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Comparative evaluation of sultry indices in the mid-south of Iran

Peyman Mahmoudi[1] · Taghi Tavousi[1] · Sylwester Wereski[2] · Mahdiye Miri Kamak[1]

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Abstract

The sultry phenomenon is considered one of the climactic events of south shorelines of Iran which are associated with humidity and high air temperature. The importance and necessity of this phenomenon on the subject of applied studies especially bioclimatology will be regarded if increasing of its severity leads to human discomfort as well as asthma and hard breathing. The main objective of this study was to conduct a comparative investigation into the estimation indices for sultry conditions in the southern half of Iran. To achieve research objectives, the hourly data for partial vapor pressure, air temperature, relative humidity, and wind speed were collected from 12 synoptic stations over a 15-year period (1995–2009). The following five indices were used to differentiate between sultry and non-sultry days: the actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion), equivalent temperature index (more than 56 °C), physiological deficit index (less than 45 hPa), the approximated heat stress index, and the sultry severity index (Castens-Lancaster criterion). To compare these indices, two quantitative and qualitative criteria were considered. The results obtained from quantitative analysis of these indices showed that the Scharlau and Castens-Lancaster criteria were the most coordinated indices in determining sultry conditions. Suitable coordination was obtained only in half the studied stations for the physiological deficit index of less than 45 hPa. The lowest coordination was between the approximated heat stress index and the equivalent temperature index of more than 56 °C. The results obtained from the qualitative evaluation of the sultry estimation indices showed that the Scharlau criterion was more capable of estimating sultry conditions since it exhibited such characteristics as robustness, tractability, transparency, sophistication, extendability, and dimensionality. In general, the conducted quantitative and qualitative analyses showed that the Scharlau criterion was the most appropriate, homogeneous, and concrete index for monitoring sultry conditions in southern Iran.

1 Introduction

According to the meteorological glossary, sultriness is defined as a subjective feeling of physiological discomfort due to an excessive amount of water vapor in the air (Niedźwiedź 2003) which can be observed in most coastal warm seas. In other words, by increasing the air temperature and relative humidity on the sidelines of warm seas, sultry climate phenomenon occurs. The importance and necessity of this phenomenon in various practical studies and especially in bioclimatology studies is clarified when its increased intensity deprives comfort and welfare and brings about asthma with respiration problems. The feeling of sultry is a subjective matter like any other feeling reflection which supposedly cannot be measured using any special tools. Many efforts are made by meteorologists and climatologists in order to feel this phenomenon, and a series of climate physiological experiments indicate that the expression of the noted feeling can be studied as a scientific and objective insight according to the empirical studies (Mahmoudi et al. 2014). It is important to set a series of appropriate and exact indicators in order to study and evaluate the sultry phenomenon. Using these indicators, duration and extent of sultry can be quantified and evaluated. In this study, the actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion), equivalent temperature index (more than 56 °C), physiological deficit index (less than 45 hPa), the approximated heat stress index, and the sultry severity index (Castens-Lancaster criterion) were used.

Scharlau (1943) describes sultry as a condition of climate which vapor partial pressure value is equal to or greater than

✉ Peyman Mahmoudi
p_mahmoudi@gep.usb.ac.ir

[1] Department of Physical Geography, Faculty of Geography and Environmental Planning, University of Sistan and Baluchestan, Zahedan 9816745639, Iran

[2] Department of Meteorology and Climatology, Faculty of Earth Science and Spatial Management, Maria Curie-Skłodowska University, Lublin, Poland

18.8 hPa. Based on this definition, Dieterichs (1957) calculated and exploited all sultry hours in San Salvador from 1952 to 1956. Castens (1925) has studied the tropical climate in East Africa during 12 years and then, in cooperation with Berke and Castens (1929), confirmed and used the boundary values presented by Lancaster (1898) and developed a graph, which later became known as the Lancaster-Castens sultriness curve. This curve, which has been approved by many climatologists and today, can be calculated using a simple formula consisting of air temperature and relative humidity and demonstrates that sultry phenomenon occurs at temperatures above 16.5 °C, and it does not occur at the temperatures below 16.5 °C, even if relative humidity reaches 100%. Steadman (1979) also has evaluated the amount of clothing required to achieve an appropriate thermal comfort in the sultry summer in two hot and humid and hot and dry climates by considering the threshold of vapor partial pressure equal to or greater than 1.6 kPa (kilopascal) as the threshold for distinguishing the sultry situations from non-sultry ones. Zarnowiecki (2003) using four indices, i.e., Scharlau criterion, physiological saturation deficit, equivalent temperature, and air enthalpy, studied the sultry periods of summer in eight different urban landscapes of Kielce in Poland. The results of his study showed that sultry periods often occur in a compact building or concrete-asphalt grounds and proximity to water sources especially still water sources. Also in areas with good ventilation and redundant vegetation, the sultry state rarely happens. Schoen (2005) has succeeded in distinguishing between sultry and non-sultry conditions by developing an empirical model based on three variables: dry-bulb temperature, relative humidity, and dew point temperature. He has compared his model with a model used by the National Weather Service (NWS) in the USA and concluded that his model, in addition to being simple, has much higher accuracy than that model. Kamoutsis et al. (2010) have measured air temperature and relative humidity at 15-min intervals during a 37-day period, from June 23 to August 28, 2007, and then calculated the thermohygrometric index for the two mountainous regions, one in the east and the other in the west of Greece, to compare the thermal comfort conditions of these two regions. The results of their study showed that from 9:00 am to 8:00 pm, the western mountainous area of Greece has more suitable conditions than the eastern mountainous regions. Zhao and Che (2001) have studied long-term changes in the time series of the days with the sultry phenomenon in Shijiazhuang, China, and observed that the most frequent occurrence of this phenomenon occurred in the 1990s. Mahmoudi et al. (2014), in spatial classification of sultry days in the southern half of Iran based on Scharlau criterion, concluded that most of the sultry days in monthly scale happen in June and July and at least it happens in January. In terms of spatial differences, also south-east of Iran has more sultry days than south-west. In some studies, equivalent temperature, physiological saturation deficit, and the approximated heat stress index are used to study the spatial-temporal behavior of sultry days. Falarz (2005) stated on the sultry phenomenon in Poland that the average redundancy of sultry days throughout Poland from north-west to south-east increases constantly and in lands higher than 1200 m, sultry days do not happen. Also, the worst environmental climate condition associated with the sultry phenomenon is observed in the south-east and the best conditions are observed in north and west parts of the country and in highlands. In addition to these results, a statistically significant increasing trend can be seen in the number of sultry days, especially in the second half of the twentieth century onwards in western parts of Poland. In addition, Blazejczyk and Matzarakis (2007) studied the spatial and seasonal differences of climate conditions in Poland using the different models of human heat balance and at last divided Poland into eight climate areas using the outputs of studied models which the south-east area has the least suitable conditions in terms of the sultry state. Wereski and Wereski (2012) studied the sultry days in Lesko, in the south-east part of Poland, using five indices: Scharlau criterion, equivalent temperature more than 56 °C index, physiological deficit less than 45 hPa, heat stress index more than 30%, and heat stress index more than 70%. The results of this study show that the number of the sultry days in this station varies in years and depends on the used methods (from 1 to 24 days based on equivalent temperature more than 56 °C index and from 42 to 100 days based on heat stress index more than 30%). Also, the duration of sultry periods and the values of sultry day trend are results from the used methods. The following studies can be mentioned as the similar studies on this topic: the studies by Kalkstein and Valimont (1986) in the USA, Matzarakis and Mayer (1997) in 12 meteorological stations in Greece, Saaroni and Ziv (2003) in Tel Aviv, Watts and Kalkstein (2004) in the USA, Endler and Matzarakis (2011) in the southwest of Germany, and Mahmoudi et al. (2017a, b) in the southern Iran. In Iran, Kaviyani (1981) was the first researcher who addressed the spatial-temporal behavior of sultry days using Lancaster-Castens sultry index. He determined the starting and ending months of sultriness in south coastal areas of the country by choosing 35 south stations in Iran and analyzing the data in a 10-year period and then compared the severity. Masoodian (2012) shows that sultriness can be observed from the middle of February to the middle of October in Iran in coastal areas and its peak is in August and at this time, 15% of the country is in the sultry state. Khoshakhlagh et al. (2011) used Lancaster-Castens severity index in order to analyze sultriness of south-west of Iran statistically. The results of that study show that sultriness happens from May in terms of time and its most severe state is related to August which all the studied stations are sultry. The results of this study are comparable with the work of Masoodian (2012). In terms of spatial differences, the highest number of days can be seen in coastal stations and sultry days are lower in northern stations.

According to the studies which some of them were mentioned, it can be observed that the most conducted studies in the world are after obtaining spatial-temporal behavior of sultry days using one sultry index and did not address a comparative study in this field. Therefore, in this study, the aim is to answer two following questions in a comparative study. (1) Are all estimating sultry indices have the same results in terms of separating sultry days from non-sultry in the southern half of Iran? (2) Among the indices of estimating sultriness, which index is more appropriate for estimating sultry conditions in the southern half of Iran?

2 Studied area

In present study, the case study is the southern Iran, from the latitude of N 32° to the northern coast of Persian Gulf and Oman Sea. This area is located between the latitudes from N 25° to 32° and longitudes from E 47° to 63°.This area ends in the West to Iraq, from north to domestic provinces of Iran, from the East to Pakistan, and in the south to the shores of the Sea of Oman and the Persian Gulf. According to the climatic classification by Masoodian (2012), southern half of the country can be divided into six climate classes: climate of heights (cold, rain, and dry), the climate of western foothills (mild, precipitation, and dry), Persian Gulf coast climate (very hot, rainy, and humid), climate of eastern foothills (mild, low rainfall, and dry), climate of eastern plateau (warm, low rainfall, and dry), and climate of Oman Sea coast (warm, low rainfall, and very wet) (Fig. 1). Spatial distribution of average annual temperature of this area has been between 20 and 34 °C, and the average most precipitation has been 346 mm and is related to Shiraz station in north-east of the area and the average least participation has been 61 mm and is related to Zabol station in east of the area.

3 Materials and methods

To conduct a comparative study on the indices estimating the sultry conditions in the southern Iran and to achieve the objectives of present study, the hourly data of partial vapor pressure (in hectopascal), air temperature (in Celsius), relative humidity (in percentage), and wind speed (in m/s) collected during a 15-year statistical period (1995–2009) in 12 synoptic stations located in the southern Iran were obtained from the Iran Meteorological Organization. These 12 stations were selected in such a way that they had no missing data and covered the southern Iran well. In Fig. 1, the locations and geographic distribution of the studied stations are shown, and their geographical characteristics are listed in Table 1.

After the studying and collecting hourly data of partial vapor pressure, air temperature, relative humidity, and wind

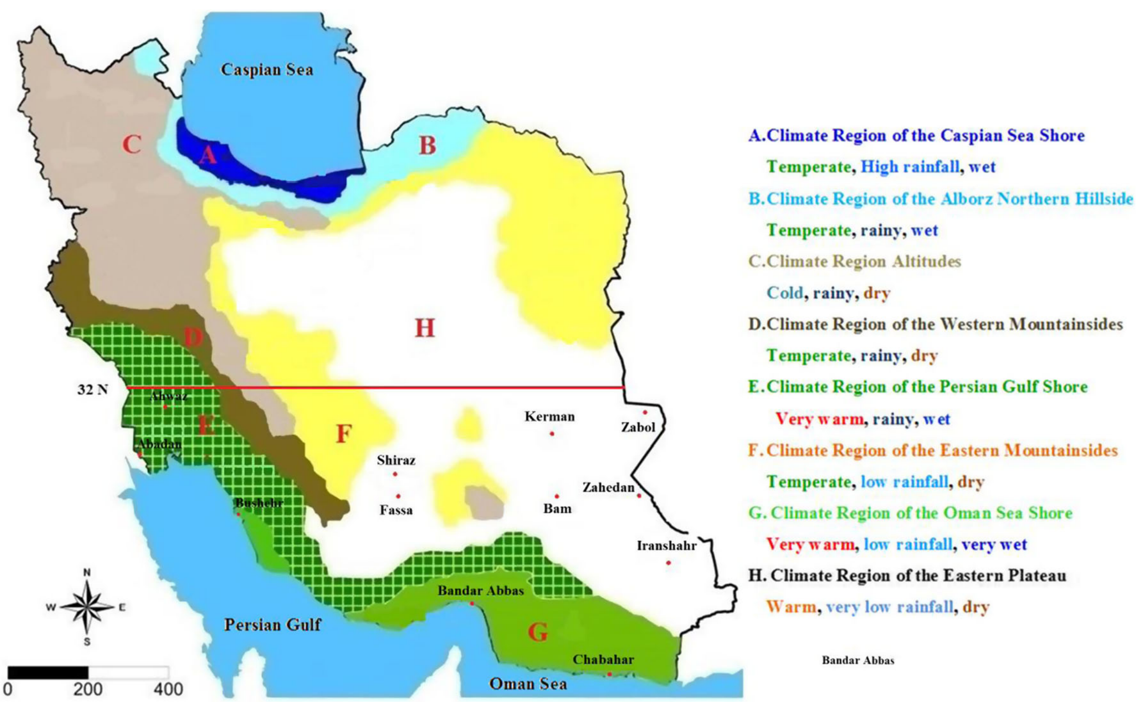

Fig. 1 Climatic classification of Iran along with the spatial position and distribution of the studied stations in the southern half of Iran

Table 1 The geographical characteristics of the studied stations in the southern half of Iran

Station	Latitude	Longitude	Elevation (m)
Abadan	30° 22′	48° 15′	6.6
Ahwaz	31° 20′	48° 40′	22.5
Bushehr	28° 59′	50° 50′	19.6
Shiraz	29° 32′	52° 36′	1484
Fassa	28° 58′	53° 41′	1288.3
Bandar Abbas	27° 13′	56° 22′	10
Kerman	30° 15′	56° 58′	1753.8
Bam	29° 06′	58° 21′	1066.9
Zabol	31° 02′	61° 29′	489.2
Zahedan	29° 28′	60° 53′	1370
Iranshahr	27° 12′	60° 72′	591.1
Chabahar	25° 17′	60° 37′	8

speed from the studied stations, the hourly values (00, 03, 06, 09, 12, 15, 18, and 21 GMT) of the actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion), equivalent temperature index (more than 56 °C), physiological deficit index (less than 45 hPa), the approximated heat stress index, and the sultry severity index (Castens-Lancaster) were calculated in order to identify and separate the sultry from non-sultry days. It has to be noted that in this study, sultry day is defined as a day which has shown on these indices of sultriness in one of the eight areas. The reason for choosing this definition of sultry days lies in the fact that using the daily average of indices can hide useful information on their behavior during a day. In the following, each of these indices is introduced.

3.1 The actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion)

The index was proposed by Scharlau in 1943. According to Scharlau criteria, sultry day is the day when its actual vapor pressure equals to or is greater than 18.8 hPa. The index is based purely on the variable actual vapor pressure and is a tool to identify sultry phenomenon in different regions.

3.2 Equivalent temperature index (more than 56 °C)

Equivalent temperature more than 56 °C index was proposed by Dufton (1929). Equivalent temperature index evaluates the average temperature effects on organisms in relation to the temperature and vapor pressure. Equivalent temperature index formula is as follows.

$$Tek = t + 1.5 \times e \tag{1}$$

where t is temperature (in Celsius) and e is vapor pressure (in hectopascal). Table 2 shows the classification equivalent temperature index.

Table 2 Specified thresholds for different classes of Tek index (in °C) (Dufton 1929)

From less than 18	Cold
18 to 24	Cool
24 to 32	Slightly cool
32 to 44	Comfort
44 to 56	Sultry, hot
From more then 56	Very hot and humid

3.3 Physiological deficit index (less than 45 hPa)

Physiological deficit index is the difference between saturated vapor pressure and actual vapor pressure in temperature 36.5 °C. The index is obtained based on the following equation:

$$DF = 60.9 - vp \tag{2}$$

where DF is physiological deficit and vp is actual vapor pressure (in hectopascal). Table 3 shows the physiological deficit index classification.

3.4 The approximated heat stress index (pHSI more than 30%)

Approximate value of heat stress index (with less than 15%) is calculated using the simplified equation of Blazejczyk and Matzarakis (2007) according to the exchange temperature model (MENEX_2002). The approximate value of physiological stress index is the only parameter required for calculations. This index is defined by the following relationship:

$$pHSI = 18.6058 - 24.7164\ \mathrm{LN}(\mathrm{pPhS}) \tag{3}$$

where $pHSI$ is approximate physiological pressure in subjects which is obtained by the following equation:

$$\mathrm{pPhS} = (2.12513 - 0.058018\ \mathrm{t})^2 \tag{4}$$

Table 4 shows the heat stress index value classification.

3.5 The sultry severity index (Castens-Lancaster)

Castens (1925) in collaboration with Berke and Castens (1929) and using the boundary values of Lancaster (1898)

Table 3 Specified thresholds for different classes of physiological deficit (Kozlowska-Szczesna et al. 1997)

45 to 53 hPa	Comfort
From more than 53 hPa	Dry
From less than 45 hPa	Sultry

Table 4 Different classes of approximate heat stress index [%] (Blazejczyk and Kunert 2011)

Below 0	Slight cool stress
From 0 to + 10	Thermoneutral conditions
From more than 10 to 30	Slight and moderate heat stress
From more than 30 to 70	Intensive heat stress
From more than 70 to 90	Very intensive heat stress
From more than 90 to 100	Maximal heat stress tolerated by young, acclimated persons
Above 100	Hazard of an organism overheating

provided a graph which later was known as Lancaster-Castens sultriness curve. The curve defines the sultriness boundary with respect to temperature (in Celsius) and relative humidity (in percentage). The following equation shows the distance from sultry border where positive values indicate sultriness and negative values indicate non-sultriness. If D equals 0, we are on the sultry border.

$$D = \frac{Rh}{21.55} - \frac{100}{T} + 1.3 \tag{5}$$

where D is sultry severity, Rh is relative humidity, and T is temperature.

At last, two quantitative and qualitative methods were used for comparative study of sultriness indices.

3.6 Quantitative assessment of indices of sultriness

In order to evaluate the differences in results of indices, Pearson's product-moment correlation coefficient, analysis of variance, and Scheffé's method were used.

Pearson's product-moment correlation coefficient It is a statistical tool used for determining the type and degree of the relationship between two quantitative variables. Pearson's product-moment correlation coefficient is defined as Eq. (6).

$$r_{xy} = \frac{n\sum XY - (\sum X)(\sum Y)}{\sqrt{\left[n\sum X^2 - (\sum X)^2\right]\left[n\sum Y^2 - (\sum Y)^2\right]}} \tag{6}$$

where X and Y are the pair of variables of interest in the calculation of the correlation coefficient. In present study, the studied variables were the number of days with sultry conditions. They were obtained from different indices of sultriness at monthly, seasonal, and annual scales. The value of this coefficient varies between − 1 and 1. The value of "1" means complete positive correlation, "0" means no correlation, and "− 1" means complete negative correlation. The significance of the correlation coefficient is also tested using T-statistics. The T-statistic with the degree of freedom n-2 is calculated using Eq. (7):

$$t = \frac{r}{\sqrt{\frac{1-r^2}{n-2}}} \tag{7}$$

where r^2 is the coefficient of determination, t is the suitable statistic for examining the significance of the correlation coefficient, n-2 denotes the degrees of freedom of t-distribution for the significance of the correlation coefficient.

Finally, the value of t obtained from Eq. (7) is compared with the critical value of t in the table. If the absolute value of the estimated t is less than critical value of t, the research hypothesis will be verified at the confidence level of $\alpha =$ 0.05 (Eq. (8)).

$$|t| > t_{\frac{\alpha}{2}} \tag{8}$$

where $|t| > t_{\frac{\alpha}{2}}$ is the rule for rejection and decision-making (Pearson 1895; Stigler 1989).

Variance analysis Variance analysis is used when the objective is to compare the means of a quantitative attribute in three or more groups. In this analysis, the null hypothesis always implies that the means of all groups are the same and alternative hypothesis implies the difference between at least two groups. Therefore, rejection of the null hypothesis in this analysis shows a significant difference between at least two groups of all groups.

In order to better understand the logic behind this analysis, first, it is necessary to understand the concept of "portioning." Portioning means to calculate the dispersion or total variance for all the subjects studied, that here, it is the number of sultry days at three monthly, seasonal, and annual scales, and then, to divide it into the components. The dispersion or total variance is the variance of all subjects of the studied groups, all of which are considered a group. The total variance can be divided into two parts: the variance between groups and the variance within the groups. The variance between the groups is the average variance of the groups around the total average, and the variance within the groups is the variance of each score around the average of the group in which the score is. The variance analysis requires a test called the F test, whose formula is as Eq. (9):

$$F = \frac{\text{variance between groups}}{\text{variance within groups}} \quad (9)$$

According to Eq. (9), if the variance between the groups is equal to the variance within the groups, the null hypothesis will be confirmed and the alternative hypothesis will be rejected, that is, there is no significant difference between the average frequencies of sultry days obtained from different indices of sultriness in the southern Iran and if there is any difference, it is due to a sampling error. But, if this ratio is significantly greater than 1, the null hypothesis will be confirmed and the alternative hypothesis will be rejected, that is, among the average frequencies of sultry days obtained from different indices, there is difference between the means of at least two groups. All statistical details of this method are available in the references of Freedman (2005) and Gelman (2005, 2008).

Scheffé's test After the results of F test in the variance analysis showed the significant difference between the means, one question is asked: among all indices, the averages of which indices differ from one another? To answer this question, the Scheffé's test is used. The steps of this analysis are as follows:

First, using Eq. (10), the standard error of the difference between the two compared averages is computed:

$$SE_{Mi-Mj} = \sqrt{S_W^2\left(\frac{1}{n_i}+\frac{1}{n_j}\right)} \quad (10)$$

where SE_{Mi-Mj} is the standard error of the difference between the two averages i and j, which are supposed to be compared with each other. S_W^2 is the variance within the groups, or the error variance, and n_i and n_j are the number of subjects in the groups i and j.

Then, the value of S is also calculated using Eq. (11):

$$S = \sqrt{(k-1)F_{0.05}(k-1,m)} \quad (11)$$

where k is the number of groups and $F_{0.05}$ is the calculated F-value in the variance analysis table for the degrees of freedom S_B^2 (i.e., *k-1*) and S_W^2 (i.e., $m = N\text{-}k$).

In following, the values obtained from Eqs. (10) and (11) are multiplied by each other:

$$S \times SE_{Mi-Mj} \quad (12)$$

Finally, the difference between the averages of the compared groups is compared with the value obtained from Eq. (12). If the difference between the averages is equal to or greater than this value, the null hypothesis, i.e., there is no difference between the averages, will be rejected; the alternative hypothesis, i.e., there is a difference between the averages, will be accepted (Freedman 2005; Gelman 2005, 2008).

3.7 Qualitative assessment of indices of sultriness

To judge the overall usefulness of the indices, a set of six weighted qualitative criteria was used for decision-making. Each evaluated criterion was considered based on a 5-point scale: 1 the lowest score and 5 the highest score. These criteria were including robustness, tractability, transparency, sophistication, extendability, and dimensionality. This list can certainly be extended or decreased, but it is believed that these six criteria provide a logical and reasonable framework for evaluating the indices of sultriness. In the following, the reason for the use of each criterion is explained in details (Redmond 1991).

Robustness A robustness criterion refers to the ability of an index to measure sultry conditions in a wide range of different climatic conditions. This criterion emphasizes on the ability to compare the indices of sultriness in terms of different spatial-temporal aspects. In other words, the desired index of sultriness should not be easily influenced by different seasonal changes (for example, the values of the two seasons of summer and winter should be comparable). Although robustness is very important, this criterion cannot assign all the positive aspects of an index to itself, especially when it cannot be easily calculated from existing data.

Tractability The tractability criterion takes into account the practical aspect of the index of sultry. For example, a complex index may require high-level numerical computations, or its calculation steps may be difficult and time-consuming. Additionally, a complex index can require the data that are scattered and rarely observed or may require a large historical database for its calculations.

Transparency The transparency criterion takes into account the clarity of the purpose and the rationale behind each index of sultriness. This criterion is also an important criterion because an applicable index can be understood not only by the scientific community, but also by the public affected.

Table 5 Weights assigned to sultry index evaluation criteria (Redmond 1991)

Criterion	Weight	Relative importance
Robustness	8	28%
Tractability	6	21%
Transparency	5	17%
Sophistication	5	17%
Extendibility	3	10%
Dimensionality	2	7%
Score for each criterion	1–5	
Max weighted score possible	145	

Fig. 2 The annual changes of the time series data for the number of the days with sultry conditions (1995–2009) in the studied stations from the southern half of Iran

Sophistication Sophistication is somewhat contradictory to transparency, but because of having the perceived values of a method, it is considered a criterion. A sultriness measurement technique may not be very clear, but it can have sophistication and ability to measure properly. For example, Einstein's theory of relativity is neither clear nor tractable, but it certainly provides a wide view contributing to understanding the laws of physics. Also, the sophistication level of an index of sultriness should be supported by the quality of available data and the accuracy of assessment method.

Extendability Extendability can be considered an aspect of tractability. But, here, it is separated from tractability for some reason. Extendability reflects the ability of the index to regenerate itself over time, that is, as the knowledge is developed and measurement tools are modified, the indices have an ability to change the thresholds of sultriness and provide the new definitions of different classes of sultriness by themselves.

Dimensionality Perhaps, dimensionality may be considered a part of transparency, but here, it is separated from transparency, because it can easily be distinguished from transparency. This criterion generally refers to the relationship between the index and the physical world. It can be more useful when the index is comprised of fundamental units (L, M, or T) or at least a proportion of physical units. Here, the simpler units are more desirable. In general, the dimensionality criterion exactly considers the index not the behavior of its dimensional data.

Determining the exact weights of the criteria, which reflect the relative importance of them, is difficult because determination of these weights will be influenced by the specialized experiences and personal judgment of individuals. Of course, it should not be forgotten that readers are completely free to change the weights according to their desired conditions. As detailed in Table 5, we consider robustness as the most important criterion in distinguishing sultry conditions from non-sultry ones, followed by

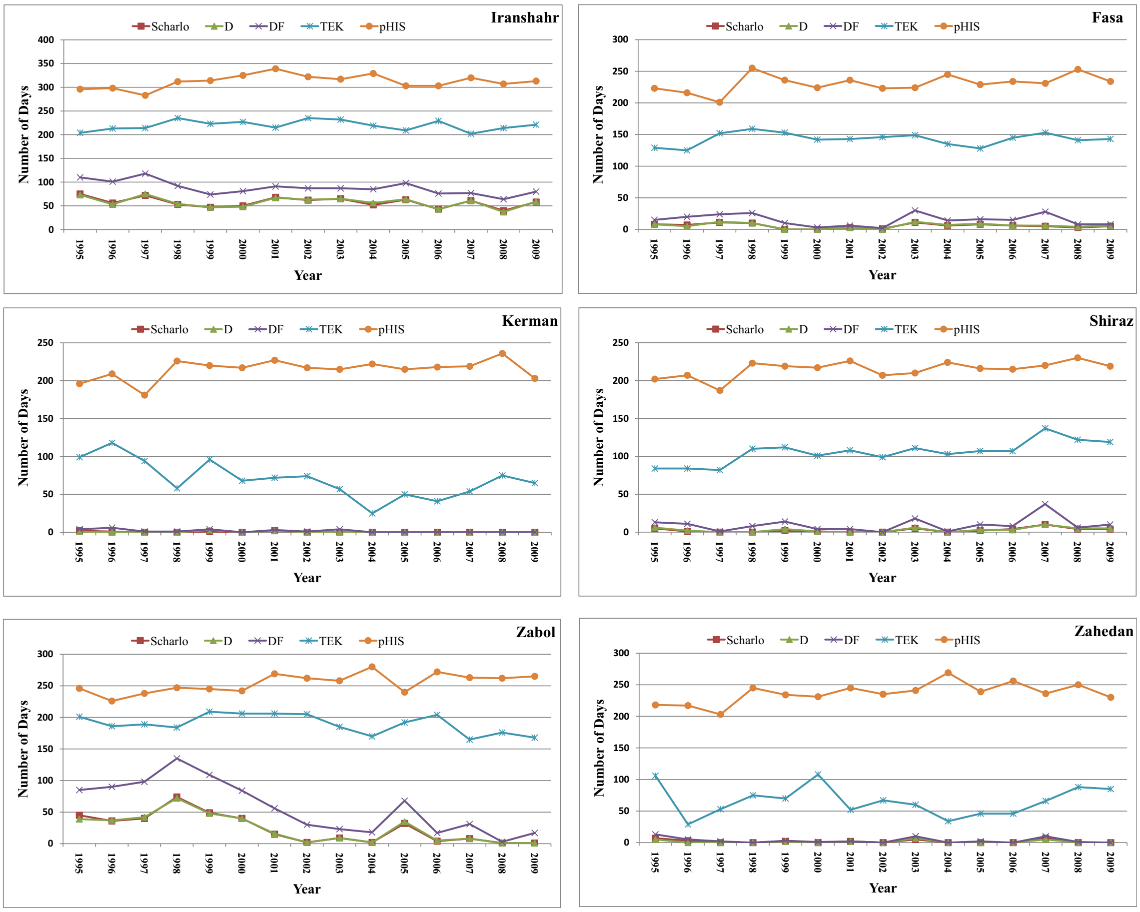

Fig. 2 (Continued)

tractability, transparency, and sophistication. In Sections 4 and 5, the selected indices of sultriness and the relationships between their inherent properties and the evaluation criteria are discussed.

4 Results and discussion

4.1 Quantitative comparison of average sultry days by different estimating indices of estimating sultry days

The actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion), equivalent temperature more than 56 °C, physiological deficit less than 45 hPa, the approximated heat stress index, and the sultry severity index (Castens-Lancaster) were calculated on an hourly time scale for all the studied stations separately. Then, the time series of sultry day's number at three time scales of monthly, quarterly, and annual were provided for each station. In here for brevity, graphs related to the changes in sultry day's number are given in annual scale. According to Fig. 2, it is shown that two indices, the actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion) and the sultry severity index (Castens-Lancaster), indicate the most agreement on showing the sultry day state. Physiological deficit index had only some coordination with the sultry severity index (Castens-Lancaster) in half of the stations. The least coordination is related to the approximated heat stress index and then the equivalent temperature index which both showed different behaviors in estimating sultry days. The results of changes in the number of sultry days in two monthly and quarterly scales were similar to annual scale.

Pearson's correlation coefficient was obtained for all stations in the study for the entire period of time scales, monthly, quarterly, and yearly, respectively. The results of correlation coefficient obtained in annual scale showed that the actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion) and the sultry severity index (Castens-Lancaster) and physiologic deficit indices had the most correlation coefficient with each other. About the actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion) and the sultry severity index (Castens-Lancaster), it has to be noted that as we get closer to coastal stations of Persian Gulf and Oman Sea,

Table 6 Correlation coefficient matrix between the numbers of the days with sultry conditions pertaining to the selected five indices for the studied stations in the southern half of Iran in an annual scale (1995–2009)

Abadan

	Scharlo	D	DF	TEK	pHSI
Scharlo	1	.991**	-.366	.659**	.669**
D	.991**	1	-.330	.633*	.607*
DF	-.366	-.330	1	-.342	-.251
TEK	.659**	.633*	-.342	1	.347
pHSI	.669**	.607*	-.251	.347	1

Ahwaz

	Scharlo	D	DF	TEK	pHSI
Scharlo	1	.991**	.823**	.684**	.370
D	.991**	1	.782**	.701**	.343
DF	.823**	.782**	1	.600*	.119
TEK	.684**	.701**	.600*	1	.261
pHSI	.370	.343	.119	.261	1

Bam

	Scharlo	D	DF	TEK	pHSI
Scharlo	1	.939**	.823**	.480	.190
D	.939**	1	.821**	.622*	.352
DF	.823**	.821**	1	.707**	.237
TEK	.480	.622*	.707**	1	.465
pHSI	.190	.352	.237	.465	1

Bandar Abbas

	Scharlo	D	DF	TEK	pHSI
Scharlo	1	.978**	.398	.475	.299
D	.978**	1	.439	.469	.359
DF	.398	.439	1	.604*	.383
TEK	.475	.469	.604*	1	.667**
pHSI	.299	.359	.383	.667**	1

Bushehr

	Scharlo	D	DF	TEK	pHSI
Scharlo	1	.928**	.766**	.402	.430
D	.928**	1	.781**	.452	.256
DF	.766**	.781**	1	.779**	.425
TEK	.402	.452	.779**	1	.433
pHSI	.430	.256	.425	.433	1

Chabahar

	Scharlo	D	DF	TEK	pHSI
Scharlo	1	.499	.790**	.527*	.177
D	.499	1	.438	.503	.927**
DF	.790**	.438	1	.464	.200
TEK	.527*	.503	.464	1	.360
pHSI	.177	.927**	.200	.360	1

Fassa

	Scharlo	D	DF	TEK	pHSI
Scharlo	1	.977**	.817**	-.021	-.219
D	.977**	1	.804**	.041	-.153
DF	.817**	.804**	1	.251	-.148
TEK	-.021	.041	.251	1	.189
pHSI	-.219	-.153	-.148	.189	1

Iranshahr

	Scharlo	D	DF	TEK	pHSI
Scharlo	1	.983**	.792**	-3.56	-.160
D	.983**	1	.790**	-.301	-.143
DF	.792**	.790**	1	-.272	-.514*
TEK	-3.56	-.301	-.272	1	.277
pHSI	-.160	-.143	-.514*	.277	1

Kerman

	Scharlo	D	DF	TEK	pHSI
Scharlo	1	.703**	.688**	.548*	-.097
D	.703**	1	.480	.363	.127
DF	.688**	.480	1	.700**	-.186
TEK	.548*	.363	.700**	1	-.423
pHSI	-.097	.127	-.186	-.423	1

Shiraz

	Scharlo	D	DF	TEK	pHSI
Scharlo	1	.969**	.874**	.582*	.111
D	.969**	1	.876**	.554*	.112
DF	.874**	.876**	1	.560*	.115
TEK	.582*	.554*	.560*	1	.730**
pHSI	.111	.112	.115	.730**	1

Zabol

	Scharlo	D	DF	TEK	pHSI
Scharlo	1	.996**	.975**	.332	-.737**
D	.996**	1	.979**	.332	-.755**
DF	.975**	.979**	1	.389	-.759**
TEK	.332	.332	.389	1	-.257
pHSI	-.737**	-.755**	-.759**	-.257	1

Zahedan

	Scharlo	D	DF	TEK	pHSI
Scharlo	1	.892**	.967**	.147	-.269
D	.892**	1	.895**	.185	-.100
DF	.967**	.895**	1	.192	-.356
TEK	.147	.185	.192	1	-.222
pHSI	-.269	-.100	-.356	-.222	1

correlation of both of them increases. The approximated heat stress index and the equivalent temperature index had the lowest correlation among the indices such that for the approximated heat stress index, there is no correlation in stations except for Bushehr station, even though these results are observed for monthly, quarterly, and annual scales (Table 6).

The variance analysis of the average number of sultry days obtained from the five studied indices is the next stage of quantitative analysis. The final results of this analysis are presented in the tables, as shown in Table 7, for the annual time scale. In these tables, the first column includes the source of the index changes, the second column includes the sum of squares of indices, the third column shows the degree of freedom between the groups (*k-1*) and the degree of freedom within the groups (*N-K*), and the fourth column also refers to the average sum of squares or variances, which is obtained by dividing the sum of squares by their degrees of freedom. The last two columns refer the *F*-value and the significance level, respectively. The results of variance analysis of the average number of sultry days obtained from the five indices studied at the monthly, seasonal, and annual scales were the same. Analysis of variance of average sultry day's number from five studied indices in monthly, quarterly, and annual scales had the same results. In annual scale in all stations, at $\alpha = 0.01$, there was a significant difference between average number of indices. The results showed that as the time scale of indices increases, these differences are more significant (Table 7). But in variance analysis, there difference between indices is not shown, meaning this analysis does not indicate that which index has a significant difference with other indices. Therefore, in order to fulfill this ambiguity, Scheffé's analysis was used.

Table 7 Variance analysis results of the mean number of the days with sultry conditions pertaining to the selected five sultry indices for the studied stations from the southern half of Iran in an annual scale (1995–2009)

Abadan

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	502880.19	4	125720	46.672	0.01
Within Groups	188557.2	70	2693.674		
Total	691437.39	74			

Ahwaz

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	571340.35	4	142835.1	388.61	0.01
Within Groups	25728.933	70	367.556		
Total	597069.28	74			

Bam

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	803309.41	4	200827.4	1427.5	0.01
Within Groups	9847.733	70	140.682		
Total	813157.15	74			

Bandar Abbas

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	24744.613	4	6186.153	69.005	0.01
Within Groups	6275.333	70	89.648		
Total	31019.947	74			

Bushehr

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	27010.667	4	6752.667	26.751	0.01
Within Groups	17670	70	252.429		
Total	44680.667	74			

Chabahar

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	17493.68	4	4373.42	7.892	0.01
Within Groups	38790.8	70	554.154		
Total	56284.48	74			

Fassa

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	629837.79	4	157859.4	1957.1	0.01
Within Groups	5632	70	80.457		
Total	635469.79	74			

Iranshahr

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	778986.72	4	194746.7	1310.3	0.01
Within Groups	10404.267	70	148.632		
Total	789390.99	74			

Kerman

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	517762.88	4	129440.7	831.98	0.01
Within Groups	10890.667	70	155.581		
Total	52865.547	74			

Shiraz

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	523260.99	4	130815.2	1485	0.01
Within Groups	6166.4	70	88.091		
Total	529427.39	74			

Zabol

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	671768.67	4	167942.2	267.73	0.01
Within Groups	43910	70	627.286		
Total	715678.67	74			

Zahedan

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	618784.27	4	15469.07	899.07	0.01
Within Groups	12044.4	70	172.063		
Total	630828.67	74			

In Table 8, the results of Scheffé's analysis of the average number of sultriness index are shown in annual scale. According to the results of the annual scale, there is no significant difference between the actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion) and the sultry severity index (Castens-Lancaster) at $\alpha = 0.01$. Results of the actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion) and physiological deficit index showed that the difference between average sultry day's numbers of these two indices is only significant in half of the stations and the differences were not significant in the other half. The results related to the equivalent temperature index imply this fact that there is a significant difference between the average number of Scharlau criterion and equivalent temperature index. This result is repeated for the approximated heat stress index with this exception that two Scharlau indices and the approximated heat stress index do not reject hypothesis 0 for Bushehr and Chabahar stations (Table 5). Also, the approximated heat stress index and the equivalent temperature index have a significant difference with Scharlau index in monthly and quarterly scales for most stations and in annual scale for all stations.

4.2 Quality evaluation of sultriness indices

The qualitative evaluation of the indices of sultriness based on the six selected criteria was the second stage of analysis. These evaluations can vary from researcher to researcher, because they are essentially based on the opinion of the researchers. In any case, it was tried to make accurate judgments in this regard (Table 9). Therefore, firstly, the strengths and weaknesses of different indices of sultriness and how to assign scores to each index were studied. The five raw points, each ranged

Table 8 Scheffé's analysis results for the mean number of the days with the sultry conditions pertaining to the selected five sultry indices for the studied stations from the southern half of Iran in an annual scale (1995–2009)

Abadan

Index		Mean difference	Sig
Scharlo	D	-1.86667	1.000
	DF	-52.86667	.112
	TEK	-161.13333*	.000
	pHSI	-197.20000*	.000

Ahwaz

Index		Mean difference	Sig
Scharlo	D	.06667	1.000
	DF	-57.00000*	.000
	TEK	-170.33333*	.000
	pHSI	-209.86667*	.000

Bam

Index		Mean difference	Sig
Scharlo	D	.60000	1.000
	DF	-8.46667	.438
	TEK	-142.40000*	.000
	pHSI	-257.93333*	.000

Bandar Abbas

Index		Mean difference	Sig
Scharlo	D	-2.93333	.948
	DF	-31.66667*	.000
	TEK	-32.93333*	.000
	pHSI	-46.33333*	.000

Bushehr

Index		Mean difference	Sig
Scharlo	D	-4.46667	.963
	DF	-51.53333*	.000
	TEK	-30.60000*	.000
	pHSI	-12.73333	.317

Chabahar

Index		Mean difference	Sig
Scharlo	D	13.60000	.646
	DF	-17.53333	.393
	TEK	-30.40000*	.020
	pHSI	-1.13333	1.000

Fassa

Index		Mean difference	Sig
Scharlo	D	-.26667	1.000
	DF	-9.40000	.095
	TEK	-137.26667*	.000
	pHSI	-225.33333*	.000

Iranshahr

Index		Mean difference	Sig
Scharlo	D	0.00000	1.000
	DF	-30.40000*	.000
	TEK	-161.80000*	.000
	pHSI	-254.40000*	.000

Kerman

Index		Mean difference	Sig
Scharlo	D	0.00000	1.000
	DF	-1.20000	.999
	TEK	-69.33333*	.000
	pHSI	-214.33333*	.000

Shiraz

Index		Mean difference	Sig
Scharlo	D	-.46667	1.000
	DF	-7.13333	.372
	TEK	-103.20000*	.000
	pHSI	-212.26667*	.000

Zabol

Index		Mean difference	Sig
Scharlo	D	.06667	1.000
	DF	-33.73333*	.013
	TEK	-165.86667*	.000
	pHSI	-230.46667*	.000

Zahedan

Index		Mean difference	Sig
Scharlo	D	.33333	1.000
	DF	-1.53333	.999
	TEK	-63.93333*	.000
	pHSI	-234.86667*	.000

from 1 to 5, were multiplied by the related weights (Table 3), and sum of the weighted scores are listed in an ascending order in Table 4. As shown in Table 4, the results of using selected weighted criteria showed that the two indices of the actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion) and the Lancaster-Castens sultry severity index are superior to other indices.

Table 9 Comparison of sultry indices across evaluation criteria

Index	Weighted total	Raw scores (1–5)					
		Robustness	Tractability	Transparency	Sophistication	Extendibility	Dimensionality
The actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion)	140	5	5	4	5	5	5
The sultry severity index (Castens-Lancaster)	135	5	4	5	5	5	3
Physiological deficit index (less than 45 hPa)	81	1	4	3	3	3	5
Equivalent temperature index (more than 56 °C)	75	1	3	2	4	3	5
The approximated heat stress index (pHSI more than 30%)	69	1	1	2	4	5	5

5 Conclusions

In this study, in order to compare the estimating indicators of sultry conditions in the southern half of Iran, the actual vapor pressure more than or equal to 18.8 hPa (Scharlau criterion), equivalent temperature more than 56 °C, physiological deficit less than 45 hPa, the approximated heat stress index more than 30%, and the sultry severity index (Castens-Lancaster) were used. Qualitative and quantitative evaluation of estimating indicators of sultry conditions in southern half of Iran included some results.

The first results of this study which is one of the answers to main questions of this paper is that various estimating indicators of sultry condition do not present similar results in terms of separating sultry from non-sultry conditions. Comparison of quantitative and qualitative indices show that among the studied indices, the approximated heat stress index is not a reliable for estimating sultry phenomenon among sample stations, because it does not indicate the behavior and comparable thresholds among other indicators. Equivalent temperature index has a lot of uncertainty due to the fluctuations in expressing sultry state. However, physiological deficit index has reasonable and acceptable procedure in some stations, but in some cases, it has completely different results. Since index inalterability is one of the important benchmarks in choosing appropriate index, all the considerations do not cover an index and this is a good reason that this index does not fit for estimating sultry phenomenon. Among the studied indices, only two indices of Scharlau and Castens-Lancaster have higher coordination than other indices in showing sultry state, start time, severity, and its continuity. Despite these two indices were more homogeneous and realistic among other indices, an index is considered more appropriate which has a different capability than the other index. Scharlau criterion has a different capability than Castens-Lancaster in order to identify the state of sultry. It is emphasized that indices with complicated executive functions relative to indices without functions do not have different results. Scharlau criterion is clarified because it has the component of transparency, and this feature differentiates this index from Castens-Lancaster. To sum up, among the proposed sultry indices in this research, Scharlau criterion is considered the most suitable index in separating sultry from non-sultry days according to the information resources and qualitative and quantitative evaluations.

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