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Abstract:

This study introduces the climates of Iran defined by Köppen-Geiger, Feddema's, and UNPEP classifications that applied to a high-resolution ground-based gridded data set relative to the 1985–2017 period. Ten Köppen-Geiger climate types were found for Iran, from which Bwh, Bsk, Csa, Bsh, and Bwk cumulatively account for more than 98% of the territory. Likewise, from 36 possible Feddema's climate types, Iran possesses fifteen climate types from which the Dry Cool, Semiarid Torrid, Semiarid Hot, Semiarid Warm, Dry warm, Semiarid Cool, and Moist Cool climates collectively occupied approximately 93% of the country. Similarly, arid, semi-arid, humid, and sub-humid UNEP climate types characterized more than 98% of Iran. A few other vertically stratified climates appeared at the highlands of Iran just because of changes in elevation and slope aspects of the mountains. The combined effect of topography and vicinity to sea also creates very distinct climate types in northern Iran. The climate maps of the three used methods reflect the joint effects of topography, latitudinal variation, and land/sea surface contrast on the climate of Iran. A pairwise comparison made between the three classifications showed a satisfactory agreement between the three schemes in representing the main climate types of Iran.

Keywords: Köppen-Geiger, Feddema, UNEP, Thornthwaite, climate classification, Iran

1. Introduction

Climatologists have long been used climate classification systems to classify the earth into different climatic zones based upon important climatic variables like precipitation and temperature. The modern climate classifications rooted back to Köppen (1900), De Martonne (1926), and Emberger (1932) who have considered precipitation and air temperature as the key variables for climate classification. Undoubtedly, the climate classifications proposed by Köppen (1900) and Thornthwaite (1948) are the most physically based classification systems.

Based on monthly total precipitation and average temperature and their seasonal variations, Köppen (1900) has divided the Earth into five major climatic regions as tropical rainy climate (A), arid climate (B), temperate rainy climate (C), snowy forest climate (D) and polar climate (E). Then he divided each of these climates into smaller climatic regions based on seasonal changes in temperature and precipitation. The Köppen classification system is inspired by the fact that the native plants of each region are the best measure to determine the climate of that region and that the boundary between different climatic regions can be determined using the biological characteristics of different plants (Trewartha 1980). The relationship between climate and vegetation assumed in the Köppen classification has attracted climatologists as well as environmental and agricultural scientists and led them to prefer it to other classification methods. Over time, many criticisms have been raised to Köppen classification, especially on how climatic boundaries are defined in the method. As a result, Köppen and Geiger (1930), Trewartha (1980), Guetter and Kutzbach (1990), and Stern et al. (2000) have proposed several modifications to Köppen classification.

Many scientists like Thornthwaite (1948) sought to provide a better way to classify climates so that they would have both a stronger physical basis and a more accurate

demarcation of climatic zones. Thornthwaite (1943) first used the concept of the moisture index to develop a classification system structured around the moisture factor and then modified it with improved water balance metrics (Thornthwaite 1948). He also made the system more “rational” by using even class intervals (Feddema 2005). Although Thornthwaite climate classification has a very high scientific validity, the Köppen classification method is still the most popular climatic classification method for drawing climate atlases at major centers for climatology around the world (FAO 1977). Köppen and Geiger (1930) manually drawn the first Köppen-Geiger climate classification map that was used in many textbooks of climatology to introduce the climate types of the world and teach students how to classify climates (Kottek et al. 2006). The need to update the world climate map of Köppen led Kottek et al. (2006) to use the monthly temperature data of the Climate Research Unit (CRU) of the University of East Anglia and the monthly precipitation of the Global Precipitation Climatic Center (GPCC) to update the world climate map of Köppen-Geiger method for the period 1951-2000. Using the long-term precipitation and temperature data from the Global Climate Historical Data Network (GHCN2), Peel et al. (2007) presented another map of the world climates using the Köppen-Geiger method. Rubel and Kottek (2010), using the CRU monthly temperature and GPCC monthly total precipitation data, presented another map of the Köppen-Geiger climates for the globe and examined the displacement of the world's climatic regions due to climate change.

The spatial accuracy of each of the aforementioned maps on a regional scale depends on the quality of the data and the number of stations used in that area. Due to the low spatial resolution of the data used in the above studies, it is necessary to use a denser network of meteorological stations to provide a more accurate map of Köppen-Geiger climate classification at the regional and national levels. In this regard, Stern et al. (2000)

have provided a climate classification map for Australia using the data of the Australian meteorological stations and making some modifications to the Köppen classification method. Using 1342 scattered meteorological stations throughout Brazil and the neighboring countries, Sparovek et al. (2007) used the Köppen-Geiger method to identify the climates of this part of the world and compared it with the available global climate classification maps. Chen and Chen (2013) have used the Köppen classification method to evaluate long-term and short-term climate variability at the global scale based on the Delaware University data set for the period 1901-2010. Chan et al. (2016) also used the Köppen-Geiger method with the University of Delaware data set for the period 1980-1999 for classifying climates over China and evaluating the effects of climate change on the climate type displacement.

Unlike the Köppen classification system, the Thornthwaite climate classification has never been used for producing a world map despite John “Russ” Mather frequently discussed the idea of producing such a map with the Thornthwaite climate classification (Feddema 2005). It is only applied to the United States, partly because Thornthwaite did not have access to sufficient climate data to do a global study (Feddema 2005), and since the Thornthwaite full classification was too complex none of his associates or other researchers attempted to produce a Thornthwaite global climate classification map. However, in 2005, Feddema (2005) revisited the Thornthwaite classification and created a less complex and more systematic climate classification approach that is easier to interpret and convey to students in a classroom setting (Feddema 2005). By introducing such simplifications to the Thornthwaite classification system, Feddema (2005) has made it easier to apply at the global scale and provided the first world map of Thornthwaite climates using his simplified Thornthwaite climate classification scheme that can be considered as a competitive approach to the Köppen classification system. Ács et al.

(2015) and Breuer et al. (2017) have applied the Thornthwaite classification revisited by Feddema (2005) to identify the climate types of Hungary during the 20th century. Similarly, Skarbit et al. (2018) have used it for identifying the climate types of the European region during the 20th and 21st centuries. Elguindi et al. (2014) also applied the modified Thornthwaite Climate Classification scheme to a 32-member ensemble of CMIP5 GCMs to evaluate model performance in the historical climate and assess the projected climate change at the end of the 21st century over the globe.

Regards Iran, utilizing the United Nations Environment Programme aridity index (UNEP, 1997) Raziei and Pereira (2013a); (Raziei and Pereira 2013b) have partitioned Iran into different climate types. By applying the extended De Martonne aridity index to 181 weather stations properly distributed across Iran, Rahimi et al. (2013) also identified eight climate types for Iran. Likewise, by utilizing monthly precipitation and temperature records of 155 synoptic weather stations with relatively regular distribution over Iran, Raziei (2017) created a new climate map for Iran using the Köppen-Geiger climate classification, and identified 9 climate types for the country.

Due to the complex topography and wide latitudinal and longitudinal extent of Iran (Figure 1) a dense network of meteorological stations is required for creating a spatially informative climate classification for the country. By using a gridded data set created based upon a dense network of regularly distributed stations over the complex topography of Iran (Figure 1), the present study aims to identify the climate types of Iran with the Köppen-Geiger, the UNEP, and the modified Thornthwaite climate classification schemes proposed by Feddema (2005). The first two climate classifications are used to update the climate classification maps of Iran created by Raziei (2017) and Raziei and Pereira (2013a); (Raziei and Pereira 2013b) while the third climate classification is used

herein for the first time to create a new climate classification map for Iran based on improved water balance metrics (Thornthwaite 1948).

2. Material and Methods

2.1 Data

Daily total precipitation, as well as maximum and minimum air temperature relative to a varying number of meteorological stations regularly distributed over Iran, were used for gridding the data into regular grid points with 0.25×0.25 degree spatial resolution. Figure 2 shows the spatial distribution of 397 meteorological stations used for gridding the daily total precipitation and the air temperatures over Iran. From these stations, 70 stations with a relatively regular distribution over the country (red circles) have full data records for the entire period 1985-2017 while the remaining stations (black circles) were gradually incorporated into the gridding process when their data records become available from 1986 onwards. In other words, from 1986 onwards the number of stations used for gridding the data gradually increases and reached a maximum of 379 stations in 2017.

2.2 Methods

2.2.1 Gridding the data

The Ordinary Kriging (OKrig) method is used for the interpolation of daily total precipitation and daily temperature records over the considered stations (Figure 2) because it is simple and widely used for gridding many geophysical fields (Biau et al. 1999; Matheron 1969). For example, Belo-Pereira et al. (2011) and Herrera et al. (2012) have used it for gridding climate variables over Portugal and Spain, respectively. Since Kriging takes into account both the relative positions of sampling points and their distances from the interpolated point (Dirks et al. 1998), it may be the most accurate method for interpolation in areas with sparse stations, as is the case for some parts of the

stations' network in the present study (Fig. 2). The OKrig method is the simplest form of Kriging that is less sensitive to the density of the station network (Belo-Pereira et al. 2011) and very useful when there is not strict confidence on the data measurements (Raziei and Pereira 2013b). It also produces visually appealing surface maps from irregularly spaced data to express existent trends in the dataset, so that high points might be connected along a ridge rather than isolated by bull's-eye type contours (Raziei and Pereira 2013b). Since the used stations are representative of the wide range of elevations and geographic features of Iran (Fig. 1 and Fig. 2), the method inexplicitly includes the role of the topography of Iran (Fig. 1).

The spatial variability of the data points as a function of distance was evaluated through inspection of the experimental variograms for all considered days and variables. The results suggested that the stable isotropic model best fitted the experimental variograms of both temperature and precipitation, indicating that the considered variables in the target area are spatially well continuous and structured. The selected theoretical model also showed a better fit to temperature than precipitation variable. As regards temperature variables, a better fit was found for the warm season than the cold season that can be related to the more uniform variability of temperature across Iran from May to October when a relatively stable weather condition dominated the area. The model also showed a very good fit to the daily precipitation of the cold season that is often produced by large-scale synoptic systems. Differently, the performance of the model slightly reduced for the warm season precipitation series that are mostly local and originated from orographical and convectional activities. The observed better fit of the theoretical variogram to the experimental variogram of precipitation records of the cold season is related to the existence of a very high spatial correlation between stations in synoptic-scale precipitation events. Contrarily, the lower performance of the theoretical model to fit the

warm season precipitation data sets can be attributed to the rapid decaying of their spatial correlation in short distances considering that they are local events induced by orographic and convective activities. A better fit was also achieved when the number of stations used in the variography process increases. This indicates that better estimates achieved at the end of the study period when the number of stations used for fitting theoretical semivariogram maximized.

Monthly total precipitation was computed from the daily total precipitation for all grid points over the study area. Similarly, the monthly average of minimum and maximum daily temperatures were computed from the daily gridded data sets and were subsequently used to compute the monthly average of air temperature at the considered grid points.

2.2.2 Köppen-Geiger climate classification

The Köppen (1900) climate classification system that was modified by later climatologists like Geiger (1961) and Trewartha (1980) is the most widely used classification. It uses temperature and precipitation that are the most important and effective climate variables in determining the spatial distribution of vegetation over the globe. It divides the Earth into tropical, dry, temperate, continental, and polar climates represented by A, B, C, D, and E, respectively. Except for B, which is defined by precipitation variation and amount, the other four climate types are defined by temperature range that allows for different vegetation growth. The second letter used in the classification system represents the seasonality of precipitation in a given climate while the third letter represents the level of heat of that climate determined by the average temperature during the coldest and warmest months of the year.

Although the Köppen classification passed several revisions, including its final version provided by Geiger (1961), its main shortcoming is that the boundaries between certain

climate types do not correspond with the observed boundaries of natural landscapes. This led Trewartha (1968) and Trewartha and Horn (1980) to introduce more realistic criteria to distinguish between the B and C climate types to match better the climate types of the mid-latitudes with the vegetative zones. Although Trewartha's scheme is more reflective of ecosystem variations, the Köppen-Geiger scheme is widely used because it is a simplified version of its original classification. Therefore, the Köppen-Geiger classification briefly described below is used herein to divide Iran into different climates. Table 1 presents the first two letters used in the Köppen-Geiger classification and the criteria with which the main climates are defined (Kottek et al. 2006). In Table 1, T_{ann} is the annual mean temperature and T_{max} and T_{min} are the monthly mean temperatures of the warmest and coldest months, respectively. P_{ann} is the accumulated annual precipitation and P_{min} is the precipitation of the driest month. Likewise, P_{smin} , P_{smax} , P_{wmin} , and P_{wmax} correspond to the lowest and highest monthly precipitation values for the summer and winter half-years on the hemisphere considered (Kottek et al., 2006). Additionally, P_{th} (mm) defined as in Eq. 1 is a dryness threshold applied to the annual total precipitation (T_{ann}) to divide the arid climates into two sub-climates.

$$P_{th} = \begin{cases} 2(T_{ann}) & \text{if at least } 2/3 \text{ of the annual precipitation occurs in winter,} \\ 2(T_{ann}) + 28 & \text{if at least } 2/3 \text{ of the annual precipitation occurs in summer} \\ 2(T_{ann}) + 14 & \text{otherwise} \end{cases} \quad (1)$$

The third letter of Köppen-Geiger classification and the criteria used for their determination are presented in Table 2 wherein the mean monthly temperature is denoted by T_{mon} . Based on the criteria listed in Table 1 and Table 2 it is possible to attain 34 different climate classes over the globe. However, since the criteria defined to approach

Csd, Cwd, and Cfd climate types never meet, only 31 climate types are computable in practice (Kottek et al. 2006).

2.2.3 Simplified Thornthwaite climate classification

The present study uses the simplified version of Thornthwaite climate classification introduced by Feddema (2005) which uses a thermal factor defined based on annual total Potential Evapotranspiration (PET), and a moisture factor defined based on a modified version of the moisture index proposed by Thornthwaite and Mather (1955). According to Feddema (2005) and Elguindi et al. (2014), the moisture index (I_m) originally devised by Thornthwaite and Mather (1955) and described in Willmott and Feddema (1992) is calculated as in Eq. 2:

$$I_m = \begin{cases} \frac{P}{PET} - 1 & \text{for } P \leq PET \\ 1 - \frac{PET}{P} & \text{for } P > PET \\ 0 & \text{for } P = PET = 0 \end{cases} \quad (2)$$

where P is total annual precipitation and PET is total annual potential evapotranspiration.

The I_m values range from -1 to $+1$, where a value of 0 indicates that the annual moisture supply (P) is equal to the annual moisture demand (PET) (Elguindi et al. 2014).

Monthly PET required for estimating I_m in Eq. 2 is estimated using the well-known Thornthwaite method (Thornthwaite 1948) calculated as in Eq. 3 through Eq. 5.

$$PET = \begin{cases} 0 & \text{for } T < 0^\circ\text{C} \\ 16 \left(\frac{10T}{I} \right)^a & \text{for } 0 \leq T < 26.5^\circ\text{C} \\ -415.85 + 32.24T - 0.43T^2 & \text{for } T \geq 26.5^\circ\text{C} \end{cases} \quad (3)$$

In Eq. 3, T is the mean monthly surface air temperature ($^\circ\text{C}$) and I is a coefficient that is computed as in Eq. 4,

$$I = \sum_{i=1}^{12} \left(\frac{T_i}{5} \right)^{1.514} \quad (4)$$

and

$$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.79 \times 10^{-2} I + 0.49 \quad (5)$$

To account for variable day and month lengths, the computed PET is adjusted as in Eq. 6.

$$PET = PET \left[\left(\frac{\theta}{30} \right) \left(\frac{h}{12} \right) \right] \quad (6)$$

Where θ is the length of the month in days and h is the duration of daylight in hours taken on the fifteenth day of the month (Elguindi et al. 2014).

Annual values of P , PET , and I_m were calculated from their monthly values, all of which were used together with their monthly values to calculate the annual and seasonal variation of thermal and moisture characteristics. According to Feddema (2005), the annual values of both thermal and moisture indices categorize into six moisture and thermal types as represented in Tables 3. When both thermal and moisture indices are combined they result in thirty-six possible climate types.

According to Table 3, regions with negative I_m are dry with different intensities defined based on I_m values classified with 0.33 intervals. Similarly, regions with positive I_m are wet with different degrees of wetness. In regions with negative I_m (dry) PET is greater than P while it is reversed in wet regions (Skarbit et al. 2018).

In the Feddema (2005) classification, the seasonality of a given location is defined based on the annual range of monthly I_m values ($I_m \text{ max} - I_m \text{ min}$). With this definition, the magnitude of climate seasonality of a given location can fall within one of the four I_m classes that range from low to extreme (Table 4). Since the I_m varies as a function of both PET and P variability, it simultaneously reflects the inherent seasonality of both variables.

In this classification, the seasonal moisture variation is estimated by calculating the annual range of precipitation variability defined as the difference between maximum

monthly precipitation ($P_{\max}$) and minimum monthly precipitation ($P_{\min}$), i.e., $P_{\max} - P_{\min}$. Likewise, seasonal thermal variation is estimated via $PET_{\max} - PET_{\min}$. As shown in Table 5, the ratio of $P_{\max} - P_{\min}$ and $PET_{\max} - PET_{\min}$ serves as an indicator for identifying the variable (P or T) that possesses seasonality. For more details, the readers are referred to Feddema (2005).

2.2.4 UNEP climate classification

Inspired by the water balance concept proposed by Thornthwaite (1948), aridity is commonly quantified by comparing the long-term average of water supply represented by precipitation to the long-term average of climatic water demand defined by potential evapotranspiration. In this definition, potential evapotranspiration measures the “drying power” of the atmosphere for removing water from land surfaces through evaporation and plant transpiration (Middleton and Thomas, 1997). The Aridity Index (AI) defined based upon the water balance concept is a simple but convenient numerical indicator of aridity represented by long-term climatic water deficit/surplus calculated as the ratio of P to PET, computed with the Thornthwaite method (Thornthwaite 1948). The United Nations Convention to Combat Desertification and FAO adopted it as a measure of the degree of dryness of a given location considering that it is a useful quantity for characterizing both an area’s heat and water availability. The UNEP climate classification can therefore be considered as a simple form of the Thornthwaite classification scheme (Thornthwaite 1948) and even Feddema’s (2005) method. In the present study, the AI classification used by Spinoni et al. (2015) for a climate classification at the global scale is adopted (Table 5).

2.2. Comparing the classification methods

To assess the consistencies between the three used classification methods in classifying the climates of Iran, the vectors of assigned climate types of the three used methods to the grids points covering Iran were cross-tabulated. This makes it possible to find out which climate type of a given classification with a lower number of categories corresponds to which climate type(s) of another classification that has a higher number of classes.

3. Results

3.1 Spatial variability of key variables for climate classifications over Iran

Figure 3 shows the spatial pattern of the long-term mean of annual average temperature, annual maximum temperature, annual minimum temperature, and annual temperature range over Iran for the period 1985-2017. As is seen, the spatial variability of temperature across Iran reflects the role of latitudinal variation and topographic features of Iran as illustrated in Figure 1. This is specifically more pronounced for the annual average temperature and the annual maximum and minimum temperatures illustrated in Figure 3a through Figure 3c. These figures depict the maximum values of the mentioned parameters over southern Iran alongside the Persian Gulf and Oman Sea as well as over central-eastern Iran. Contrarily, the minimum of the considered variables is seen over northern and western Iran and the sporadic elevated areas of central, southern, and eastern Iran. However, the spatial variability of the annual temperature range shown in Figure 3d is significantly different from those of the annual average temperature, annual maximum temperature, and annual minimum temperature. In contrast to the maps of later variables that reflect the spatial structure of the topography of Iran, Figure 3d shows a relatively uniform pattern of the high annual temperature range over Iran, except for the coastal

areas of northern and southern Iran where the adjacent water bodies significantly modulate the annual temperature range. This map shows that most parts of Iran have distinctive winter and summer seasons with a very wide annual temperature range.

Figure 4a shows the spatial variation of the annual total precipitation over Iran. As depicted, the highest annual total precipitation is observed over the coastal areas of the Caspian Sea and some parts of the Zagros mountains in western Iran while central, eastern, and southern Iran is characterized by far lower annual total precipitation. While the total annual precipitation of central-eastern Iran is almost less than 250 mm, it is between 350 and 950 in the mountainous areas of western Iran and over 1000 mm in the central and western parts of the coastal areas of the Caspian Sea. Figure 4a also shows the significant role of topography and vicinity to water bodies in shaping the spatial pattern of precipitation over Iran.

Figure 4b also shows the spatial variability of PET over Iran, computed with the Thornthwaite method for the period 1985-2017. This map also clearly shows the role of topography in representing the spatial distribution of PET over Iran. As is seen, southeastern and southwestern Iran show the highest PET values that range between 2200 and 3400 mm, followed by central-eastern Iran wherein the PET is between 1300 and 2200 mm. The lowest PET values ranging between 400 and 1300 mm correspond to the mountainous areas of western and northern Iran that are characterized by the lower annual average temperature, annual maximum temperature, and annual minimum temperature as depicted in Fig.4a through Fig.4c).

Considering that the combined effects of precipitation, temperature, and PET are the determinant factor in creating the climate types of a given location, the spatial variation

of the mentioned variables shown in Figures 3 and 4 can determine the spatial structure of climate types of Iran.

3.2 Köppen-Geiger climate classification

Figure 5 shows the map of climate types of Iran defined with the Köppen-Geiger method. It illustrates that the BW, BS, and Csa are the dominant climate types of Iran. According to Figure 5, the lowland areas of central-eastern and southern Iran and the southern part of Khuzestan province in the southwest of Iran have BWh climate type while its surrounding areas that have higher altitude are characterized by BWk climate type. The eastern slopes of Zagros and the southern slopes of Alborz, the mountainous areas of the northeastern country, and a large part of the northwest of Iran have a BSk climate type. BSh climate type is limited to the southern slopes of Zagros mountains in Khuzestan, Fars, and Bushehr provinces, as well as a small part of Golestan province in the northeast of the country.

According to Figure 5, the temperate Csa climate characterized by dry and very hot summers dominates a large part of the mountainous region of Alborz in the north and Zagros in the west of the country. Dsa climate type characterized by cold and snowy winters and dry and very hot summers appears at the highlands of Zagros in the west of Iran where the altitude of the locations substantially increases. Figure 5 also shows that some parts of the Alborz ranges in the north have a Dsb climate that has a cooler summer compared to Dsa climate type observed over Zagros ranges. A small part of the western coastal areas of the Caspian Sea has Csb temperate climate type that is hot and dry in summers. Likewise, the Cfa climate type which is a temperate rainy climate with no dry season but hot summers characterized two spots areas over the Alborz ranges in the north. According to Figures 5, from 31 possible Köppen-Geiger climate types that can be found

over the earth, ten climate types were found in Iran, from which only Bwh, Bsk, Csa, Bsh, and Bwk with 35.98%, 23.69%, 17.03%, 15.70%, and 5.94% occupied area cover very large parts of the country (Table 7). The Cfa, Cfb, Csb, Dsa and Dsb climate types with less than 1% areal coverage (Table 7) are created under the strong influence of altitude, latitude, vicinity to water bodies or a combination of them.

The present climate classification is highly consistent with that created by Raziei (2017) despite a few negligible differences were observed, which can be related to the different periods of data records and different numbers of stations used for gridding the data in both studies. Most importantly, the Dfa and Dfb climate types observed at a few spot areas on the climate classification map of Raziei (2017) were not observed in the present study. Differently, the Cfb climate type observed herein for a few grid points was not found by Raziei (2017) which can be related to the artifacts of the gridding procedure in both studies. The present climate classification map is also consistent with the global climate classification maps of Kottek et al. (2006), Chen and Chen (2013) in representing the climate types of Iran. However, the present climate classification presents more details regarding the climate types of Iran due to using a large number of stations with good spatial coverage over the country for gridding the data sets required for classification.

3.3 Feddema's climate classification

Figure 6 depicts the spatial variation of the moisture and thermal factors of Feddema's climate classification over Iran for the period 1985-2017, created based upon the maps of Figure 3 and Figure 4 that show the spatial pattern of temperature parameters, precipitation, and PET throughout Iran. As shown in Figure 6a, most parts of central-eastern and southern Iran are semi-arid, and only very limited spot areas of southeastern

Iran are hyper-arid. The second-largest moisture type of Iran is dry which occupies the mountainous areas of western, northern, and northeastern Iran. Finally, the coastal areas of the southwestern Caspian Sea plus two small isolated highlands in the mountainous areas of Zagros are moist regarding the Feddema's moisture factor. According to Figure 6b, the whole of southern Iran from the border with Iraq to the border with Pakistan plus a few isolated small patches of central-eastern Iran is torrid considering the Feddema's thermal factor. The thermal factor of central areas of central-eastern Iran along a band from south to north is hot while its outside areas in all directions are occupied by warm thermal type that extends further northeastward up to the southeastern Caspian Sea and the borders with Turkmenistan and Afghanistan. Most parts of the mountainous areas of western, northern, and northeastern Iran are cool regarding the thermal factor, while the thermal factor of three highland areas located in the north and northwest of Iran are cold due to the combined effects of their high latitude and altitude.

By combining moisture and thermal factors described above the Feddema's (2005) climate types of Iran formed and mapped in Figure 7.

The Feddema's (2005) climate types of Iran referring to the period 1985–2017 are presented in Figure 7a while the associated causes of the seasonality are shown in Figure 7b. As illustrated in Figure 7a, very small patches of arid-torrid climate are seen in southeastern Iran, more importantly along the coast of the Oman Sea whereas the arid-hot climate is limited to a single grid point at the coast of the Oman Sea. Similarly, the arid-warm climate characterized only a single grid point near the border with Pakistan and Afghanistan. The semiarid-torrid climate characterized entire southern Iran along the Persian Gulf and Oman Sea, with a northward expansion into central Iran where it appears as three isolated spots. On the northern side of the semiarid-torrid climate, the semiarid-

hot climate appears, from which a tongue extends into central Iran in a south-north direction. Away from the central part of Iran towards the mountainous areas of Zagros in the west and the mountain ranges of northeastern Iran, the semiarid-warm climate emerges and surrounds the semiarid-hot climate. Moving further towards west and east, the semiarid-cool climate comes out because of the strong effects of relief on the thermal factor. Moving from the center of Iran towards west, east, and north clearly shows that the thermal type changes from torrid to cool in very short distances due to the strong influence of relief whereas the moisture type component (i.e., semiarid) remains the same in this vast area.

Moving further westwards, eastwards, and northwards towards the mountain ranges, the thermal type changes to dry due to the changes in moisture factor as it is strongly influenced by relief and topography. The dry-torrid and dry-hot climates are almost found in southwestern Iran along the southern slope of Zagros mountain ranges where the dry-torrid climate is seen on the southern side of the dry-hot climate. To the north, along the southern slope of Zagros mountain ranges, the dry-hot climate changes to the dry-warm climate with more occupied areas than those for dry-torrid and dry-hot climates. It also occupies a noticeable part of the northern face of the central lowlands of Iran from which it extends farther north to southeastern the Caspian Sea. Also, there observed a strip of dry-warm climate along the border with Afghanistan and Turkmenistan. The dry-cool climate is the largest climate type in Iran as it occupies most parts of mountainous areas of western, northern, and north-eastern Iran. The dry-cold climate is limited to two isolated spots over the highlands areas of northern Iran and a highland area of central-southern Iran, where the temperature significantly increases due to the very high elevation.

The moist climates appear over the coastal areas of the Caspian Sea and the Zagros mountain ranges due to the combined effect of latitude and altitude. The moist-warm and moist-cold climates are occupied very limited areas; the former occupied only two single grid points at the coast of the Caspian Sea whereas the latter appears as three isolated patches seen over the Alborz mountain ranges near the Caspian Sea and the Zagros mountains in the west of Iran. The emergence of moist-cold climate in these spot areas is related to their very high elevation that brings there lower temperature and higher precipitation amount. Differently, the moist-cool climate is the dominant climate of the coastal areas of the southwestern Caspian Sea and the elevated areas of Alborz and Zagros mountains in the north and west of Iran, respectively.

Figure 7b shows the spatial pattern of the causes of seasonality in Feddema's climate classification implemented for Iran. As is shown, the temperature is the sole cause of seasonality in most parts of Iran. Except for the coastal areas of the Caspian Sea and the elevated areas of the Zagros Mountains in the west of Iran where both temperature and precipitation possess extreme seasonality, varying degrees of seasonality in temperature characterized most parts of Iran. It shows that the inland areas of Iran are mostly characterized by extreme seasonality in temperature whereas in the coastal areas of the Oman Sea and the easternmost of the Persian Gulf it changes to high seasonality in temperature. Towards the coast, there appear two spot areas with medium seasonality in temperature created by the cooling effect of the nearby water bodies.

Table 8 shows the areal coverage of the climate types of Iran determined with Feddema's classification method. As is seen, the largest climate types of Iran are Dry Cool, Semiarid Torrid, Semiarid Hot, Semiarid Warm, and Dry warm climates that respectively occupied 26.80%, 17.13%, 15.72%, 15.00%, and 9.95% of Iran's

1648000.00 square kilometers area. The Semiarid Cool, Moist Cool, Arid Torrid, Dry Torrid, and Dry Hot climates with 4.41%, 3.96%, 2.29%, 2.13%, and 1.93%, respectively, have also occupied noticeable areas of Iran. The other climate types, namely the Arid Hot, Arid Warm, Dry Cold, Moist Warm, and Moist Cold have with less than 1.0% areal coverage have occupied very negligible areas of Iran, as depicted in Figure 8a.

The present climate classification is well consistent with the global maps of Feddema's climate classification provided by Feddema (2005) and Elguindi et al. (2014) in representing the main climate type of Iran. However, the present climate classification map gives more details on the small-sized climate types created as the response of increases in elevation of the area, closeness to the water bodies, or their combined effects.

3.4 UNEP climate classification

Figure 8 shows the climates of Iran determined with the UNEP classification for the period 1985-2017. As depicted, the majority proportion of the studied area in central-southern Iran has an arid climate wherein several spot areas situated in the southeastern country are characterized by hyper-arid climate. The semi-arid climate also features the mountainous areas of western, northern, and northeastern Iran where the climate may change to dry, sub-humid, and humid types depending on the elevation of the points. Accordingly, the elevated areas of Zagros mostly have dry climates wherein the spot areas with very high elevation are either humid or sub-humid depending on their elevation. The coastal areas of the Caspian Sea and the nearby mountainous areas of central Alborz are featured by humid climate whereas the climate of the southeastern Caspian Sea and the southern face of the Alborz ranges are sub-humid.

The UNEP climate classification of Iran shown in Figure 8 is very similar to Feddema's climate classification illustrated in Figure 7b. This is not a surprise if one notes

that both the UNEP and Feddema's climate classifications are based on the water balance concept computed with the Thornthwaite (1948) method. However, Feddema's climate classification presents more details than the UNEP classification since it benefits the combined effects of thermal and moisture factors to categorizes the climate of the world into 36 possible categories. Table 9 presents the areal extents of the UNEP climate types of Iran identified in the present study. Based on the UNEP climate classification more than half of Iran is arid (52.85%), 34.26% is semi-arid, and 6.95% has a dry climate. The humid and sub-humid climate types also occupy 3.98% and 1.65% of the country. According to Table 9 and Figure 8, no desert climate was found in Iran despite that the Iranians call deserts many parts of central-southeastern Iran in their public communications, more specifically the main playas of central-southeastern Iran labeled desert.

Despite Raziei and Pereira (2013a; 2013b) have used far lower stations and different AI classes than those used in the present study (Table 6), Figure 8 is highly comparable with the UNEP climate classification maps of Raziei and Pereira (2013a; 2013b). It is also consistent with the global climate classification map of Spinoni et al. (2015) in determining the main climate types of Iran.

3.5 Comparing the three used classifications

Figure 9 shows the cross-tabulation of the climate types of Iran obtained by the three used climate classifications. As illustrated in Figure 9a, more than 90% of the grid points characterized by Arid Torrid, Arid Hot, and Arid Warm climates in Figure 7a correspond to Bwh climate type in Köppen-Geiger climate classification shown in Figure 5. A large proportion (60%-90%) of grid points characterized with Feddema's Semiarid Torrid,

Semiarid hot and Semiarid Warm climates match with Bwh climate type whereas a minor proportion of the grids correspond to Bwk or Bsh climate types. The most proportion of Feddema's Semiarid Cool climate (50%-60%) corresponds to Bwk climate while the rest (40%-50%) assigned to Bsk climate. The Feddema's dry torrid climate mostly matches with Bsh (>80%) while a minor proportion corresponds with Csa climate. With a relatively similar proportion, the Dry Hot climate is either match with Bsh or Csa climate types. Dry Warm climate mostly agrees with Bsk climate but a noticeable proportion of it may either match with Bsh or Csa climate types. Feddema's Dry Cool and Dry Cold climates mostly match with Bsk in the map of Köppen-Geiger climate classification, but they correspond to Csa climate type at a very small proportion of the grid points. As is seen, Feddema's Moist warm climate mostly corresponds to Csa but a minor proportion of it matches with Csb climate type. Finally, the Moist Cool climate distributes between Csb, Dsa, and Dsb climate types with relatively similar proportions.

According to Figure 9b, the Hyper-arid climate type of the UNEP classification fairly fits with the Bwh climate type of the Köppen-Geiger climate classification. Similarly, the Arid climate type mostly agrees with Bwh climate but it may find the Bwk and Bsh climate types as its counterpart at less than 30% of the grid points. The semi-arid climate also mostly coincides with Bsk but it may match Bsh or Csa at less than 30% of the grid points. As is seen, the Dry and Semi-dry climates of the UNEP well coincide with the Csa climate type of the Köppen-Geiger climate classification whereas its Humid climate type mostly concords to Csa (>80%); however, it matches the Csb climate type at less than 20% of grid points.

Figure 9c clearly shows that the Arid Torrid, Arid Hot, Arid Warm, Semiarid Torrid, and Semiarid Hot climates of Feddema's classification fairly matches with the Arid climate type of UNEP. As is seen, the Feddema's semiarid warm and Semiarid Cool

climates also correspond to the UNEP Arid climate type in most of the grid points they occupied but they match with Semi-arid climate at only less than 30% of the grid points. Feddema's Dry Torrid climate type mostly agrees with the Semi-arid climate of UNEP but corresponds to the Arid climate at less than 50% of the grid points. The Dry Hot climate well consistent with the Semi-arid climate type of UNEP whereas the Dry Warm and Dry Cool of Feddema mostly match with the Semi-arid climate of UNEP and to a lesser extent with the Dry or Arid climate types. The Feddema's Dry Cold climate distributes equally between the UNEP Semi-Arid and Dry climate types. More than 70% of the grid points identified with Feddema's Moist Warm climate is consistent with the UNEP Humid climate type, and the rest match with the UNEP Sub-humid climate type. The Feddema's Moist Cool climate is mostly consistent with the Humid and Sub-humid climate types of UNEP but it corresponds to Dry climate at a small proportion of the grid points.

4. Discussion and conclusion

The present study identifies the climate types of Iran, employing the Köppen-Geiger, Feddema's, and the UNPEP climate classification systems applied to a high-resolution ground-based gridded data set relative to the 1985–2017 period. Based on the Köppen-Geiger classification scheme Iran encompasses ten out of the 31 possible climate types, from which Bwh, Bsk, Csa, Bsh, and Bwk are the five major climate types of Iran that cumulatively account for more than 98% of the territory. Likewise, from the 36 possible Feddema's climate types, fifteen are found in Iran from which the Dry Cool, Semiarid Torrid, Semiarid Hot, Semiarid Warm, Dry warm, Semiarid Cool, and Moist Cool climates are the seven main climate types of the country that collectively occupied approximately 93% of land area. Similarly, from the six climate types of the UNEP

classification, the arid, semi-arid, humid, and sub-humid climate types characterized more than 98% of the studied area.

The climate maps of the three used methods well reflect the joint effects of topography, latitudinal variation, and land/sea surface contrast on the climate of Iran, as they are the main geographical controls on the climate of the study area. Aside from the five (seven) main climate types identified by Köppen-Geiger (Feddema's) classification for Iran, other appeared climate types in Iran are created due to changes in temperature with elevation or vicinity to water bodies or as a function of their combined effects. The Cfa, Cfb, Csb, Dsa, and Dsb are of these kinds of climates that mostly appear as patches of vertically stratified highland climates because of changes in elevation as well as slope aspects, i.e., windward and leeward. The combined effect of topography and vicinity to the Caspian Sea creates very distinct climate types in this area as well. The number and occupied areas of these kinds of climate types may increase if more stations from the highlands areas as well as from central-eastern Iran are available and incorporate in updating the maps. The maps could be updated using a combination of high-resolution remote sensing and reanalysis data that provide appropriate estimates of climate variables for remote areas with no observed climate variables. It is particularly of paramount importance to have a better picture of climate types of central-eastern Iran for which no climate information is available because it is mostly inhabitant due to its harsh climate conditions.

Although it is difficult to compare various climate classifications with different classes derived based upon different concepts and definitions, a pairwise comparison was made between the three climate classifications to evaluate their degrees of agreement in characterizing the grids points distributed across Iran. The result showed a satisfactory agreement between the three schemes in representing the main climate types of Iran. The

comparison showed that any given climate type of the classification with a lower number of categories may distribute between different climate types of other classification that has more classes. This implies that for example, a climate type of UNEP classification that has a lower number of classes distributes between more classes of the other two classifications. Nonetheless, according to the results obtained, it seems that Feddema's (2005) climate classification provides a more detailed representation of the climate types of Iran because it has more classes than the other two classifications and also since it is a more physically based method that enables it to produce a finer portray of the climate types of Iran.

The maps of three climate classifications obtained in this study are in agreement with the climate map of Rahimi et al. (2013) produced using the modified De Martonne (1926) and a gridded dataset created with a different network of stations and data period. The climate classification maps provided by the present study can serve as a valuable basis for a variety of agricultural, environmental, and infrastructural studies in Iran, particularly the activities that need to know the water balance, energy, thermal, and moisture magnitudes and variability of the region of study.

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Figures

Figure 1

Due to the complex topography and wide latitudinal and longitudinal extent of Iran (Figure 1) a dense network of meteorological stations is required for creating a spatially informative climate classification for the country. By using a gridded data set created based upon a dense network of regularly distributed stations over the complex topography of Iran (Figure 1), the present study aims to identify the climate types of Iran with the Koppen-Geiger, the UNEP, and the modified Thornthwaite climate classification schemes proposed by Feddema (2005). The first two climate classifications are used to update the climate classification maps of Iran created by Raziei (2017) and Raziei and Pereira (2013a); (Raziei and Pereira 2013b) while the third climate classification is used herein for the first time to create a new climate classification map for Iran based on improved water balance metrics (Thornthwaite 1948).

Figure 2

Figure 2 shows the spatial distribution of 397 meteorological stations used for gridding the daily total precipitation and the air temperatures over Iran.

Figure 3

Figure 3 shows the spatial pattern of the long-term mean of annual average temperature, annual maximum temperature, annual minimum temperature, and annual temperature range over Iran for the period 1985-2017. As is seen, the spatial variability of temperature across Iran reflects the role of latitudinal variation and topographic features of Iran as illustrated in Figure 1.

Figure 4

Figure 4a shows the spatial variation of the annual total precipitation over Iran. As depicted, the highest annual total precipitation is observed over the coastal areas of the Caspian Sea and some parts of the Zagros mountains in western Iran while central, eastern, and southern Iran is characterized by far lower annual total precipitation. While the total annual precipitation of central-eastern Iran is almost less than 250 mm, it is between 350 and 950 in the mountainous areas of western Iran and over 1000 mm in the

central and western parts of the coastal areas of the Caspian Sea. Figure 4a also shows the significant role of topography and vicinity to water bodies in shaping the spatial pattern of precipitation over Iran. Figure 4b also shows the spatial variability of PET over Iran, computed with the Thornthwaite method for the period 1985-2017. This map also clearly shows the role of topography in representing the spatial distribution of PET over Iran. As is seen, southeastern and southwestern Iran show the highest PET values that range between 2200 and 3400 mm, followed by central-eastern Iran wherein the PET is between 1300 and 2200 mm. The lowest PET values ranging between 400 and 1300 mm correspond to the mountainous areas of western and northern Iran that are characterized by the lower annual average temperature, annual maximum temperature, and annual minimum temperature as depicted in Fig.4a through Fig.4c).

Figure 5

According to Figure 5, the temperate Csa climate characterized by dry and very hot summers dominates a large part of the mountainous region of Alborz in the north and Zagros in the west of the country. Dsa climate type characterized by cold and snowy winters and dry and very hot summers appears at the

highlands of Zagros in the west of Iran where the altitude of the locations substantially increases. Figure 5 also shows that some parts of the Alborz ranges in the north have a Dsb climate that has a cooler summer compared to Dsa climate type observed over Zagros ranges. A small part of the western coastal areas of the Caspian Sea has Csb temperate climate type that is hot and dry in summers. Likewise, the Cfa climate type which is a temperate rainy climate with no dry season but hot summers characterized two spots areas over the Alborz ranges in the north. According to Figures 5, from 31 possible Köppen-Geiger climate types that can be found over the earth, ten climate types were found in Iran, from which only Bwh, Bsk, Csa, Bsh, and Bwk with 35.98%, 23.69%, 17.03%, 15.70%, and 5.94% occupied area cover very large parts of the country (Table 7). The Cfa, Cfb, Csb, Dsa and Dsb climate types with less than 1% areal coverage (Table 7) are created under the strong influence of altitude, latitude, vicinity to water bodies or a combination of them.

Figure 6

Figure 6 depicts the spatial variation of the moisture and thermal factors of Feddema's climate classification over Iran for the period 1985-2017,

Figure 7

By combining moisture and thermal factors described above the Feddema's (2005) climate types of Iran formed and mapped in Figure 7.

Figure 8

Figure 8 shows the climates of Iran determined with the UNEP classification for the period 1985-2017. As depicted, the majority proportion of the studied area in central- southern Iran has an arid climate wherein several spot areas situated in the southeastern country are characterized by hyper-arid climate. The semi-arid climate also features the mountainous areas of western, northern, and northeastern Iran where the climate may change to dry, sub-humid, and humid types depending on the elevation of the points. Accordingly, the elevated areas of Zagros mostly have dry climates wherein the spot areas with very high elevation are either humid or sub-humid depending on their elevation. The coastal areas of the Caspian Sea and the nearby mountainous areas of central Alborz are featured by humid climate whereas the climate of the southeastern Caspian Sea and the southern face of the Alborz ranges are sub-humid.

Figure 9

Figure 9 shows the cross-tabulation of the climate types of Iran obtained by the three used climate classifications. As illustrated in Figure 9a, more than 90% of the grid points characterized by Arid Torrid, Arid Hot, and Arid Warm climates in Figure 7a correspond to Bwh climate type in Köppen-Geiger climate classification shown in Figure 5. A large proportion (60%-90%) of grid points characterized with Feddema's Semi-arid Torrid, Semi-arid hot and Semi-arid Warm climates match with Bwh climate type whereas a minor proportion of the grids correspond to Bwk or Bsh climate types. The most proportion of Feddema's Semi-arid Cool climate (50%-60%) corresponds to Bwk climate while the rest (40%-50%) assigned to Bsk climate. The Feddema's dry torrid climate mostly matches with Bsh (>80%) while a minor proportion corresponds with Csa climate. With a relatively similar proportion, the Dry Hot climate is either match with Bsh or Csa climate types. Dry Warm climate mostly agrees with Bsk climate but a noticeable proportion of it may either match with Bsh or Csa climate types. Feddema's Dry Cool and Dry Cold

climates mostly match with Bsk in the map of Koppen-Geiger climate classification, but they correspond to Csa climate type at a very small proportion of the grid points. As is seen, Feddema's Moist warm climate mostly corresponds to Csa but a minor proportion of it matches with Csb climate type. Finally, the Moist Cool climate distributes between Csb, Dsa, and Dsb climate types with relatively similar proportions.