresses, thermal comfort will decrease, resulting in more heat stress. Rising global temperatures will cause significant changes in climate patterns and heat stress occurrences. Using models like CanESM2 and SDSM can help understand heat stress distribution and inform preventive policies in Iran.

Acknowledgments

This study was supported by a research grant (No. 18846) from Iran University of Medical Sciences. The authors would like to thank the Iranian Meteorological Organization for providing the meteorological data.

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Competing interests

The authors declare that there is no conflict of interest in this study.

Ethical issues

Ethical approval for this study was obtained from the Research Ethics Committee of Iran University of Medical Sciences (Code: IR.IUMS.REC.1400.020).

Funding

This study was financially supported by a research grant (No. 18846) from Iran University of Medical Sciences.

Declaration of AI usage

This study employed Gemini, an advanced AI language model, along with Monica, to improve the linguistic quality of the manuscript and to create several summaries.

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