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Defining thermal comfort boundaries for heating and cooling demand estimation in Iran's urban settlements

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ABSTRACT

Iran has diverse climate variability, comfort boundaries for each geographic region must be defined in order to present current architectural design recommendations and proper mechanical systems design to meet building's heating and cooling energy demand. Therefore, two components of the temperature and relative humidity of 148 stations with the longest common statistical period of twenty years (1994–2014), which have been in daily scale were selected to calibrate and redefine the thermal boundary conditions in Iran. Givoni chart was used to define and visualize the bioclimatic conditions in buildings. The results of this study indicate that only 18% of the 148 stations days, falls in the thermal comfort bioclimatic conditions. After calibration of the base comfort temperature, we found that the upper threshold of this component varies from at least 22.62 °C for Ardebil to 25.94 °C for Dorudzan station and the low threshold of this component belongs to Ardebil with at least 20.13 °C up to its maximum value with 22 °C which belongs to Dorudzan. Spatial distribution of cooling and heating days show that their maximum threshold has been for cores in Northeastern half of Iran, Iran's Western half and some Central parts of Iran and the minimum threshold of these two components belongs to the beaches of north and south of the country. The findings present updated thermal comfort boundaries that can be used by architects, engineers and policy makers to achieve, in turn, more energy efficient homes and high quality indoor and outdoor living environments.

1. Introduction

Building designers require accurate climate characterization and updated articulation of comfort boundary conditions for every project they design and build [1]. Controlling climatic conditions is one of the factors affecting human life, well-being and physical health. The essence of architectural design is to benefit from the favorite climate conditions in every project site using passive and bioclimatic design strategies to achieve thermal comfort with minimum use of active systems [2]. In most of the times, it is impossible to achieve summer and winter comfort in buildings using only passive and bioclimatic design measures. Therefore, mechanical engineers intervene to cover the cooling or heating demand periods using active system, such as heating and cooling system and mechanical ventilation. An essential step for architectural and mechanical engineers in the early design strategies is to define and understand the thermal comfort boundaries of their project to come up with fit to climate design strategies (passive or active) [3]. Givoni's Bioclimatic Chart (see Fig. 1) is one of the most used charts to characterize the climate for newly designed buildings [4]. Architects and engineers consider the use of bioclimatic and psychrometric charts as essential in building performance simulation tools to understand and visualize the climate in relation to thermal comfort. The Bioclimatic Chart is based on bioclimatology and aims to help designers to assess their design strategies and their impact on health and human thermal comfort.

In this context, this study aims to inform building professionals and designers about the dominant climatic patterns and comfort thresholds for different regions of Iran. By redefining thermal comfort boundaries for heating and cooling demand in Iran's urban settlements the study presents a significant input that serves as guideline for architects and mechanical engineers. Givoni's Bioclimatic Chart was used to visualize the calibrated comfort boundary conditions and plots from 148 stations that monitor temperature

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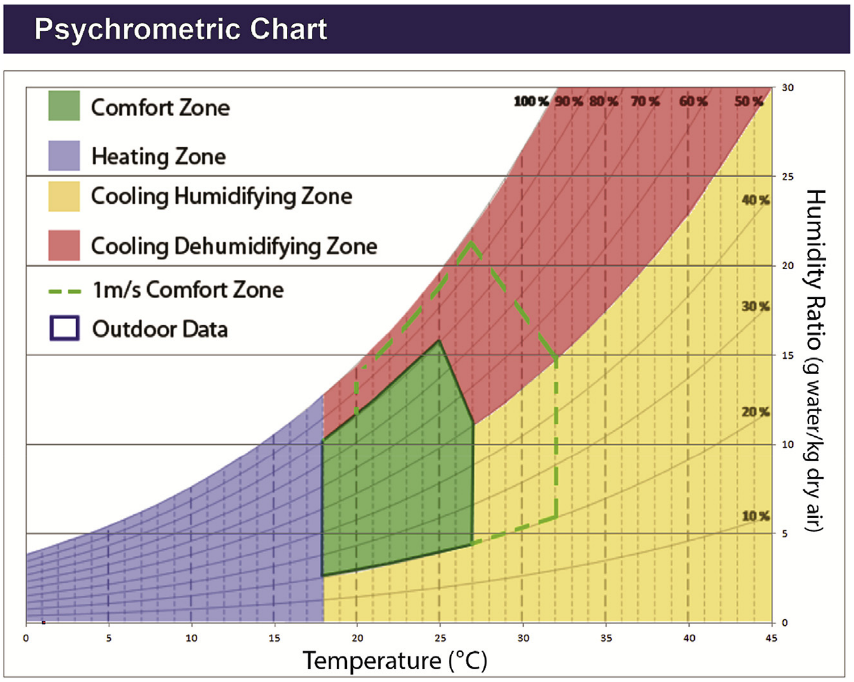


Fig. 1. An example of a psychrometric chart [6].

and humidity between 1994 and 2014. A series of figures identify the different climatic zones in Iran and provide updated psychometric charts for the six main urban cities to assess their potential of thermal comfort and bioclimatic design strategies. The research methodology is based on statistical analysis and climatology models. The study sheds the light on the quantity and quality of frequency of occurrence of days with thermal comfort and illustrates the bioclimatic conditions for some selected stations including Rasht, Gorgan, Bushehr, Bandarabbas, Esfahan, Ahvaz, Ardebil, Shahrekord, Hamedan, Tabriz, Qom, Tabas, Mashhad and Sanandaj. The characterization of different climatic regions and calibration of base temperatures for heating and cooling degree days leads to more accurate estimation of energy supply in the building sector. The paper key findings open the discussion on the implications for building designs and give to architects and engineer an overall view and guidance to better understand the climate characteristics and comfort boundary conditions. Strength of this article is based on defining the bioclimatic comfort boundary thresholds for Iran and the HDD and CDD, which was not reported previously in any similar studies. The study of Roshan et al. [5], is the only study that calibrated temperatures of the upper and lower thresholds for thermal comfort using Olgyay chart. However, Olgyay is mainly appropriate for bioclimatic conditions outside the building and in mid geographical latitudes of Iran. The strength in this study relies on using the Givoni-Milne bioclimatic chart, which is appropriate for assessing the potential thermal comfort conditions inside buildings.

This paper is organized into six sections. The first section identifies the research context and purpose. The second section is a literature review that defines the history of bioclimatic charts and their role to achieve thermal comfort and recommends climate responsive design strategies for architects and engineers. The literature review forms the basis for the calibration and statistical analysis and is discussed in the materials and method section (3). The monitoring and analysis results are discussed in section four. The final two sections are discussing the findings and providing feedback to climatologist and building designers.

2. Literature review

This section presents the state-of-the-art with respect to climate and weather characterization coupled to thermal comfort and bioclimatic charts for design decision support. The content is intended to aid the reader in better understanding areas of active research in comfort threshold identification and as well as guidelines and methods commonly used by designers and climatologists.

2.1. Bioclimatology

Bioclimatology is the science of studying and assessing the impact of weather and climate on living organisms including plants, animals and humans [7,8]. The comfort conditions mean a set of conditions which is thermally tolerable for 80% of people or in other words the condition in which human does not feel cold and hot. In fact, thermal comfort is where there is broad satisfaction with the thermal environment i.e. most people are neither too hot nor too cold [9]. Based on ASHRAE Standard 55 thermal comfort is “*that condition of mind that expresses satisfaction with the thermal environment*” [10]. As an appropriate strategy to interpret the climatic conditions of a region, comfort zone has always been determined based on several climatic parameters and it has been displayed on a graph so that by implementing daily or monthly climatic conditions one can determine if comfort conditions for occupants of buildings have been provided or they have failed to provide it. The most important variables which influence the condition of thermal comfort are: activity level (heat production in the body), thermal resistance of the clothing (clo-value), air temperature, mean radiant temperature, relative air velocity, and water vapor pressure in ambient air. In many comfort studies all the above-mentioned six variables have not been controlled, measured or reported. In other studies the variables have been controlled and the effect of one or two variables has been determined, with no attempt to generalize the results beyond the actual test conditions [11]. In the proposed graphs two climatic variables have been shown combined with each other to determine the thermal comfort zone. For example, the relationship between air temperature and mean radiant temperature (MRT) is shown by the graph in Fig. 1a. The shaded region indicates an average zone for human thermal comfort. The graph is based on test data from lightly clothed subjects engaged in sitting activities. Relative humidity is 50% and air velocities range from about 0.08 to 0.3 m/s for the data presented. The relationship between moving air stream temperature (i.e., amount above or below room air temperature) and air velocity is shown by the graph in Fig. 2b. The shaded region indicates an average zone for human thermal comfort. The relationship between air temperature and relative humidity is shown by the graph in Fig. 2c. The graph is based on test data from lightly clothed subjects engaged in sitting activities. The shaded region indicates an average zone for human thermal comfort [12].

2.2. *History of bioclimatic chart*

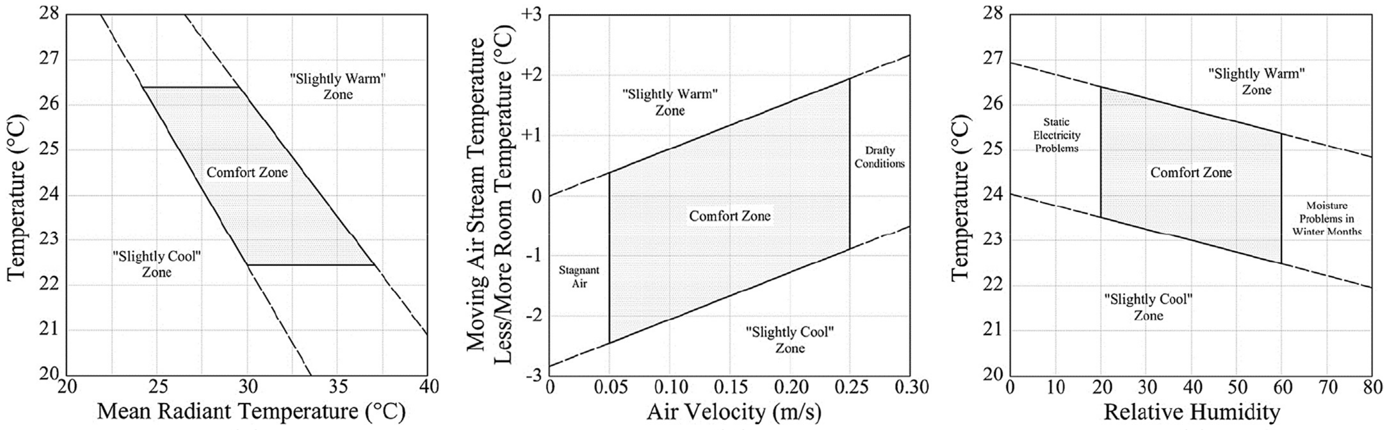
Houghton and Yaglou in 1923 for the first time generated Effective Temperature index by displaying comfort lines on the psychrometric chart. The advantage of this index compared to other studies was considering three variables of temperature, humidity and air flow. Later Corrected Effective Temperature replaced this index in which radiation also was considered as the fourth factor (Fig. 3a). Actually it has been found, however, that if globe thermometer readings are used in these nomograms in lieu of the dry bulb temperature values, the subjective reactions to radiant heat exchange are adequately allowed for [13]. Victor Olgyay is the first researchers attempting to draw the bioclimatic chart. Bioclimatic design employs appropriate technologies and design principles based on a reflexive focus on the climate and environment [14]. Olgyay arrived at the idea, that there is no point in constructing a single-figure index, as each of the four components are controllable by different means. In his bioclimatic chart, the comfort zone is defined in terms of dry bulb temperature and relative humidity, but subsequently it is shown by additional lines, how this comfort zone is pushed up by the presence of air movement and how it is lowered by radiation [13]. Olgyay drew bioclimatic chart for men doing sitting activities (Met = 1) and typical clothing insulation (Clo = 1) in tropical regions (Fig. 3b). In fact, the most effective variables in Olgyay bioclimatic chart are temperature and humidity and he had failed to establish a direct link between the six comfort factors (four climatic factors and two human factors). Also the use of the chart is directly applicable only to inhabitants of the temperate zone of the United States, at elevations not in excess of 305 m (1000 feet) above sea level. To apply the chart to climatic regions other than approximately 40° latitude, the lower perimeter of the summer comfort line should be elevated about 0.42 °C (0.75 °F) for every 5° latitude change toward the lower latitudes. The upper perimeter may be raised proportionately, but not above 29.5 °C (85 °F) [15]. Givoni presented his building bioclimatic diagram on the psychrometrics chart in 1976 [16]. In addition to determining the comfort zone on this chart, he showed the design proposals and required installation by determining some zones in this chart in case if the conditions are not consistent with the comfort zone conditions (Fig. 3c).

Givoni bioclimatic diagram has been divided into different zones for which it is necessary to use strategies to achieve human comfort within a building [16].

From this chart it can be inferred that sometimes there are several architectural statements for a particular range of building bioclimatic index, in these cases, the task of the architect is critical, because he must sum up different and perhaps contradictory statements. To make correct decisions in such cases, a thorough knowledge of the behavior of buildings against heat flow and its role in the regulation of environmental conditions is essential [18]. Milne and Givoni [19] have amended and expanded the building bioclimatic chart in 1979 so that they determine more zones to make design suggestions for architects. The Givoni-Milne bioclimatic chart has been widely used in practice and research [14,20–23]. This bioclimatic chart can be used as a tool to decide the proper strategies of bioclimatic design ought to be selected for specific climatic conditions. Therefore it is a pre-design analysis tool that can be used as a guide for the sketch design stage [24]. In Fig. 4a, the Givoni-Milne bioclimatic chart determines the limits of effectiveness of each design strategy to meet the needs of indoor comfort conditions [25]. One of the problems of working with building bioclimatic chart is the complexity of its axis which has made it difficult to find climatic data on it. DeKay and Brown [26] redrew Givoni's bioclimatic chart with the idea of the structure of Olgyay's chart and indeed they implemented Givoni's different and diverse strategy zones on the Olgyay's rectangular chart (Fig. 4b).

In this chart, five cooling strategies and two heating strategies have been set. In the present study, the proposed bioclimatic chart of DeKay and Brown was drawn more precisely. Also according to Milne-Givoni chart two heating strategies of “Internal Gains” and “Conventional Heating” were added. Also “Humidification” zone for dry climatic condition was added to this chart (Fig. 5).

Experience has shown that the human adapt their physical



(a) (b) (c)

Fig. 2. Comfort Zone in three charts; Relationship between temperature and MRT (a), Relationship between different of temperature of wind and air and air velocity (b), Relationship between temperature and RH (c) [12] (redrawn by authors).

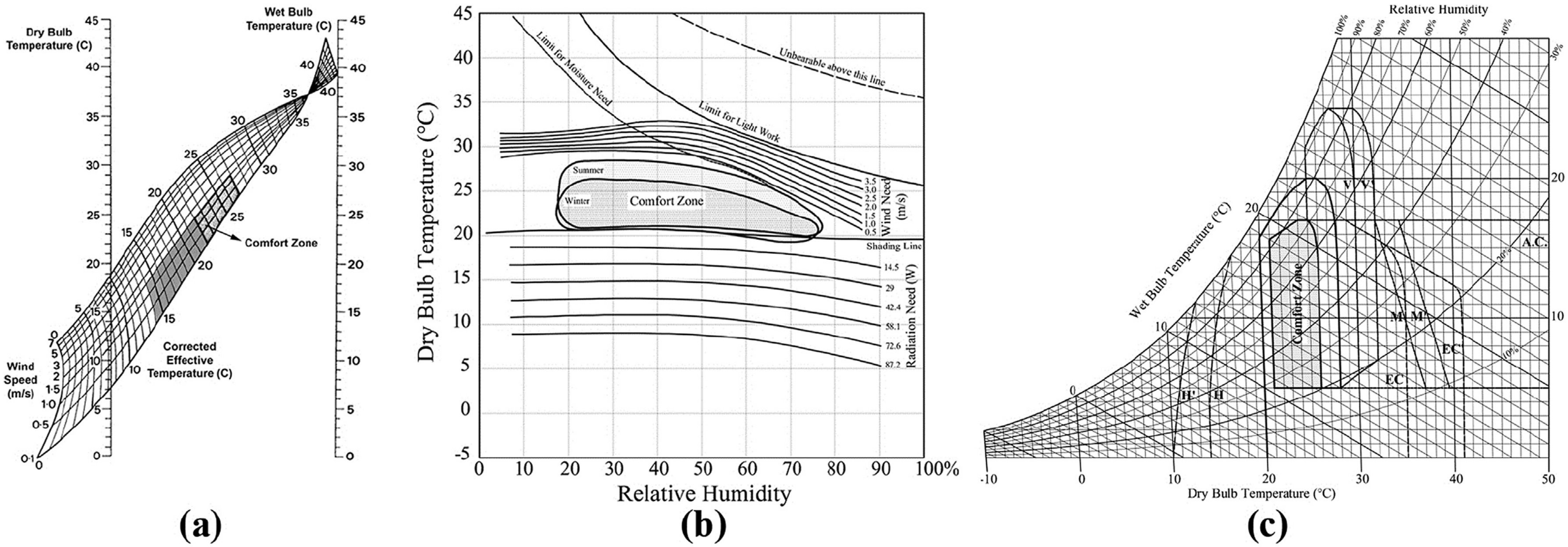


Fig. 3. Three comfort chart; Corrected effective temperature [13] (a), Olgyay bioclimatic chart [15] (b), Givoni bioclimatic chart [17] (c); all redrawn by authors.

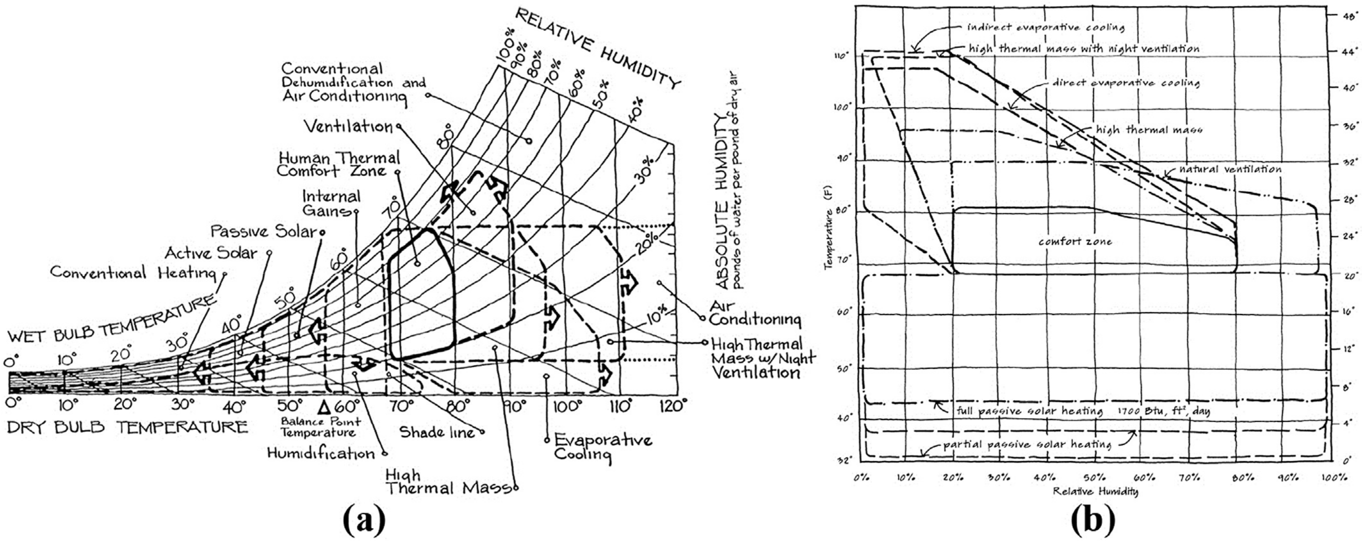


Fig. 4. Milne-Givoni bioclimatic chart [27] (a), Milne-Givoni bioclimatic chart redrawn by DeKay and Brown [26] (b).

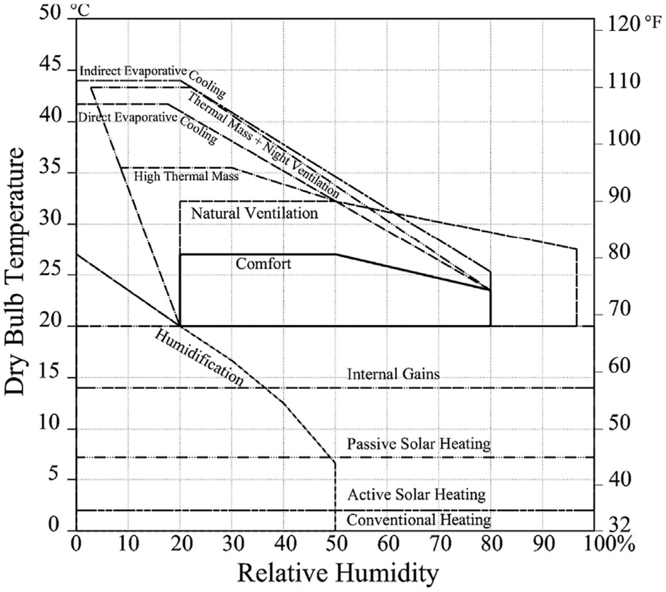


Fig. 5. Completed exactly drawn bioclimatic chart of Milne-Givoni by authors.

condition with the surrounding environment and climate, therefore, contrary to what is stated in the comfort models, comfort zone is never fixed. For example in the adaptive model of thermal comfort, indoor design temperatures or acceptable temperature ranges related to outdoor meteorological or climatological parameters [3,28]. In this study, researchers have attempted that by calibration of the comfort zone in Milne-Givoni bioclimatic chart for different regions of Iran achieve new numbers in defining comfort in accordance with climatic environmental conditions.

Therefore, redefining new thermal comfort boundaries to adapt to the environment is a useful guide for architects and engineers who create environmental designs for buildings that are energy efficient and in harmony with the climate. A calibrated and monitoring based comfort determination is essential to facilitate precise estimation of HDD and CDD for optimal selection and sizing of building services and systems [29].

3. Materials and methods

In order to define the thermal comfort boundaries of Iran's settlements. We calibrated the thermal comfort boundaries using the maximum of stations, which jointly have the statistical period of the last twenty years. For this purpose, only 148 stations had the most complete daily statistics of temperature and relative humidity for the years from 1995 to 2014. Therefore, these stations were selected and analyzed. The only limitation we had was 5% of the selected stations had data gaps of 3%, which was recreated using neighboring stations based on linear regression. There are some papers that explain apply of regression model for recreate of data gaps [30–35].

It should be noted that the meteorological data was obtained from Iran Meteorological Organization [36]. In Fig. 6, the geographical location of the studied stations with their names have been shown. It should be noted that due to climate diversity of Iran, about 14 stations were selected as representatives of Iran's diverse climatic zones. Some of research processes have been carried for these stations with more details. In Table 1, the name and climatic characteristics of these 14 stations are shown.

Since the aim of this research is to define and calibrate thermal comfort boundaries for some sample cities in Iran, we identified two dominant methods that can be used. The first method is the based on questionnaires. In this method, people's reactions in different meteorological and bioclimatic conditions, in different seasons of the year, are analyzed for a period of approximately two to three years. On the basis of obtained questionnaires results, the comfort boundaries and bioclimatic classes can get identified. However, despite the strengths of this method two basic problems can slow down the process of research. One is having access to a specified range of participants with specific features and the other is the expectation of the occurrence of different bioclimatic events over seasons of the year. On the other hand, the second method is mainly based using statistical techniques. One advantage of statistical techniques is that with access to climatic data one can achieve good results to calibrate the bioclimatic comfort classes in less time. Therefore, in this study, given that about 148 stations of Iran will be assessed, we eliminated the use of questionnaires because this method will need a very long time with high uncertainty. We decided to use the statistical method or define the dominant climatology behaviors and models.

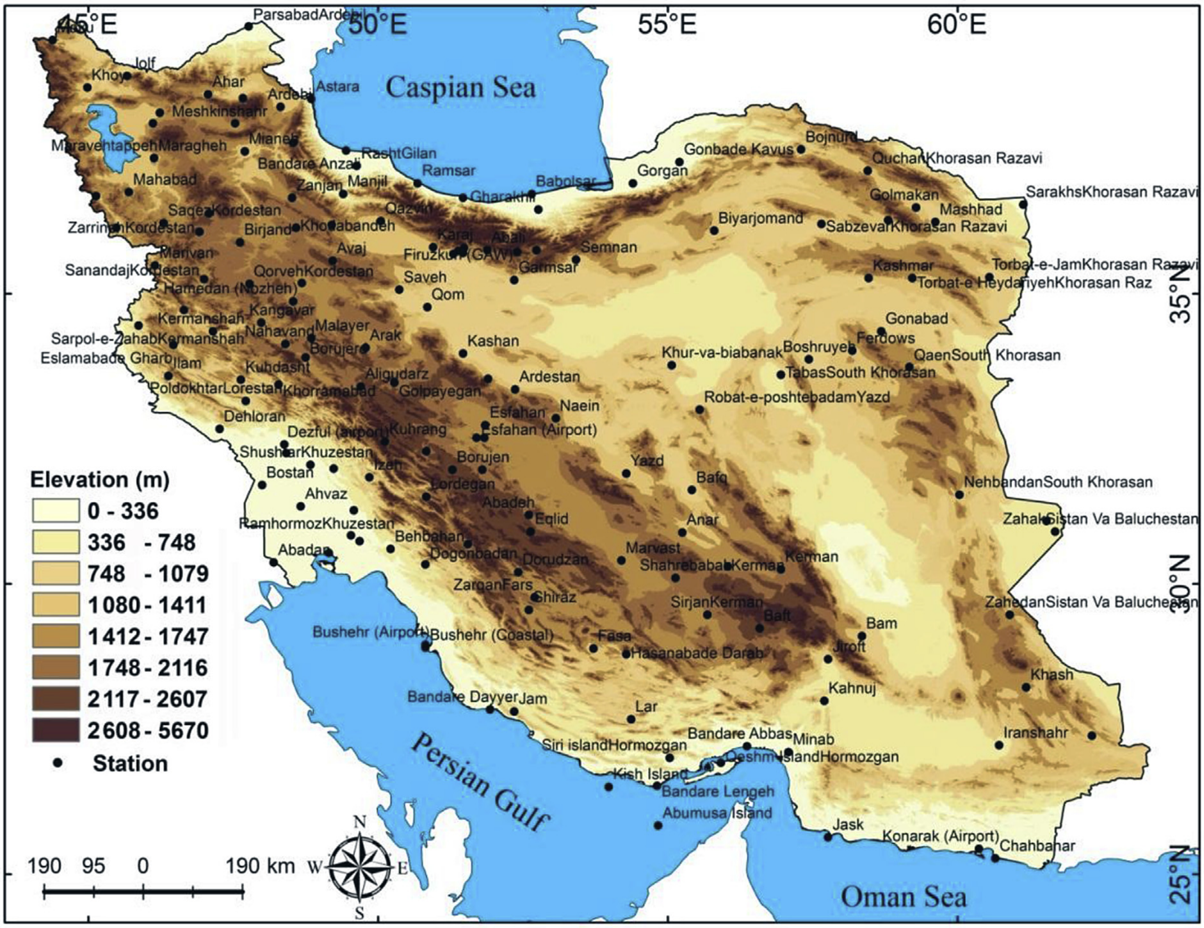


Fig. 6. Distribution of the studied stations across Iran's zone.

Table 1
Various climatic types according to their climatic characteristics [37].

Geographical region	climatic characteristics	Selected stations	Climatic type
Plains spots in the margins of Caspian sea and Turkmen Sahara plain in the east of Caspian	Relatively cold winter High humidity and soil	Rasht and Gorgan	Caspian region
Beaches and islands of the Sea of Oman and the Persian Gulf	very hot and humid summer Mild winter High humidity of air and soil	Bushehr and Bandar Abbas	The climate of beaches and islands of the South
Areas located in Iran's plains	Hot and dry summer Cold winter	Esfahan	Plain climate
Khuzestan plain and watershed of Jazmurian	very hot and dry summer Mild winter high Relative humidity	Ahvaz	The climate of Khuzestan plain and Jazmurian
High mountains	Pleasant summer Cold winters with very long frosts	Ardebil and Shahrekord	Climate of high mountains
Mountainous areas with relatively high altitude	Somewhat hot summer Cold winter	Hamedan and Tabriz	Climate of high foothills
The margins of central deserts of Iran	very hot and dry summer Cold winter	Qom and Tabas	Climate of desert area
Mountainous areas with low altitude	Relatively warm and dry summer Cold winter	Mashhad and Sanandaj	Low-lying foothills

Based on the climatology model, defining and calibrating the comfort boundaries of each station or geographic region is affected by the repeating pattern and frequency of occurrence of days with thermal comfort. In other words, according to of climatic diversity of different geographical areas, each station has a different experience of the frequency of days with thermal comfort so that it is possible that in most cases a station experience these comfort conditions in high humidity and low temperatures. But some stations considering their prevailing climatic conditions experience their maximum frequency of the occurrence of days with comfort at higher temperatures with lower relative humidity. As a consequence people adapt in each area with its prevailing weather conditions. The person who lives in cold and dry weather conditions has a different experience from the comfort days compared with someone who is living in hot and humid climate. The cause of this different feeling about bioclimatic conditions is the existence of different climatic adaptation and behavior change in these climatic zones. Therefore, we are trying to determine a scope of comfort boundaries in which maximum repetition and its frequency for each station has occurred. In other words, by eliminating rare cases of thermal comfort occurred in each station, we are seeking to identify the dominant model of thermal comfort and introduce a new boundary within the scope of thermal comfort.

In this study, the new modified Milne-Givoni chart, which has an appropriate application in monitoring of thermal comfort inside the building, is used. As it can be seen in Fig. 5, this diagram has different bioclimatic zones but our goal is to focus solely on the comfort boundaries. Studying and calibration of other bioclimatic zones is outside the scope of this article. Another important point is that calibrating the comfort boundaries is done just inside the comfort zone that is marked by Givoni chart and the new boundaries of comfort will not extend beyond this zone. Therefore, we determined the maximum concentration zone of data for comfort days of each station, first, using the mean of daily temperature and relative humidity of every day. The distribution of 7305 spots, which belonged to the statistical period of 1995–2014, were plotted on different the Givoni charts. Then, to separate and identify the days inside and outside comfort zones, these days were coded 1 and 0 respectively so days out of the comfort zone which were marked with the code 0, were excluded from the data set. The next step was to focus on the data that had been in the comfort zone. Therefore, corresponding to the days with comfort event, their values of temperature (T) and relative humidity (RH) were determined.

In the next step, based on the average and standard deviation of temperature (relative humidity) total days with the event of comfort of each station were determined (Fig. 6). In fact, this process was calculated separately for both temperature and relative humidity. Now based on these temperature thresholds and relative humidity extracted from the previous process, a new comfort zone was defined within the comfort zone of Givoni chart for each station. But the important point is that, if instead of $\pm\sigma$, $\pm 2\sigma$ and more is used, it causes a part of calibrated comfort zone goes beyond the comfort zone of Givoni chart and its boundary spread to other bioclimatic zones. Therefore, this study focuses only on $\pm\sigma$. The novelty of this study, apart from introducing new base temperatures in order to monitor degree-days of heating and cooling energy demand of Iran's stations, is that the study has managed to calibrate the comfort zone based on two components of temperature and relative humidity and has introduced a new zone. Based on the output of this article, the zoning map of upper and lower threshold of temperature and relative humidity of calibrated comfort zone were drawn and prepared using Kriging Interpolation method.

After determining the threshold of new base temperatures for each station, the amounts of degree-day heating and cooling energy demand of each station was calculated using equations (1) and (2) and these amounts were compared with temperature threshold of 18 °C for heating degree-days and 22 °C for the demand of cooling degree-days.

$$\mathrm{CDD} = \sum_{1}^{\mathrm{N}} (\mathrm{T} - \theta), \quad \theta < \mathrm{T} \tag{1}$$

$$\mathrm{HDD} = \sum_{1}^{N} (\theta - T), \quad \theta > T \tag{2}$$

In Formula (1) and (2), cooling requirement is calculated by CDD and heating requirement is calculated by HDD for a given period of N days. In these formulae, T is the average daily temperature and θ is the base temperature that with regard to the threshold of different percentiles, different numbers are proposed for each station. In Iran, one of the most widely used temperature threshold that is applied for monitoring of degree-days demand of heating and cooling energy is the zone of 18–22 °C [38–42]. Therefore the results of present work with the zone of 18–22 °C were compared.

4. Results

In this section, we will report the research major findings. We will present the outcomes of applying the statistical models mentioned in the methodology section and describe through illustrations and tables the frequency of occurrence of days that falls within the comfort zone. Also, this section will report the calibrated thermal comfort boundaries in relation to temperature and humidity. Finally, we compare the results of conventional and calibrated base temperature to estimate the degree-day demand for heating and cooling energy.

4.1. Monthly and yearly zoning of frequency of days in comfort zone

In order to prepare a zoning map of the frequency of occurrence of days in the comfort zone, the number of days with the event of comfort were determined based on the statistical period of 1995–2014. The scope of comfort zone is based on Givoni's chart. At this step, the process of thermal boundaries calibration was not done. Based on the total amount of comfort event and regardless of the monthly scale we found that the minimum amount with 401 days of comfort belongs to Anzali station on the Southwest Coast of the Caspian Sea. On the opposite, Karaj station has the maximum amount with 2978 days of comfort event. A significant difference between the maximum and minimum of number of days with comfort event can be seen in Iran. In general, based on the average of all studied stations it was determined that Iran has been in the comfort conditions for 1317 days i.e. 18% of the statistical period of 1995–2014. But based on Fig. 7, areas such as the far Northwest, Northeast of the country, and the strip along the middle of the southern coast of the country have had the maximum amount of days with the event of comfort. This includes the area, which starts from the Central Plateau of Iran and includes the Middle East Regions of the country and also the Southern coast strip of the Caspian Sea especially the Southwest Coast of the Caspian Sea have had the minimum amount.

In Fig. 8, the values of comfort occurrence for different months of the year are shown. What is certain is that a large number of stations have not experienced even one day of comfort during the cold season of winter. For example, on January 54, February 57 and

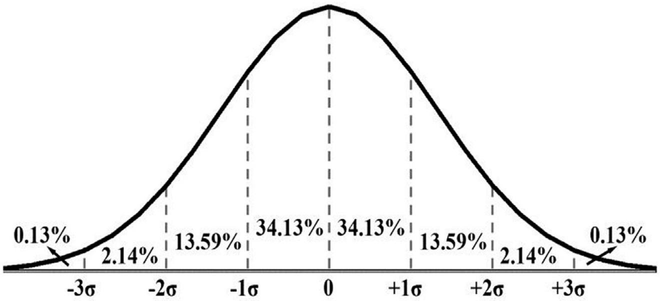


Fig. 7. Typical normal frequency distribution of the daily temperature (relative humidity) of days with event thermal comfort.

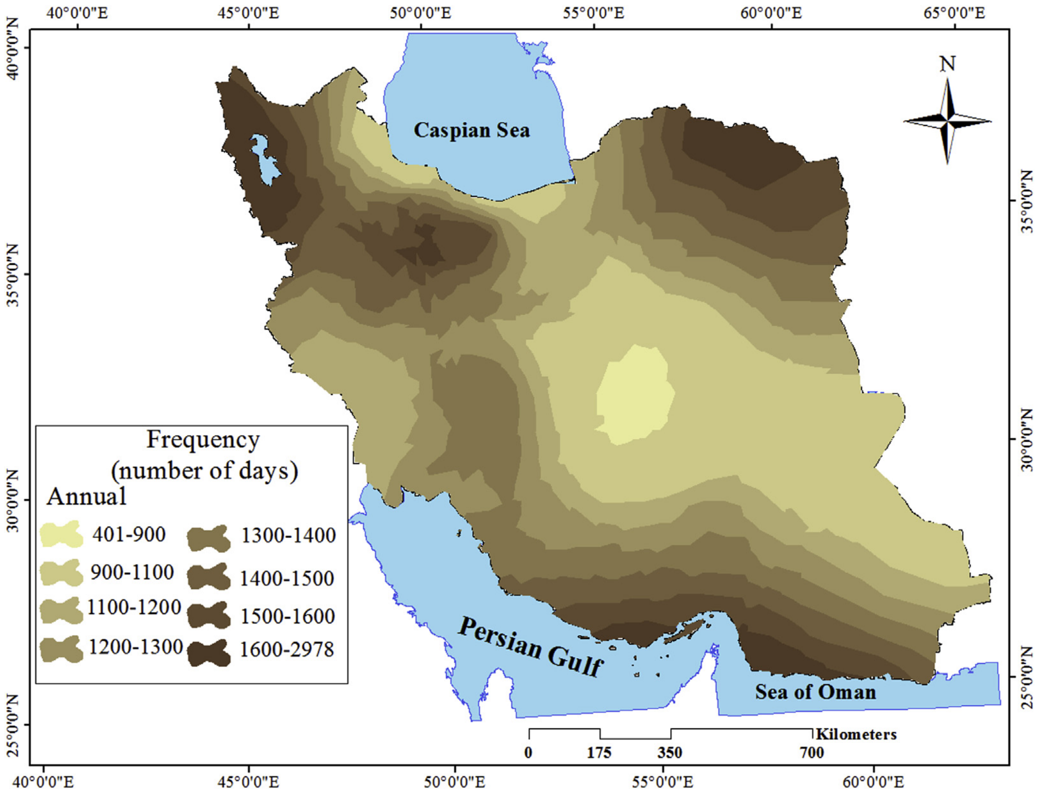


Fig. 8. Zoning of Iran based on the frequency of the number of days in the comfort zone for the entire study period from 1995 to 2014.

March 105 stations in the country had no experience of the event of climate comfort that distribution and spatial distribution of these areas often include northern and western half of the country. Earlier this season, the cold systems of earth's northern latitudes, if having high intensity and penetrating power, include large area even low-latitudes of Iran, this causes cold weather and the conditions of lack of comfort in most regions of Iran. Only in this season, Southern Coastal Strip of Iran have limited experience of cold stress because of the low latitude and due to the effects of the Persian Gulf and Oman Sea water zone, which adjust the cold conditions. This factor has made these regions one of the most ideal areas in terms of thermal comfort in winter. On the other hand, with the coming of the end of winter and beginning of spring. Cold systems from the Southern Hemisphere limit to the Northern and Northwest Strip of the country. Therefore, in the final days of this season, there is a potential for the occurrence of days with cold stress. However, in January, Southeast Areas, the Northern Coast of the Persian Gulf, Oman Sea and the core in the Southern part of Yazd province have the maximum of days with climate comfort. In January, the maximum amount of comfort with 465, 455, 425 and 380 days are for the stations of Abumusa Island, the island of Siri, Jask and Chabahar respectively. But in February, a greater zone of southern half of the country have experienced the occurrence of days with thermal comfort that Abumusa Island with 472 days, Siri Island with 435 days and Jask and Konarak with 413 and 400 days have had maximum comfort event. In March, the condition become a little more different and the minimum of comfort event expands as a strip from the North West to North East of Iran and another strip has expanded from the North West on the Zagros Mountains to the middle of Iran. In this month, the stations of Bandarabbas, Mynab and Bandare-lengeh respectively with 449 days, 444 days and 443 days, have first to third place of the days with maximum comfort.

With the onset of spring and moderation of cold, more stations have experienced climate comfort conditions so that in April, May and June, respectively with 132, 139 and 113 stations have had some experience of the occurrence of days with bioclimatic comfort which shows more days compared to winter. As a climatic transition, in the beginning and the end of winter a significant difference in terms of the occurrence of minimum and maximum thermal comfort can be seen for different regions of Iran. At the beginning of this season, in other words, in April, the Northwest to the Northeast Strip of Iran and the strip located on the Zagros Mountains show the minimum of days with comfort event. On the other hand, the South West of Iran and Middle Eastern borders of Iran have maximum comfort days. However, upon reaching the middle and end of the spring, the strip of Northwest to Northeast of the country, the northern slopes of the Alborz along with the Zagros Mountains experience a different situation compared to the beginning of the season which is maximum comfort days for these regions. Interestingly, the Southern Coast of Iran and a core in the center of Iran, which is the location of the central deserts, including the Loot Desert have the minimum frequency of days with comfort. In April, Safiabad station with 440 days, Tehran-Shemiran station with 731 days in May and in June two stations of Kabutarabad in Esfahan and Kangavar in Kermanshah with 517 days jointly have had the maximum of the event. With the start of summer in Iran, the number of stations that have experience climate comfort conditions decreases compared to the spring so that in July, 104 in August 110 and in September by decreasing of the hot period of the year, 123 stations have experienced bioclimatic comfort conditions. As it can be seen in Fig. 8, at the beginning of this season, eastern and southern half and Southern Coasts of Iran are outside the threshold of thermal comfort but the differences between these zones in terms of the mechanism of the event of lack of comfort can be seen. So that for desert and dry areas of central Iran, extremely

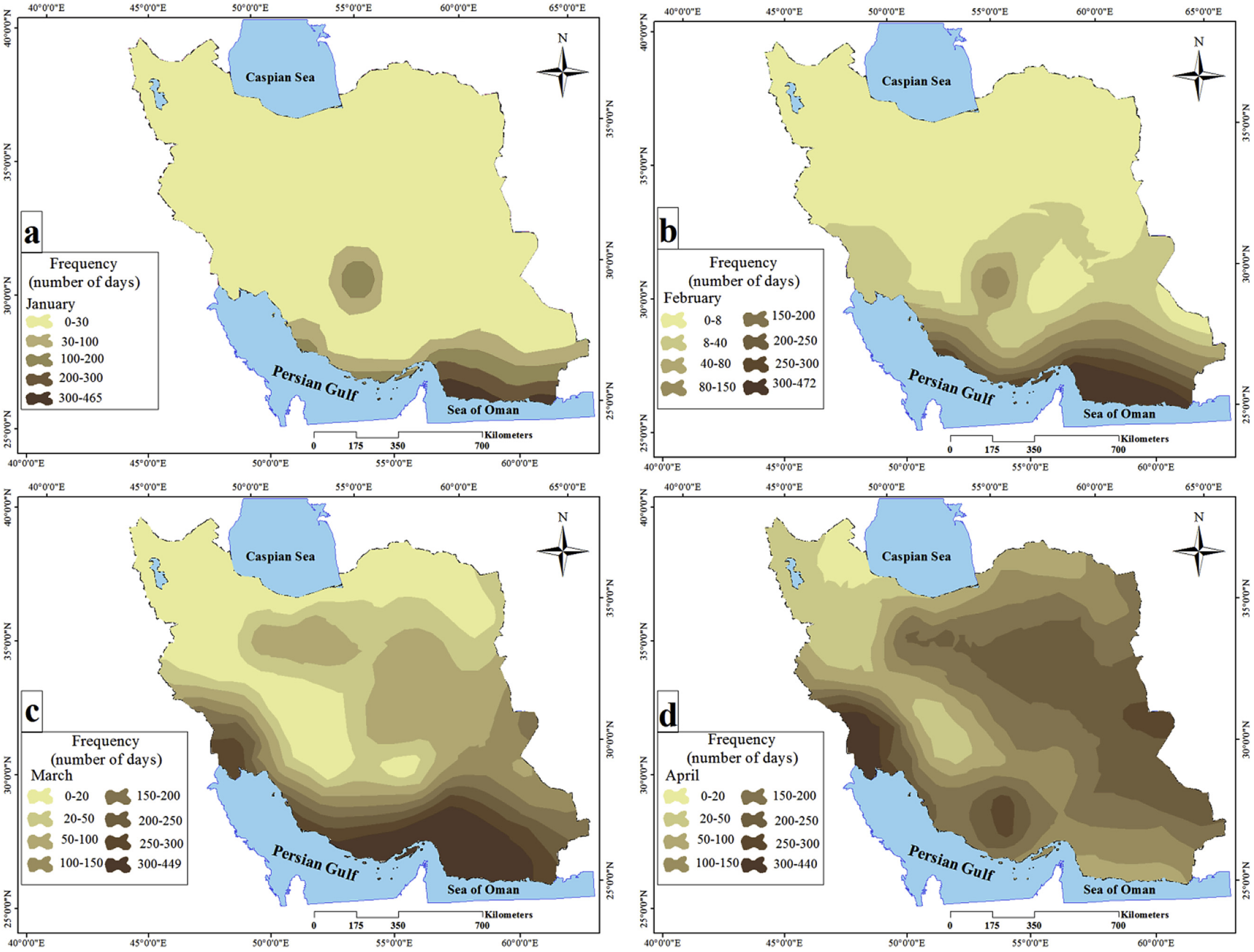


Fig. 9. Monthly zoning of Iran based on the frequency of the number of days in the comfort zone for the entire study period from 1995 to 2014. Figures 9a, 9b, 9c and 9d are for January, February, March and April. Figures 9e, 9f, 9g and 9h are for May, June, July and August. Figures 9i, 9j, 9k and 9l are for September, October, November and December.

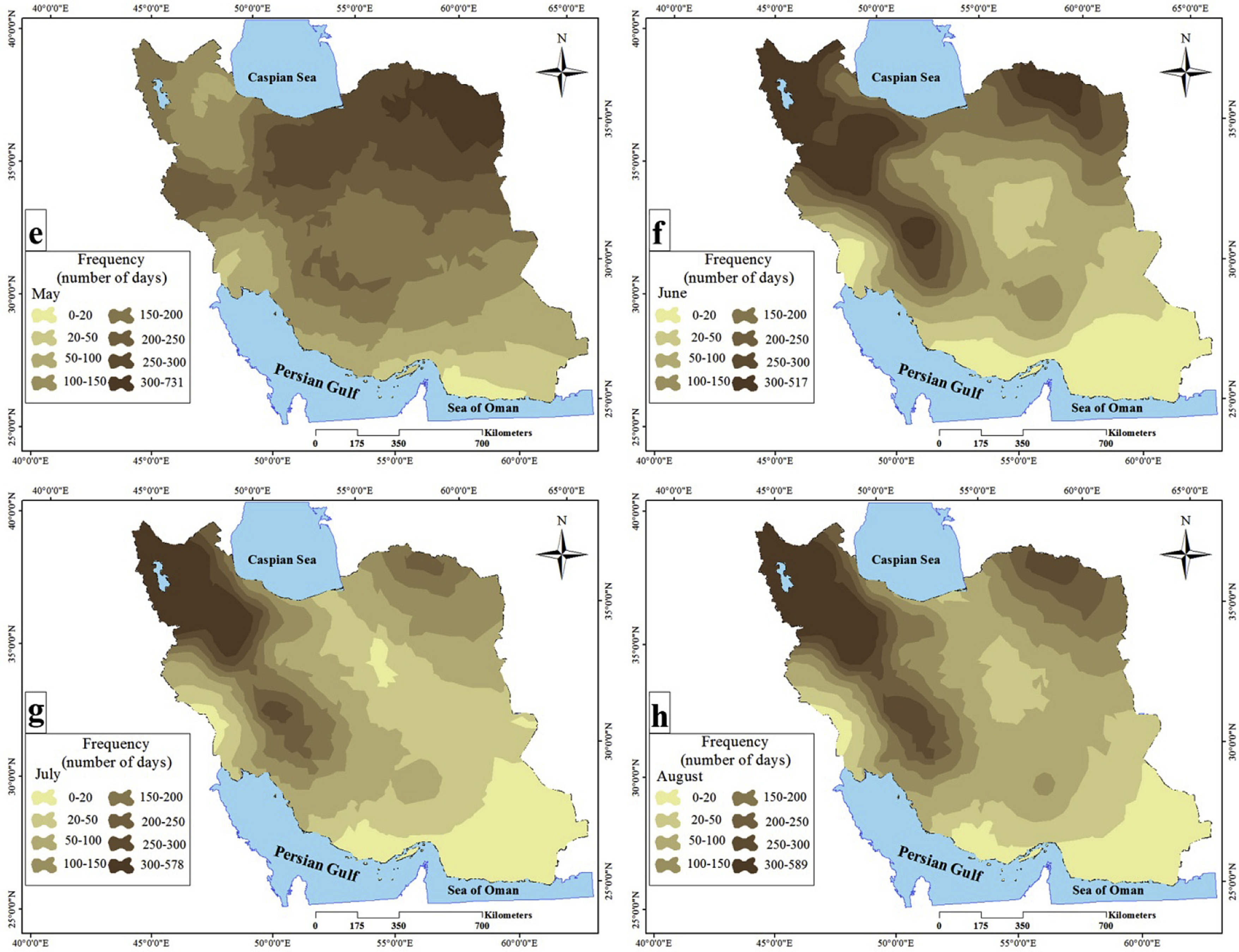


Fig. 9. (*continued*).

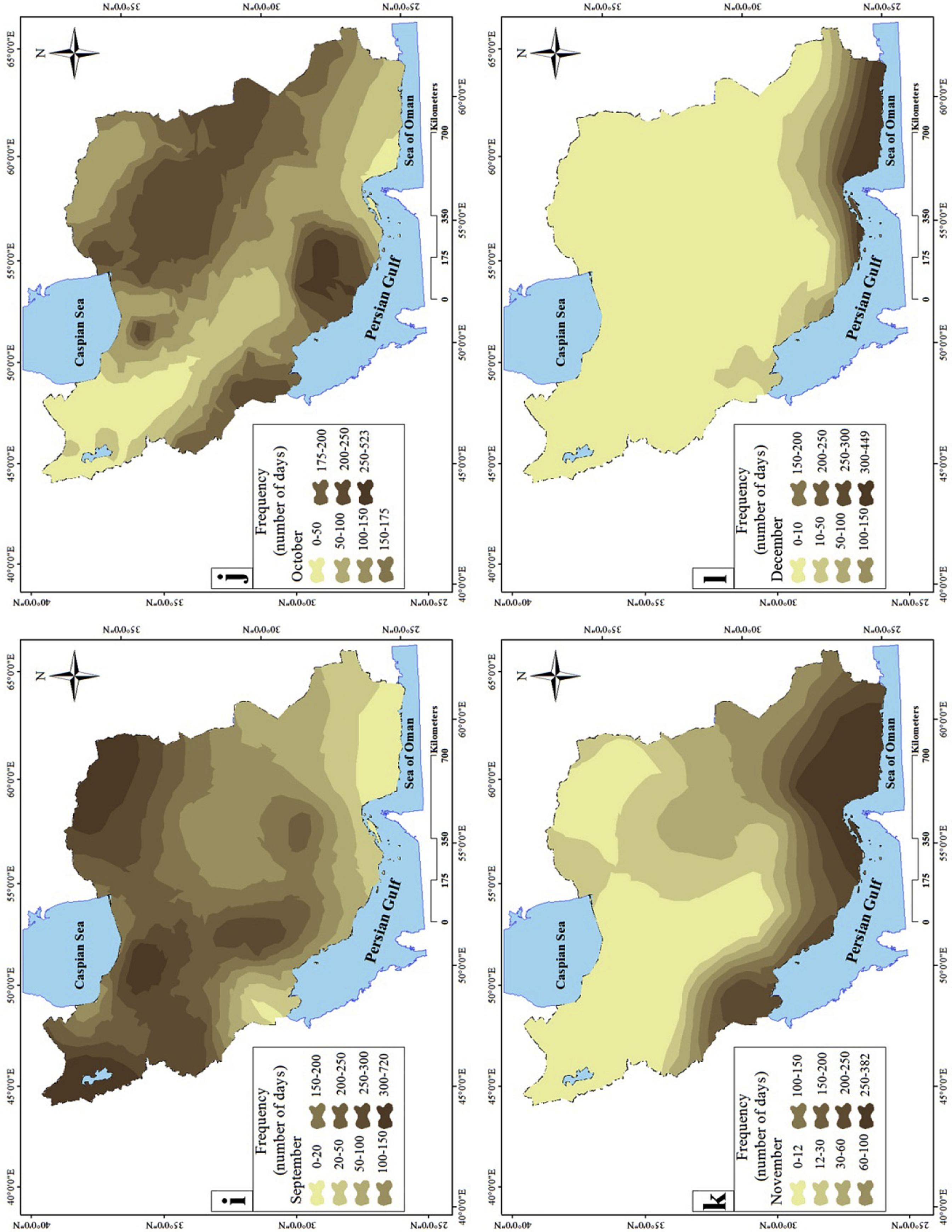


Fig. 9. (*continued*).

high temperatures during the day and low relative humidity in these areas are main factors limiting comfort conditions that these conditions can be observed for the eastern half of the country. But in the coastal strip of South Iran, the maximum temperature and relative humidity can cause heat stress. On the other hand, the Southern Coasts due to the low latitude are strongly influenced by the Azores high pressure in summer, which prevents air masses rise and causes increased rainfall which consequently causes humid conditions. Moreover, in some parts of this coastal strip especially the Southwest, warm and dry systems are originated from the territory of Saudi Arabia and Iraq, penetrate into these areas and exacerbate the conditions of lack of comfort and thermal stresses. In this season, the country's highlands which are mostly in North West and the northern slopes of the Alborz experience more ideal comfort conditions. However, the output shows that generally two stations of Kuhrang with 578 days in July, Shahrekord with 589 days in August and Tehran-Shemiran with 720 days in September have maximum of days with comfort.

By the end of summer and beginning of autumn, thermal stresses in Iran decline sharply, so that in October 134 stations, from among all stations, with different frequencies are located in the comfort zone. In this month, Safiabad station with 379 days compared to other stations has had the highest frequency of the comfort event. As it gets colder in November and December, the number of stations in the comfort zone has reduced, and its number reaches to 78 in November and in December its number reduces to 42 stations. In other words, the outputs show that despite desirable bioclimatic conditions in the beginning of autumn the minimum occurrence of thermal comfort regarding the frequencies of the stations belongs to the middle and the end of this season. In October, the spatial distribution of the maximum frequency of comfort event belongs to the South West and North East of Iran. Also in November and December, the maximum frequency of comfort event shifted to the southern of half of country and special North of Coast Sea of Oman.

In general, in November Jiroft with 382 days and in December Jask with 442 days have experienced more comfort event compared to other stations (Fig. 9k and l).

In Fig. 9, the percentage of the number of stations which in each month have been in the comfort conditions are shown. This graph shows that in the cold months from November to February more undesirable comfort condition can be observed. Also this figure show coefficient of variation (CV) of frequency of the number of days in the comfort zone for difference months. This graph shows that maximum CV is belong to the cold months from November to February and minimum CV have been calculated for spring and summer seasons.

4.2. *Calibrated comfort zone for selected stations*

The outputs of this section of the study show upper and lower thresholds of calibrated comfort zone using the values of temperature and relative humidity components based on which this zone has been identified for each station. Based on Table 2, the values of these thresholds are exactly specified for each study station but based on Fig. 10, spatial distribution of these thresholds are shown in the form of zoning on Iran's map. As Table 2 indicates, based on the component of above threshold relative humidity, the minimum of this component with 24.68% is for Eghlid station and its maximum with 80% belongs to Rasht station. While the fluctuations of the component of below threshold relative humidity vary from at least 20.05% for Kerman to 68.95% for Babolsar station. In total, the existence of the Persian Gulf and Sea of Oman in the Southern Strip and Caspian Sea in the Northern Strip of the country, increase the maximum threshold of relative humidity. On the other hand, the Iranian Plateau and Eastern border regions have the minimum threshold of relative humidity. However, by moving from the center to the northern half and the southern coast of Iran the amount of this component has increased.

Regarding the component of above threshold temperature, fluctuations based on the study stations have varied from its minimum with 22.62% for Ardebil to 25.94% for the station of Dorudzan. However, the difference between the minimum and the maximum threshold of the component of below threshold temperature also shows that Ardebil station with 20.13 °C has the minimum value and its maximum value with 22 °C belongs to Dorudzan. The interesting point is that the difference between mini-max thresholds of the component of above threshold temperature in Iran is greater than the component of below threshold temperature (Table 2). According to the Fig. 11c, d, the spatial distribution of two components of above and below threshold temperature has been shown. It is important to note that the maximum threshold for these two components for some areas of the half of the Northeast, western half and some central parts of the country can be seen and the minimum threshold of these two components can be seen for South and North Coasts of Iran. As it can be observed in Fig. 11a and b, high relative humidity is the cause of low threshold temperature of thermal comfort for two components of above and below threshold temperature in the North and South coastal areas so that the occurrence of days with comfort in these areas occurs as the result of combination of relatively lower temperature with high relative humidity. But for other areas such as the North East, North West and also cores in the West and the Center of Iran, thermal comfort occurs in higher temperatures and low relative humidity. Furthermore in order to reveal some details for the calibrated comfort zone for different climatic zones of Iran, 14 stations were used as the representatives of these areas which the results of this calibration can be seen in Fig. 11. Rasht and Gorgan stations are representatives of Caspian climatic type are located in Southwest and Southeast coasts of Caspian Sea respectively. For both of these stations, relative humidity thresholds of the calibrated comfort zone show higher values compared to other stations. The minimum threshold of relative humidity for Rasht was 58.41 and it has been 57.63% for Gorgan and the upper threshold of the relative humidity for the two stations has been 80 and 74.21%, respectively. On the other hand the threshold of temperature component in these two stations compared to other study stations show almost a lower value. This condition for Rasht station with the minimum temperature threshold of 20.95 °C and maximum amount of 23.70 °C compared to Gorgan with minimum and maximum temperature threshold of 21.23 and 24.43 °C is more considerable. As Fig. 12a and b indicates, calibrated comfort zone for Rasht compared to Gorgan, is concentrated on the extreme eastern border of the diagram's comfort zone but the situation is less severe for Gorgan. In the following, two stations of Bushehr and Bandar Abbas from the coastal climatic zone and Southern Islands of Iran have been selected.

As Fig. 12c and d shows calibrated bandwidth of the comfort zone for Bandar Abbas is further spread compared to Bushehr and these two stations compared with two stations of Caspian climatic region have higher frequency of comfort days. In Bandar Abbas station, upper and lower thresholds of calibrated relative humidity include values of 49.18 and 75.36% that for Bushehr this threshold includes the values of 51.45 and 70.65%. Whereas the minimum and maximum temperature thresholds for Bandar Abbas are 20.82 and 24.15 °C but for Bushehr they are 21.03 and 24.69 °C respectively. The comparison between the stations representatives of northern and southern coasts of the country specifies that the difference between the maximum and minimum base comfort temperature for the northern coasts has been less than the southern coasts and

Table 2
Upper and lower thresholds for temperature and relative humidity for calibration of thermal comfort zone.

Name of station	Above threshold relative humidity in %	Bellow threshold relative humidity in %	Above threshold temperature in C°	Bellow threshold temperature in C°	Name of station	Above threshold relative humidity in %	Bellow threshold relative humidity in %	Above threshold temperature in C°	Bellow threshold temperature in C°
Abadan	56.65	32.33	25.5	21.32	Kuhdasht	38.85	23.12	25.51	21.46
Abadeh	29.81	20.10	25.28	21.28	Kuhrang	32.19	22.75	23.8	20.85
Abali	34.94	21.87	24.16	20.78	lar	45.24	26.31	25.46	21.41
Abumusa	71.66	50.53	24.33	21.15	lordegan	34.66	22.08	25.69	21.55
Ahar	56.94	36.35	24.16	20.83	Mahabad	44.04	26.73	25.69	21.75
Ahvaz	54.6	31.25	25.43	21.38	Maku	49.35	31.49	25.09	21.33
Aligudarz	30.81	20.49	25.35	21.41	Malayer	33.13	21.31	25.72	21.67
Anarkerman	32.32	21.16	25.12	21.12	Manjil	67.58	47.25	25.11	21.41
Arak	36.86	21.68	25.69	21.58	Maragheh	40.47	25.53	25.74	21.79
Ardebil	71.15	47.25	22.62	20.13	Maravehtapeh	62.96	37.76	25.42	21.55
Ardestan	34.97	21.16	25.38	21.3	Marivan	40.75	26.47	25.52	21.65
Astara	78.5	61.06	24.26	21.05	Marvast	31.92	20.67	25.21	21.19
Avaj	41.75	23.18	25.07	21.31	Mashhad	46.59	25.49	25.75	21.63
Babolsar	78.65	68.95	23.58	21.02	Masjedsolyman	50.67	27.23	25.27	21.3
Bafqyazd	33.98	20.89	25.16	21.15	Meshkinshahr	58.26	34.5	23.67	20.58
Baft	38.98	22.85	25.56	21.73	Miyaneh	47.38	29.63	25.8	21.82
Bam	34.69	21.53	25.14	21.18	Myanab	69.41	42.46	24.79	21.13
Bandarabbas	75.36	49.18	24.15	20.82	Nayeian	32.53	20.64	25.29	21.24
Mahshahr	57.9	32.4	25.45	21.33	Nahavan	37.53	23.59	25.71	21.69
Anzali	79.9	62.36	23.72	21.01	Natanz	34.17	21.63	25.57	21.41
Bandaredayyer	67.45	39.02	24.83	20.97	Nehbandan	35.75	20.42	25.28	21.23
Bandare-lengeh	71.86	46.78	24.32	20.9	Nyshabur	41.53	24.66	25.69	21.69
Behbahan	52.24	27.98	25.55	21.41	Noshahr	80.18	68.19	23.56	21.03
Bijar	38.77	22.69	25.2	21.35	Omidiyeh	54.77	29.64	25.48	21.36
Birjand	32.24	20.96	25.7	21.71	Orumiyeh	53.3	36.93	24.89	21.37
Biyarjomand	43.53	27	25.78	21.64	Parsabad	72.53	55.68	24.91	21.33
Bojnurd	58.25	32.07	25.32	21.53	Piranshahr	42.94	26.45	25.78	21.75
Borujen	30.37	20.64	24.91	21.25	Poldokhtar	45.94	23.95	25.24	21.19
Borujerd	34.05	20.77	25.42	21.28	Qaen	34.16	21.87	25.72	21.68
Boshruyeh	37.63	22.64	25.53	21.46	Qazvin	49.12	32.09	25.77	21.81
Bostan	55.98	32.49	25.52	21.45	Qeshm	76.66	53.39	23.81	20.78
Bushehr-airport	70.65	51.45	24.69	21.03	Qom	40.46	23.79	25.47	21.47
Bushehr-costal	72.77	54.14	24.46	20.94	Qorveh	35.99	21.97	25.4	21.4
Chabahar	74.41	47.93	24.01	21.01	Quchan	49.51	26.96	25.07	21.32
Dehloran	51.15	27.49	25.28	21.23	Rafsanjan	30.48	20.45	25.65	21.5
Dogonbadan	34.19	26.03	25.17	21.2	Ramhourmoz	52.1	27.42	25.41	21.24
Dorudzan	31.201	25.35	25.94	22.01	Ramsar	79.61	67.13	23.69	21.02
Doshantapeh	31.96	24.17	25.32	21.32	Rasht	80	58.41	23.71	20.96
Eghlid	24.68	20.90	25.45	21.08	Ravansar	35.27	20.74	25.12	21.02
Esfahan-airport	33	21.54	25.75	21.57	Robate-poshte-badam	34.56	21.78	25.35	21.24
Garmsar	38.701	23.30	25.36	21.39	Sabzevar	39.78	24.1	25.58	21.43
Gharakhil	78.63	66.20	23.67	21.13	Safiabad	63.1	42.96	25.48	21.4
Golmakan	44.44	24.56	25.73	21.51	Sahand	43.16	25.57	25.07	21.25
Golpayegan	34.085	21.17	25.46	21.42	Sanandaj	35.3	22.97	25.8	21.53
Gonabad	36.54	21.69	25.55	21.44	Saqez	41.82	24.55	25.02	21.33
Gonbad	69.00	46.34	25.12	21.33	Sarab	54.07	34.77	23.38	20.4
Gorgan	74.21	57.63	24.43	21.23	Sarakhs	48.54	26.57	25.66	21.56
Hamedan-airport	40.87	24.74	25.52	21.56	Saravan	39.4	21.48	25.34	21.31
Hamedan-Nozeh	40.59	24.44	25.67	21.67	Sardasht	38.33	23.73	25.77	21.74
Darab	41.70	26.12	25.44	21.33	Sare-pol-zahab	49.2	28.72	25.74	21.6
Ilam	33.45	20.97	25.38	21.26	Saveh	39.34	22.91	25.41	21.37
Iranshahr	45.76	23.18	25.27	21.16	Semnan	39.3	23.33	25.54	21.54
Izeh	48.31	25.58	25.36	21.35	Shahrebabak	31.22	20.6	25.21	21.06
Jam	51.78	27.86	25.57	21.52	Shahrekord	34.2	23.9	24.89	21.33
Jask	71.62	48.71	24.33	21.33	Shahreza	32.69	21.58	25.67	21.67
Jroft	54.44	31.51	25.34	21.2	Shiraz	34.09	22.51	25.47	21.41
Jolfa	53.26	36.25	25.67	21.5	Shushtar	54.14	28.58	25.28	21.19
Kabutarabad	37.05	23.66	25.64	21.45	Siri Island	70.66	50.6	24.4	21.19
kahnuj	55.47	29.86	25.37	21.23	Sirjan	33.36	21.19	25.55	21.46
kangavar	39.02	27.08	25.68	21.64	Tabas	37.27	20.64	25.27	21.26
karaj	44.60	26.61	25.63	21.58	Tabriz	43.95	28.57	25.64	21.77
kashmar	37.99	22.88	25.62	21.51	Takab	42.45	25.03	24.84	21.21
Kerman	31.35	20.00	25.32	21.32	Tehran-Geophysic	36.85	22.7	25.52	21.42
Kermanshah	36.15	21.51	25.22	21.13	Tehran-shemiran	40.75	24.93	25.76	21.6
Khalkhal	50.95	32.32	23.78	20.45	Torbatr-Heydareih	38.66	23.43	25.69	21.69
Khash	34.91	20.58	25.33	21.35	Torbat	41.37	23.41	25.77	21.59

Table 2 (*continued*)

Name of station	Above threshold relative humidity in %	Bellow threshold relative humidity in %	Above threshold temperature in C°	Bellow threshold temperature in C°	Name of station	Above threshold relative humidity in %	Bellow threshold relative humidity in %	Above threshold temperature in C°	Bellow threshold temperature in C°
Khodabanbeh	40.87	23.66	25.10	21.28	Yasuj	33.46	21.78	25.79	21.75
Khoramabad	39.60	21.81	25.15	21.31	Yazd	33.64	20.59	24.85	20.91
Khoramdareh	47.89	28.52	25.21	21.31	Zabol	43.11	24.58	25.65	21.48
Khoy	52.95	36.94	25.63	21.63	Zahak	38.77	22.26	25.39	21.31
Khurbiarjemand	35.99	21.52	25.22	21.32	Zahedan	34.28	20.11	25.05	21.26
Khurbiabanak	36.31	22.11	25.47	21.50	Zanjan	49.74	30.83	24.9	21.22
Kish	73.45	53.33	24.20	20.81	Zarqan	38.07	24.12	25.45	21.4
Konarak	70.60	44.45	24.56	21.04	Zarrineh	39.62	23.35	23.7	20.79

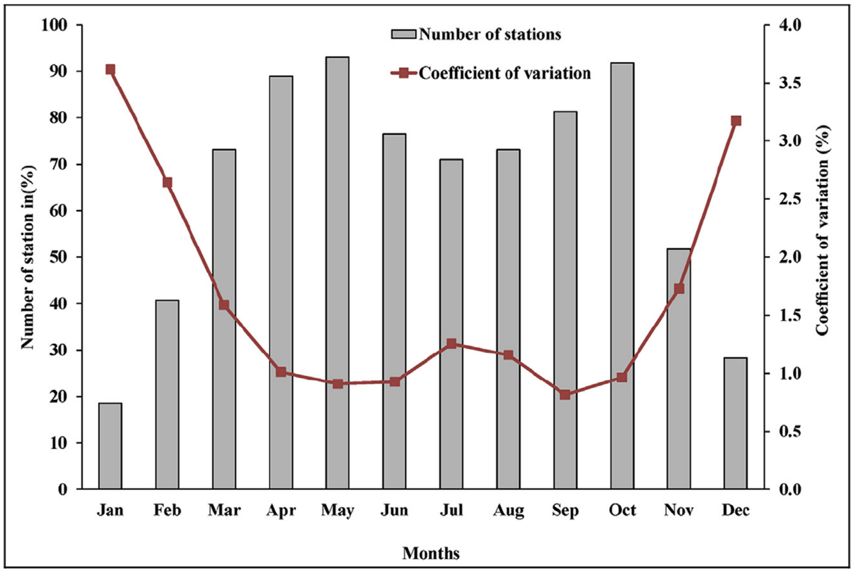


Fig. 10. The percentage of the number of stations in the comfort condition and their coefficient of variation for per month.

in other words this bandwidth of thermal comfort is slightly greater for southern coasts. For example, in Rasht this bandwidth of thermal comfort is 2.75 °C while its value for Bushehr is 3.66 °C. Only Esfahan has been selected from plain climatic zone which it can be seen that the range of calibrated comfort zone for temperature is from at least 21.57 to the maximum of 25.75 °C and relative humidity has been from the minimum of 21.54 to the maximum of 33%. As (Fig. 12e) shows one of the characteristics of this station is the occurrence of comfort days in the combination of low relative humidity and relatively high temperature. As this condition is clearly visible on the diagram, the calibrated area has concentrated on the western borders of the diagram. Ahvaz station is the representative of Khuzestan and Jazmurian plain climatic type which is both influenced by the Persian Gulf water zone and hot and dry land of Saudi Arabia. In this station, relative humidity thresholds are slightly larger compared to plain climatic type which Esfahan is its representative so that minimum and maximum threshold of the relative humidity includes the values of 31.25 and 54.60% respectively and for temperature, Minimum and maximum amounts with values of 21.38 and 25.54 °C are partially smaller compared to Esfahan station. As Figure 12f shows for Ahvaz, the calibrated zone for this station is more concentrated on the central parts of the diagram. In the following two stations of Ardebil and Shahrekord from the mountainous climatic region are considered. In Shahrekord station calibrated minimum and maximum relative humidity thresholds include values of 23.90 and 34.19%, on the other hand minimum and maximum values of calibrated temperature are 21.33 and 24.89 °C respectively. As it can be seen in Figure 12h, Calibrated range of the comfort zone for this station has been transferred to the western borders of the diagram and actually comfort conditions for this station is experienced low relative humidity and almost high temperature threshold. On the other hand, for Ardebil minimum and maximum threshold of relative humidity and calibrated temperature include values of 47.25 and 71.15% respectively and for temperature they have been 20.13 and 22.26 °C. Based on Figure 12g, it is clear that calibrated zone lean towards the right side of the diagram and unlike Shahrekord station, mostly comfort conditions occur in higher relative humidity and lower temperature. In the difference between the thermal comfort zone of these two stations is seen that its width for Shahrekord has been 3.56 °C which shows greater value compared to Ardebil with 2.48 °C. for the climatic zone of elevated foothills two stations of Hamedan and Tabriz were selected which the calibrated range of minimum and maximum relative humidity and temperature are very close to each other for these two stations so that relative humidity values for Tabriz include 24.74 and 40.87% and for Hamedan they have been 28.56 and 43.95% and on the other hand for temperature, Tabriz station shows values of 21.76 and 25.63 °C and with little difference this threshold for Hamedan includes 21.56 and 25.52 °C. Therefore in these two stations, the range of Calibrated comfort zone leans towards western half of the diagram and morphologically, the calibrated range is very similar to

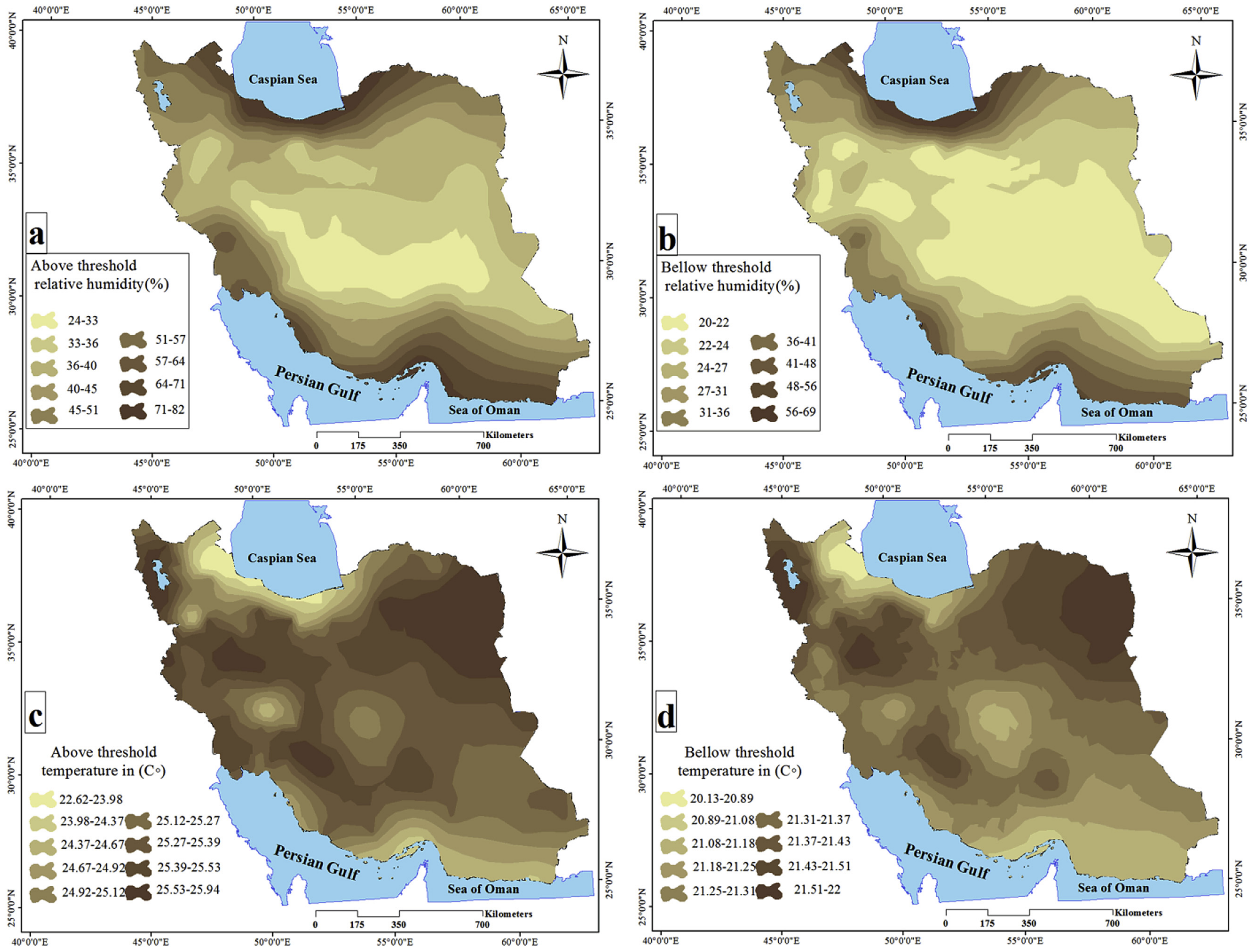


Fig. 11. The upper and lower thresholds of temperature and relative humidity to introduce calibrated thermal comfort zone. Figure 11a, upper threshold of the calibrated relative humidity. Figure 11b, lower threshold of the calibrated relative humidity. Figure 11c, upper threshold of the calibrated relative humidity. Figure 11d, lower threshold of the calibrated relative humidity.

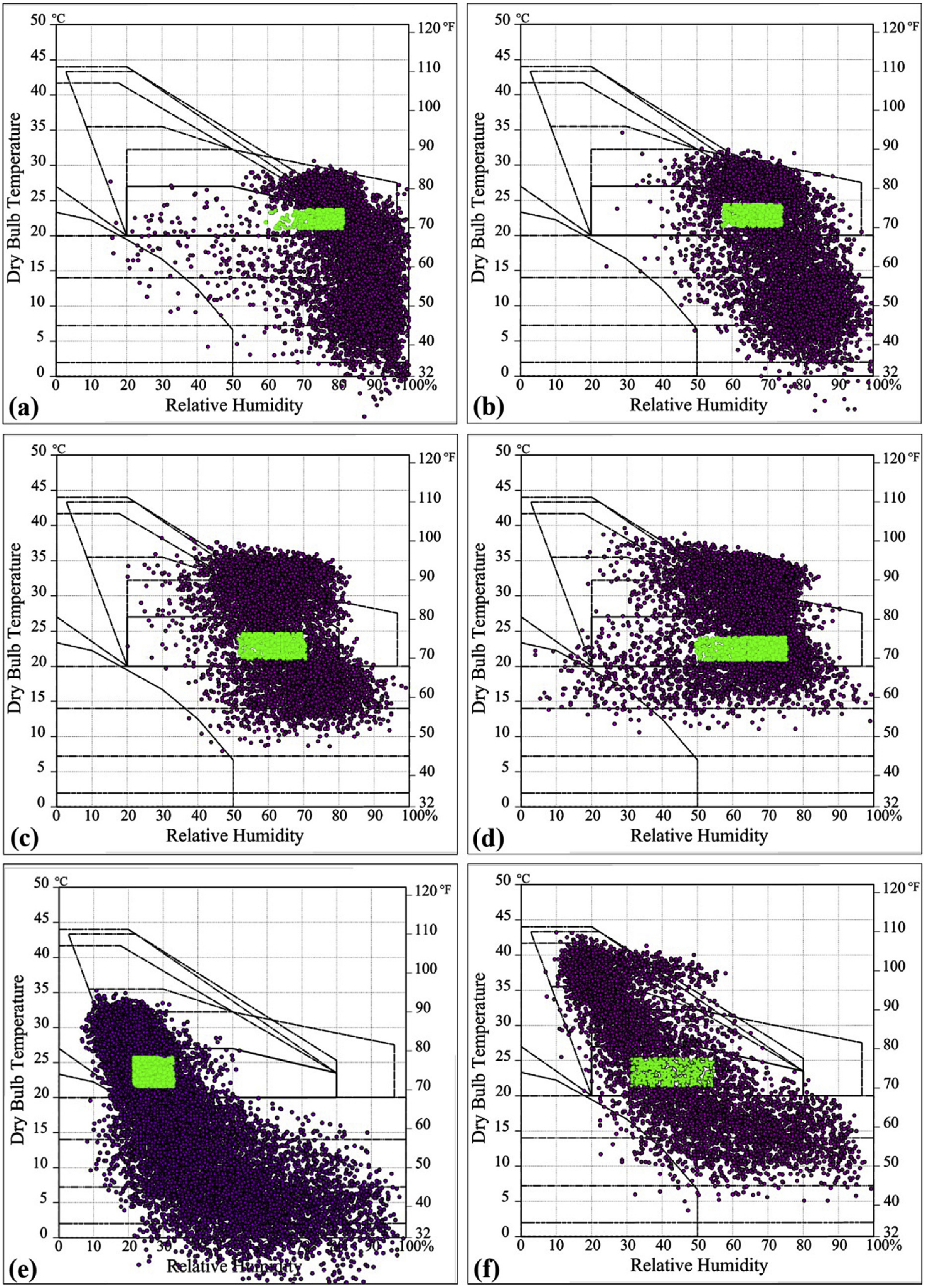


Fig. 12. (A) The distribution of bioclimatic conditions of the selected study stations for the period of 1995–2014. B: determining the range of calibrated comfort zone for the selected stations. (a)Rasht, (b)Gorgan, (c)Bushehr, (d)Bandarabbas, (e)Esfahan, (f)Ahvaz, (g)Ardebil, (h)Shahrekord, (i)Hamedan, (j)Tabriz, (k)Qom, (l)Tabas, (m)Mashhad, (n)Sanandaj.

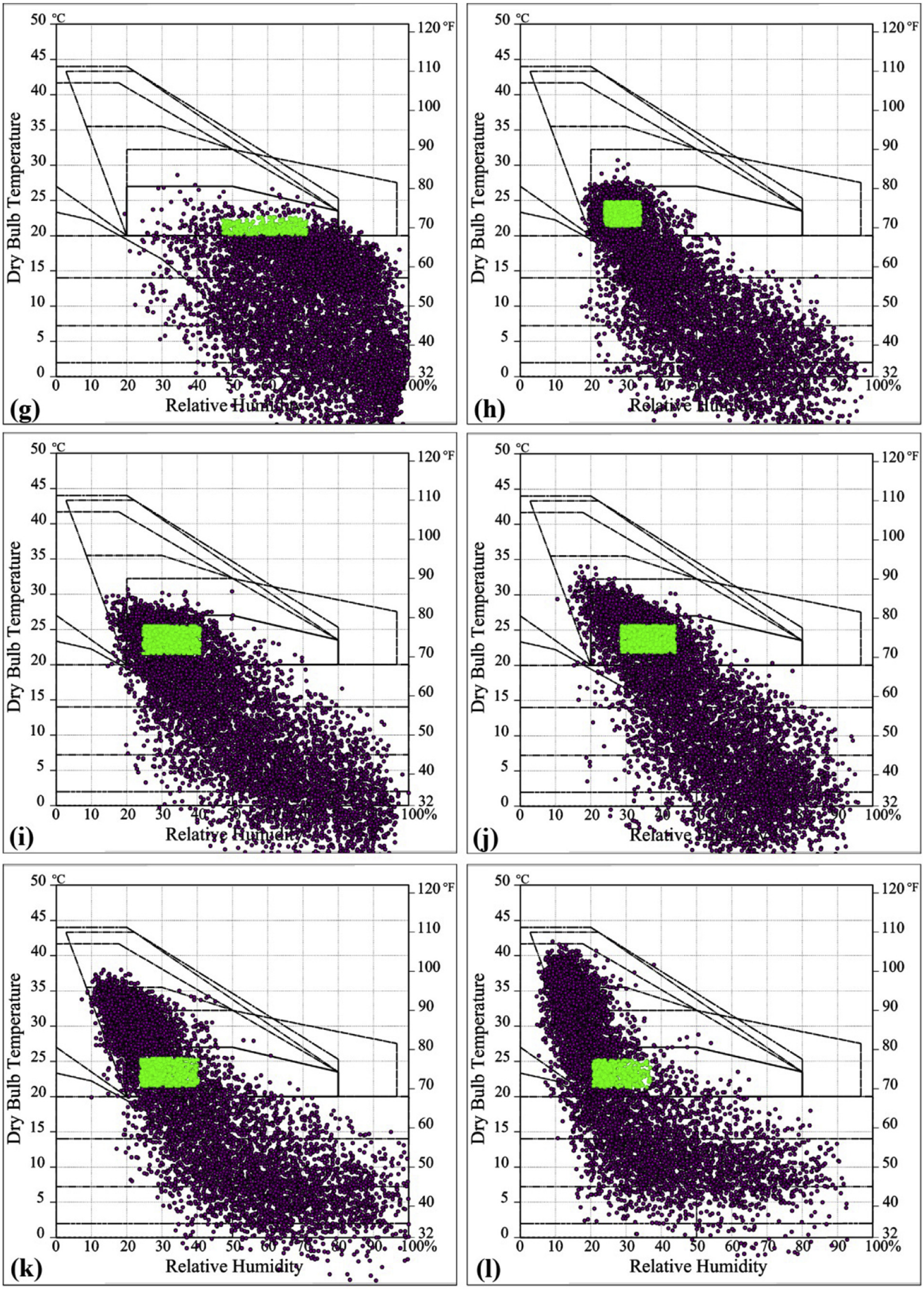


Fig. 12. (*continued*).

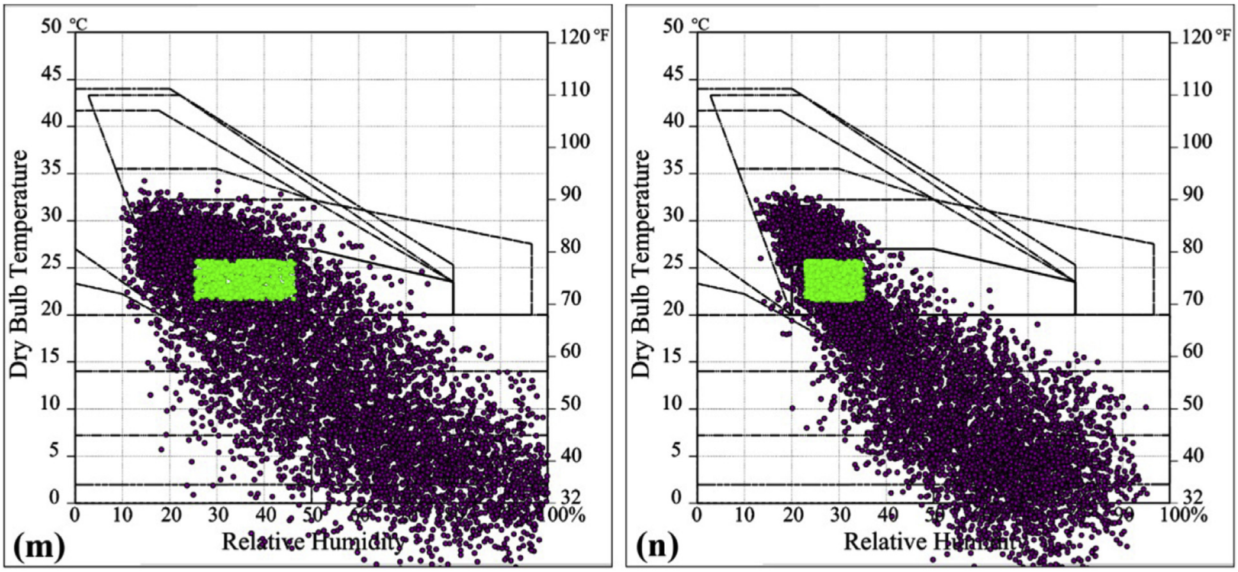


Fig. 12. (*continued*).

each other for these two stations (Fig. 12j and k).

Qom and Tabas stations have been selected as samples of climatic zone of deserted area which primarily based on the Fig. 12l. In both of these stations similar to Hamedan and Tabriz stations, the range of calibrated comfort zone has leaned towards western half of the diagram. On the other hand, other similarities between the two stations of the climatic zone of deserted area with climatic type of elevated foothills are very little difference of sample stations of these two climatic types with each other in the thresholds of the base comfort temperature and also their slight difference in bandwidth of the comfort temperature. So that for Qom and Tabas this bandwidth is approximately 4 °C but for Hamedan and Tabriz it is almost 3.90 °C. Also in both climatic types calibrated relative humidity thresholds of the stations are in the same range. However, calibrated range of minimum and maximum relative humidity and temperature for Qom has been 23.78% and 40.45%. On the other hand, these ranges for Tabas include 20.64 and 37.27% and for temperature they have been 21.26 and 25.26 °C. The only difference between these two stations of the desert climatic type is higher calibrated relative humidity for Qom compared to Tabas (few percent) and also lower calibrated temperature threshold of Tabas compared to Qom (a few hundredths of a percent). Finally, from low-lying foothills two cities of Mashhad and Sanandaj were selected. The first comparison between two stations of this climatic type reveals that thermal comfort for Sanandaj can be observed in nearly a lower relative humidity compared to Mashhad. In fact, the calibrated zone for Sanandaj is limited to the western end of the diagram while for Mashhad; it extends from the half of diagram towards western borders. On the other hand merely because of the Fig. 12m and n it becomes evident that the width of calibrated comfort zone for Mashhad is wider than Sanandaj. So if the calibrated values are considered, it is observed that minimum and maximum calibrated relative humidity for Mashhad includes values of 25.48% and 46.58% that the difference of these values shows a width of 21.10%. But for Sanandaj, this width based on the minimum and maximum values of 22.97 and 35.29% includes the value of 12.32%. On the other hand, regarding the threshold of the calibrated base temperature, bandwidth and specified thresholds very little difference can be seen. So that the minimum and maximum base comfort temperature for Mashhad include values of 21.63 and 25.75 °C and for Sanandaj they are 21.52 and 25.79 °C.

4.3. *Comparing the base temperatures used to monitor degree-day demand for heating and cooling energy*

Many studies have been conducted in Iran on the monitoring of heating and cooling energy demands by using HDD and CDD [5,43–45]. In these studies, regardless of bioclimatic characteristics and prevailing climatic conditions of the region, thresholds such as 18 to 22 or 18 to 24 or 25 °C are used to monitor HDD and CDD so that in the previous studies no difference in selecting base temperature of the different climatic types is seen and all stations with different types of climate are assessed for their need to degree-day cooling and heating energy based on a similar threshold. Therefore, at this point of the study, using calibrated base temperature, HDD and CDD values were calculated for different stations and these results with base temperature of 18 °C were used for calculating HDD and the temperature of 22 °C was used to monitor CDD. It should be noted that Fig. 12 has been drawn based on the annual average of degree-day heating and cooling energy demand using the statistical period from 1995 to 2014. At first, based on the CDD atlas using base temperature of 22 °C it is observed that northern half of Iran requires less cooling energy for cooling the indoor environment compared to Iran's southern half however northeast areas of Iran, North West and parts of the southwest coasts of the Caspian Sea have the minimum need for cooling energy While the coastal strip of the south has the maximum cooling energy demand. On the basis of calibrated base temperature (Fig. 13a) in terms of spatial distribution, minimum and maximum values of CDD for different regions of Iran have no difference with Fig. 13c, which is based on the base temperature being 22 °C and constant for all zones. Whereas in terms of the amount, the differences are remarkable in some areas. In general, the average of CDD demand based on the all study stations is 770 degree-day calories while based on the base temperature of 22 °C, this average for Iran is 1137 day-degree calories. Based on the both, the minimum energy requirements of CDD belong to Ardebil which its annual average based on the calibrated base temperature is 5.77 grade-day calories and on the basis of the threshold of 22 °C, the number of 9.26 degree-day is calculated per year. On the other hand, maximum demand for CDD belongs to Doshantapeh station which has been calculated to be 5121 degree-day calories based on the calibrated base temperature. This amount regarding the base temperature of

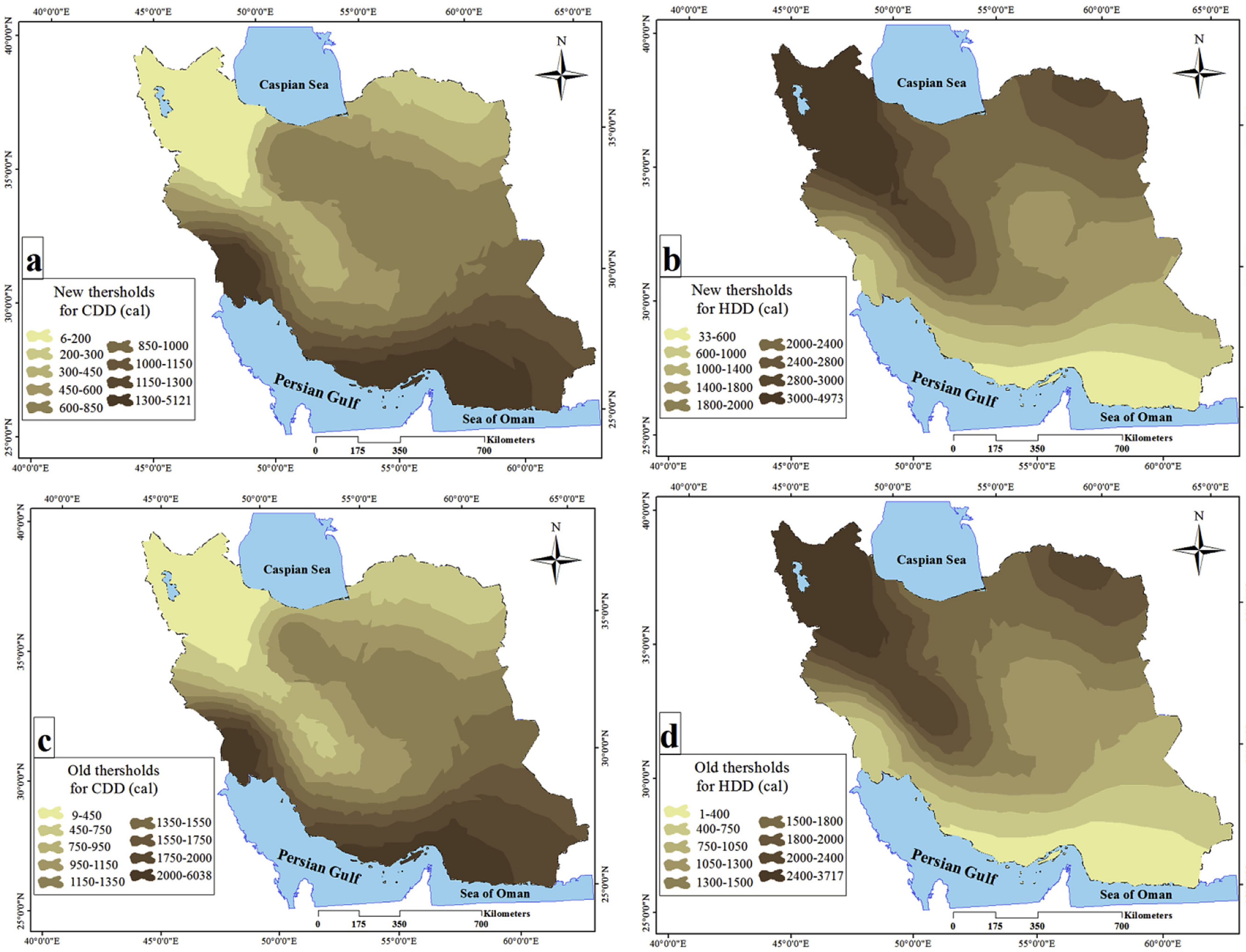


Fig. 13. Annual average of energy needs for HDD and CDD using calibrated base temperature and base temperature without calibration. Figure (a): CDD using calibrated thresholds. Figure (b): HDD using calibrated thresholds. Figure(c): CDD using the threshold temperature of 22 °C. Figure (d): HDD using the threshold temperature of 18 °C.

22 °C is 6038 degree-day calories per year. On the other hand, based on the criterion of a minimum of 1000 degree-day calories of cooling energy and considering the basis of the calibrated base temperatures, it becomes clear that 40 stations require annual amounts of more than 1000 degree-day calories so that comfort conditions inside the building can be provided and only 4 stations of Dehloran, Ramhourmoz, Shushtar and Doshantapeh require values more than 2000 degree-day calories be provide comfort conditions inside the building. The focus of these stations has been on the south-western regions of Iran i.e. Persian Gulf's North-western Coast. But based on the base temperature of 22 °C it is revealed that the number of 65 stations needs at least 1000 degree-day calories per year for cooling that by considering the criterion of at least 2000 degree-day calories per year their number has reduced to 26 stations of which 25 stations require an annual average of 2031–2091 degree-day cooling energy and only Doshantapeh station with 6038 degree-day calories, requires more cooling power compared to the other station. However, on the basis of a base temperature of 22 °C, the focus of stations that require at least 2000 degree-day calories per year for cooling has extended from southeastern half of Iran to the Northeast Coast of the Persian Gulf and Oman Sea, Fig. 13c.

The results of calibration of the base temperature for calculation of HDD show that the average of this index for the entire of Iran is 2168 degree-day per year and based on the base temperature of 18 °C it has been 1551.4 degree-day calories per year. But the difference between the minimum and maximum of this index based on the calibrated base temperature belongs to Abumusa Island with 33 degree-day calories and its maximum with 4973 degree-day has been for Esfahan-airport. But considering the base temperature of 18 °C it is found that Abumusa island station needs an average of 1.19 degree-day calories for heating during the year and Zarrineh with 3717 degree-day calories per year has had the maximum heating energy demand. Therefore, a significant difference can be seen between the results of calibrated base temperature with base temperature of 18 °C based on Fig. 13d, it can be seen that by using base temperature of 18 °C, the maximum need for heating energy belongs to two main cores in the far North East and North West of Iran and the southern half of the country with a focus on the northern coast of the Persian Gulf and Sea of Oman has had the minimum HDD. However, by using calibrated base temperatures show that the maximum need for heating energy has expanded further than a small core in the extreme northeastern and north-western Iran and this zone has been extended particularly on the Zagros mountains in a strip from North West -South East to central areas of Iran (see Fig. 13b). Finally, based on the minimum heating energy of 1000, 2000 and 3000 degree-day calories per year for the calibrated base temperature it was found that 119, 86 and 41 stations are located in each of these classes that by providing required energy meet the comfort conditions inside the building. But for base temperature of 18 °C, 104, 50 and 10 stations require minimum of 1000, 2000 and 3000 degree-day calories in order to provide comfort conditions inside the building.

5. Discussion and conclusion

By analyzing long-term monitored weather data we identified the behavior and prevailing climate patterns in Iran based on the bioclimatic chart. In order to calibrate the thermal comfort boundaries of different ecological regions of Iran, the perspective of the dominant climatic pattern of each region, with regard to the quantity and quality of frequency of occurrence of days with thermal comfort, has been used. The following discussion highlights the key study findings and elaborates on the study strength, limitations and future work.

5.1. Summary of main findings

Among the results of the current study it was found that the upper threshold of this component varies from at least 22.62 °C for Ardebil to 25.94 °C for Dorudzan station and the lower threshold of this component belongs to Ardebil with at least 20.13 °C up to its maximum value with 22 °C which belongs to Dorudzan. Therefore, significant differences can be seen in the upper threshold of the base comfort temperature among Iran's stations but regarding the lower threshold of the calibrated comfort temperature, this difference shows a significant decrease. A similar result can be seen in the work of Roshan et al. [5] for 12 selected stations of Iran. So that there is a little difference between lower threshold of the base comfort temperature for the observation stations but considering the upper threshold, the difference is more evident among stations.

Another finding of this study is the combination of the two components of temperature and relative humidity in the spatial distribution of bioclimatic comfort conditions in Iran So that the maximum temperature threshold for the occurrence of bioclimatic comfort conditions belong to cores in the northeastern half of Iran, Iran's western half and some central parts of Iran and the minimum of the component of calibrated temperature threshold belong to north and south beaches of the country. The reason for this event is the occurrence of comfort days especially in the coastal strip in the south of the country due to the combination of relatively lower temperatures with high relative humidity while for other areas such as the North East, North West as well as areas in the West, the occurrence of thermal comfort has occurred at higher temperatures and lower relative humidity. Similar results have been obtained in the study for the North West and West regions of Iran by Orosa et al., [46]. These results based on the Humidex index that combines two components of temperature and relative humidity showed that the most ideal comfort conditions for these areas are from the late spring to late summer. Also similar to the results of the present study, Dehghan, et al. [47] in a study for southern coast of Iran showed that the most important inhibiting factor of bioclimatic comfort in these areas, particularly in the hot period of the year, are temperature and relative humidity. Therefore the event of comfort in these areas occurs in the situation that one of these two components is lower compared with the other one. Based on the frequency of days of comfort it became clear that spring is the most ideal season in terms of climatic comfort in Iran. With the onset of spring and moderation of cold, more stations experience climatic comfort conditions. So that in April, May and June, respectively 132, 139 and 113 stations have had some experience of days with bioclimatic comfort conditions. But in the other seasons, the frequency of the stations which have experienced comfort event is less than spring.

In the present study it also was found that maximum need for CDD belongs to Doshantapeh station which is located in Khuzestan plain. So that based on the calibrated base temperature, it has been calculated to be 5121 degree-day calories per year and this amount considering base temperature of 22 °C is 6038 degree-day calories per year. Roshan et al. [8] in order to investigate the moderating effect of Urumieh water zone on the moderating of heating and cooling energy needs of the neighboring towns indicated that in case of drying of the Urumieh Lake generally, the values of heating and cooling energy requirements for the neighboring towns will increase. But in general, the maximum energy requirement of the cities during the year belongs to HDD and the need for CDD is in the lower range. As it can be seen in the current study, for the cities of western half and North West of the country, the demand for heating energy is higher than cooling energy which is a confirmation of the results of the present study.

5.2. Strengths and limitations of the study

The study strength is based on its methodology using statistical analysis to determine the comfort boundaries for different Iranian cities and regions based on the repetition and frequency of temperature and humidity values. Moreover, the use of 14 representative weather stations for the period of 1995–2014 allowed us to generate valuable maps and thresholds for heating and cooling degree days and their spatial distribution over the whole country. We claim that this methodology can be used in other countries and regions to determine the cooling and heating degrees thresholds rapidly and accurately. According to the results described in this study, in some other studies similar results have been found which confirm the findings of the present study. The findings of Daneshvar et al. [48] showed that spring months, especially April, had the most appropriate condition for thermal comfort in most regions of Iran [48]. Daneshvar et al. used long-term average monthly data to estimate PET index and examined thermal comfort conditions during different months of the year. Their results showed that thermal comfort conditions prevail during the winter months on the southern part of the country and along the shores of the Persian Gulf and Oman Sea. In the stations of west to northwest of Iran, for example in Tabriz, the most frequent thermal comfort condition appears in the form of two peaks, i.e., in late spring as well late summer and early fall. Farajzadeh and Matzarakis [49,50] and Farajzadeh et al. [51] investigated thermal climate and tourism climate conditions for the areas of northwest of Iran using PET. Based on calculations of PET in Urumieh Lake coast, it is shown that the months June to September are located in the comfortable class representing the most suitable months for tourist activities. Esmaili and Fallah Ghalhari [52] proved that the highest potential of thermal comfort in Iran was related to spring.

In the following, the results obtained from examining the maps of frequency of days with comfort and annual need for degree-day heating and cooling in the country suggest the Segmentation of Iran into two macro climatic flat)plain) or Mountains zones. In the warm half of the year, the plain segment of the country which includes plains, southern coasts and Central Plateau of Iran have minimum days of thermal comfort that due to thermal stresses, these areas have maximum need of cooling energy. Roshan et al. [53] in a study showed that the most important inhibiting factor of bioclimatic comfort in Iran are different for different areas. For the Northern Half and the cold season of the year, the most important factor is cold stresses and for the southern half and in the hot period of the year, hot stresses are the most important inhibiting factor of comfort in Iran. Also Esmaili et al. [54] and Rezvani and Mesgarian [55] presented similar results which are similar to the findings of the present study. From the perspective of Ecology, Low-pressure thermal conditions have caused Sultry conditions in the Persian Gulf and the existence of tropical high pressure conditions have created Hot and dry conditions in Khuzestan plain and caused maximum temperature of Iran in this season and in these areas. This is while the effect of humidity of the sea and the arrival of monsoon air masses in the coast of Oman Sea have caused more balanced conditions of temperature compared to the coasts of the Persian Gulf. The average of annual cooling also indicates that the degree of cooling is consistent with altitude changes, latitude, and especially atmospheric moisture content. Northern coasts despite their low altitude but due to higher latitudes and central plateau of Iran, despite being low lands but because of lower relative humidity in warmer seasons and influx of cold and dry air masses in cold seasons have less cooling demand than southern coasts of Iran. But in the cold period of the year, the mountain part of the country which includes mountainous and foothill strip due to maximum cold stresses and minimum thermal comfort have the highest amount of energy needed for heating that its maximum belongs to Azarbaijan plateau in the North West, Zagros Mountains, Alborz and Khorasan province the North East. The energy level of the Caspian Sea coasts because of advancing of the Alborz mountainous points is identical to mountainous areas. In some studies, Masoudian and colleagues [43,44] investigated the mean total degree days needed (heating and cooling) in the territory of Iran. Based on the threshold temperature of 25 °C, they showed that maximum demand of cooling energy belongs to Khuzestan plain and Hormozgan coasts.

5.3. Implications for practice and future research

Finally, it is expected that based on the calibrated bioclimatic comfort zone of the study stations, one could have a more appropriate estimate of the amount of energy supply and demand to provide environmental comfort inside buildings. And heating and cooling energy risk management of the urban settlements can be done with more rational criteria. Also it is expected that these new comfort zones can be considered in the architectural design of buildings and planning of heating and cooling installation systems in different climatic zones of Iran in order to reduce extra costs of energy supply. The future work will focus on identifying solar passive features related to building form and orientation, envelope design, shading, use of natural ventilation, internal space arrangements and activities of the habitants for all the climatic zone of Iran.

References

[1] H. Belkhouane, J. Hensen, S. Attia, Thermal comfort models for net zero energy buildings in hot climates, Second International Conference on Energy and Indoor Environment for Hot Climates, Doha, 2017.

[2] S. Attia, I. Duchhart, Bioclimatic landscape design in extremely hot and arid climates, PLEA 2011: Architecture & Sustainable Development: Conference Proceedings of the 27th International Conference on Passive and Low Energy Architecture, Louvain-la-Neuve, Belgium, 13-15 July, 2011, Presses univ. de Louvain, 2011, p. 459.

[3] S. Attia, S. Carlucci, Impact of different thermal comfort models on zero energy residential buildings in hot climate, Energy Build. 102 (2015) 117–128.

[4] S. Attia, A. De Herde, Early design simulation tools for net zero energy buildings: a comparison of ten tools, Conference Proceedings of 12th International Building Performance Simulation Association, 2011, 2011.

[5] G.R. Roshan, A. Ghanghermeh, S. Attia, Determining new threshold temperatures for cooling and heating degree day index of different climatic zones of Iran, Renew. Energy 101 (2017) 156–167.

[6] A. Lenoir, G. Baird, F. Garde, Post-occupancy evaluation and experimental feedback of a net zero-energy building in a tropical climate, Archit. Sci. Rev. 55 (3) (2012) 156–168.

[7] S. Akbarian Ronizi, G.R. Roshan, S. Negahban, Assessment of tourism climate opportunities and threats for villages located in the northern coasts of Iran, Int. J. Environ. Res. 10 (4) (2016) 601–612.

[8] G. Roshan, J.M. Samakosh, J.A. Orosa, The impacts of drying of Lake Urmia on changes of degree day index of the surrounding cities by meteorological modelling, Environ. Earth Sci. 75 (20) (2016) 1387.

[9] CIBSE, CIBSE KS06: Comfort, the Chartered Institution of Building Services Engineers2006.

[10] A.S. Committee, ASHRAE Handbook: Fundamentals 2013, Ashrae, 2013.

[11] P.O. Fanger, Thermal comfort. Analysis and applications in environmental engineering, Thermal comfort. Anal. Appl. Environ. Eng. (1970), 244 pages.

[12] M.D. Egan, Concepts in Thermal Comfort, Prentice Hall, 1975.

[13] O.H. Koenigsberger, Manual of Tropical Housing & Building, Orient Blackswan, 1975.

[14] V. Anna-Maria, Evaluation of a sustainable Greek vernacular settlement and its landscape: architectural typology and building physics, Build. Environ. 44 (6) (2009) 1095–1106.

[15] V. Olgyay, Design with Climate: Bioclimatic Approach to Architectural Regionalism, Princeton University Press, 1963.

[16] D. Morillón-Gálvez, R. Saldaña-Flores, A. Tejeda-Martınez, Human bioclimatic atlas for Mexico, Sol. Energy 76 (6) (2004) 781–792.

[17] B. Givoni, Man, Climate and Architecture, second ed., Applied Science, London, 1976.

[18] M. Razjouyan, Comfort Design with Climate, 2 ed., Shahid Beheshti University Press, Tehran, 2009.

[19] M. Milne, B. Givoni, Architectural Design Based on Climate, McGraw-Hill, New York, 1979.

[20] S. Attia, v.M. Geoffrey, Bioclimatic Design in Casablanca (Morocco): Decision

Support through Building Performance Simulation, Proceedings of the 4th Biennial subtropical cities conference, Fort Lauderdale, FL, 2013.
[21] A.-T. Nguyen, Q.-B. Tran, D.-Q. Tran, S. Reiter, An investigation on climate responsive design strategies of vernacular housing in Vietnam, Build. Environ. 46 (10) (2011) 2088–2106.
[22] M.K. Singh, S. Mahapatra, S. Atreya, Bioclimatism and vernacular architecture of north-east India, Build. Environ. 44 (5) (2009) 878–888.
[23] S. Visitsak, An Evaluation of the Bioclimatic Chart for Choosing Design Strategies for a Thermostatically-controlled Residence in Selected Climates, Texas A&M University, 2007.
[24] A.A. Zuhairy, A. Sayigh, The development of the bioclimatic concept in building design, Renew. energy 3 (4–5) (1993) 521–533.
[25] S. Visitsak, J.S. Haberl, An analysis of design strategies for climate-controlled residences in selected climates, (2004).
[26] M. DeKay, G. Brown, Sun, Wind, and Light: Architectural Design Strategies, John Wiley & Sons, 2014.
[27] D. Watson, The Energy Design Handbook, The American Institute of Architects Press, Washington D.C, 1993.
[28] A. Standard, Standard 55-2004, Thermal Environmental Conditions for Human Occupancy, 2004, pp. 9–11.
[29] S. Attia, M. Hamdy, S. Carlucci, L. Pagliano, S. Bucking, A. Hasan, Building Performance Optimization of Net Zero-energy Buildings, Modeling, Design, and Optimization of Net-zero Energy Buildings, 2015, pp. 175–206.
[30] M. Valipour, Hydro-module determination for vanaei village in Eslam Abad Gharb, Iran. ARPN J. Agric. Biol. Sci. 7 (12) (2012) 968–976.
[31] M. Valipour, Analysis of potential evapotranspiration using limited weather data, Appl. Water Sci. (2014) 1–11.
[32] M. Valipour, Cariations of land use and irrigation for next decades under different scenarios, IRRIGA 1 (01) (2016) 262–288.
[33] M. Valipour, How much meteorological information is necessary to achieve reliable accuracy for rainfall estimations? Agriculture 6 (4) (2016) 53.
[34] M. Valipour, Global experience on irrigation management under different scenarios, J. Water Land Dev. 32 (1) (2017) 95–102.
[35] M. Valipour, M.E. Banihabib, S.M.R. Behbahani, Comparison of the ARMA, ARIMA, and the autoregressive artificial neural network models in forecasting the monthly inflow of Dez dam reservoir, J. Hydrol. 476 (2013) 433–441.
[36] I.M.O. (IRIMO), Iran Meteorological Data, C.D. Office, Tehran, 2015.
[37] M. Tahbaz, S. Jalilian, Architectural Design Principal Compatible with Climatic Conditions of Iran, Shahid Beheshti University Press, Tehran, 2008.
[38] M. Hegger, M. Fuchs, T. Stark, M. Zeumer, Energy manual-sustainable architecture, Institut für Internationale Architekturdokumentation/Birkhäuser2008.
[39] M. Kasmai, Climatic & Architecture, Baztab Press, Tehran, 1993.
[40] M. Razjouyan, Comfort with Using Climate Adaptable Architecture, Shahid Beheshti University Press, Tehran, 1988, p. 289.
[41] J. Riazi, Climate and Comfort in Building, Center of Houses and Building Researches, Tehran, 1977.
[42] F. Taghavi, Linkage between climate change and extreme events in Iran, J. Earth Space Phys. 36 (2) (2010) 33–43.
[43] S.A. Masoudian, R. Ebrahimi, M. Mohammadei, Spatiotemporal zoning, the annual and seasonal cooling and heating need in Iran, Sci. Res. Quart. Geogr. Data (SEPEHR) 23 (2014) 33–46.
[44] S.A. Masoudian, R. Ebrahimi, E. Yarahmadei, Spatiotemporal analysis of the monthly procedure of degree-day heating in Iran territory, J. Geogr. Reg. Dev. Res. 23 (2014) 18–27.
[45] G.R. Roshan, J. Orosa, T. Nasrabadi, Simulation of climate change impact on energy consumption in buildings, case study of Iran, Energy Policy 49 (2012) 731–739.
[46] J.A. Orosa, G. Roshan, S. Negahban, Climate change effect on outdoor ambiences in Iranian cities, Environ. Monit. Assess. 186 (3) (2014) 1889–1898.
[47] H. Dehghan, S.B. Mortazavi, M.J. Jafari, M.R. Maracy, Evaluation of wet bulb globe temperature index for estimation of heat strain in hot/humid conditions in the Persian Gulf, J. Res. Med. Sci. Off. J. Isfahan Univ. Med. Sci. 17 (12) (2012) 1108.
[48] M.R.M. Daneshvar, A. Bagherzadeh, T. Tavousi, Assessment of bioclimatic comfort conditions based on physiologically equivalent temperature (PET) using the RayMan model in Iran, Cent. Eur. J. Geosci. 5 (1) (2013) 53–60.
[49] H. Farajzadeh, A. Matzarakis, Quantification of climate for tourism in the northwest of Iran, Meteorol. Appl. 16 (4) (2009) 545–555.
[50] H. Farajzadeh, A. Matzarakis, Evaluation of thermal comfort conditions in Ourmieh Lake, Iran, Theor. Appl. Climatol. 107 (3–4) (2012) 451–459.
[51] H. Farajzadeh, M. Saligheh, B. Alijani, A. Matzarakis, Comparison of selected thermal indices in the northwest of Iran, Nat. Environ. Change 1 (1) (2015) 1–20.
[52] R. Esmaili, G. Fallah Ghalhari, Seasonal bioclimatic mapping of Iran for tourism, Eur. J. Exp. Biol. 4 (3) (2014) 342–351.
[53] G. Roshan, R. Yousefi, J.M. Fitchett, Long-term trends in tourism climate index scores for 40 stations across Iran: the role of climate change and influence on tourism sustainability, Int. J. Biometeorol. 60 (1) (2016) 33–52.
[54] R. Esmaili, A. Gandomkar, H. Nokhandan, Assessment of comfortable climate in several main Iranian tourism cities using physiologic equivalence temperature Index'Physical geography research quarterly, Phys. Geogr. 75 (2011) 1–18.
[55] M. Rezvani, H. Mesgarian, Comparison of the standard equivalent temperature (SET) in the houses of Yazd (case sample: the house of Lariha, Arabzadeh, Shokuhi, Golshan, Mahmudi, Lariha2, olia, J. Appl. Environ. Biol. Sci. 4 (2015) 38–46.