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Assessment of Bioclimatic Comfort Conditions based on Physiologically Equivalent Temperature (PET) using the RayMan Model in Iran

Research Article

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Abstract: In this study thermal comfort conditions are analyzed to determine possible thermal perceptions during different months in Iran through the Physiologically Equivalent Temperature (PET). The monthly PET values produced using the RayMan Model ranged from −7.6°C to 46.8°C. Over the winter months the thermal comfort condition (18–23°C) were concentrated in southern coastal areas along the Persian Gulf and Oman Sea. Most of the country experienced comfort conditions during the spring months, in particular in April, while during the summer months of July and August no thermal comfort conditions were observed. In November coastal areas of the Caspian Sea had the same physiological stress level of thermal comfort as April. The map produced showing mean annual PET conditions demonstrated the greatest spatial distribution of comfortable levels in the elevation range from 1000 to 2000 meter a.s.l., with annual temperatures of 12–20°C and annual precipitation of under 200 mm. The statistical relationship between PET conditions and each controlling parameter revealed a significant correlation in areas above 2000 meter, annual temperature over 20°C and annual precipitation of 200–400 mm with a correlation coefficient (R^2) of 0.91, 0.97 and 0.96, respectively.

Keywords: RayMan Model • Physiologically Equivalent Temperature (PET) • Bioclimatic Comfort Conditions • Tourism • GIS

1. Introduction

The tourism industry is an important part of the world economy and is strongly affected by climate conditions. Interaction of climate and tourism has led to a new branch of climatology, known as tourism climatology, which re-

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lies on applied climatology and human biometeorology [1]. Tourism climatology can be represented by thermal, physical (rain or snow) and aesthetic conditions (visibility, sunshine and cloud cover) [2]. Therefore passengers, tour organizers, travel agencies, tourism planners, and stakeholders need to be reliably informed about the role of climate conditions [1]. It is a fact that climate and tourism are interconnected in diverse ways. Several indices have been developed over the last 40 years to assess the suitability of climate for tourism activities [3–10]. The simplest approach is to assess a thermal environment using a single climate factor such as air temperature, relative humidity, or number of sunshine hours. Notably, drought, heat waves, and sea surface temperatures have also been utilized to assess thermal environments [11]. An advanced scheme integrates factors using empirical equations for evaluating thermal environments, such as the wind–chill index [12], apparent temperature [13] and tourism climate index [14]. However, these indices only address some of the relevant meteorological parameters and do not include thermal physiology or heat balance of the human body. Although these indices may prove effective in very specific situations, they have significant disadvantages [15]. The most widely known and applied index is the Tourism Climate Index proposed by Mieczkowski [14], which combines seven factors and parameters. Also, a full application of thermal indices on the human energy balance gives detailed information about the calculation of thermal comfort [16]. Common applications are Predicted Mean Vote (PMV), Physiologically Equivalent Temperature (PET), Standard Effective Temperature (SET) and Perceived Temperature (PT) [1]. All these thermal indices are well documented and include important meteorological and thermo–physiological parameters [17]. The advantage of these thermal indices is that they all require the same meteorological input parameters such as air temperature, air humidity, wind speed, and short and long wave radiation fluxes. When tourists are exposed to an outdoor thermal condition that causes thermal stress, i.e., extremely high or low temperatures, tourist health can be adversely affected. Conversely, when tourists experience thermal conditions that are close to their thermal comfort zones, the number of tourists visiting resorts and scenic destinations can increase [18]. In order to thermal characteristics of tourism climate must be selected a suitable thermal index to assess outdoor thermal environments. As a thermal index derived from the human energy balance, the Physiologically Equivalent Temperature (PET) is well suited to the evaluation of the thermal component of different climates [19]. As well as having a detailed thermo physiological basis, PET addresses most climatic parameters [8] which are affected in their temporal and spatial behavior by the natural and artificial morphology on the meso and micro scale [20]. Compared to other thermal indices PET offers the advantage of a widely known unit (degrees Celsius), which makes results more easily understandable for regional or tourism planners, who may be not so familiar with human bio–meteorological terminology [15]. The current study assesses the thermal comfort conditions of tourism bioclimate based on the Physiologically Equivalent Temperature (PET) using the RayMan Model. The aim of the present study was spatial mapping of bioclimatic comfort conditions in Iran.

2. Study area

With a total area of 1.648 million km^2, Iran lies between 45°–63°East and 25°–40°North in the south west of the Middle East. Iran lies in the temperate zone in the arid and semi–arid belt of the world, and has four distinct seasons due to its wide range of latitude. The climate varies from cool temperate in the north and northwest to subtropical in the south and southeast. Central Iran has hot and dry summers and cool winters. The climate varies with the change in topography across Iran, for example there is a central plateau surrounded by two mountainous zones of Alborz in the north and Zagros in the west with elevation ranges of –56 to 5415 m a.s.l. The mountains avoid Mediterranean moisture bearing systems cross through this region to the east therefore the most parts of Iran, especially in the warm season, are affected by a subtropical high mass of the air. This causes warm summers in the country. A major percentage of the precipitation is produced by Mediterranean air masses that are brought in with the western winds in the cold season.

3. Materials and methods

3.1. Data analysis

In the present study the climatic data of 48 synoptic stations over a 30-year time period (1976–2005) were obtained in a quality controlled format from the Meteorological Organization of Iran via (http://www.irimo.ir). The selected stations for this study have complete 30 years records, representing a good spatial distribution over elevation ranges in Iran (Fig. 1). The values of air temperature, air relative humidity, wind velocity and cloud covering were collected from each synoptic station to obtain the mean monthly values of Physiologically Equivalent Temperature (PET) in the RayMan Model. The station base results were extended to pixel base values by spatial analysis operations in Geographic Information Sys-

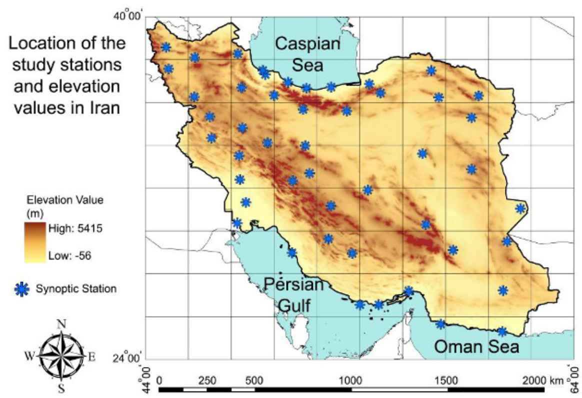

Figure 1. Distribution of study stations and elevation values in Iran.

tem (GIS). GIS allows the production of spatial mapping of PET in Iran based on Digital Elevation Models (DEM). The elevation data with spatial resolution of 2.5 arc minute (~5×5 km) pixel size was the basis for producing the distribution map of PET in GIS. Also, to evaluate the final map of bioclimatic comfort conditions spatial distribution of controlling parameters including elevation range, mean annual temperature and precipitation were analysed (Fig. 2).

3.2. RayMan Model

The RayMan model, developed according to Guideline 3787 of the German Association of Engineers [16] calculates the radiation flux in simple and complex environments on the basis of various parameters [21]. The model "RayMan" estimates the radiation fluxes and the effects of clouds and solid obstacles on short wave radiation fluxes. The final output of this model is the calculated mean radiant temperature, which is required in the energy balance model for humans. Consequently, it is also required for the assessment of bioclimatic comfort and thermal indices, such as Predicted Mean Vote (PMV), Physiologically Equivalent Temperature (PET), and Standard Effective Temperature (SET).

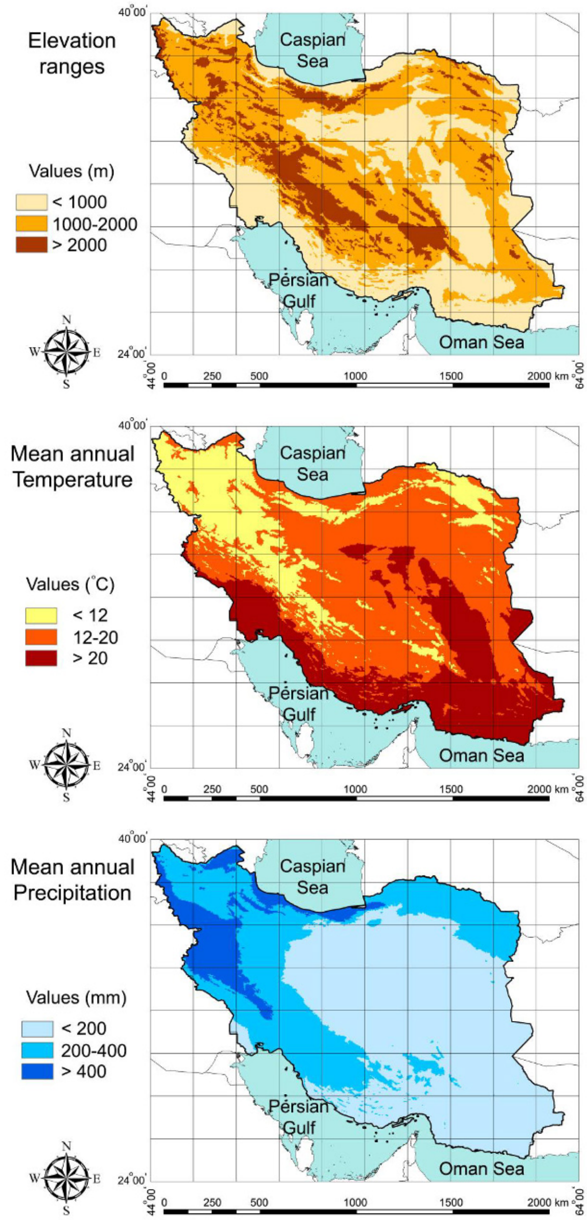

Figure 2. The controlling parameters of elevation, temperature and precipitation.

3.3. Physiologically Equivalent Temperature (PET)

PET is a thermal index that gives an estimation of the thermal component of a given environment. The PET not only provides an integrated index for thermal environments but also allows tourists to predict their thermal perception of weather conditions. Therefore, it is important to analyze the characteristics of thermal adaptation and comfort range of residents from different regions to adequately describe the perception of these people [22]. PET is based on the Munich Energy–balance Model for Individuals (MEMI) which models the thermal conditions of the human body in a physiologically relevant way [19]. PET is applicable for both the indoor and outdoor environment which can be calculated with the radiation and bioclimate model of RayMan. To calculate PET, it is necessary to determine all meteorological variables that are important for the human energy balance at a human biometeorologically significant height. These variables includes air temperature (Ta), vapour pressure (VP), relative humidity (RH), wind velocity (v), mean cloud cover (C) and mean radiant temperature (Tmrt). Human parameters influencing PET, such as activity, heat resistance of clothing, height, and weight are usually standardized in MEMI [23], as the focus is not on individual human characteristics but on the climate conditions at different sites. In order to quantify the perception of the thermal environment by humans, threshold values for PET have been developed, which indicate different levels of thermal stress in the form of a graded index [24] (Table 1). Threshold values of the PET for different thermal perceptions and levels of thermal stress, related to a metabolic rate of 80W (walking) and a heat transfer resistance of clothing of 0.9 clo (summer clothing); according to [16, 24] are used. The calculated PET values referred to a person (default: 1.75 m, 75 kg, 35 years old standing male) who stays in the sun [16].

Table 1. Physiologically Equivalent Temperature (PET) for different grades of thermal sensation and physiological stress on human beings during standard conditions (after Matzarakis and Mayer, 1996).

PET (°C)	Thermal sensation	Physiological stress level
<4	very cold	extreme cold stress
4–8	cold	strong cold stress
8–13	cool	moderate cold stress
13–18	slightly cool	slight cold stress
18–23	comfortable	no thermal stress
23–29	slightly warm	slight heat stress
29–35	warm	moderate heat stress
35–41	hot	strong heat stress
>41	very hot	extreme heat stress

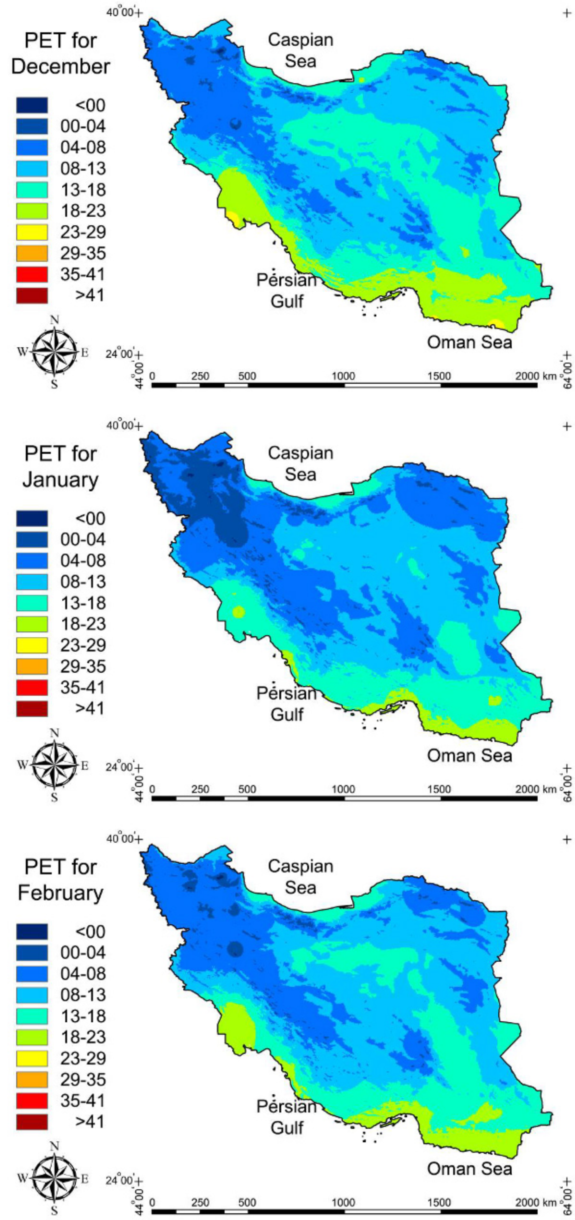

Figure 3. Monthly values for PET in winter.

4. Results and Discussion

The mapping of PET values was performed on a monthly basis for the climatic normal period of 1976–2005. The maps represent mean monthly values of PET based on the parameters of air temperature, air relative humidity, wind velocity and cloud covering. The mean monthly maps are shown in Figures 3 to 6 which show PET for the study area from 25°to 40°latitude and from 45°to 63°longitude. The same map legend is used in each case in order to allow for a better comparison of the months. According to these maps, the PET values ranged from –7.6°C to 46.8°C in Iran. The coldest PET values were observed in the northeast (Khorasan region) and northwest (Azerbaijan region) particularly in the winter months (Fig. 3). Over the winter months the thermal comfort condition (18–23°C) were concentrated to the south coastal areas, along the Persian Gulf and Oman Sea. The PET values for spring months ranged between 0.9°C in the northwest (Azerbaijan region) to 38.8°C in the southeast (Baluchestan region) of the country (Fig. 4). Temporary comfort conditions were experienced across most of Iran in the spring, with April showing the most widespread comfort conditions. In the spring favorable conditions along geographical latitudes

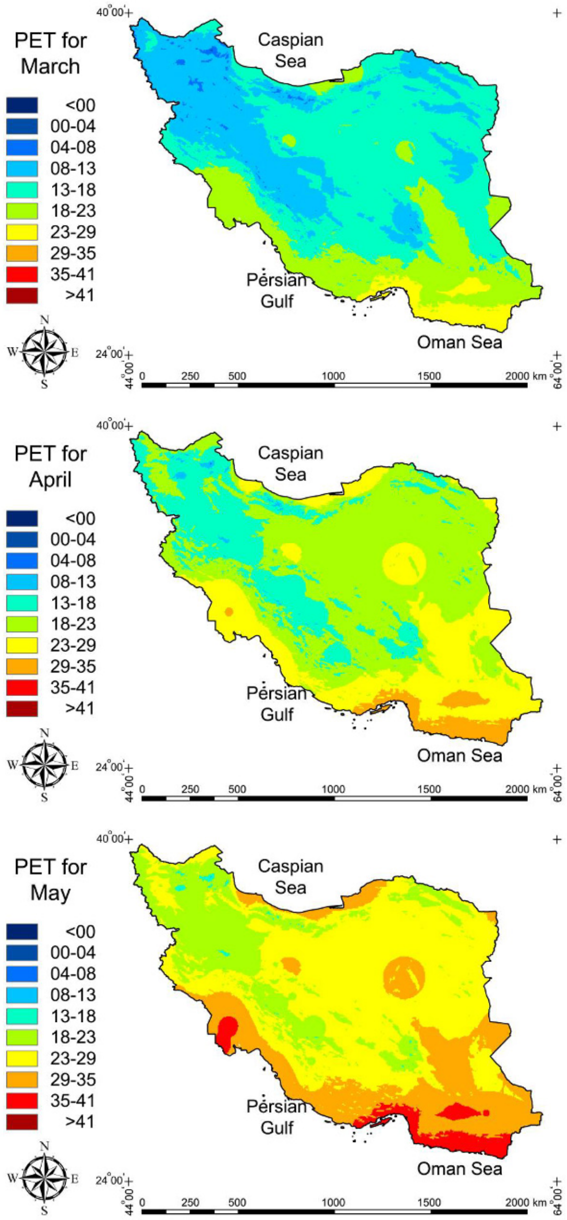

Figure 4. Monthly values for PET in spring.

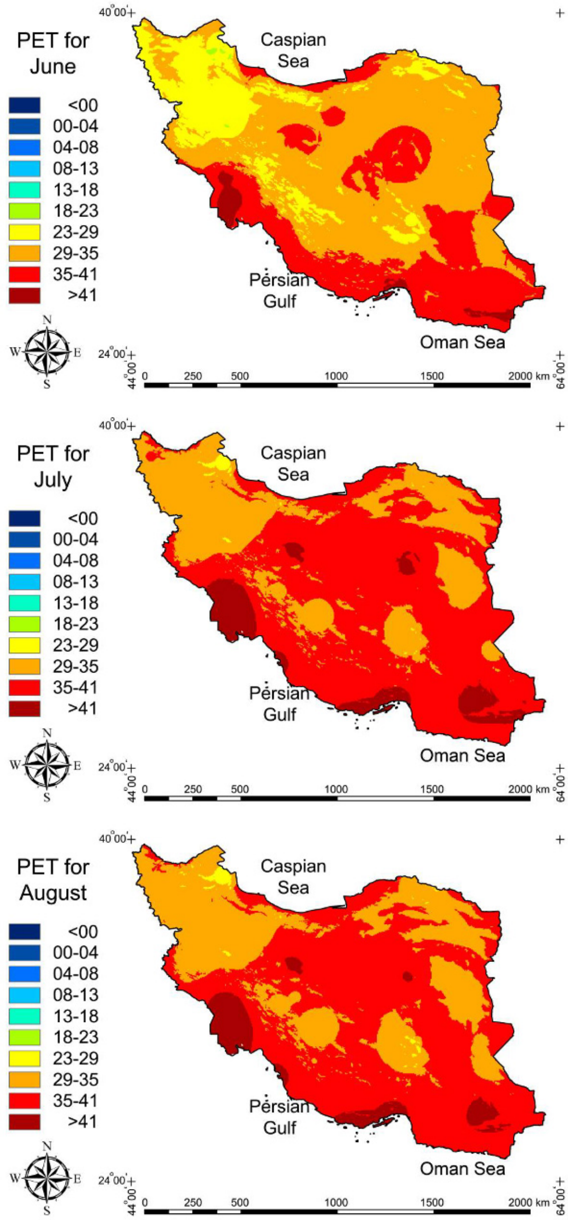

Figure 5. Monthly values for PET in summer.

can be found in areas of higher elevation. In summer months the PET values ranged from 16.8 to 46.8°C and dominantly represent a physiological level of strong heat stress, however June is characterized by mild conditions with a slightly warm thermal sensation in the northwest of Iran (Fig. 5). It was demonstrated that the hottest PET values over the summer months correspond to the southeast (Baluchestan region), southwest (Khuzestan region) and scattered areas in the central plateau of the country. During the summer months of July and August most of Iran experienced no thermal comfort conditions. In the autumn months it was observed that November experienced the same physiological stress level of thermal comfort as April, with this level of thermal comfort extending to include coastal areas of the Caspian Sea and most populated areas for tourism absorption in center of Iran (Fig. 6). The PET which describes the effect of the thermal environment on humans is shown in Figure 7 as a bioclimate diagram after [17]. Strong cold stress (PET<8°C) was found in the period from December to February with the high-

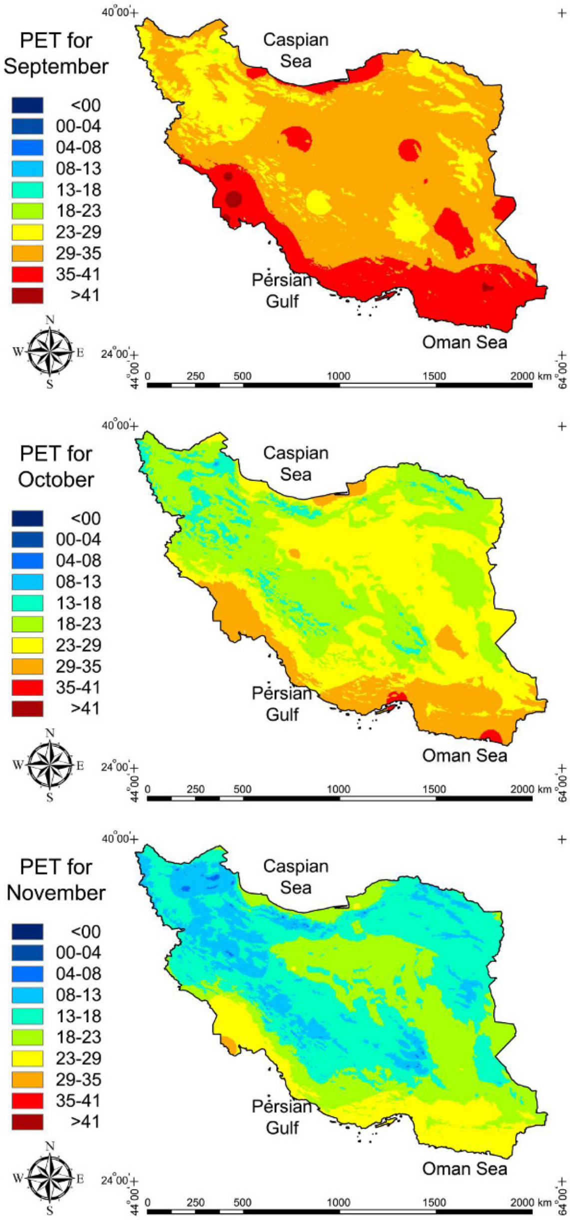

Figure 6. Monthly values for PET in autumn.

est percentage of surface area in January (about 38.4%). Correspondingly, the strong heat stress (PET>35°C) was observed in the period from May to September with the highest percentages of surface area in July (about 69.8%). It was observed that the highest spatial distribution of comfortable condition with no thermal stress occurred in April, October and November, with 48.8%, 38.7% and 30.9% of the surface area respectively. The lowest and highest PET values were observed in December and August with –7.6ºC and 46.8ºC, respectively (Fig. 8). It was also demon-

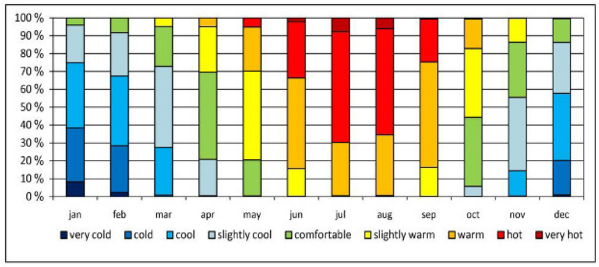

Figure 7. The bioclimate diagram for spatial derivation of monthly PET conditions (percentages of surface area).

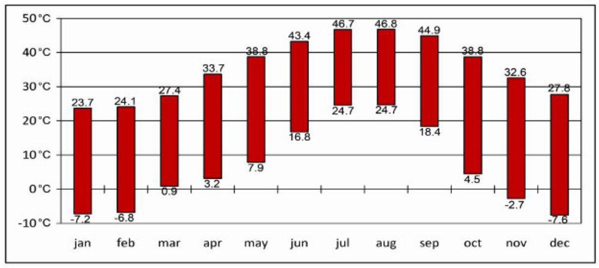

Figure 8. Mean monthly values of PET and ΔPET.

strated that the highest ΔPET value was in over autumn and early winter (35.3ºC in November and December), while the lowest was obtained in summer (22.1ºC in July and August). Low PET values can be observed in the areas of higher latitude, especially along the Alborz mountain range from Azerbaijan to the Khorasan regions, which are affected principally by the Mediterranean and Siberian air masses, respectively. Along the Zagros mountain range, from the northwest to southeast Iran, the bioclimatic conditions are strongly heterogeneous with high PET values

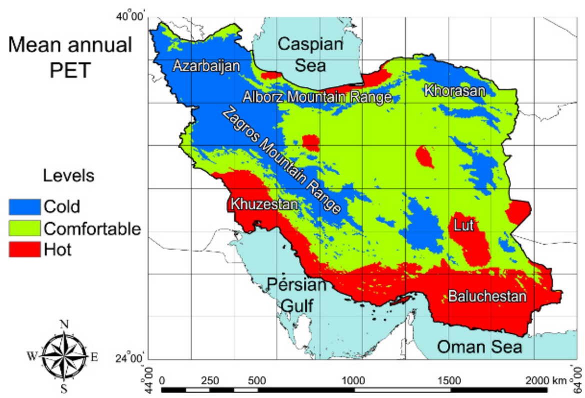

Figure 9. Spatial distributions of PET levels based on mean annual values.

due to the different mountain topography. In the central plains the PET values are higher in warm months due to the dominant subtropical high pressure (STHP) system. In comparison to other regions of the world, i.e. Greece and China, it can be concluded that the PET values in the northwest of Iran (Azerbaijan region) follow the same pattern of thermo–physiological conditions as in southeast Europe [21], while in the other parts of Iran the PET values corresponds well with east Asian countries [9]. Based on mean annual PET values in Iran an additional analysis was performed to produce a distribution map of bioclimatic comfort conditions (Fig. 9). The mean annual PET conditions were categorized into three new classes including cold (slight to extreme cold stress), comfortable (no thermal stress) and hot (slight to extreme heat stress). To evaluate the map we analyzed the spatial distribution of controlling parameters based on each new PET category. Accordingly the hot level was found in lowland coastal regions in the north and south as well as the Khuzestan plain in the southwest and the Lut Desert to the southeast, which corresponds to areas <1000 meter a.s.l (83.5%), annual temperatures >20°C (90.8%) and annual precipitation <200 mm (78.1%), (Table 2). About 38.8% of the cold level was on high areas over 2000 meter, with 67.1% at less than 12°C and 20.5% above 400 mm precipitation. Also, the elevations ranging from 1000 to 2000 meter a.s.l with annual temperature of 12–20°C and annual precipitation <200 mm had the greatest spatial distribution of comfortable levels of PET (Table 3). The statistical relationships between the comfortable level of PET and each controlling parameter revealed a significant correlation with areas above 2000 meter height, annual temperature over 20°C and annual precipitation over 200 mm showing a correlation coefficient (R^2) of 0.91, 0.97 and 0.93-0.96 respectively (Table 3). Our results showed that the PET condition has a direct relationship with annual temperature and indirect relation with elevation range and annual precipitation in Iran.

Table 2. The percentage of spatial distribution of elevation range, mean annual temperature and precipitation classes at each PET category.

Controlling parameter	Class	PET (%)		
		Cold	Comfortable	Hot
Elevation (m)	<1000	1.0	37.6	83.5
	1000–2000	60.2	55.5	16.5
	>2000	38.8	6.9	0.0
Annual Temperature (ºC)	<12	67.1	2.4	0.0
	12–20	32.9	82.0	9.2
	>20	0.0	15.6	90.8
Annual Precipitation (mm)	<200	23.2	70.1	78.1
	200–400	56.3	25.1	17.2
	>400	20.5	4.8	4.7

Table 3. The statistical relationship between comfortable level of PET and elevation range, mean annual temperature and precipitation classes

Controlling parameter	Class	PET		
		Sig.	*Correlation (R)*	R^2
Elevation (m)	<1000	0.28	0.91	0.82
	1000–2000	0.62	–0.57	0.32
	>2000	0.19	–0.96	0.91
Annual Temperature (ºC)	<12	0.30	–0.89	0.80
	12–20	0.89	–0.18	0.03
	>20	0.11	0.98	0.97
Annual Precipitation (mm)	<200	0.71	0.44	0.20
	200–400	0.13	–0.98	0.96
	>400	0.18	–0.96	0.93

5. Conclusion

In this study the PET was used as an indicator of thermal stress and thermal comfort. This bioclimatic index is widely used by tourism planners and decision makers. The monthly PET values observed in Iran by using the RayMan Model varied between –7.6°C and 46.8°C. On this basis the coldest PET values were found in the northeast (Khorasan region) and northwest (Azerbaijan region) especially during winter months. Also the hottest PET values found during the summer months correspond to the southeast (Baluchestan region), southwest (Khuzestan region) and scattered areas in the central plateau. Our results revealed that the bioclimatic comfort condition in November has the same physiological stress level of thermal comfort as April, extended to include most parts of the country. The map produced showing mean annual PET conditions showed that the areas with the highest spatial distribution of comfortable level occur in the elevation range from 1000 to 2000 meter a.s.l, with annual temperature of 12–20°C and annual precipitation <200 mm. Our results showed the significant correlation between comfortable level of PET in areas above 2000 meter height, annual temperature over 20°C and annual precipitation over 200 mm with a correlation coefficient (R^2) of 0.91, 0.97 and 0.93-0.96 respectively.

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