Spatial analysis of bioclimatic patterns over Iranian cities as an important step in sustainable development

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Highlights

- In this study determined the bioclimatic component loading patterns over Iran.
- The results showed that the first Varimax-rotated loading pattern accounts for 51.82% of the total variances.
- This study presented novel insights into the identification of bioclimatic regions in Iran.
- Cluster analysis demonstrated that Iran can be divided into five bioclimatic regions based on PCA.
- Spatial distribution of bioclimatic zones showing geographical dependency.

Abstract

The main objective of this paper is to classify bioclimatic regions in Iran for optimal environmental planning. Mean daily meteorological data of 155 well-distributed synoptic stations during 1995-2017 were extracted from Iran's Meteorological Organization. Percentage of occurrence of each thermal sensation classes was determined over all studied stations using five bioclimatic indices including Perceived Temperature (PT), Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), Standard Effective Temperature (SET) and Universal Thermal Climate Index (UTCI). An R-mode Principal Component Analysis (PCA) was applied to a N × M (155×40) matrix of N = 155 stations and M = 40 total thermal thresholds based on all used indices during the considered time period. According to the results of PCA, the five loading PCs that approximately account for 98.5% of the total variance were selected for further analysis. In addition, Ward method was used for Cluster Analysis (CA) to divide the stations into different bioclimatic groups. The results illustrated that the first Varimax-rotated loading pattern which accounts for 51.82 percent of total variance characterized Northwest of Iran with more than 0.8 PC scores. Furthermore, cluster analysis demonstrated that Iran can be divided into five bioclimatic regions based on the R-mode PCA.
Keywords: Bioclimatic Regions, Principle Component Analysis, Cluster Analysis, Environment, Iran.

1. Introduction

Energy demand has increased due to urbanization and technological developments all over the world (Demirtas 2013). Fossil fuels cover most of this energy demand and cause negative environmental impacts such as climate change (Dincer and Rosen 2012, Zanon and Verones 2013, Camara, Kamsu-Foguem et al. 2017, Hamdaoui, Mahdaoui et al. 2018, Martins, Felgueiras et al. 2019). It is predicted that cooling energy demand will increase about 34.6–50.2% by 2060 under the effect of climate change (Nematchoua, Yvon et al. 2019, Ucal and Xydis 2020). Promoting innovative applications to land use planning can contribute to preservation of the environment (Omer 2008, Sanei, Zakaria et al. 2020, Schmidt-Traub, Locke et al. 2020). One of the most important tools of sustainable development is land use planning (Cetin, Adiguzel et al. 2018). Land use and sustainable energy planning can organize spaces mainly based on their natural potentials in order to achieve optimal productivity of the land. Climate and bioclimatic conditions as natural potentials, are key answers to sustainable energy planning in urban areas (Senes and Toccolini 1998, Lovell 2010). Therefore, ecological and climatic potentials of urban areas can be utilized in order to estimate cooling and heating energy supply and provide gains in terms of energy efficiency (Bardhan, Debnath et al. 2020).

By understanding bioclimatic conditions of the urban environment, we can design energy conscious cities (Pourvahidi and Ozdeniz 2013). Classifying bioclimatic conditions can help designers provide comfortable conditions for occupants (Nicol and Humphreys 2002). It can also cope with negative impacts of urbanization, and consequently energy consumption in modern lifestyles (Yaghmaei, Soltani et al. 2009). The first studies on bioclimatic comfort have been conducted by Olgyay, Givoni and Fanger in 1963, 1969 and 1970, respectively (Olgyay 2015). Since then, various simple to complex thermal indices have been developed by researchers to calculate bioclimatic and thermal comfort conditions (Landsberg 1972, Steadman 1979, Mieczkowski 1985, Gagge, Fobelets et al. 1986, Höppe 1993, Taffé 1997). These bioclimatic indices consider human body's physiological system response to climatic conditions which can affect energy demand in buildings (Cetin, Adiguzel et al. 2018).

It should be noted that the effects of bioclimatic conditions on human health, thermal comfort, activities, and energy supply have been well documented in more recent literature using bioclimatic indices. Matzarakis et al. (2010) have developed bioclimatic maps for tourism purposes (Matzarakis, Rudel et al. 2010). Their results revealed the importance of bioclimatic conditions for tourists' wellbeing. Daneshvar et al. (2013) assessed bioclimatic conditions based on Physiological Equivalent Temperature (PET) index in Iran and showed that most of the country experienced comfortable thermal comfort conditions during the spring months (Daneshvar, Bagherzadeh et al. 2013). Nastos et al. (2013) presented that both extreme heat/cold stress conditions are increasing in Greece based on PET bioclimatic index which can affect human health as well as energy consumption (Nastos and Matzarakis 2013). Also, bioclimatic indices can help stake holders adapt and increase resilience to foreseen climate change in coastal areas (Bleta, Nastos et al. 2014). Increasing resilience by reversing maladaptive trends could be an important option to reduce coast al vulnerability to climate variability and change. This approach will usually address more than climate issues alone and involve a change in adaptation strategy, for example, nourishing beaches instead of constructing seawalls, or introducing a building setback instead of allowing construction next to the coast (Klein, Nicholls et al. 2001).

Quantification of the role of separate climatic factors on thermal conditions of different regions is an issue which should be addressed by multivariate statistics (Bukantis 2002). This issue can be efficiently calculated by using Principal Component Analysis (PCA) method which is a modern data analysis tool in multivariate statistics (Uddin, Islam et al. 2019). PCA can reduce variables quantities into a smaller number of variables that is widely used in previous climatic studies (Ehrendorfer 1987, Baeriswyl and Rebetez 1997, Chan and SHI 1997, Munoz-Diaz and Rodrigo 2004, Praene, Malet-Damour et al. 2019, Tadić, Bonacci et al. 2019, Bayatvarkeshi, Mohammadi et al. 2020). Bioclimatic clustering can be considered as a useful method to identify bioclimatic zones (Choi, Lim et al. 2017). Several studies have classified the climatic zones on a global, national and regional level to determine homogenous zones (Kottek, Grieser et al. 2006, Zscheischler, Mahecha et al. 2012, Alvares, Stape et al. 2013, Iyigun, Türkeş et al. 2013, Raziei 2017, Ullah, Akbar et al. 2020). However, few of these studies have considered bioclimatic classification. Roshan et al. (2019) have divided Iran into eight climatic clusters. Their results showed that each cluster requires specific strategies for comfort level estimation (Roshan, Farrokhzad et al. 2019). Ahmadi et al. (2017) classified Iran’s climate based on geo-statistical methods and bioclimatic indices (Effective Temperature (ET) and Temperature Humidity Index (THI). They presented six different bioclimatic zones around the country; from very uncomfortable to comfortable conditions (Ahmadi and Ahmadi 2017). Topay (2013) classified bioclimatic conditions of Isparta Province (Turkey) by using PET and concluded that thermal comfort level changes throughout the year in the region temporally and spatially (Topay 2013).

Evaluation of bioclimatic conditions of environment is necessary for sustainable energy planning and designing energy conscious cities and ensure overall thermal comfort. The aim of this study is to identify bioclimatic potentials and limitations of different regions in Iran. Although numerous studies have been done on zoning and climatic classification for Iran, but most of these zonings and clusters are not based on bioclimatic views. On the other hand, previous studies have often been done with regard to climatic variables (such as temperature, precipitation, etc.). However, in this research, the basis of zoning and clustering is the use of bioclimatic indices, which are a combination of different variables, including physiological characteristics and climatic variables. Therefore, this paper presents novel insights into bioclimatic clustering based on different thermal and bioclimatic indices. The results could be useful in land use planning and sustainable energy management. The following parameters are addressed in this research:

1- Determine the bioclimatic component loading patterns over Iran.
2- Classify the bioclimatic zones on the basis of similarities in the thermal indices using a newly suggested bioclimatic clustering method.

2. Data and methods

2.1. Data

In order to determine the bioclimatic homogenous regions,. mean daily climatic elements of 155 spatially distributed synoptic stations was acquired from Iran's Meteorological Organization (IRIMO) for the observational period of 1995–2017. The studied time period included approximately total of 8,030 mean daily data (= 22 years x 356 days). For the purpose of the study the Köppen Climate Classification were included for Iran (Fig 1).

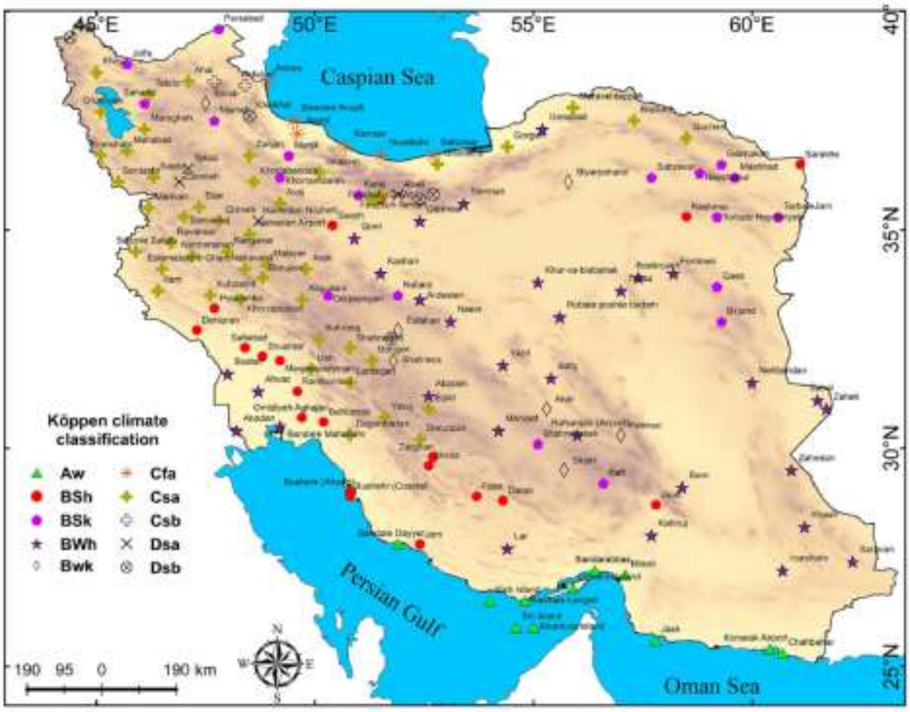


Fig.1. Spatially distributed synoptic stations and corresponding Köppen Climate Classification (Roshan, Almomenin et al. 2019).

2.2. Methods

2.2.1Thermal Indices

The climate variables in the database was used to calculate five bioclimatic indices including Perceived Temperature (PT), Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), Standard Effective Temperature (SET) and Universal Thermal Climate Index (UTCI) using RayMan (Table1). The complete description of this model is available from Matzarakis et al., (2010). In addition to abovementioned climatic variables, non-meteorological or human parameters are needed to calculate the bioclimatic conditions by RayMan (Matzarakis, Rutz et al. 2010). The calculation was performed for a male subject of average 1.75m height, 75 kg weight and 35 years old. Also, thermo-physiological parameters such as heat resistance of clothing (Clo) and human activity (W) were set to 0.9 Clo and 80 W, respectively (Table1).

Table 1. Thermal Perception of studied indices

Level of thermal stress	SET (°C)(Gagge, Fobelets et al. 1986)	PET(°C)(Matzarakis and Mayer 1996)	UTCI (°C) (Bröde, Jendritzky et al. 2010)	PT(°C) (Staiger, Laschewski et al. 2012)	PMV(Fanger 1970)
Extreme cold stress	--	<4	−40 < UTCI ≤27-	<−39	>-3.5
Very strong cold stress	--	4–8	−27 < UTCI ≤ -13	−39 to −26	-
Strong cold stress	--	8–13	−13 < UTCI ≤ 0	−26 to −13	-3.5 to -2.5
Moderate clod stress	--	13–18	0 < UTCI ≤ 9	−13 to 0	-2.5 to -1.5
Slight cold stress	<17	18–23	9 < UTCI ≤ 26	0 to 20	-0.5 to 0.5
Comfortable	17-30	23–29	-	20 to 26	0.5 to 1.5
Moderate heat stress	30-34	29–35	26 < UTCI ≤ 32	26 to 32	1.5 to 2.5
Strong heat stress	34-37	35–41	32 < UTCI ≤ 38	32 to 38	2.5 to 3.5
Very strong heat stress	>37	>41	38 < UTCI ≤ 46	>38	-
Extreme heat stress	--	-	>46	--	>3.5

In the next step, an R-mode Principle Component Analysis (PCA) and Cluster Analysis (CA) was applied to identify different bioclimatic regimes in Iran. Thereafter, the homogeneity of the identified bioclimatic regions was evaluated and discussed.

2.2.2 Principal Component Analysis (PCA)

To perform PCA, correlation matrix or scattering matrix between variables is needed (Jolliffe 1972). Correlation matrix is used to standardize data by giving them equal weight. Different methods such as Scree Plot and North test are used to select the appropriate number of PCs and estimate sampling errors (North, Bell et al. 1982). Also, selected components are usually rotated (orthogonal or oblique) to better interpolate and display the data properties. Varimax-rotation (orthogonal) and Promax rotation (oblique) are the most common rotation methods (Richman 1981).

In this research, five bioclimatic indices were calculated in the mean daily time scale. Percentage of frequency for each thermal threshold in all studied stations were determined and their standard score were computed. Thereafter, an R-mode PCA was applied to a N × M (155×40) matrix of N = 155 stations and M = 40 total thermal thresholds based on all used indices during the period of 1995 to 2017. It should be noted that there are four modes of PCA in climatology including T, S, R, and P (Yarnal 1993) which R mode is used more frequently. R-mod PCA is performed by grouping stations that divide the target area into different sub-regions in terms of the interaction of different variables (such as different bioclimatic indices) (Richman 1986). The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (Eq.1) was used to determine the adequacy of selected matrix for a PCA application (Sheskin 2020).

$$KMO = \frac{\sum i{\neq}j r_{ij}^2}{\sum i{\neq}j r_{ij}^2 + \sum i{\neq}j^u} \qquad (1)$$

Where:

R = [r_{ij}] is the correlation matrix

U = [U_{ij}] is the partial covariance matrix

Σ = summation notation

KMO takes values between 0 and 1. A value near 0 indicates that the sum of the partial correlations is large compared to the sum of the correlations (Akbulut 2008). It also shows that the correlations are widespread and so are not clustering among a few variables (not fit for the PCA application). A value near 1 indicates a good fit for PCA application.

2.2.3 Cluster Analysis

The retained PCs were rotated using Varimax method and rotated loadings pattern of the PCs were determined using Scree Plot (Fig.2). Thereafter, PC scores for Varimax rotated were subsequently used in a cluster analysis to partition the stations into different groups being characterized by different bioclimatic regimes. For this purpose, the Ward method was selected for classifying stations into different groups or bioclimatic regimes. Furthermore, the average silhouette index was used to determine the appropriate number of clusters, defined as in Eq. 2:

$$S(i) = \frac{(b(i) - a(i))}{\max\,[a(i), b(i)} \tag{2}$$

Where a(i) is the average distance from the i_{th} member of a cluster to all other members within the same cluster, b(i) is the minimum average distance from the i_{th} member of a given cluster to all members of another cluster (Rousseeuw 1987, Raziei 2018). The silhouette ranges from −1 to +1, where a high value indicates that the object is well matched to its own cluster and poorly matched to neighboring clusters (Gupta and Panda 2019).

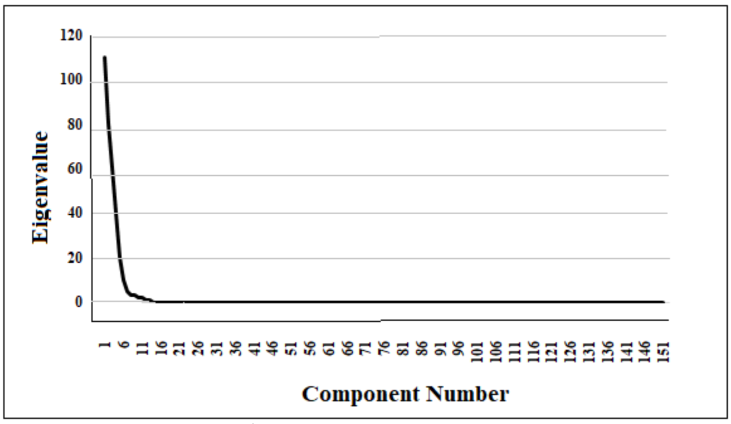


Fig.2 Eigenvalues of components associated with error bars at 95% confidence level.

3. Results and Discussion

3.1 Suitability and Variance of Principle Components

Applying the Kaiser-Meyer-Olkin (KMO) test with the value of 0.98 showed that the data matrix fits with the PCA application. Thus, R-mode PCA was used to identify different bioclimatic regions over Iran. For further analysis, five loading PCs that totally account for 98.58% of total variances were selected using Scree Plot. These five PCs identify stations with similar bioclimatic conditions over Iran. The selected PCs were rotated using Varimax method for better representation of data structure. Table 2 illustrates percentage of variance and total variance calculated by un-rotated and Varimax-rotated PCs. Based on Table 2, the first and second un-rotated component accounts for 72.86% and 20.39% of the total variances, respectively. Therefore, first and second components account for 93.25% of the cumulative variance. Whilst, third to fifth un-rotated loading patterns explain the rest of the variances. The large difference between variances (between one and five component) represents that un-rotated loading patterns cannot represent spatial structure of the data, properly. Hereupon, it is necessary to rotate the PCs for better representation of data structure. The Varimax method was used to rotate PCs to represent better distribution of variance between PCs. Spatial distributions of the Varimax-rotated loadings of the PCs show that the first Varimax-rotated loading pattern accounts for 51.82% of the total variance. Whereas 28.24% and 15.87% of the total variances are presented by second and third Varimax-rotated loading patterns, respectively. Furthermore, less than 2% of the total variances are explained by fourth and fifth Varimax-rotated PCs. Finally, five selected Varimax-rotated PCs explain approximately 98.58% of the cumulative variance.

Table 2. The percentage of variance and total variance of un-rotated and Varimax-rotated PCs using R-mode PCA

PC number	**Un-rotated**		**Varimax rotated**	
	% of Variance	**Cumulative Variance (%)**	% of Variance	**Cumulative Variance (%)**
1	72.86	72.86	51.82	**51.82**
2	20.39	93.25	28.24	**80.06**
3	2.87	96.13	15.87	**95.93**
4	1.69	97.82	1.81	**97.75**
5	0.75	98.58	0.83	**98.58**

3.1.1 Spatial analysis of bioclimatic loading patterns over Iran

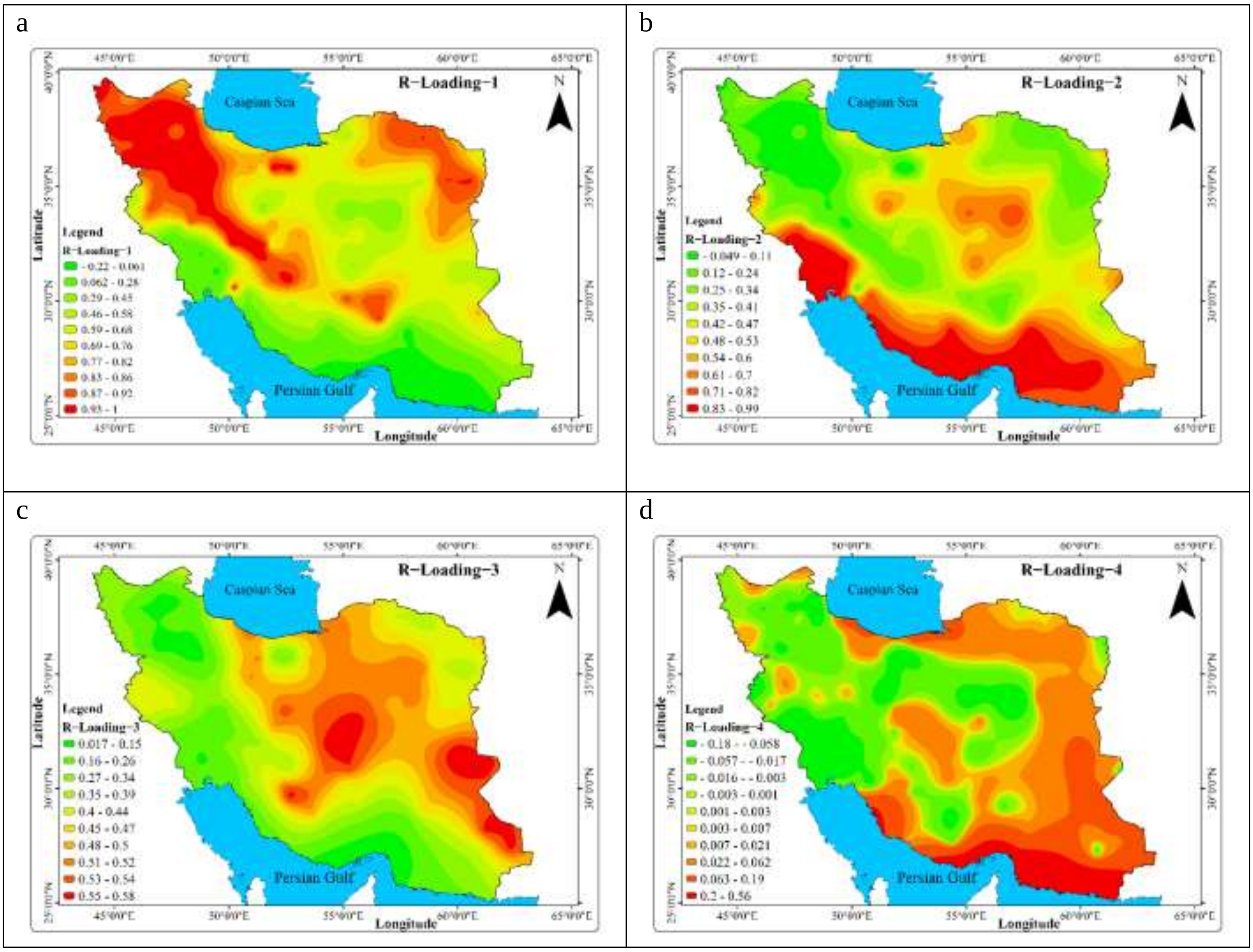
Figs. 3 represents spatial distributions of the Varimax-rotated loadings of the PCs and the associated PC scores. The first Varimax-rotated loading pattern is evident on northwest of Iran with high positive loading values. This loading pattern is expanded as a belt over the Zagros Mountains. There is another core of the first Varimax-rotated PC over northeast of Iran. Furthermore 46% of studied stations have experienced more than 0.8 PC score based on the first Varimax-rotated loading pattern. The highest PC score is related to Avaj, Khodabandeh, Zanjan, Ahar, and

Aligoudarz stations with the value of 0.99. The lowest loading pattern for the first PC belongs to southern coast of Iran (adjacent to Persian Gulf and Oman sea) with negative value of -0.3 for Minab (Fig 3-a).

Spatial distribution of the second Varimax-rotated loading pattern represents that the highest PC score of the second rotated loading pattern is related to southern coasts of Iran, whereas the lowest values is observed on northwest, northeast of Iran and Zagros Mountains. The Firuzkoh station represents very low negative value (-0.11) while the very high positive values belong to Kahnouj, Ramhormoz, Bandar-e- deyer, Dezful, Shoshtar, and Jiroft (0.97). Generally, 33% of the studied stations represent more than 0.8 PC score based on the second rotated loading pattern (Fig 3-b).

The third rotated loading pattern shows two cores of the highest PC score on central and southeast of Iran. However, the third rotated loading pattern did not represented PC score greater than 0.8. Saravan, Shiraz, Kish, and Nehbandan stations experienced the highest PC score (0.66), whilst the lowest PC score experienced as a belt on northwest of Iran along the Zagros Mountains toward Persian Gulf and Oman Sea (Fig 3-c). The lowest PC score for the third rotated loading pattern belongs to Zarine station (-0.1). Finally, the results depicted that the fourth and fifth rotated loading patterns that explain the smallest percentage of the total variance (2%) demonstrate a similar spatial distribution. Based on the fourth and fifth PCs, the eastern half of the country experienced more loading pattern than western parts. The highest PC score for the fourth rotated loading pattern is varied between 0.1 to 0.6, which accounts for 11% of the studied stations. Furthermore, the very high values of this PC score (between 0.1 to 0.33) counts for 13% of the studied stations based on the fifth rotated loading pattern (Fig 3- d and e).

These findings show the separation of different bioclimatic regions of Iran according to the R-mode PCA. Accordingly, identification of bioclimatic zones is more significant based on the first three PCs.



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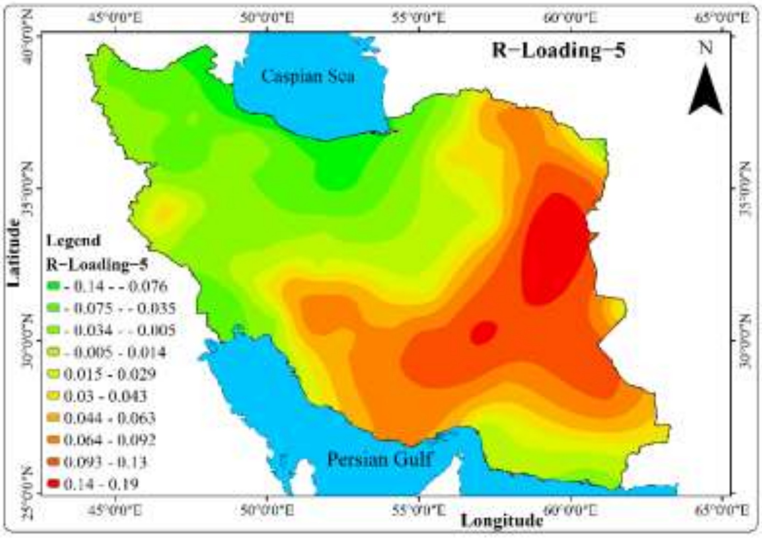

Fig.3. Bioclimatic variability depicted by the Varimax-rotated loading patterns.

3.2 Bioclimatic clusters of Iran

This section represents bioclimatic clusters based on the five PCA loading patterns over Iran. The Ward agglomerative clustering method was applied 20 times to identify the appropriate number of clusters representing the bioclimatic classification of the stations. The average silhouette index was computed for each cluster in order to determine the quality of the different classifications. Fig. 4 represents the average silhouette index for each classification. Due to the climatic diversity of the country and in order to achieve the most realistic classification of the stations, Iran divided into five clusters by average silhouette index score of 0.5. The dendrogram of clustering stations into five clusters as an appropriate number of clusters is given in Fig.5.

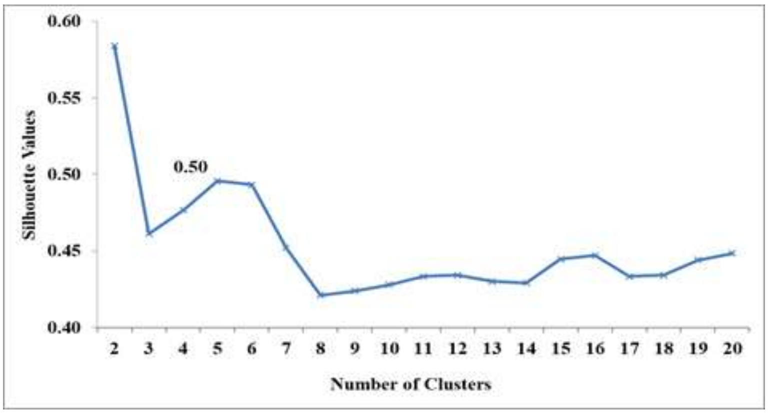

Fig.4. The average silhouette index computed for different number of clusters

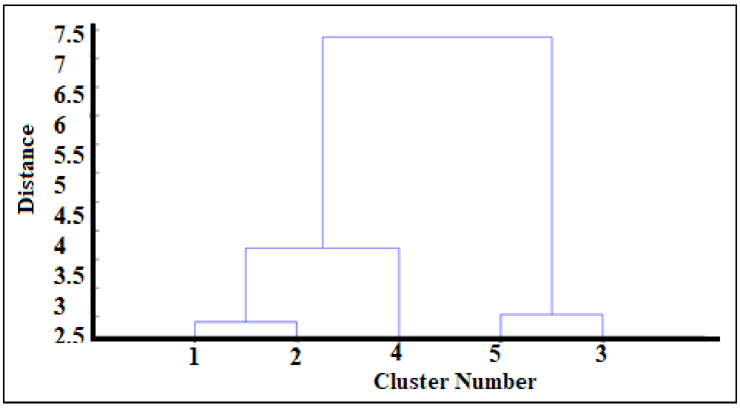

Fig.5. Dendrogram of Ward hierarchical agglomerative cluster analysis

As shown in Fig.6, Iran could be divided into five bioclimatic zones. In other words, clustering stations into five groups provides the highest inter-cluster similarity. Each cluster represents special bioclimatic conditions. These clusters have not been homogeneously distributed over Iran. These separations are mainly due to differences in the local climate of the studied stations. For instance, factors such as elevation, latitude, humidity, temperature, wind speed and direction, airflows and etc. can be effective in the geographical distribution of bioclimatic clusters.

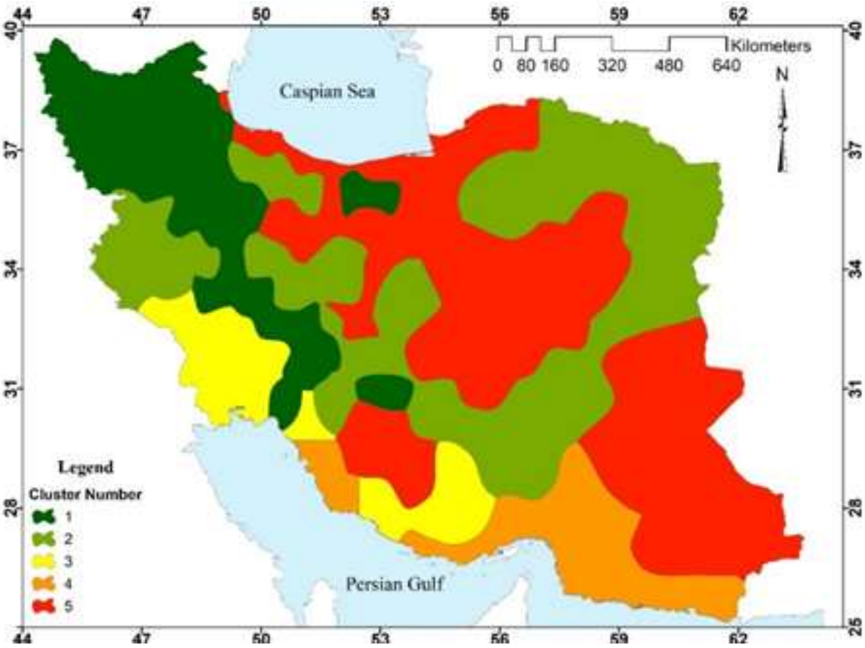

Fig 6. Bioclimatic clusters over Iran

To simplify the outputs of five studied bioclimatic indices (which include 40 bioclimatic thresholds), new proposed bioclimatic classes were defined including five thresholds (see Table 3). The mean frequencies of new proposed thresholds were calculated for each cluster. It is expected to provide an overview of the composition of all indices through this method. In order to provide an appropriate view into bioclimatic conditions over Iran, PET was used as a representative index of all studied indices to display variability pattern of bioclimatic conditions for each cluster.

Composition of used bioclimatic classes	Proposed bioclimatic conditions	Proposed Degree of physiological stress
PET(Cold-Very cold) , PT(Cold), PMV(Cold), UTCI(Extreme stress, Strong cold stress, Very strong cold stress)	Cold-Very Cold	High Cold Stress

PET(Slightly Cool, Cool), PT(Slightly Cool, Cool), PMV(Slightly cool, Cool), SET*(Slight cold stress), UTCI(Slight cold stress)	Slightly Cool-Cool	Low Cold stress
PET(Comfortable),PT(Comfortable),PMV(Neutral), SET*(Comfortable),UTCI(No thermal stress)	Comfortable	No-Stress
PET(Slightly warm, Warm), PT(Slightly warm, Warm), PMV(), SET*(Moderate heat stress), UTCI(Moderate heat stress)	Slightly Warm- Warm	Low Heat Stress
PET(Hot, Very Hot), PT(Hot, Very hot), PMV(Hot), SET*(Strong heat stress, Very strong heat stress), UTCI(Extreme heat stress, Strong heat stress, Very strong heat stress)	Hot- Very Hot	High Heat stress

Table 3. Definitions of new proposed bioclimatic classes considering all studied bioclimatic indices thresholds

3.2.1 First Cluster

Spatial distribution of this cluster showed that it mostly experiences over northwest of Iran. It has extended as a strip to the southeast and distributed over the mountainous areas (Zagros Mountains). Furthermore, some small cores of this cluster can be seen on central and north parts of Iran which corresponds to Eghlid and Abali stations. In total, 32 studied stations are put in this cluster. It was observed that the first cluster reflects the characteristics of mountainous according to climate and geographical factors the average altitude of regions is 1762 m). Meanwhile, a comparison between bioclimatic maps of Iran with the Köppen climate classification (Fig.1) represents that first cluster is mainly included SCa or Mediterranean climate type which are typically located along the western sides of continents, between 30º and 45 º latitudes.

Bioclimatic analysis depicted that the first cluster accounts for 20% of the studied stations. Based on the new bioclimatic thresholds in Table 3 (which are obtained from the composition of 40 thresholds of the five studied indices), bioclimatic conditions of the first cluster can be explained as follow:

In the first cluster, 36.4% of the total conditions is associated with "comfort" conditions, while "Slightly Cool-Cool" and "Slightly Warm-Warm" conditions represent 18% and 15.3%, respectively. Other bioclimatic conditions account for 7% of the studied period (Table 3). Furthermore, the frequency of occurrence of each threshold was evaluated based on PET index. As fig.5 shows, "Very Cold" conditions account for 17.2% of the total frequencies while "Slightly Warm" and "Warm" conditions include 15.4% and 14.7% of the total frequencies, respectively. Based on the PET index, 12.4% of the total conditions were associated with "comfort" conditions. Also, "Cold- Very Cold" conditions account for 27.8% of the total frequencies whilst "Hot-Very Hot" conditions have been experienced only 5.7% of the studied period in the first cluster (Fig.7&8).

3.2.2 Second Cluster

Geographic distribution of this cluster is not focused on a single spatial position. It is distributed in different parts of the country from northeast to central and west of Iran. The second cluster has vastly extended over the country. this cluster covers 43 stations in different parts of the country with average altitude of 1403 m. From spatial and geographical points of view, the second cluster's distribution is mainly consistent with cold semi-arid climates (Bsk) of Köppen climate classification (Fig.1). It is distributed over northeast, central and western parts of Iran and separated by mountains (Alborz and Zagros mountains).

The second cluster accounts for 27.7% of the studied stations. The highest frequency of the bioclimatic thresholds is related to “comfortable”, “Slightly Warm-Warm” and “Slightly Cool-Cool” levels which account for 34.9%, 18.9% and 15% of the total frequencies, respectively. Other bioclimatic thresholds cover less than 20% of the frequencies. Based on the PET index outputs, “Warm” conditions cover 18.5% of the total frequencies while “Slightly-Warm” and “Hot” conditions account for 14.6% and 14.2% of the total frequencies, respectively. In comparison with the first cluster, frequency of “comfortable” conditions have decreased, and it accounts for 11.6% of the total frequencies. Also, “Warm stress” conditions are more occurred (16.4%) than “Cold stress” conditions (13%) in this cluster (Fig.7&8).

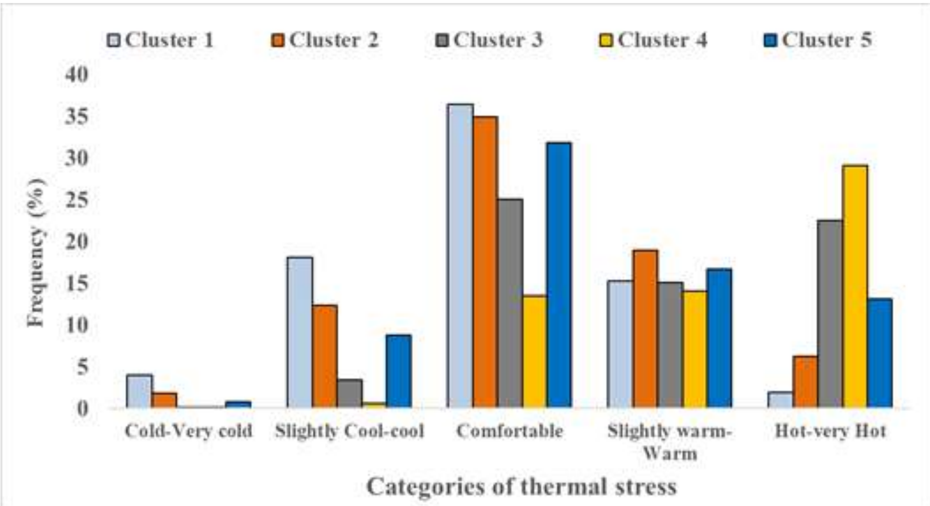

Fig.7. Frequency of thermal thresholds based on average of all studied indices (PET, PT, SET, UTCI and PMV) for each cluster.

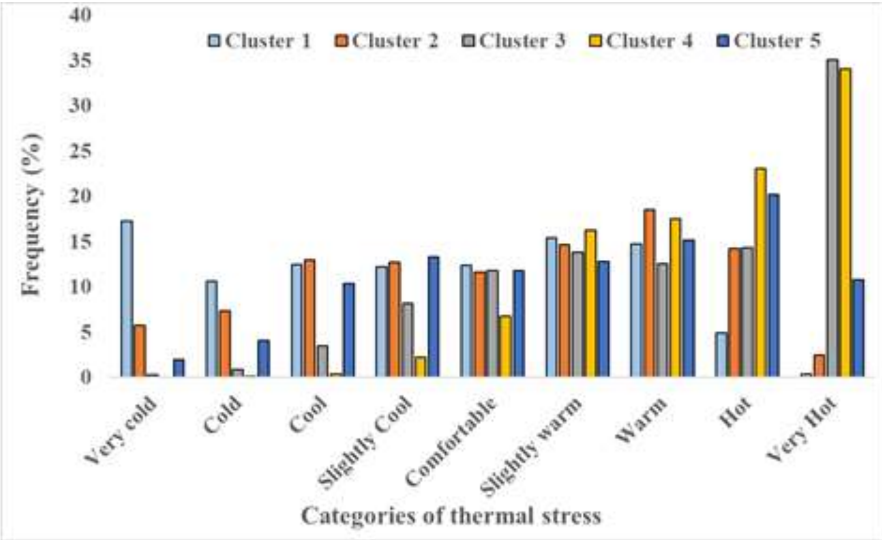

Fig.8. Frequency of thermal thresholds based on average of PET for each cluster.

3.2.3 Third Cluster

The third cluster covers only 26 stations mainly located in southwest and southern parts of Iran. This cluster is not evenly distributed, and it is separated by the fourth and fifth clusters in southern regions. The average latitude of regions which covers by the third cluster is 477 m. From geographical point of view, the third cluster is mainly affected by climatic elements such as high humidity due to the proximity to Persian Gulf and Oman Sea. Also, this cluster is positioned in low altitudes which can gain more solar radiation specially in warm periods of the year. For this reason, the occurrence of “Very Hot” bioclimatic conditions are predominant in this cluster. Furthermore, the third cluster is consistent with Bwh and Bsh of Köppen climate classifications which represent desert and hot semi-arid climate types.

The third bioclimatic cluster includes 16.7% of the studied stations. The highest frequency of bioclimatic conditions in this cluster is related to “Comfortable”, “Slightly Warm-Warm” and “Hot-Very Hot” conditions which account for 25%, 22.5% and 6.2% of the total bioclimatic conditions, respectively (Table 3). Hence, in this cluster “Warm stresses” are more tangible than

“Cold stresses” conditions. A similar result has been obtained from the PET index. The total frequencies of “Warm” and “Very Hot” bioclimatic conditions are more than “Cool” and “Very Cold” thermal thresholds. More than 35% of the frequencies belong to “Very Hot” bioclimatic conditions whereas 14.3% of the frequencies are related to “Hot” thermal conditions. Finally, 11.8% of the total frequencies belong to “Comfortable” conditions in the third cluster (Fig.7&8).

3.2.4 Fourth Cluster

This cluster is mainly distributed in southern parts of Iran (close to Persian Gulf and Oman Sea). The fourth cluster mainly complies with Aw or tropical wet and dry climate type in Köppen climate classification. Most of coastal islands in southern parts of Iran are located in this cluster. The average altitude of the regions is 99.1 m.

From bioclimatic conditions point of view, the fourth cluster accounts for only 9.7% of the studied stations. The lowest occurrence of “Comfortable” conditions belongs to this cluster (13.5%). Meanwhile, the “Hot” stress occurrence is more than “Cold” stress. The total frequency for “Slightly Warm-Warm” bioclimatic conditions is 14% while it is 29% for “Hot-Very Hot” conditions (Table 3). Evaluation of PET index represented that “Slightly Cool” and “Very Cold” conditions only was experienced in 10% of the studied period while 34% of the frequencies belong to “Very Hot” bioclimatic conditions which is consistent with the climate type of this area. furthermore, “Comfortable” conditions occurred 6.8% during the studied period (Fig.7&8).

3.2.5 Fifth Cluster

Geographically, the fifth cluster is located mainly on north parts of Iran and southern coast of Caspian Sea. Moreover, two single cores of the fifth cluster can be seen in southern and southeast parts in Shiraz and Sistan provinces. The Fifth cluster covers 39 stations, and the average altitude of these stations is 894.6 m. Geographical positions of this cluster shows that it is affected by different elements such as sea in north and southeast of Iran. The fifth cluster falls into Bwh or Hot desert climates in Köppen climate classification. Also, some special climatic phenomena such as Monsoons can develop this cluster mainly in south east of Iran.

The fifth cluster covers the most areas of Iran which accounts for 25.1% of the studied stations. The "Comfortable" conditions which accounts for 31.8% of the total frequencies has the highest distribution in the year. "Slightly Warm-Warm" and "Hot- Very Hot" thresholds cover 16.7% and 13.2% of the total frequencies, respectively. Furthermore, based on PET index analysis, "Warm" and "Very Hot" bioclimatic thresholds with amount of 46% have the highest potential for occurrence compared to "Cool" and "Very Cold" conditions. In addition, the PET index illustrated that "Hot" and "Comfortable" thresholds occur in 20.2% and 11.7% of the studied period, respectively. The similar pattern has been observed for the "Comfortable" threshold in the second and third clusters.

Bioclimatic homogenous regions are mainly determined by their climatic parameters such as air temperature, relative humidity, wind speed, and solar radiation (Roshan and Moghbel 2020). However, their geographical distribution is affected by spatial parameters like latitude, altitude, proximity to the water bodies, atmospheric systems and microclimate of the region (Nematchoua, Orosa et al. 2020). There is a direct relationship between bioclimatic conditions of regions and their energy load (Eludoyin 2014, Kishore and Rekha 2018, Chi, Cubasch et al. 2019). For this purpose, the R-mode PCA with Varimax coupled with the Ward agglomerative clustering were applied to the mean daily time series of different atmospheric elements of the 155 stations distributed over Iran. Five thermal indices (PET, PT, UTCI, SET and PMV) were used to identify bioclimatic regions. R-mode PCA revealed five sub regions characterized by stations with similar bioclimatic conditions over Iran. Spatial distribution of five Varimax-rotated loading patterns resulted in different sub regions, although some of them have partially overlap. The highest PCs cores among the five determined regions are mainly related to northwest, southern coasts, central to southeast and eastern parts of the country based on the first to fifth PCA Varimax-rotated loading patterns, respectively. Hence, Iran can be divided into different bioclimatic regions according to the R-mode PCA. The identified loading patterns showed that the spatial distribution of bioclimatic zones of Iran are in good agreement with the geographical and climatic characteristics of the regions. The first Varimax-rotated loading pattern overlaps mountainous regions of Iran. These regions are associated with cold winter and warm/ dry summers.

The second Varimax-rotated loading pattern is mainly predominant over southern coasts of Iran (Persian Gulf and Oman Sea) which is characterized by very humid and warm climate conditions in summer.

The main core of the third Varimax-rotated loading pattern is located on eastern borders of Iran which expands as a stripe to the center of the country. These regions are determined by cold winters and hot summers (Roshan, Farrokhzad et al. 2017).

The fourth and fifth Varimax-rotated loading patterns are predominant over south, southeast and eastern parts of Iran which are related to a variety of climates including hot, humid and warm in southern parts while a desert climate conditions in central and eastern section. These results are in accordance with another study on the bioclimatic sub-regions of Iran by Roshan et al. (2019). The identified bioclimatic zones using PCs are also in good agreement with Ahmadi et al. (2017) who applied geo-statistical methods and bioclimatic indices or mapping thermal and bioclimatic conditions over Iran. As mentioned earlier, the Ward clustering method was applied to the five retained PC scores resulted from the R-mode PCA application. Then, the studied stations were divided into different clusters to characterize similar/dissimilar bioclimatic conditions for energy and land use planning purposes. Considering diverse climatic conditions over Iran, results showed that classifying all the stations into five clusters can represents bioclimatic zones of Iran based on the outputs of different thermal indices. Regarding the cluster analysis, Iran is partitioned into five sub-regions characterized by different bioclimatic conditions. However, the inhomogeneous spatial distribution of the clusters is affected by geographic conditions as well as atmospheric circulation patterns which influenced each zone. Based on the studied comfort indices, results revealed that the highest "Comfortable" thermal conditions are experienced by subset regions of the first cluster (36.4%). This cluster is mainly experienced over mountainous areas in northwest of Iran which expands as a strip toward southeast. Roshan et al. (2018) found similar results when they calculated the highest frequency of comfort threshold occurs in northwest, Zagros Mountains and northeast altitudes of Iran (Roshan, Yousefi et al. 2018). Despite the first cluster, the least experience of "comfortable" threshold is occurred in the fourth cluster (13.4%). The fourth cluster is expanded mainly in southern coast of Iran and adjacent to Persian Gulf and Oman Sea. High relative humidity during the year is the prominent feature of this cluster which in warm seasons can produce unbearable thermal conditions for people. On the other hand, the highest occurrence of "Cold-Very Cold" thermal threshold belongs to the first cluster mainly due to compatibility with mountainous areas (4%) while the fourth cluster has experienced no "Cold stresses" due to the its climate type. The invers behavior is observed between these two clusters for "Very Hot" and "Hot" thermal thresholds. The highest and lowest "Hot" stresses are experienced in the fourth and first clusters which generally account for 29.4% and 1.8% of the total studied period, respectively. Hence, there is an inverse bioclimatic conditions between these two clusters. This is in consistent with Roshan et al. (2020) who have reported that the threshold of thermal stress values belongs to the southern coastal region of Iran (Roshan, Grab et al. 2020). In southern parts of Iran, the comfort conditions occur during winter time (Farajzadeh and Matzarakis 2009, Daneshvar, Bagherzadeh et al. 2013, Roshan, Yousefi et al. 2016). From energy management point of view, it can be concluded that the subset regions of the first cluster need more heating strategies especially during the cold seasons whereas cooling strategies are the main requirements of the fourth cluster subsets. The results show the impact of local climate on the distribution of thermal classes between the clusters. In this regard, the fourth cluster experiences “Hot- Very Hot” thermal conditions more than the other clusters due to higher relative humidity, lower latitude, more solar radiation, lower altitudes and sub-tropical high pressure. In contrast, the first cluster is affected by mountainous, and different atmospheric flows which enter mainly from the western borders of Iran. This can moderate the bioclimatic sensation during summer while causes cold conditions during winter. Despite different geographical and spatial distribution, the most similar behaviors were observed between the third, fourth and fifth clusters. This similarity is caused by their distances from mountainous regions. However, there are some slight differences between these clusters, as well. Finally, comparison of different thermal thresholds displayed that the “Comfortable”, “Slightly Warm-Warm” and “Hot-Very Hot” conditions have the highest occurrences over the country by 28.3%, 16% and 14.5% in a year. “Very Cold-Cold” and “Slightly Cold-Cold” thresholds accounts only for 1.8% and 8.6% of the total frequency, respectively (Fig.7).

The above mentioned results show that the majority of the regions over the country need cooling strategies than heating for energy management. This is in a good agreement with Mohammadi et al. (2018) who analyzed spatial thermal stress over Iran and found out that 31.7% of Iran has gone towards warming conditions over the years while cold bioclimatic conditions have been seen in only 21.3% of Iran (Mohammadi, Gholizadeh et al. 2018).

PET was selected as the representative of all studied indices. The highest and lowest occurrence of “Comfortable’ threshold is related to the first (12.4%) and fourth (6.7%) clusters. In addition, the highest occurrence of “Very Cold-Cold” and “Slightly Cool-Cool” thresholds belong to the first (27.7 % and 24.6%) cluster, while the fourth cluster accounts only for 0% and 2.5% of this thresholds during the year. The invers conditions occurred for “Very Hot-Hot” and “Slightly Warm-Warm” thresholds between the first and fourth clusters. This finding is in good agreement with previous studies on thermal bioclimatic conditions over Iran (Esmaili and Fallah Ghalhari 2014, Roshan, Yousefi et al. 2018).

Moreover, the results indicated that PET has recorded different values in each determined cluster during the year. The annual averages of PET index in the five clusters during 1995-2017 are given in figure 9. The average of PET was 16.8 ºC in the first cluster which represents “Moderate Cold Stress” threshold. The maximum and minimum PET values in this cluster were 32.1ºC (Moderate Heat Stress) and 0.29ºC (Extreme Cold Stress), respectively. The annual average PET for second cluster was 22.3ºC. Comparing with the first cluster, it is increased and represented as “Slight Cold Stress” threshold. The highest and lowest values of PET for the second cluster was 37 ºC (Strong Heat Stress) and 6.2ºC (Very Strong Cold Stress” during the year, respectively. In the third cluster, the annual average PET is 33.6ºC and shows warmer conditions compared to first and second clusters (Moderate Heat Stress). Similarly, the maximum and minimum thresholds of the PET in the third cluster have increased and reached to 47.4ºC (Very Strong Heat Stress) and 17ºC (Moderate Cold Stress), respectively. The fourth cluster is the warmest cluster with the temperature of 35.7ºC (Strong Heat Stress), 45.7ºC (Very Strong Heat Stress) and 22ºC (Slight Cold Stress) for annual average, maximum and minimum PET, respectively. Finally, the annual average of PET for the fifth cluster was 26.4ºC (Comfortable), while the maximum and minimum temperatures are

40.8ºC (Strong Heat Stress) and 10.8ºC (Strong Cold Stress), respectively. Based on the annual PET results, the highest and lowest PET values occur in July and January, respectively. From the energy management point of view, the peak of “Heat” and “Cold” stresses are mainly experienced in these months of the year which require more attention to the allocation and supply of heating and cooling energy. It should be noted that climatic zoning is an appropriate method for most building energy efficiency programs (Walsh, Cóstola et al. 2017, Praene, Malet-Damour et al. 2019).

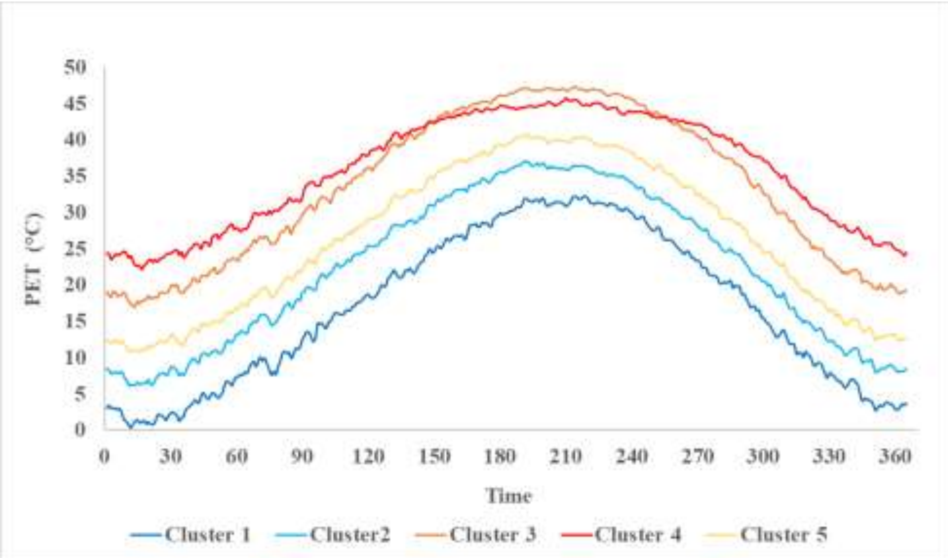

Fig.9. Annual average of PET index in five clusters during 1995-2017.

3.3 The impact of bioclimatic zones on energy management and land use

Here it should be noted that although urbanization has a profound impact on local microclimate (like the urban heat island effect), climate affect energy use and consequently sustainable land use management. Thermal comfort requirements significantly affect energy use. A study by Sailor (2002) showed that electricity demand (cooling energy use) in residential sector increases 1.5–2.0% for every 0.6°C increase in air temperatures (Sailor 2002). Considering the fact that such a small change in air temperature could affect energy supply in a city or region scale, shows the importance of understanding thermal comfort conditions. This paper used five most well-known thermal comfort indices to determine bioclimatic zones in Iran. Higher (or lower) air temperatures (which are derived from bio-climatic zones) do not only affect cooling load, but also affect land use and future developments in urban/regional scale. As such, water scarcity is one of the most dominant barriers in the development of new urban settlements in Iran (Zehtabian, Khosravi et al. 2010). It affects residential and industrial sectors, as well as agriculture. Therefore, understanding bioclimatic zones do not affect thermal comfort and heat/cold stress only, but also provides clearer perspectives for future development plans.

3.4 Strength and limitations of the study

This study presented novel insights into the identification of bioclimatic regions in Iran. The present study has implemented a new methodology by estimating bioclimatic thresholds based on five different thermal indices including PET, PT, SET, UTCI, and PMV. The novelty of this methodology lies in the application of the PCA for quantification of the role of separate climatic factors on thermal conditions of different regions. Most previous studies have only applied a single thermal index, whereas in this study five most reliable indices have been implemented to determine bioclimatic zones of Iran. We acknowledge that this research has limitations, including the lack of detail investigations into local and geographical factors as well as human thermal perception which is influenced by gender, type of clothing, activity level, etc.

4. Conclusions

As one of the significant challenges of modern human societies is energy management, the results of this research can be effective in land use by prioritizing energy management in different bioclimatic zones. The results showed that the first Varimax-rotated loading pattern accounts for

51.82% of the total variances. Geographically it is located in northwest of Iran with the highest positive loading value (0.8). The fifth Varimax-rotated loading pattern which accounts for 0.83% of the total variances (eastern parts of Iran with lowest positive loading values (0.1 to 0.33). Furthermore, cluster analysis demonstrated that Iran can be divided into five bioclimatic regions based on PCA. Each cluster has specific patterns regarding the occurrence of thermal thresholds which can be considered for land use and energy planning. The first and fourth clusters should be given priority for energy management planning according to their extreme bioclimatic threshold experiences (cold stresses-heat stresses) among all clusters. The inverse bioclimatic behaviors of these clusters can effectively increase energy consumption during the year. The first and fourth clusters should be given priority to achieve sustainable development and land use planning. The fourth cluster hardly experiences "Comfortable" threshold and the highest frequency belongs to "Very Hot and Warm" thresholds in this cluster. In contrast, the "Comfortable" and "Very Cold" thresholds are mostly experienced in the first cluster. Therefore, the energy management planning is more crucial for these cluster. The methodology and results of this bioclimatic research can be used in housing design, public transportation planning, and urban space planning.

Author declaration

- ✓ Funding was received for this work.
- ✓ we attest that all authors contributed significantly to the creation of this manuscript.
- ✓ The manuscript has been read and approved by all named authors.
- ✓ The order of authors listed in the manuscript has been approved by all named authors.
- ✓ Authors declare no conflict of interest.

Acknowledgments

This work was partially supported by the Iran National Science Foundation (INSF) under grant No. 99000532. We wish to thank Professor Ghanghermeh from Golestan University for his comments and intellectual guidance, which helped improve an earlier version of the paper. The authors thank Iran Meteorological Organization for providing the meteorological data.

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