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Evaluating the wind cooling potential on outdoor thermal comfort in selected Iranian climate types

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ABSTRACT

Wind is one of the main factors affecting people's outdoor thermal sensation. Ongoing urbanization and urban densification are transforming the urban climate and complicating the pedestrian-level wind environment. Therefore, the main aim of this research is to evaluate the potential wind-cooling effect on human outdoor thermal conditions. Accordingly, the current research attempts determine the best wind directions for thermal comfort at the studied stations and how these factors will be changed under the effects of global warming. Outdoor thermal conditions were modeled based on the physiologically equivalent temperature (PET) thermal index using RayMan software for the decades of the 2000s and the 2040s in different climate types of Iran (Csb, BWh, Csa, and BSh) To estimate the potential cooling effect of wind, the PET was calculated (1) under actual wind conditions, and (2) under calm wind (0.05 m/s) conditions. Then, the ΔPET for these two conditions, which indicates the cooling potential effect (CPE) of the wind, was calculated for four representative stations (Ardebil, Bandar Abbas, Gorgan, and Shiraz). In comparison with the 2000s, the results indicated that by the 2040s, the predicted wind cooling potential will have increased in Ardebil, Shiraz, Bandar Abbas and Gorgan (CPE of 13.2 °C, 13.1 °C, 11.2 °C, and 11 °C, respectively). Based on the overall average of two climate change scenarios (A2 and B1) used in this study, the occurrence of "comfortable" conditions by the 2040s will have increased in Bandar Abbas, Shiraz, and Ardebil by 1.1%, 0.4%, and 0.3%, respectively, while it will have decreased in Gorgan by 1.5%. Accounting for the cooling effect of wind, the comfort cooling potential of wind is predicted to rise by an average of 1.6 °C in the 2040s compared with the 2000s in all the studied stations. Therefore, this will affect the microclimates positively and could reduce the urban heat island effects.

1. Introduction

Climate science shows that an unprecedented rate of climate change on Earth will occur in the current century (Rosselló-Nadal, 2014). Furthermore, urbanization has been rapidly increasing as a large part of the world population is migrating from rural to urban areas. Thus, city-induced climate change has severe consequences for public health, tourism, and outdoor activities. Therefore, researchers have been increasingly interested in studying the adverse effects of urbanization on thermal sensation and conditions in cities (Jamei et al., 2016; Roshan et al., 2020).

Wind is a significant factor affecting thermal sensation in urban climates (Sadeghi et al., 2018). Ketterer and Matzarakis (2014) indicate that air temperature alone is not an appropriate measure to quantify the intra-urban spatial variability of climate with respect to human thermal comfort. As shown in Fig. 1, wind is one of the principal climatic factors, along with urban morphology, surface coverage, and traffic, that should be evaluated to determine urban thermal comfort. Ancient builders in temperate and hot climates manipulated the shade coverage and wind velocity to improve the microclimate (Attia, 2006). Therefore, the study of wind is essential to assess urban climates.

Wind is characterized by mean speed, including but not limited to wind speed, direction, and turbulence intensity (Attia and Duchhart, 2011). These wind characteristics have been proven to have a mechanical and thermal effect on the human body. However, the outdoor environment represents a complex climatic element for urban climate assessments (Sadeghi et al., 2018). Although the importance of wind has been acknowledged in literature (Yuan, 2018), few studies have

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quantified the cooling potential of wind and estimated the climate change impact on the cooling effect.

Because of the limited knowledge regarding the cooling potential of wind on outdoor thermal comfort, the current study was motivated by the convergence of various large weather datasets and climate modeling techniques. Cities have complex microclimates, and wind is a significant component of urban climate due to wind nuisance, human thermal comfort, and tourism, and hospitality industries (Matzarakis et al., 2013). In this paper, we present a unique and validated urban climate modeling approach that can yield valuable insights for various economic sectors. We used state-of-the-art urban climate modeling tools to assess thermal comfort conditions in different seasons. Therefore, the findings of this research can aid outdoor and urban designers, city operators, and developers as well as help in attaining environmental and economic benefits.

In urban environments, the evaluation of the cooling potential of wind is imperative to reduce negative impacts during extreme events, such as heatwaves and heat stress. Therefore, in this study, we aimed to quantify the cooling potential of wind under different climatic conditions of Iran. More specifically, the following questions are answered:

- What are the thermal comfort conditions with regard to different wind directions?
- What are the most desirable wind conditions for the stations studied?
- What are the best wind directions from an urban climate point of view?
- What will be the effects of climate change on the cooling effect of wind by 2040?

1.1. Literature review

The effects of wind on the human outdoor thermal comfort play a vital role in cities (Stathopoulos, 2006; Liu et al., 2019). Wind has the potential to ventilate cities and disperse pollutants thereby positively influencing public health (Fadl and Karadelis, 2013; Hang and Li, 2010; Wu and Niu, 2017). Climate elements that have a direct impact on human perception are temperature, humidity, sunshine, radiation, precipitation, and wind (Grillakis et al., 2016). Among the driving factors behind thermal sensation, wind in the outdoor environment represents a complex climatic element (Sadeghi et al., 2018). With rising climate change and the intensification of urbanization, average temperatures are increasing, with more extended periods of intense heat in subtropical, tropical, and arid climates (Gill et al., 2007). Therefore, it is essential to assess the cooling effect of wind and maintain a pleasant wind environment from both urban planning and public health perspectives.

To assess the effect of wind cooling potential on thermal comfort, meteorological data and outdoor thermal comfort criteria should be combined. Meteorological data are typically available from national meteorological services and local weather stations (Soligo et al., 1998). The choice of outdoor thermal comfort is a crucial part of the assessment of wind cooling potential. In the past, a wide range of outdoor thermal comfort criteria have been proposed.

Early studies of outdoor human thermal comfort began in the 1900s in the factories and mines of Western Europe. The earliest outdoor thermal comfort index was the ‘effective temperature’ by Houghten and Yaglou in the USA (Houghten, 1923). This index was initially established to provide a method for determining the relative effects of air temperature and humidity on comfort. In 1957, Yaglou and Minard developed the ‘wet-bulb globe thermometer’ index (Yaglou and Minard, 1957). Their paper described methods of investigating the total heat stress imposed by physical training, temperature, radiation, humidity, and wind on men in three military camps. This was followed by the development of the ‘discomfort index’ by Thom (1959). Steadman developed the ‘wind-chill’ index and refined it in 1979 through the ‘apparent temperature’ index (Steadman, 1971, 1979a; 1979b). The previous studies were primarily designed for the calculation of thermal quantities of the body, i.e., skin temperature, core temperature, sweat rate, or skin wetness, and did not explicitly address air movement.

As a more universally applicable model than those previously presented, Peter Höppe developed the ‘physiological equivalent temperature’ (PET) index —a universal index for the biometeorological assessment of the outdoor thermal environment (Höppe, 1999). PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed. The basis for the calculation of the PET is the Munich energy balance model for individuals (MEMI) (Höppe, 1984, 1994). Individual heat flows (measured in Watts) are affected directly by air temperature, air humidity, air velocity, and mean radiant temperature. The advantage of the PET index is that it is based on a thermo-physiological heat-balance model, which allows the prediction of the cooling effect of wind.

Among the relevant studies regarding wind cooling potential on outdoor thermal comfort is the work of Xie et al. (2018), who studied the sensitivity of outdoor thermal comfort to wind speed. Their results demonstrated that increasing the wind speed from “breeze” to “mild

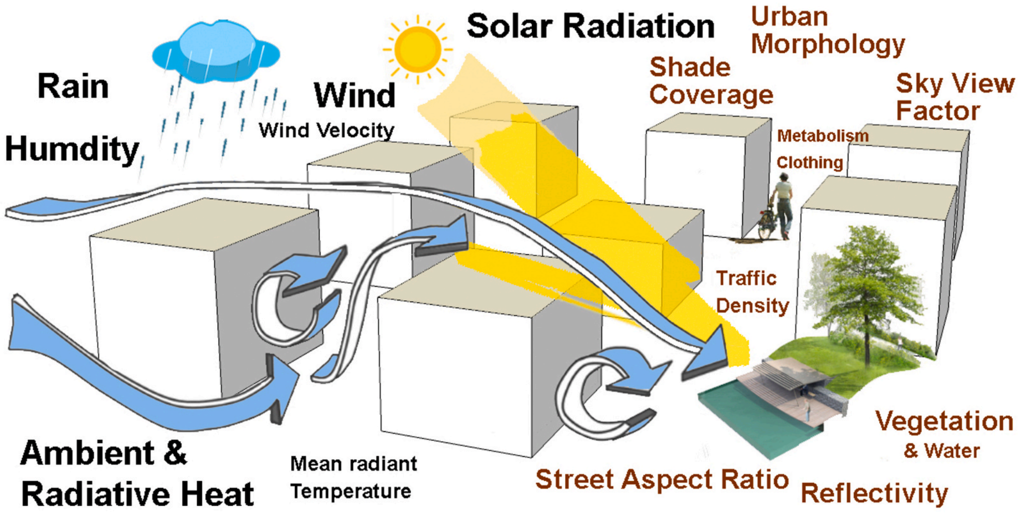

Fig. 1. Factors that influence urban thermal comfort (climate factors in black and design factors in brown).

wind" could create a considerable cooling effect when the operative temperature was lower than 34 °C. Sadeghi et al. (2018) developed a bioclimatic wind rose tool integrating wind parameters on thermal comfort in Sydney. Their results indicated that wind from the East-North-East during 90 h of "strong heat stress" generated a cooling potential of 3 °C. Additionally, they predicted that the comfort cooling potential of wind could rise by an average of 2.7 °C by 2030 compared with 2013. Niu et al. (2015) documented that significant local variations in thermal comfort could be generated due to the combined effects of shading and wind amplification. Furthermore, an assessment of wind characteristics and the outdoor thermal comfort in East Malaysia demonstrated that the wind cooling effect could moderate stable heat stress conditions (Hanipah et al., 2017). Therefore, evaluating the impact of the wind cooling potential on outdoor thermal comfort reveals to architects or urban designers that winds are desirable from a thermal comfort point of view. Wang et al. (2019) explored the relationship between wind speed and the seasonal comfort level in Nanjing. They concluded that understanding the impacts of different landscape designs on the wind could support urban designers in improving the wind environment.

However, thus far, limited studies have investigated the passive cooling potential of wind for outdoor comfort (Adamek et al., 2017; Al-Sallal and Al-Rais, 2012; Shashua-Bar et al., 2012). In general, extensive assessments of wind comfort have been conducted using wind tunnels or numerical computational fluid dynamic (CFD) simulations (Adamek et al., 2017; Blocken and Carmeliet, 2004; Du et al., 2017a,b; Hang et al., 2010; Liu et al., 2017). However, those studies focused mostly on pedestrian-level wind comfort and the thermal cooling effect of wind as separate entities. Therefore, more extensive research on the wind cooling potential on outdoor thermal comfort is needed, especially regarding the relation between the thermal wind effect and the urban heat island effect, causes of urban heat stress, impacts of climate change, and seasonal trends of wind on outdoor thermal comfort.

In this paper, we present the results of a simulation that was designed to evaluate the wind cooling potential on outdoor thermal comfort in four climate types in Iran to address several points mentioned above. The most significant aspect of this study considered the cooling effect of the wind direction in four different climates, which can be used as a bioclimatic wind rose to identify wind cooling effects for these climate types. Therefore, the results of this research could be used not only in the study area but also in any region with the same climate.

2. Materials and methods

The physiologically equivalent temperature (PET) index was used to evaluate the cooling potential of wind on human thermal comfort for the decades of the 2000s and the 2040s using the RayMan model software. RayMan uses different variables to calculate PET. These variables can be classified into three categories as follows (Matzarakis et al., 2007; Matzarakis et al., 2010):

- Geographical information of the location in question, such as latitude, longitude, and altitude.
- Meteorological and climate data, including dry air temperature (°C), relative humidity (%) or vapor pressure (hPa), wind speed (m/s), and cloudiness (octas).
- Human related variables, such as age, gender, weight, height, and clothes type. In this research, the default of model used was of males with a height of 1.75 cm, weight of 75 kg, and age of 35. For clothing insulation, a value of 0.9 clo was taken, and 80 W was considered for the amount of activity. The complete description of this model can be found in the research of Matzarakis et al. (2007, 2010).

It should be noted that the calculation of PET was performed for four different climate types in Iran including 1) Ardebil with Mediterranean warm/cool summer climates (Csb), 2) Bandar Abbas with a tropical savanna climate (Aw/As), 3) Gorgan with a Mediterranean hot summer climate (Csa), and 4) Shiraz with hot semi-arid climate (Bsh), based on the Köppen climate classification. Fig. 2 and Table 1 represent the geographical location and climatic characteristics of these four stations.

Two separate PET index calculations were made to evaluate the wind cooling potential on outdoor thermal conditions for the typical meteorological year (TMY[1]): one with the actual TMY wind speed and the other a "calm" wind speed (set to a constant 0.05 m/s) (Boland, 2008). The differences between the two PET calculations, with and without wind, were then defined as the cooling potential effect (CPE) of the wind expressed as ΔPET or CPE degrees (°C) (Sadeghi et al., 2018) (Eq. (1)).

$$\Delta PET\ or\ CPE = PET(windy\ condition) - PET(Calm\ condition) \tag{1}$$

The outputs from the PET calculations have been classified into a set of nine broad categories, as defined in Table 2 (Matzarakis and Mayer, 1996).

2.1. Cooling potential calculation

To better identify the cooling potential of the wind, the wind directions were divided into eight main categories: 0–44° (North-Northeast), 45–89° (Northeast-East), 90–134° (East-Southeast), 135–179° (Southeast-South), 180–224° (South-Southwest), 225–296° (Southwest-West), 270–314° (West-Northwest), and 315–360° (Northwest-North). Then, the "no-thermal stress or comfort" zone was determined for each wind direction for the studied stations in the TMYs of 2000s and 2040s.

The TMY data included weather data for all four locations comprising data of 8760 h (1 yr). The data for each decade also consisted of the long-term average of the 8760 h of recorded data. These data were extracted for the 2000s from the data records of Iran's Meteorological organization, while the 2040s climate data were predicted using the Meteonorm software (Remund, 2008) with the most recent version of the HadCM3 general circulation model (Collins et al., 2001).

2.2. Scenarios calculation

The Meteonorm software was also used for the climate change scenarios (Remund et al., 2010; Remund and Grossenbacher, 2019). The results of IPCC emission scenarios were used as the inputs. The anomalies in the temperature, precipitation, and global radiation parameters, and three scenarios B1, A1B, and A2 were included in this model. However, for this study, we selected Scenarios A2 and B to simulate the effects of climate change (by the 2040s) on wind cooling effects for the studied stations.

The A2 scenario describes an extremely heterogeneous world, with an underlying theme of the self-reliance and preservation of local identities. Fertility patterns across the regions converge slowly, which results in a continuously increasing global population. Economic development is primarily regionally oriented, and the per capita economic growth and technological changes are more fragmented and slower than in other scenarios (Nakicenovic et al., 2000).

The Bl scenario describes a convergent world with the same global population as in the A1 scenario that peaks in mid-century and then declines. However, B1 simulates a rapidly changing economic structure toward a more service- and information-based economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives (Nakicenovic et al., 2000).

Meteonorm could apply Scenarios A2 and B1 and to extract climatic data by interpolation for each site on an hourly and minutely time scale. The global radiation data were acquired from the Global Energy Balance

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[1] -Typical Meteorological Year.

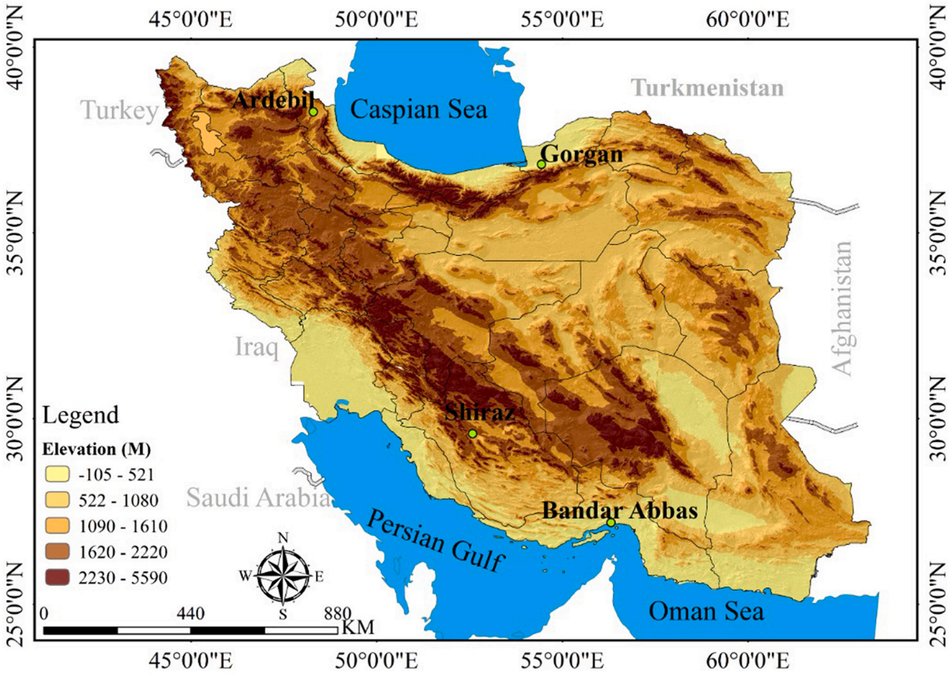

Fig. 2. Location of studied stations in Iran.

Table 1
Geographical and climatic characteristics of studied stations.

Station	Longitude	Latitude	Elevation (M)	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)	Mean Relative Humidity (%)	Climate Type (Koppen-Geiger Classification)
Ardebil	48.30°E	38.25°N	1338	10	295	71	Csb
Bandar Abbas	56.17°E	27.11°N	10	28	171	67	BWh
Gorgan	54.26°E	36.50°N	160	18	601	70	Csa
Shiraz	52.32°E	29.37°N	1540	18	317	40	BSh

Table 2
Traditional thresholds of PET, as well as the proposed category boundaries, used in the present study.

Level of thermal stress	Thermal perception for PET	PET (°C)
Extreme cold stress	Very cold	<4
Strong cold stress	Cold	4–8
Moderate cold stress	Cool	8–13
Slight cold stress	Slightly cool	13–18
No thermal stress	Comfortable	18–23
Slight heat stress	Slightly warm	23–29
Moderate heat stress	Warm	29–35
Strong heat stress	Hot	35–41
Extreme heat stress	Very hot	>41

Archive (GEBA, http://protogeba.ethz.ch). All meteorological data for this software were obtained from WMO, NCDC, and five meteorological satellites. In Meteonorm, the Markov chain random generator method was used to generate the daily net radiation data, and the auto regression method was used to create hourly and minutely data. Additionally, the temperature data were based on the net radiation and measured values from approximately 5000 meteorological sites and stations worldwide. The software was also able to produce other meteorological data, such as precipitation, wind speed, and humidity.

Finally, after accessing the desired climate data, the PET index values were calculated for both the 2000s and 2040s for the winds in eight primary geographical directions, and the CPE of the winds were determined for all the climate types studied in Iran.

3. Results

In this section, we group the results for each climate type and city separately. For each city, we discuss the existing urban climate and CPE of the wind. Then, we present the results of the future wind scenarios.

3.1. Model validation

The outputs of the general circulation models (GCMs) have uncertainties due to their low resolution, inability to reflect local features, and insufficient skill in the physical simulation of some climatic variables. Therefore, their outputs must be downscaled using dynamic or statistical methods for use in local or regional research. For instance, Mohan and Bhaskaran (2019) used the quantile matching method to correct the systematic errors of the wind speed calculations provided by GCMs to overcome these errors using statistical methods (Mohan and Bhaskaran, 2019). Therefore, for our study, we improved the output of the GCMs spatiotemporally using the Meteonorm software, observation values, and remote sensing data to address the uncertainties. Hence, to improve the data quality spatially and temporally, the interpolation methods and the Markov chain random approach were used, respectively (Meteotest, 2009; Remund et al., 2010; Robert and Kummert, 2012; Bellia et al., 2015; Herrera et al., 2017; Dodoo and Ayarkwa, 2019; Nematchoua et al., 2019; Osman and Sevinc, 2019; Bienvenido-Huertas et al., 2020; Roshan, 2020). Accordingly, R^2, normalized root mean square error (NRMSE), and bias (BIAS) were used to evaluate and validate the GCM. The GCM was implemented for the 2000s, and its results were compared with observational data. Table 3 represents the statistical determinants for air temperature, humidity, wind speed, and radiation.

The model evaluation indicates that the smallest simulation errors were produced for radiation and temperature due to their lowest coefficients of variation throughout the year, while the maximum error was estimated for the wind speed component (Table 2). This indicates that any element with lower variability is simulated with fewer errors. According to Table 2, the lowest errors for temperature and humidity belong to the Bandar Abbas station. Bandar Abbas is a port city whose climate pattern is strongly influenced by the Persian Gulf and Oman Sea and has low daily and seasonal temperature and humidity fluctuations (Roshan et al., 2012). This low variability caused the simulated values to have slight errors when compared with the observed values and to estimate the lowest errors for Bandar Abbas compared with the other stations.

Conversely, Shiraz has a semi-desert climate type that has high temperature and humidity fluctuations throughout the year. Precipitation, which is affected by humidity in this region, is concentrated in the autumn and winter, while the temperature rises during the spring and summer with no rain events. These factors cause more variability in the temperature and humidity in the area throughout the year (Setoodeh et al., 2004; Fitchett et al., 2014). Because of this high variability, the most elevated modeling errors for these components were observed for the Shiraz station.

Although the bias value of the model is positive for all the climate variables, it is negative for the wind speed component. Its results indicate that the simulated data are less valuable than the actual data for the observation period. However, Gorgan is an area with a diverse topography, natural features, and is surrounded by water bodies, forests, and mountains. Therefore, its climate is affected by the atmospheric systems and varied local features. During the cold seasons, Siberian high pressure and westerlies affect its environment, while the Azores high pressure from the south controls its climate during the warm seasons. The activity and variability of these systems throughout the year significantly alter the wind flow (Ghanghermeh et al., 2015; Hashemi-Tilehnoee et al., 2016; Jahromi et al., 2017). As shown in Table 3, the highest errors of wind speed modeling were observed for this station. Finally, the lowest error for radiation was found for Shiraz, probably due to its semi-desert climate and clear skies through most of the year (Fazelpour et al., 2013) causing little sunshine variability.

3.2. Wind cooling potential in Mediterranean warm/cool summer climate (Csb)

The Ardebil station was selected to identify the cooling potential of the wind in a Mediterranean warm/cool summer climate (Raziei, 2017). The long-term average PETs for windy and calm conditions for all wind directions at this station were approximately 9.90 and 22.80 °C, respectively. These results indicate that in the absence of wind, Ardebil inhabitants would feel as if it were 12.90 °C warmer than it would feel with the wind.

The wind direction analysis indicates that the prevailing wind at the Ardebil station was from the West-Northwest and Northwest-North (270–360°), with a total of 2832 h or 35% of the time (the 2000s). These predominant winds are known as Germich winds, created by Mediterranean and Black Sea air masses. The detailed bioclimatic interpretation of these winds is given as follows:

- These winds provide the "comfortable" or "no thermal stress" status for more than 34% of the studied period, with an average cooling potential (ΔPET) of 12.7 °C.
- The West-Northwest and Northwest-North winds in Ardebil were associated with "very cold stress" conditions (PET < 4 °C) for 733 h (26%) with an average cooling potential of 13 °C.
- For the 2000s, West-Northwest and Northwest-North winds were associated with "cold" conditions (4–8 °C PET) for 331 h (11.7%) with an average cooling potential of 11.5 °C.
- No "very hot" conditions (PET > 41 °C) occurred in Ardebil because of West-Northwest and Northwest-North winds in the 2000s.
- These winds were associated with "hot" conditions (35–41 °C PET) for only 19 h (0.67%) with a CPE of 7.40 °C.
- "Slightly warm/cool" conditions (23–29 °C and 13–18 °C PET) were caused by winds in these directions for 282 h (9.9%) and 463 h (16.3%), with CPEs of 11.70 °C and 13.10 °C, respectively.
- Finally, "warm/cool" conditions (29–35 °C and 8–13 °C PET) were recorded for 83 h (2.9%) and 437 h (15.4%), with an average cooling potentials of 12.70 °Cand 9.10 °C, respectively, for the West-Northwest and Northwest-North winds in Ardebil in the 2000s.

These findings clearly reflect Ardebil's climate characteristics. In this region, the average number of frost days were approximately 6–8 months per year. Therefore, forcing the wind speed to calm can reduce the number of "no heat stress" hours to 2832 h, while it can expand the comfort conditions for the remaining 4873 h. Overall, desirable winds blow from the West-Northwest and Northwest-North (270–360°) at the Ardebil stations with the highest comfortable effects (between 18 and 23 °C PET), while the other directions generate a chill effect. This observation confirms the cooling effect of the winds for the expansion of "comfortable" conditions, which is strongly related to the climate of the area. Accordingly, from the architectural and urban design points of view, Northeast winds (with PET of <4 °C), which generate chill effect, should be considered in the building designs to create barriers to save energy in a climate such as Ardebil.

Subsequently, the impact of climate change on Ardebil's comfort conditions was assessed. All the previous simulations for Ardebil in the 2000s were repeated using the 2040s TMY data with the A2 and B1 scenarios. Comparing the wind characteristics of the 2000s with the 2040s represents some changes, especially in the prevailing winds under the effect of climate change. Table 4 indicates the number of hours for each PET level and the percentage of the total number of hours in the TMY files for the 2000s and the 2040s. The average number of hours of warm-to-hot conditions is expected to increase, according to both the A2 and B1 scenarios. It is predicted that the number of cold spells will decline in Ardebil by the 2040s, mainly as a result of increasing temperatures and escalating solar radiation. For instance, very cold (PET < 4 °C) and cold (4–8 °C) conditions will decline, on average, by 4.9% and 4.3%, based on the A2 and B1 scenarios, respectively. The simulated long-term average PETs will be approximately 14.4 and 13.9 °C for the A2 and B1 scenarios (with ΔPET of 13.2 °C), respectively.

Table 5 compares the estimated cooling potential of the wind in the 2000s with the wind forecast for the 2040s based on the A2 and B1

Table 3

Statistical determinants for appropriate model selection when simulating climate variables for the 2000s.

stations	Temperature			Relative Humidity			Wind Speed			Radiation		
	R^2	BIAS	NRMSE (%)	R^2	BIAS	NRMSE (%)	R^2	BIAS	NRMSE (%)	R^2	BIAS	NRMSE (%)
Ardebil	0.65	0.8	22.8	0.75	12.2	18.1	0.67	−0.9	17.3	0.53	238	31.5
Gorgan	0.60	0.78	26.2	0.69	11.3	17.5	0.78	−1.8	23.6	0.65	161	20.5
Bandar Abba	0.55	0.71	20.4	0.65	10.2	17.6	0.72	−1.2	16.2	0.57	189	23.1
Shiraz	0.73	0.95	27.5	0.78	15.7	23.7	0.64	−1.6	22.7	0.49	321	35.1

Table 4
PET index and number and percentage of hours for each PET level in Ardebil's 2000s and 2040s TMY files.

PET Levels (°C)	2000s (h) (%)	2040s-A2(h) (%)	2040-B1 (h) (%)	Difference between 2040s-A2 and 2000s (h) (%)	Difference between 2040s-B1 and 2000s (h) (%)
Very cold (<4)	2477 (29.7%)	2009 (22.8%)	2070 (23.7%)	−468 (−6.8%)	−407 (−5.9%)
Cold (4–8)	1054 (12.6%)	817 (9.5%)	854 (9.9%)	−237 (−3%)	−200 (−2.7%)
Cool (8–13)	1342 (16.3%)	1023 (12.2%)	1031 (12.1%)	−319 (−4.2%)	−311 (−4.2%)
Slightly cool (13–18)	1312 (16.2%)	1233 (14.7%)	1225 (14.5%)	−79 (−1.5%)	−87 (−1.7%)
Comfortable (18–23)	1233 (14.5%)	1242 (14.8%)	1244 (14.9%)	+9 (0.3%)	+11 (0.4%)
Slightly warm (23–29)	678 (8%)	1056 (12.1%)	1090 (12.3%)	+378 (4.1%)	+412 (4.4%)
Warm (29–35)	219 (2.6%)	722 (8%)	648 (7.3%)	+503 (5.4%)	+429 (4.7%)
Hot (35–41)	28 (0.3%)	405 (4.5%)	373 (4.2%)	+377 (4.2%)	+345 (3.9%)
Very hot (>41)	1 (0.0%)	101 (1.3%)	86 (1.1%)	+100 (1.2%)	+85 (1.1%)

scenarios. The average cooling potential of wind is generally expected to be 2.00 and 1.90 °C higher by the 2040s according to the A2 and B1 scenarios, respectively. Thereby, under the effect of climate change, the wind is expected to be a more valuable resource in the 2040s. Furthermore, the comfort cooling effect of the wind increases because the human subject will lose more heat through the combined latent and convective processes in the warmer temperatures of the 2040s.

From the architectural and urban design standpoint, it would be beneficial to integrate natural ventilation solutions, especially in the West-Northwest and Northwest-North directions, which will provide the highest comfortable conditions in Ardebil in the 2040s. Additionally, the average cooling potential of the wind will generally be 1.90 and 1.80 °C higher by the 2040s according to the A2 and B1 scenarios, respectively.

3.3. Wind cooling potential in hot desert climate (BWh)

Conversely, Bandar Abbas is considered to have a hot desert climate (BWh) based on the Köppen-Geiger climate classification (Raziei, 2017). Its average annual temperature is 27.20 °C, with approximately 136 mm of annual precipitation. In the 2000s, the predominant wind directions in this station were N, W, NW, and E winds, for a total of 4053 h, while the lowest winds were from the SW direction for 579 h. A detailed bioclimatic interpretation of these predominant wind directions are given as follows.

- The contribution of the N, W, NW, and E predominant winds to the creation of "comfortable" conditions are higher than other winds (1046 h) with a CPE of 14.50 °C. These results indicate that by forcing the wind speed to calm, people in the Bandar Abbas, would feel 14.5 °C warmer than actual conditions during these 1046 h.
- In the prevailing wind directions N, NW, and W, forcing the wind speed to calm would decrease the "comfortable" conditions to less than ten hours compared with the actual windy conditions.
- Additionally, the PET analysis illustrates that, even in windy conditions (wind speed of more than 0.05 m/s), this station is primarily associated with "hot and very hot" climate conditions (>29 °C PET) and the cooling potential of the wind is reduced to an average of 7.50 °C. In calm conditions (without wind), the situation is worse. Therefore, higher wind speeds are needed to compensate for heat stress at this station.
- No "cold and very cold" conditions (PET < 8 °C) were observed with winds from any direction due to Bandar Abbas's hot desert climate.

Generally, compared with the Ardebil station, the PET index shifts to >18 °C PET in Bandar Abbas, which is clearly consistent with its climate. Additionally, the data show that in a hot climate such as that experienced by Bandar Abbas, the cooling potential of the wind is more effective in generating more "comfortable" conditions. Overall, it can be concluded that comfortable conditions would be reduced by 97% in the absence of the wind at this station (it would decrease to only 31 h for all wind directions).

To summarize, in the warmest six months of the year, the most desirable winds in Bandar Abbas came from the North-Northwest and West, which represent the most significant orientations for architectural and urban design considerations. Table 6 presents the number of hours for each PET comfort level in Bandar Abbas for the 2000s and 2040s. The amount and percentage of hours for each PET level for both decades are represented in Table 5 as well. No considerable changes are expected regarding cold spells in Bandar Abbas by 2040 (A2, B1), while the comfortable and very hot conditions will increase by 2.2% and 2.6%, respectively. The long-term average PET of the actual and calm conditions (with and without wind) for all wind directions in Bandar Abbas is about 33.2 and 43.1 °C, respectively (ΔPET of 9.900 °C). The climate of this station is generally associated with "warm" conditions (PET > 29 °C). The PET prediction demonstrates that the temperatures will increase by about 0.4% and 0.6%, respectively, by the 2040s in A2 and B1 scenarios. Hence, it is expected that the wind will provide more comfort in warm and hot climates. Accordingly, the average cooling potential of wind will be approximately 1.60 and 2.00 °C higher by the 2040s according to the A2 and B1 scenarios, respectively (Table 7), and the CPE of the wind in "comfortable" conditions will increase by approximately 1.8 °C or 2.2%. This confirms the benefit of the wind flow on the expansion of comfortable conditions in a warm and hot climate.

3.4. Wind cooling potential in moderate and humid climate (Csa)

In general, Gorgan has a moderate and humid climate, which is locally known as "the moderate Caspian climate." The predominant winds blow from the NWW and E-SE. A detailed bioclimatic interpretation of the prevailing wind directions is given as follows:

- The PET index and CPE analysis indicate that compared with the Bandar Abbas and Ardebil stations, the PET index of the Gorgan station is distributed across all categories, mainly under the effect of its climate.
- Approximately 458 h (13.5%) of "comfortable" conditions were provided by the W, NW, and E-SE prevailing winds at the Gorgan station with cooling potential of 12.20 °C.
- A total of 1254 h (36.6%) are associated with "cool to very cold" conditions of PET (<18 °C) for the prevailing wind directions, with a CPE of 10.50 °C.
- A total of 1709 h (49.9%) of data are associated with "warm to very hot" conditions of PET (>23 °C) for the prevailing wind directions with a CPE of 8.40 °C.

In general, the PET analysis of Gorgan station depicted that the long-term average PETs of windy (more than 0.05 m/s) and calm conditions (set to a constant 0.05 m/s) for all wind directions in Gorgan were approximately 22.40 and 32.70 °C, respectively (with ΔPET of 10.30 °C). Among the recorded data for all directions, 14.7% is associated with "comfortable" conditions (between 18 and 23 °C PET) with the CPE of 12.20 °C. In other words, without wind, in 14.7% (3420 h) of the studied period, people would feel warmer conditions. Approximately 48.1% and 37.2% of the wind conditions are associated with "no thermal comfort or warm/clod" conditions (PET > 29 °C and PET < 4 °C), respectively. Conversely, at the Ardebil station, there was a tendency toward lower

Table 5

Average cooling potential of wind in Ardebil in the 2000s and 2040s (A2–B1) in all directions, and average wind cooling potential differences between the 2000s and 2040s TMY files.

PET Levels (°C)	Average wind cooling potential 2000s (°C)	Average wind cooling potential 2040s-A2 (°C)	Average wind cooling potential 2040s-B1 (°C)	Differences between average wind cooling potential in 2040s-A2 and 2000s (°C)	Differences between average wind cooling potential in 2040s-B1 and 2000s (°C)
Very cold (<4)	13.0	13.7	13.6	+0.7	+0.7
Cold (4–8)	12.3	13.6	13.8	+1.3	+1.5
Cool (8–13)	13.1	13.7	13.7	+0.6	+0.6
Slightly cool (13–18)	13.2	14.1	14.2	+1.0	+1.0
Comfortable (18–23)	13.0	14.2	14.0	+1.2	+1.0
Slightly warm (23–29)	12.1	13.1	13.2	+1.0	+1.1
Warm (29–35)	9.0	10.4	10.5	+1.4	+1.5
Hot (35–41)	4.6	9.1	8.9	+4.5	+4.3
Very hot (>41)	0.0	5.8	4.9	+5.8	+4.9

Table 6

PET index and number and percentage of hours for each PET level in Bandar Abbas in the 2000s and 2040s.

PET Levels (°C)	2000s (h) (%)	2040s-A2(h) (%)	2040-B1 (h) (%)	Difference between 2040s-A2 and 2000s (h) (%)	Difference between 2040s-B1 and 2000s (h)
Very cold (<4)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Cold (4–8)	0 (0.0%)	20 (0.2%)	22 (0.2%)	+20 (0.2%)	+22 (0.2%)
Cool (8–13)	56 (0.6%)	60 (0.7%)	82 (0.9%)	+4 (0.1%)	+26 (0.3%)
Slightly cool (13–18)	348 (4%)	390 (4.5%)	488 (5.3%)	+42 (0.5%)	+140 (1.3%)
Comfortable (18–23)	1046 (12.2%)	1047 (12.3%)	1282 (14.4%)	+1 (0.1%)	+236 (2.2%)
Slightly warm (23–29)	1384 (16.3%)	1429 (16.6%)	1458 (16.5%)	+45 (0.3%)	+74 (0.2%)
Warm (29–35)	1459 (16.6%)	1619 (17%)	1507 (17.2%)	+160 (0.4%)	+48 (0.6%)
Hot (35–41)	1730 (18%)	1921 (20.2%)	1837 (19.9%)	+191 (2.2%)	+143 (1.9%)
Very hot (>41)	1969 (23%)	2493 (28.4%)	2313 (25.6%)	+524 (5.4%)	+344 (2.6%)

PETs (<4 °C), while in Bandar Abbas, higher PETs (>29 °C) were common. However, at the Gorgan station, the winds have different roles during the year based on the directions. At times, the wind can act as a moderator, but at other times, it can worsen the thermal comfort conditions, because of the higher humidity at this station.

Furthermore, the simulation predicted that the number of hours that a person in Gorgan would be exposed to thermal heat stress (higher than 35 °C) will increase by an average of 2.4% and 1.7% and those during which they will be subjected to cold stress (less than 4.00 °C) will decrease by an average of 1.7% and 2.5% by the 2040s based on the A2 and B1 scenarios, respectively (Table 8). Assuming that the CPE of the winds in Gorgan do not change appreciably, the simulated long-term average PET for the actual conditions will be approximately 23.30 and 22.80 °C by the 2040s for the A2 and B1 scenarios (ΔPET of 10.00 °C, same as the 2000s), respectively (Table 9). Although the CPE will not have changed, the occurrence of the PET levels and the number of hours with cold and hot conditions will have changed. Overall, the simulated climate conditions for Gorgan indicate that its climate of will get warmer with reduced comfortable conditions because of no change in the CPE conditions by the 2040s.

3.5. *Wind cooling potential in hot semi-arid climate (BSh)*

Shiraz's climate has distinct seasons and is classified as a hot semi-arid climate (Bsh- Köppen-Geiger climate classification) (Raziei, 2017). The summers are hot, with a July average high of 38.8 °C, and the winters are cool, with average low temperatures below freezing in December and January. In this climate, the prevailing winds blow from the N, NW, E, SE, and W (5819 h in total). The detailed bioclimatic interpretation of the prevailing wind directions are given as follows:

- 870 h (15%) of "comfortable" conditions are provided by the predominant N, NW, E, SE and W winds, with cooling potential of 11.10 °C.
- 1910 h or 32.8% of the data are associated with "cool to very cold" conditions of PET (<18 °C) for the prevailing wind directions with a CPE of 11.60 °C.

Table 7

Cooling potential of the wind in Bandar Abbas in the 2000s and 2040s (A2–B1), and average wind cooling potential differences between the 2000s and 2040s TMY files.

PET Levels (°C)	Average wind cooling potential 2000s (°C)	Average wind cooling potential 2040s-A2 (°C)	Average wind cooling potential 2040s-B1 (°C)	Differences between average wind cooling potential in 2040s-A2 and 2000s (°C)	Differences between average wind cooling potential in 2040s-B1 and 2000s (°C)
Very cold (<4)	0.0	0.0	0.0	0.0	0.0
Cold (4–8)	0.0	5.8	8.3	+5.8	+8.3
Cool (8–13)	12.6	13.2	14.7	+0.6	+2.2
Slightly cool (13–18)	13.7	15.0	14.8	+1.2	+1.0
Comfortable (18–23)	13.8	15.6	15.6	+1.8	+1.8
Slightly warm (23–29)	12.1	13.9	14.0	+1.7	+1.8
Warm (29–35)	10.1	11.4	11.6	+1.3	+1.5
Hot (35–41)	8.5	9.8	9.8	+1.4	+1.3
Very hot (>41)	6.8	7.2	7.2	+0.3	+0.4

Table 8
PET index and number and percentage of hours for each PET level in Gorgan in the 2000s and 2040s.

PET Levels (°C)	2000s (h) (%)	2040sA2 (h) (%)	2040-B1 (h) (%)	Difference between 2040s-A2 and 2000s (h) (%)	Difference between 2040s-B1 and 2000s (h) (%)
Very cold (<4)	355 (5%)	472 (6.8%)	529 (7.5%)	+117 (1.7%)	+174 (2.5%)
Cold (4–8)	425 (5.9%)	373 (5.4%)	376 (5.5%)	−52 (−0.6%)	−49 (−0.5%)
Cool (8–13)	810 (11.6%)	758 (11.1%)	773 (11.5%)	−52 (−0.5%)	−37 (0.0%)
Slightly cool (13–18)	1041 (14.7%)	883 (13.4%)	865 (13%)	−158 (−1.3%)	−176 (−1.6%)
Comfortable (18–23)	1106 (14.7%)	837 (12.9%)	781 (12.2%)	−269 (−1.8%)	−325 (−2.5%)
Slightly warm (23–29)	1048 (15.1%)	885 (13.3%)	907 (13.7%)	−163 (−1.8%)	−141 (−1.3%)
Warm (29–35)	1144 (16.4%)	1054 (15.8%)	1104 (16.5%)	−90 (−0.6%)	−40 (0.1%)
Hot (35–41)	863 (12.1%)	941 (13.7%)	909 (13.2%)	78 (1.5%)	46 (1.1%)
Very hot (>41)	321 (4.5%)	527 (7.8%)	459 (6.8%)	206 (3.3%)	138 (2.3%)

- 3039 h (52.2%) of the data are associated with “warm to very hot” conditions of PET (>23 °C) for the prevailing wind directions with a CPE of 7.60 °C.

Among all the recorded data, 21% of the winds in all directions at Shiraz station could be considered as desirable with “comfortable” conditions (between 18 and 23 °C PET). Among all the orientations, S, SE NW winds are more involved in the creation of thermal comfort. Therefore, these directions are significant from a bioclimatic and thermal comfort point of view in urban design. The CPE of these orientations is approximately 10.80 °C. The largest distribution of the PET index is between 8.00 and 35.00 °C (cool-comfort-hot conditions). The number of hours with “very cold” conditions (PET < 4 °C), which are mainly created by the NE winds, are negligible for this station. Accordingly, it can be concluded that due to the semi-arid climate of Shiraz, winds can moderate its climate conditions, with no apparent chill effect. Calming the wind speeds would decrease the “comfortable” conditions to less than 50% at this station (from 1194 h to only 676 h for all wind directions) (Table 10).

Compared with the 2000s, the simulated results of the A2 and B1 scenarios predicted that the number of hours with “slightly cool to very cold” conditions, based on the PET index, will increase by an average of 3.3%. The number of hours with “slightly warm to very hot” conditions will decline by an average of −3.3%. However, the overall impact these effects is equal, and its influence on the climate of Shiraz will be neutral on average. Compared with the conditions associated with heat/cold stress, the comfortable conditions will have a slight increase by an average of 0.3% and 0.5% for the A2 and B1 scenarios, respectively (Table 10). However, the average cooling potential of the wind is generally expected to be 2.80 °C higher by the 2040s (Table 11). The cooling potential of the wind in comfortable conditions will be 3.20 and 3.10 °C based on the A2 and B1 scenarios, respectively. The long-term average PET index of the 2000s (24.50 °C) and 2040s (20.90 and 20.50 °C based on A2 and B1) confirms that the cooling potential of the wind will increase by the 2040s.

3.6. PET index comparison in the four climates

Fig. 3 illustrates the results of the PET index calculated for all the climate types studied for the 2000s and 2040s in windy conditions. The Ardebil station had the highest wind cooling potential for the 2000s (CPE of 12.9 °C) among all the stations potentially because the Ardebil station has the highest annual wind speed compared with other cities in Iran, as determined by previous studies (Al-Yahyai et al., 2016). The average annual wind speeds for Ardebil, Bandar Abbas, Gorgan, and Shiraz are 1.6, 1.10, 1.1, and 0.88, respectively.

The calculated CPEs for Gorgan, Bandar Abbas, and Shiraz are 10.30 °C, 9.90 °C, and 9.7 °C, respectively. Compared with the 2000s, the wind cooling potential will increase by the 2040s in Ardebil, Shiraz, Bandar Abbas, and Gorgan (CPEs of 13.20, 13.10, 11.20,110 °C, respectively) based on the A2 and B1 scenarios.

The analysis of the outdoor thermal comfort for all the stations in question indicated that there is a significant relationship between the climates of the stations and the occurrence of the PET classes. The total number of hours with “comfortable” conditions (18–23 °C of PET) in all wind directions of the studied stations for the 2000s are 1,294, 1,233, 1,106, and 1046 h in Shiraz, Ardebil, Gorgan, and Bandar Abbas, respectively. Fig. 3 shows that the occurrence of outdoor thermal comfort conditions in Shiraz and Ardebil is higher than the other climate conditions. Overall, the average of the A2 and B1 scenarios indicated that the occurrence of “comfortable” conditions by the 2040s will increase in Bandar Abbas, Shiraz, and Ardebil by 1.1%, 0.4% and 0.3% respectively, while it will decrease in Gorgan by −1.5%. Changes in “comfortable’ conditions under the effect of climate change depend on the current climate of each station. For instance, in cold climate types such as Ardebil, increasing temperatures will lead to a desired thermal comfort, while in hot and humid climate types such as Gorgan, increasing temperatures will lead to increased sultry conditions due to more evaporation from the Caspian Sea.

In the 2000s, the total data associated with “slightly cool” to “very cold” thermal conditions (PET <18 °C) are 74% (for Ardebil), 10.9% (for Bandar Abbas), 37.2% (for Gorgan), and 32.4% (for Shiraz). Furthermore, the total data associated with “slightly warm” to “very hot”

Table 9
Cooling potential of Gorgan’s wind in 2000s and 2040s (A2–B1), and average wind cooling potential difference between 2000s and 2040s TMY files.

PET Levels (°C)	Average wind cooling potential 2000s (°C)	Average wind cooling potential 2040s-A2 (°C)	Average wind cooling potential 2040s-B1 (°C)	Differences between average wind cooling potential in 2040s-A2 and 2000s (°C)	Differences between average wind cooling potential in 2040s-B1 and 2000s (°C)
Very cold (<4)	7.8	8.3	8.3	+0.5	+0.5
Cold (4–8)	10.4	10.8	11.7	+0.4	+1.3
Cool (8–13)	11.9	12.9	12.5	+1.0	+0.6
Slightly cool (13–18)	11.7	12.1	11.8	+0.4	+0.1
Comfortable (18–23)	12.0	11.6	11.9	−0.4	−0.1
Slightly warm (23–29)	11.2	10.8	11.0	−0.3	−0.2
Warm (29–35)	9.2	9.0	9.1	−0.3	−0.2
Hot (35–41)	7.4	7.2	7.2	−0.2	−0.2
Very hot (>41)	6.0	5.8	5.9	−0.2	−0.1

Table 10
PET index and number and percentage of hours for each PET level in Shiraz in the 2000s and 2040s in actual conditions.

PET Levels (°C)	2000s (h) (%)	2040sA2 (h) (%)	2040-B1 (h) (%)	Difference between 2040s-A2 and 2000s (h) (%)	Difference between 2040s-B1 and 2000s (h) (%)
Very cold (<4)	117 (1.4%)	466 (5.7%)	597 (6.4%)	+349 (4.4%)	+480 (5%)
Cold (4–8)	358 (4.5%)	656 (9.2%)	795 (9%)	+298 (4.7%)	+437 (4.5%)
Cool (8–13)	963 (12%)	1173 (15.5%)	1317 (15%)	+210 (3.5%)	+354 (3%)
Slightly cool (13–18)	1140 (14.5%)	1175 (15.2%)	1392 (16.2%)	+35 (0.7%)	+252 (1.7%)
Comfortable (18–23)	1294 (15.5%)	1238 (15.8%)	1260 (16%)	+56 (0.3%)	+34 (0.5%)
Slightly warm (23–29)	1279 (16.9%)	1030 (13.3%)	1112 (12.7%)	−249 (−3.6%)	−167 (−4.3%)
Warm (29–35)	1097 (14.2%)	794 (10.8%)	858 (9.8%)	−303 (−3.5%)	−239 (−4.4%)
Hot (35–41)	904 (11.4%)	684 (8.2%)	800 (8.7%)	−220 (−3.2%)	−104 (−2.7%)
Very hot (>41)	732 (9.5%)	523 (6.3%)	559 (6.2%)	−209 (−3.2%)	−173 (−3.3%)

conditions (>23 °C PET) comprise 73.9% (for Ardebil), 4.6% (for Bandar Abbas), 48.1% (for Gorgan), and 52% (for Shiraz). Therefore, Ardebil and Bandar Abbas are the most exposed to cold and heat stresses. By the 2040s, "slightly cool" to "very cold" thermal conditions will increase in Shiraz (3.3%), Gorgan (0.7%), and Bandar Abbas (0.3%) based on the average of A2 and B1. additionally. by the 2040s, "slightly cool" to "very cold" thermal conditions will decrease by −3.8% at the Ardebil station. Furthermore, the simulated data predicted that the number of hours with "slightly warm" to "very hot conditions" would increase for Ardebil, Bandar Abbas, and Gorgan by 7.2%, 1.7%, 0.5% on average by the 2040s.

4. Discussion

Outdoor thermal comfort in the urban environment is a relevant field for the well-being of people and mitigate climate change impacts on cities (Shashua-Bar et al., 2012).

Based on the PET index, the findings of this study indicate that the highest long-term average of the PET index in windy conditions for the 2000s was recognized for the Bandar Abbas station with 33.2 °C, while it was 9.9 °C, 22.4 °C, and 24.5 °C for Ardebil, Gorgan, and Shiraz, respectively. Therefore, the total number of hours with "comfortable" conditions (18–23 °C of PET) for all wind directions for studied stations was 1294 h, 1233 h, 1106 h, and 1046 h in Shiraz, Ardebil, Gorgan, and Bandar Abbas, respectively. These results show that the occurrence of outdoor thermal comfort conditions in Shiraz and Ardebil is higher than in the other climates due to their climate types. The occurrence of thermal comfort conditions in the summertime of the cold areas such as Ardebil and the winter time in Shiraz is more than the other stations.

By the 2040s, these conditions will change to 14.4 °C (A2) and 13.9 °C (B1) in Ardebil, 33.6 °C (A2) and 32.9 °C (B1) in Bandar Abbas, 23.3 °C (A2) and 22.8 °C (B1) in Gorgan, and 20.9 °C (A2) and 20.5 °C (B1) in Shiraz. Accordingly, the PET index will increase in Ardebil and Gorgan, while it will decline in Shiraz. Because the relative humidity is a significant parameter in the PET calculation, in the semi-arid climate of Shiraz, increasing the temperature will lead to a decrease in the relative humidity. No appreciable changes were found in the simulated long-term average of the PET in Bandar Abbas. Overall, the average of the A2 and B1 scenarios indicated that the occurrence of "comfortable" conditions by the 2040s will increase in Bandar Abbas, Shiraz, and Ardebil by 1.1%, 0.4%, and 0.3%, respectively, while it will decrease in Gorgan by −1.5%.

Finally, Ardebil and Bandar Abbas are the most exposed to cold and heat stresses. The comfort cooling potential of the wind (PET with and without wind) is predicted to rise by an average of 1.60 °C in the 2040s compared with the 2000s in all the studied stations.

4.1. *Strength and limitations of the study*

This study presents novel insights into the effects of wind on the urban climate of four cities representing the Mediterranean warm/cool summer climates (Csb), hot desert climate (BWh), Mediterranean hot summer climate (Csa), and hot semi-arid climate (Bsh), based on Köppen-Geiger climate classification. The results are not only beneficial for local Iranian interests but also contain sufficient contributions to the body of knowledge in regions with similar climates worldwide. Assuming that in the 2040s, the air temperature and mean radiant temperature will be higher than they are currently and that relative humidity will be proportionately lower, while the wind speeds will not have changed appreciably, the comfort cooling potential of wind (PET with and without wind) is predicted to rise by an average of 1.60 °C by the 2040s compared with the 2000s for all the studied stations.

Additionally, the results are consistent with the reports by Sadeghi et al. (2018), who indicated that the comfort cooling potential of wind (ΔUTCI with and without wind) is predicted to rise by an average of 2.70 °C by 2030 compared with 2013 in Sydney, Australia. Accordingly, Müller et al. (2014) represented that wind speed affects thermal comfort in urban areas and concluded that the wind's ventilation effect is particularly significant for city planning and architecture. Furthermore, Sadeghi et al. (2018) assessed the impact of wind on human thermal comfort by preforming outdoor urban climate comfort simulations and demonstrated that the direction of desirable and predominant winds is a significant factor in enhancing natural ventilation effectiveness and

Table 11
Cooling potential of Shiraz's wind in 2000s and 2040s (A2–B1), and average wind cooling potential difference between 2000s and 2040s TMY files.

PET Levels (°C)	Average wind cooling potential 2000s (°C)	Average wind cooling potential 2040s-A2 (°C)	Average wind cooling potential 2040s-B1 (°C)	Differences between average wind cooling potential in 2040s-A2 and 2000s (°C)	Differences between average wind cooling potential in 2040s-B1 and 2000s (°C)
Very cold (<4)	9.5	15.5	15.3	+6.0	+5.8
Cold (4–8)	12.3	15.4	15.5	+3.1	+3.2
Cool (8–13)	12.1	14.9	15.0	+2.8	+2.9
Slightly cool (13–18)	11.5	14.6	14.7	+3.1	+3.2
Comfortable (18–23)	11.0	14.2	14.1	+3.2	+3.1
Slightly warm (23–29)	10.2	13.1	13.0	+2.9	+2.8
Warm (29–35)	8.3	10.4	10.6	+2.1	+2.3
Hot (35–41)	6.9	8.3	8.4	+1.4	+1.5
Very hot (>41)	5.4	5.9	6.1	+0.5	+0.7

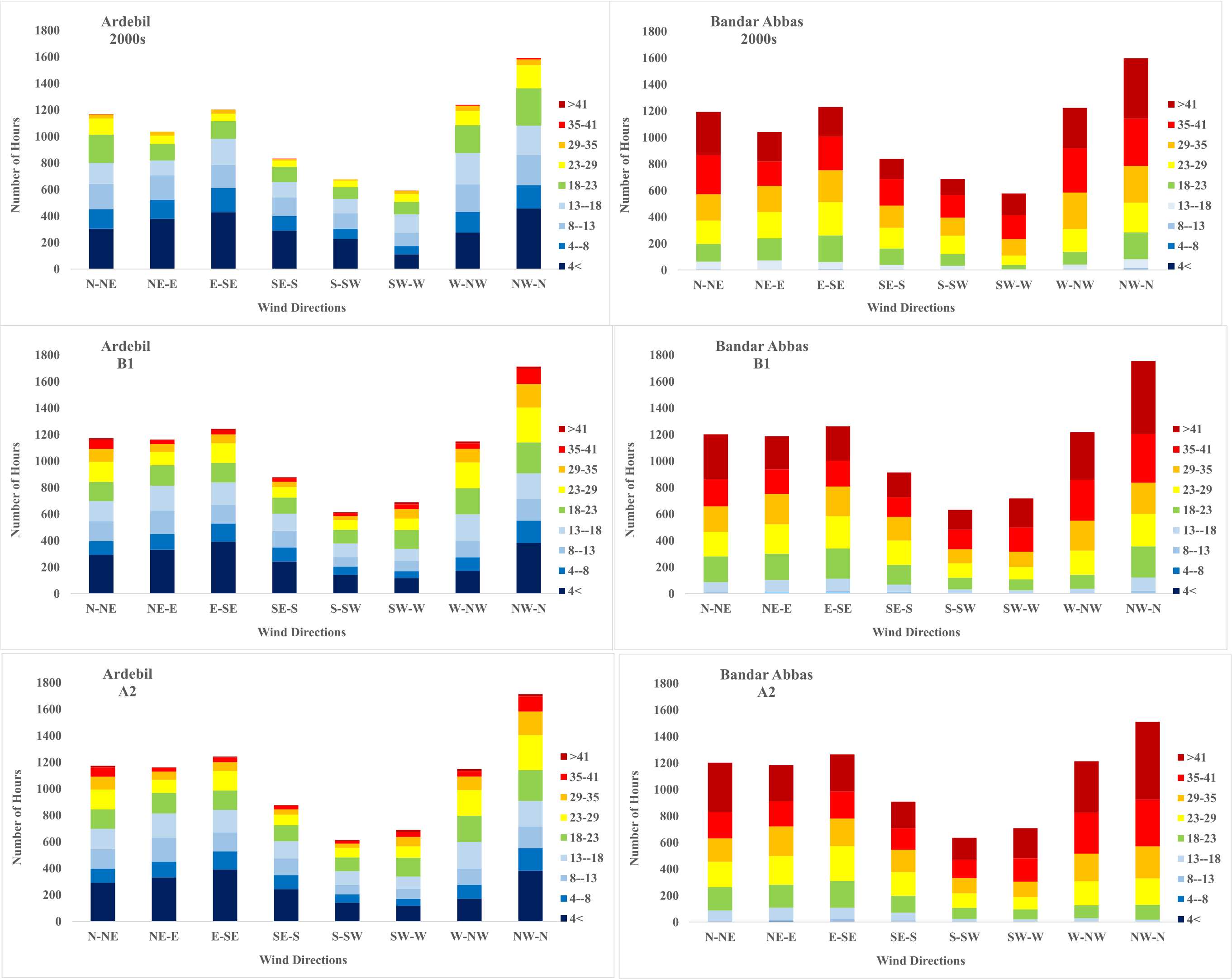

Fig. 3. PET index calculated for all climate types studied for the 2000s and 2040s in windy or actual conditions. The color of each band shows the PET for the primary wind directions.

bioclimatic comfort.

Regarding the methodology, we estimated the cooling potential effect of the wind based on the PET calculation (1) with actual wind conditions and (2) under calm wind (0.05 m/s) conditions. The original part of our methodology included the use of the CPE of the wind as an index. The CPE is based on the ΔPET of these two wind conditions. To the knowledge of the authors, none of the previous studies found in literature calculated the CPE based on the PET. Despite the slight similarities between our research approach and the one of Sadeghi, we discovered that our methodology is novel and unique because Sadeghi et al. used the Universal Thermal Climate Index (UTCI) and not the PET index (Sadeghi et al., 2018). According to the latest literature reviews, PET is the most reliable and universally used thermophysiological heat-balance-based model (Baruti et al., 2019; Potchter et al., 2018; Dunjić, 2019; Paramita and Matzarakis, 2019). Almost all other studies that investigated the cooling potential effect focused on vegetation and urban morphological aspects or addressed wind comfort at the pedestrian level, excluding the thermal effects. Therefore, we believe that our methodology, despite its complexity, can be an example that will allow future researchers to assess the potential cooling effect of wind in urban outdoor environments. Our suggested methodology can provide easily understandable information for the assessment of the wind cooling effect in urban climates.

However, this study has some limitations. The most significant limitation is that the data used were from airport weather stations that are kilometers away from the centers of the cities' urban heat islands. Ideally, the study would have relied on meteorological data from local weather stations, which take into account most of the aspects illustrated in Fig. 1, including the sky view factor (Cohen et al., 2019). However, the urban weather data were not available for the selected cities. Another limitation of the study is that it lacked an investigation into the in situ human thermal perception of the cooling effect of wind. This would allow the exploration of sensitive parameters, such as the kind of clothing, or validate the sensation scale. However, the use of subjective thermal perception would have required expensive time and cost investments. Therefore, we consider our methodology useful to characterize the wind cooling potential on outdoor thermal comfort in different climate types. This methodology can be considered as a primary step for local urban climate monitoring and human perception investigation to generate more accurate and city-specific evaluations (Du et al., 2017a, b).

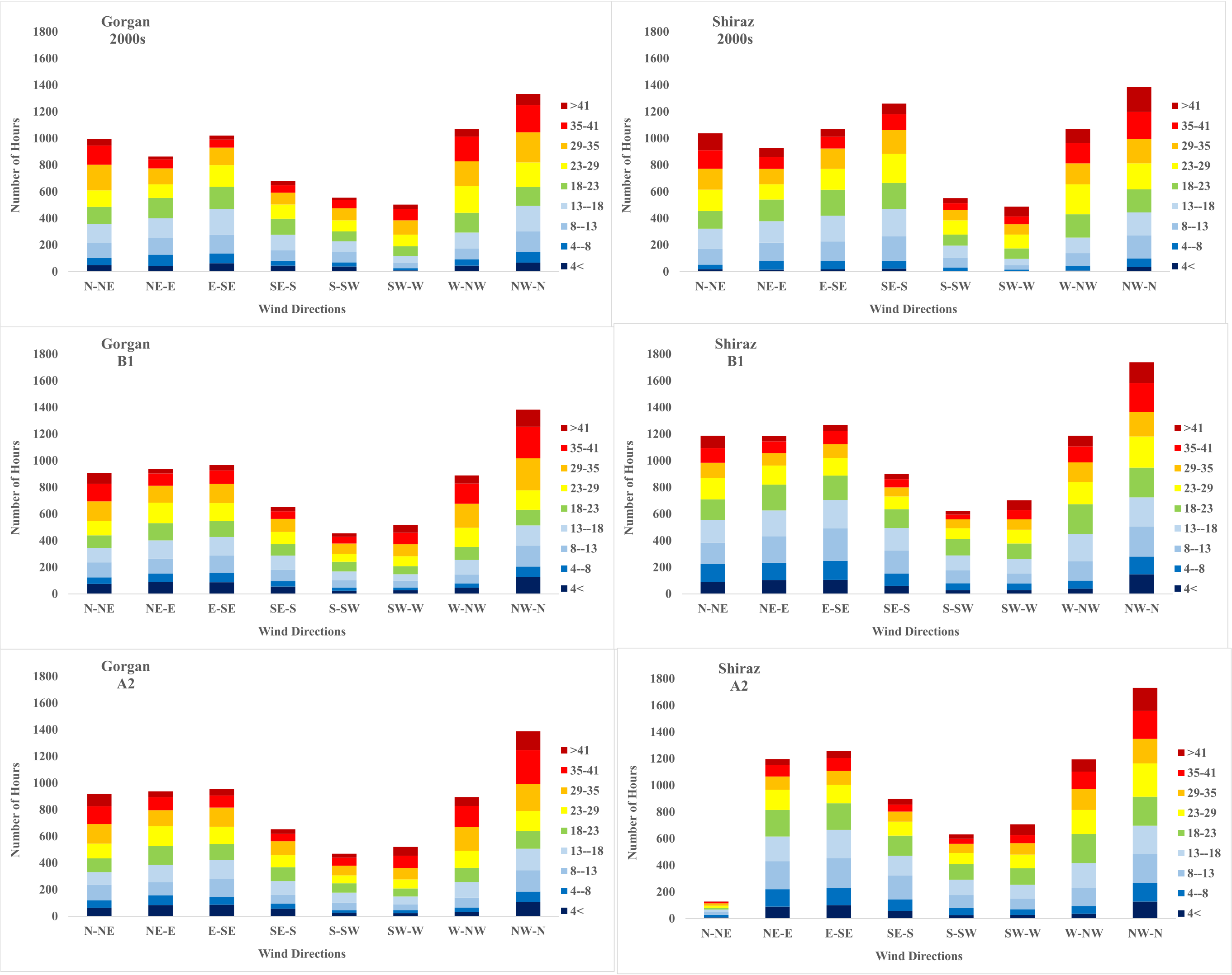

Fig. 3. (*continued*).

4.2. *Implications for the practice and future research*

This study identified the wind cooling effect on outdoor thermal comfort in four climate types in Iran. Based on our findings, we advise against urban planners and landscape architects underestimating the passive cooling effect of wind in warm and hot climates. In the Mediterranean hot summer climate, like in Gorgan, attention to wind potential is necessary. Therefore, urban designers and city planners should learn how to use air to flow in urban areas and public spaces and prepare the outdoor spaces to host people during extreme heat stress conditions. Natural ventilation and airflow manipulation are essential design elements for a city's urban fabric. The shape, orientation, and location of buildings or building clusters should be designed to encourage the wind to penetrate cities, while maintaining wind comfort conditions at pedestrian levels. The wind cooling effect should be considered along with other elements, such as buildings geometry and the location of appropriate trees, that can improve the outdoor thermal comfort and habitability of cities by urban heat island mitigation (Adamek et al., 2017; Bajšanski et al., 2015; Tan et al., 2017; Milošević et al., 2017; Attia et al., 2019; Morakinyo et al., 2020). Therefore, these factors should be considered during the early design stages and urban redevelopment stages.

Future research should focus on coupling the wind cooling effect with the comfort criteria needed to achieve wind comfort at pedestrian levels. It is difficult to couple both approaches with meteorological data of specific locations to assess wind comfort holistically. Additionally, the urban outdoor thermal perception should be investigated through field surveys to evaluate the local comfort based on urban structure and fabrics. It is also suggested for Urban Weather Generators to use this method to identify the cooling affects inside cities and the actual environment in future research. The authors are aware that the PET index alone cannot predict the wind cooling effect; behavioral and psychological adaptations have been proven to have a significant impact on thermal perception (Baruti et al., 2019). Furthermore, there is an increasing demand for bio-meteorological information in daily weather reports and by urban and regional planners intending to create comfortable microclimates. Therefore, more detailed and city-specific approaches can inform the urban design decision making and provide effective measures to mitigate the impact of climate change and the urban heat island effect.

5. Conclusions

The main objective of the present research was to evaluate the effect of the wind cooling potential on outdoor thermal comfort in four different climate types in Iran. Overall, the comparison of all the stations demonstrated that there is a significant and strong relationship between the cooling potential effects of wind with outdoor comfort conditions.

The presence of windy conditions reduces the amount of the PET index. However, this cooling potential varies for the different Iranian climate types based on the wind directions and varying atmospheric systems of the unique latitudes and thermal conditions. Wind and its thermal comfort impacts should be taken into account as a moderator, especially in urban areas with a high potential of heat events and higher population density. Given these findings, although climate change, urbanization, and demographic trends will continue to contribute to a change in thermal sensations, using new bioclimatic approaches such as the CPE can help reduce the negative impacts on thermal thresholds affected by climate change. Considering the wind frequently changes, which has implications on human outdoor thermal comfort, it will be necessary to plan adaptation strategies and use the positive impact of these changes for enhancing bioclimatic thermal comfort, especially in the urban areas of Iran. The simulations in this paper predict that wind speed will have an even higher value for human thermal comfort in the 2040s than in the current climate. Considering the desirable wind cooling potential in urban morphology and landscape planning is a practical approach to combat negative impacts and the risk of extreme events in the future.

CRediT authorship contribution statement

Gholamreza Roshan: Conceptualization, Data curation, Formal analysis, Funding acquisition, Software, Visualization. **Masoumeh Moghbel:** Investigation, Methodology, Project administration, Supervision, Writing - original draft. **Shady Attia:** Formal analysis, Resources, Validation, Writing - review & editing.

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Appendix A. Supplementary data

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