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An aridity index defined by precipitation and specific humidity

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SUMMARY

The United Nations Environmental Programme (UNEP), defined an aridity index (*AI*) by the ratio of the annual precipitation and potential evapotranspiration (PET) totals. In this work, specific humidity was used instead of PET and a new aridity index (I_q) has been defined using the ratio of annual precipitation totals and annual mean specific humidity (S_h). As shown in this study, S_h can be easily computed with very high accuracy (3.569% error rate) with mean temperature, relative humidity and local pressure which are most commonly and widely measured meteorological data. The single point correlation graph of S_h which shows the entrance of aridity through the South Eastern Anatolia Region into Turkey and the distribution of the aridity over Turkey explains the relationship with S_h and aridity. According to the common and different aspects of arid zones found with *AI*, I_q and Erinç aridity index (I_m), I_q found to be applicable for monitoring climate change and distribution of arid zones.

1. Introduction

Various climatological or meteorological indexes are used for characterizing and determining aridity which is a complex process. All these indexes have distinctive characteristics and have advantages against each other. Determination of aridity requires selection of proper aridity index or aridity definition methods. A proper index must be calculated with data provided from meteorological, hydrological or agricultural observations or measurement systems. Besides, a proper index must monitor, predict or determine aridity with minimum information loss. Using several aridity indexes gives an opportunity to characterize the aridity, compare and support the results.

Potential evapotranspiration (PET) is a vital part of the hydrological cycle and it has been used in dry and wet condition analysis of climate such as drought and aridity. PET is the rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation which has access to an unlimited supply of soil water, and without advection or heat storage effects. The concept was introduced as part of a scheme for climate classification by Thornthwaite (1948), who intended it to depend essentially on climate and to be largely independent of surface characteristics.

The United Nations Environmental Programme (UNEP, 1993), defined an aridity index (*AI*) by the ratio of the annual precipitation and PET totals. Due to lack of the measured PET data and difficulties of accurate estimation of PET or various input requirements of empirical or semi-empirical equations to estimate PET, the *AI* defined by UNEP has not been widely used especially in developing countries. Monitoring evaporation is a great challenge since specific and costly equipments are required. Unfortunately measurements of evapotranspiration are scarce and expensive. Real measurements of vapor fluxes require specialized instruments such as lysimeters (López-Urrea et al., 2006), Bowen ratio equipments (Jara et al., 1998) or specific instrumentation to calculate instantaneous fluxes of momentum and vapor to apply methods such as “Eddy covariance” (Rana et al., 2005). In such circumstances, simple empirical equations are often used despite of its non-universal suitability. As an alternative, agronomists and engineers use semi-empirical equations such as the Penman–Monteith Formula (PM) to estimate potential evapotranspiration based on surface weather observations which require numerous items of weather data. Application of PM in many areas particularly in developing countries has been limited by the unavailability of the enormous climatic data required, in many areas, the necessary data are lacking, and simpler techniques are required. Calculation of PET from the PM equation requires eight predictors that are not always available in developing countries. Unfortunately in Turkey weather stations are scarce and do not always have the instrumentation to measure relevant variables for the calculation of PET.

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In practice, PET is defined by the method used to calculate it, and many methods have been preferred. These methods can be classified on the basis of data requirements (Jensen et al., 1990).

1.1. Temperature-based methods

There are some efforts to estimate PET with minimal data requirements in the literature. PET estimation methods that require only temperature as input variable are considered as temperature-based methods. The relation of ET to air temperature dates back to the 1920s (see Jensen et al., 1990). Most temperature-based equations take the form

$$ET = c_1 d_1 T(c_2 - c_3 h) \tag{1}$$

in which ET is evaporation or potential evapotranspiration, T is air temperature, h is a humidity term, c_1, c_2, c_3 are constants, d_l is day length (Xu and Singh, 2001). It is generally accepted that empirical formulae may be reliable in the areas and over the periods for which they were developed, but large errors can be expected when they are extrapolated to other climatic areas without recalibrating the constants involved in the formulae (Hounam, 1971). Singh and Xu (1997) reported in their study that when an equation with parameters obtained at one site was applied to compute evaporation at another site, the computed evaporation was not in good agreement with observed values. Therefore, the reliability of computing PET data with temperature based methods must be investigated.

Thornthwaite (1948) developed a complex empirical formula for calculating PET as a function climatic average monthly temperature and day length which is the most well known T_a-based model:

$$\mathrm{PET} = C\left(\frac{10T_a}{I}\right)^a \left(\frac{d}{12}\right)\left(\frac{N}{30}\right) \tag{2}$$

where C is 1.6, I is the yearly sum of $(T_a/5)^{1.514}$ for each month, d is the average number of daylight hours per day for each month, N is the number of days in the month, and the superscript a is $(6.75 \times 10^{-7} I^3) - (7.711 \times 10^{-7} I^2) + 0.01792I + 0.49239$. This equation was based primarily on data from the USA, and has since been modified and extended for various applications (e.g. Willmott et al., 1985). T_a-based models may be inaccurate or wrong altogether; however, depending on where they are applied (Fisher et al., 2009). Thornthwaite suggested his method could be replaced by a more physically based method when the theory and suitable data become available (Thornthwaite, 1948).

Xu and Singh (2001) reviewed seven most widely temperature based PET models (Thornthwaite, 1948; Blaney and Criddle, 1950; Hamon, 1961; Romanenko, 1961; Hargreaves, 1975; Linacre, 1977; Kharrufa, 1985), all of which include some empirical calibration. According to their study the seasonal bias (i.e. higher intercepts and non-unit values of slopes) is a problem for the Linacre, Kharrufa and Hamon methods. All seven methods can calculate well the mean seasonal evaporation with locally determined parameter values. As far as monthly evaporation estimates are concerned the Linacre, Kharrufa and Hamon methods are not recommended for evaporation estimation in their study region.

1.2. Radiation-based methods

Slatyer and Mcllroy (1961) reasoned that air moving large distances over a homogeneous well-watered surface would become saturated, so that the mass transfer term in Penman Equation would disappear. They defined the evapotranspiration under these conditions as the equilibrium potential evapotranspiration, $\mathrm{PET_{eq}}$. Subsequently, Priestley and Taylor (1972) compared $\mathrm{PET_{eq}}$ with values determined by energy-balance methods over well-watered surfaces and found a close fit if $\mathrm{PET_{eq}}$ was multiplied by a factor α_{PT} to give

$$\mathrm{PET_{PT}} = \frac{\alpha_{\mathrm{PT}} \cdot \Delta \cdot (K + L)}{\rho_u \cdot \lambda_v \cdot (\Delta + \gamma)} \tag{3}$$

A number of field studies of evapotranspiration in humid regions have found $\alpha_{\mathrm{PT}} = 1.26$, and according to theoretical examinations that value in fact represents equilibrium evapotranspiration over well-watered surfaces under a wide range of conditions (Eichinger et al., 1996). Eq. (3) gives an estimate of PET that depends only on net radiation and air temperature. This relationship has proven useful in hydrologic analyses.

1.3. Combination models

The most widely-used PET models fall within a class that combines energetic drivers such as R_n and T_a with atmospheric drivers such as vapor pressure deficit (VPD) and surface wind speed (u) – based on an equation developed by Penman (1948):

$$\mathrm{PET} = \alpha \frac{\Delta}{\Delta + \gamma} R_n + 2.6 \frac{\Delta}{\Delta + \gamma} VPD \gamma \lambda \rho (1 + 0.54u) \tag{4}$$

where D and g are as defined for the Priestley–Taylor model, l is the latent heat of vaporization (c. 2448 MJ $\mathrm{Mg^{-1}}$, depending on T_a) and r is air density (c. 1.234 kg $\mathrm{m^{-3}}$, depending on Ta and pressure). VPD is equal to the amount of moisture the air can hold minus how much moisture is actually in the air; it is a function of relative humidity and T_a (and surface temperature, if available). The first part of the equation, equilibrium evaporation, is the same as the Priestley and Taylor (1972) radiation-based equation, but instead of multiplying it by an empirical coefficient (a), the equation extends to include the atmospheric components of VPD and u. The Penman equation was originally designed to eliminate the need for surface temperature data and to be parameterized with standard meteorological data; Penman tested the equation against open water, bare soil and turf. The equation is particularly sensitive to u and has no explicit vegetation component (Allen et al., 1998; Fisher et al., 2005). The Penman model is for PET only.

1.4. Pan-based methods

The potential evapotranspiration for short vegetation is commonly very similar to free-water evapotranspiration (Linsley et al., 1982; Brutsaert, 1982). This may be because lower canopy conductance over the vegetation fortuitously compensates for the lower atmospheric conductance over the pan (Dingman, 2002). In any case, annual values of pan evaporation are essentially equal to annual PET, and pan evaporation via Eqs. (2) and (3) can be used o estimate PET for shorter periods.

$$E_{fw} = 0.7[E_{pan} \pm 0.064 \cdot \alpha_{pan} \cdot (0.37 + 0.00255 \cdot v_{pan}) \cdot |T_{span} - T_a|^{0.88}] \tag{5}$$

In this equation, E_{fw} and E_{pan} are daily free-water and pan evaporation, respectively, in mm $\mathrm{day^{-1}}$, P is atmospheric pressure in kPa, v_{pan} is the average wind speed at a hight of 15 cm above the pan in km $\mathrm{day^{-1}}$. T_{span} is the water-surface temperature in the pan, temperatures are in °C, and the operation following E_{pan} is + - when $T_{span} > T_a$ and – when $T_{span} < T_a$. The factor α_{pan} is the proportion of energy exchanged through the sides of the pan that is used for, or lost from, evaporation; it can be estimated as

$$\alpha_{pan} = 0.34 + 0.0117 \cdot T_{span} - (3.5 \times 10^{-7}) \cdot (T_{span} + 17.8)^3 + 0.0135 \cdot v_{pan}^{0.36} \tag{6}$$

using the same unit in Eq. (6) (Linsley et al., 1982).

Jensen et al. (1990) compared PET models computed by 19 different approaches with measured reference-crop evapotranspiration in weighing lysimeters at 11 calculations covering a range of latitudes and elevations. The Penman–Monteith method gave the best overall results. Equilibrium evapotranspiration (Eq. (2) with α_{pt} = 1.26) gave reasonable agreement up to rates 4 mm day^{-1} but considerable underestimation at higher rates. Monthly Class-A pan evaporation correlated well with measured PET, but with considerable scatter presumably due to variability of heat exchange through the pan walls.

There are many other methods or models available to estimate PET, but these methods or models give inconsistent values due to their different assumptions and input data requirements, or because they were often developed for specific climatic regions (Grismer et al., 2002). The various equations of potential evapotranspiration show great differences in magnitude. But due to the limited availability of validation data, it is difficult to assess which method is the physically most reasonable to be applied. Consequently, it is very hard to apply *AI* accurately in global scale. The only study in the international literature that investigates the distribution of *AI* values throughout Turkey (Türkeş, 1999) was able to use 94 stations.

S_h is the concentration of water vapor expressed as the mass of water vapor per unit mass of air. S_h shows the amount of the atmospheric moisture for influencing surface conditions and S_h may explain the basic effect of temperature on soil moisture. There is a close relationship between moisture availability at the surface (soil moisture) and in the atmosphere (specific humidity) which are moisture-balance components. S_h can be easily calculated with mean temperature, relative humidity and local pressure which are most commonly and widely measured meteorological data. In this work, S_h values were calculated for 211 stations in Turkey.

In this work an aridity index (I_q) was defined by the ratio of annual precipitation totals and annual mean S_h. First, to investigate the relationship with aridity and S_h, single-point correlation graph of S_h was drawn. Single-point correlation graph of S_h has been showed the entrance of aridity through the South Eastern Anatolia Region into Turkey and the distribution of the aridity over Turkey. The I_q index was divided into six major classes by comparing the results of the index with the spatial distribution of vegetation formations over Turkey as Erinç (1965). Romanenko (1961) model were applied for 211 stations in Turkey and the results were compared with Türkeş (1999). Then, the aridity index maps were prepared according to I_q, Erinç aridity index (I_m) and the distribution of aridity throughout Turkey was investigated and the results were compared spatially and temporally.

2. Data and methodology

The data used in this study has been provided by the State Meteorological Service of Turkey and it consists of the monthly total precipitation (P_t), the monthly mean temperature (T_m), the monthly relative humidity (R_h), and the monthly local pressure (P_s) covering the time period between 1974 and 2008. First, the number of 220 stations that have records of pressure (P_s) was decreased to 211 due to high number of missing values. Distributions of these values were grouped in continuous months which affect missing value estimation. For example, the expectation maximization (EM) algorithm and the methods that will be derived from it in subsequent sections are only applicable to datasets in which the missing values are missing at random not grouped. The records of P_t, T_m and R_h were available in 232 stations for the period 1974–2008. However, the stations that have P_s records have limited the number of stations used in this study.

Table 1 shows the basic statistics of seasonal averages of monthly data recorded at 211 stations. Missing values percentages change between 1.087% and 4.662%. Because the set of Turkish meteorological data was incomplete, the monthly missing values were estimated for the further analysis. The missing data analysis

Table 1
Basic statistics of seasonal data and total number of missing values recorded between 1974 and 2008.

		Winter	Spring	Summer	Autumn
Mean temperature (°C)		−15.167	−0.067	10.900	3.400
	Maximum	14.333	21.567	35.100	23.600
	Arithmetic mean	3.090	11.531	22.943	14.222
	Standard deviation	5.385	3.549	3.414	3.750
	Skewness	−0.450	−0.153	0.137	0.095
	N. of. miss. val.	1033	853	840	865
	Miss. val. percent. %	4.662	3.850	3.791	3.904
Local pressure (HPa)	Minimum	810.067	806.400	807.267	809.733
	Maximum	1025.033	1018.633	1016.133	1020.467
	Arithmetic mean	945.097	942.007	939.796	944.669
	Standard deviation	64.111	63.143	61.996	62.634
	Skewness	−0.206	−0.206	−0.209	−0.205
	N. of. miss. val.	1190	1255	1163	1157
	Miss. val percent. (%)	5.371	5.664	5.249	5.222
Total precipitation (mm)	Minimum	3.633	5.267	0.000	0.000
	Maximum	459.933	273.833	345.200	414.667
	Arithmetic mean	78.822	57.559	21.256	52.796
	Standard deviation	54.736	26.982	26.986	42.908
	Skewness	1.619	1.490	3.419	2.898
	N. of. miss. val.	241	243	396	285
	Miss. val percent. (%)	1.087	1.097	1.787	1.286
Relative humidity (%)	Minimum	36.000	33.767	12.933	29.667
	Maximum	90.767	88.000	90.367	87.767
	Arithmetic mean	72.022	65.149	55.987	63.702
	Standard deviation	6.765	7.965	12.888	8.656
	Skewness	−0.726	−0.041	−0.011	−0.153
	N. of. miss. val.	866	839	861	867
	Miss. val. percent. (%)	3.909	3.787	3.886	3.913

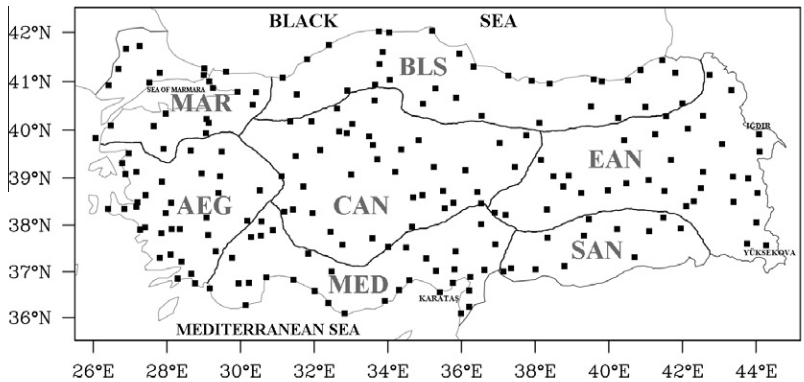

Fig. 1. Geographical regions of Turkey and distribution of 211 stations used in this study.

was performed for 4 parameters for 211 stations. The expectation maximization (EM) algorithm based on the iterated linear regression analyses was applied in this study for the missing value estimation. The EM algorithm, like all methods for incomplete data that ignore the mechanism causing the gaps in the data set, rests on the assumption that the missing values in the dataset are missing at random, in the sense that the probability that a value is missing does not depend on the missing value (Rubin, 1976). Please see Schneider (2001) for properties and details of EM algorithm.

The geographical distribution of 211 stations is shown in Fig. 1. The complete information table for these stations was omitted here due to the scarcity of space. In Turkey there have been seven geographical zones conventionally accepted by Turkish climatologists since the beginning of the 20th century (Erinç, 1984). The climate characteristics of these regions are presented below.

2.1. The Mediterranean region (MED)

Mediterranean region has weather characteristics of both polar (cold) and temperate zone and tropical (hot) zone. Rainy and cold weather conditions and sometimes storms formed by frontal middle-latitude low pressure systems prevail in winters. Winters with high precipitation rate and hot and dry summers are characteristics of MED. The spring season is generally short and mixed with winter regime. Hot, dry and calm weather conditions which are special to hot zone prevail in summers. The weather types are so diverse and variable in the autumn and especially spring seasons. In short-term air systems affected by mobile middle-latitude low pressure systems; snowy, cold and windy and then warm and sunny and later thunder stormy weather conditions may sometimes prevail within the same day. On the other hand, long-term and stable weather types are dominant in the summer season.

2.2. The Marmara region (MAR)

Marmara region is dominated by a common regional climate. However, this region has a distinctive climate due to variations in the characteristics of factors such as topography, altitude, relative position, exposure and vegetation. Due to its geographical position, Marmara region has the characteristics of a transition climate between Mediterranean and Black Sea climates. However, this region is generally under the influence of Mediterranean region. Large-scale atmospheric circulations of Atlantic origin are effective in this region in winter and autumn seasons and that the effect of local factors such as orography and topography are slight (Türkeş and Erlat, 2003). In this region, "altered Black Sea climate" prevails. Summers are hotter and winters are colder as compared to Black Sea climate. However, it is considered that this climate is similar to that of BLS region rather than the continental climate that is under the influence of Mediterranean climate that prevails in a major part of Marmara region.

2.3. The Aegean region (AEG)

Aegean region is under the influence of Mediterranean climate. Due to the mountains with vertical axis to the sea, the spreading area of the climate is expanded. Through valleys and gulleys among mountains, the effect of the sea climate can move into the inner parts. Winters are warm and rainy, whereas summers are hot and dry on the coasts and neighboring area under the influence of Mediterranean climate. The mean temperature decreases and the degree of continentality increases from the coasts towards the inner parts. In the inner parts, winters are cold and snowy whereas summers are hot and dry.

2.4. The Black Sea region (BLS)

According to various studies on precipitation in connection with precipitation climatology of Turkey, variations and variability in long-term precipitation, pressure on sea surface, high atmospheric conditions, and atmospheric oscillation indexes (Kutiel et al., 2001; Türkeş, 1996, 1998; Türkeş et al., 2002, etc.); it is found that the BLS has special precipitation characteristics such as high total precipitation rate, precipitation in all seasons, low inter-annual variation in precipitation, the formation of orographic precipitation, and being affected all the year round by synoptic weather types that bring precipitation.

Due to the effect of the adjacent sea, summers are cool whereas winters are warm. The precipitation regime of the region is regular. Maximum precipitation falls in the autumn season while minimum precipitation falls in the spring season.

2.5. The central Anatolian region (CAN)

Continental climate with hot and dry summers and cold and snowy winters prevails in the Central Anatolia region. The reason for this is that moist air masses cannot move into the inner parts due to the surrounding mountains. The mountains in the south and the north serve as barriers against moist air and prevent it from moving into the inner parts. This is the region with the lowest precipitation in Turkey. This region remains under the influence of continental polar (cP), maritime polar (mP) and maritime tropical (mT) air masses and west-directed cyclones (Erinç, 1984). Semi-arid and arid-semihumid climate conditions prevail in the inner continental parts of Anatolia. (Türkeş, 1998). In summers, Polar front and mP and cP air masses move towards the north and thus Turkey is affected by tropical air masses. Consequently, considerably dry cT air masses appear in summers.

2.6. The eastern Anatolian region (EAN)

The continental climate prevails in the Eastern Anatolia region. The factors leading to continentality include high altitudes and remoteness from the sea. Summers are hot and dry whereas winters are cold and snowy. With the effects of topographic conditions and continentality, higher and more rapid changes in temperature are observed. Mean temperature of January is below 0 °C in the entire region. The temperature may fall up to −30 °C or −40 °C in winters. All seasons are rainy and considerably high precipitation falls in the spring season or at the beginning of the summer due to delayed frontal activities. The minimum precipitation falls in winters. High altitudes and the strengthening of high pressure conditions linked to cold and stable air masses constitute an obstacle to high precipitation in the region. Therefore, frontal precipitation is not so effective in the winter season. Convective precipitation prevails in the spring and summer seasons. More precipitation falls in high mountains.

2.7. The southeastern Anatolian region (SAN)

The properties of Southeastern Anatolia region with high precipitation in winters and low precipitation in summers resemble the characteristics of Mediterranean precipitation regime. This shows that this region remains under the influence of warm and moist air masses of Mediterranean. This region is relatively drier though it receives more precipitation when compared to Central Anatolia. The reason for this is that high temperature values in the summer season cause severe condensation and that Southeastern Taurus mountains prevent polar air masses from East Anatolia to move into the inner parts. The degree of seasonality in this region decreases towards the north (Türkeş, 1998, 1999).

In this study, the names of these regions were used while evaluating the results.

Among existing PET models Romanenko (1961) model is one of the simplest for practical use, since it requires only two easily accessible parameters, mean temperature and relative humidity. Besides, Xu and Singh (2001) reported no drawback using in Romanenko (1961) model in their study area. Therefore, Romanenko (1961) model was applied in this study to see how *AI* performs with most easily accessible data. Romanenko (1961) model was defined as follows;

$$\mathrm{PET} = 0.0018(25 + T_a)^2(100 - R_h) \tag{7}$$

where T_a is the mean air temperature (in °C), R_h is the mean monthly relative humidity. Applying Romanenko (1961) model gave us the opportunity to compare the results of *AI* and I_q with the same number of stations and indicate why the I_q index can be considered instead of *AI* in Turkey.

The United Nations Environmental Programme (UNEP, 1993), defined an aridity index *AI* as:

$$AI = P/\mathrm{PET}$$

where *P* and PET are the annual precipitation and potential evapotranspiration (mm) totals, respectively. According to the UNEP, *AI* values below 1.0 show an annual moisture deficit in average climatic conditions. The following general criteria in Table 2 are used to characterize the drylands and wetlands:

Erinç's Aridity Index (precipitation efficiency) (I_m) (Erinç, 1965) is based on the precipitation and the maximum temperature that causes the water deficiency by evaporation. The basic equation of I_m is defined as follows:

$$I_m = \frac{\bar{P}}{\bar{T}_{max}}$$

where *P* and $T_{\max}$ equal the long-term average of the annual precipitation total (mm) and of annual maximum temperature (°C) respectively. It must be noted that this index is not valid for negative T_{max} values.

In this work a new aridity index has been defined as follows;

$$I_q = \frac{\bar{P}}{\bar{S}_h}$$

where *P* is long-term average of the annual precipitation total (mm) and S_h is the long-term average of the annual mean specific humidity (g/kg), respectively.

I_q index was divided into six major classes by making analogy with Erinç aridity index as in Table 3. Erinç (1965) compared the results of the index with the spatial distribution of vegetation formations over Turkey. In this work the same procedure was applied during the formation of the climate classes.

2.8. Calculation of the specific humidity data

The specific humidity data has been calculated using monthly mean temperature T_a, monthly mean relative humidity (R_h) and monthly mean local pressure (P_a) data in the formula given by Gill (1982) is as follows:

$$q_e = \frac{0.622e_a}{p_a - 0.378e_a} \tag{8}$$

where q_a is the specific humidity (kg/kg), e_a is the vapor pressure of the air (Pa) and P_a: Local pressure (Pa). Vapor pressure of the air e_a is calculated using the formula given by Gill (1982) as follows:

$$e_a = r_h 10^{[(0.7859+0.03477T_a)/(1.0+0.004212T_a)+2]} \tag{9}$$

where T_a is the monthly mean temperature (°C) and r_h is the monthly mean relative humidity (%).

S_h data has been calculated for 211 stations since the P_s data are available in 211 stations between the time period 1974 and 2002.

2.9. A comparison between the measured and the calculated vapor pressure data

As the specific humidity may easily be computed using the vapor pressure (VP) data, the data from 108 stations in Turkey have been used. Because the measurements of VP data were performed

Table 2
Climate types corresponding to the *AI* index defined by UNEP (1993).

AI	Climate type
0.05 ⩽ *P*/*PE* < 0.20	Arid
0.20 ⩽ *P*/*PE* < 0.50	Semi-arid
0.50 ⩽ *P*/*PE* < 0.65	Dry sub-humid
0.65 ⩽ *AI* < 0.80	Semi-humid
0.80 ⩽ *AI* < 1.0	Humid
1.0 ⩽ *AI* < 2.0	Very humid

Table 3
Climate types corresponding to the Erinç aridity index (*Im*) and vegetation types (from Kutiel and Türkes (2005) based on Erinç (1965).

I_m	I_q	Climate type	Vegetation type
<8	<20	Severe arid	Desert
8–15	20–35	Arid	Desert-like steppe
15–23	35–60	Semi-arid	Steppe
23–40	60–90	Semi-humid	Dry forest
40–55	90–120	Humid	Humid forest
>55	>120	Perhumid	Perhumid forest

only in 108 stations in Turkey, the number of the stations was 108 for the purpose of comparison. As data from 27 stations are not placed in an appropriate period and no measurement has been performed in some of these stations, the data from these stations have not been used for the purpose of comparison.

Considering all stations, maximum monthly VP value was measured in August 1987 at Karataş/Adana was calculated with an error margin of 1.201% using Gill equation (Gill, 1982). The minimum monthly VP value was measured in January 1989 at Yüksekova/Hakkari and calculated with an error margin of 14.97%. This error margin of 14.97% may be related to temperature and vapor pressure relationship that changes with altitude. The locations of these two stations were shown in Fig. 1. Specific humidity is highly related with temperature. The lowest and the highest monthly T_a values were generally observed in January and August in Turkey. The Karataş/Adana is located near the Mediterranean Sea shore with an altitude 22 m and the Yüksekova/Hakkari is located in inner parts of southeastern EAN region with an altitude 1877 m. Because of the temperature and local pressure conditions, highest and lowest monthly specific humidity values were calculated in these stations. Considering the period from 1970 onwards, one of the most intense and widely spread aridity events was observed in 1989 (Türkeş and Erlat, 2005). Calculated VP does not involve any data deficient as the deficient data regarding the relative humidity, the mean temperature and the station pressure applied in the course of measuring VP data have been estimated using expectation maximization (EM) method.

Table 4 shows error statistics of calculated monthly VP data compared to measured monthly VP data in percentages. The term ‘negative error’ indicates that a value lower than measured value has been figured out. The mean value of the calculated errors is −1.259 explaining that the lower values of the measured data on the basis of the data size have been figured out. The fact that the value of the maximum negative error is higher than the value of the maximum positive error can be explained with this information. The absolute value has been applied for calculating the standard deviation and the mean of the absolute values of the errors computed in the percentages. Considering the calculated errors according to the mean of absolute values, Gill formula (Gill, 1982) has yielded results with an error ratio of 3.569% while calculating VP data regarding meteorology stations in Turkey. This figure is considerably low.

Table 5 shows that the distribution of errors regarding the calculated VP data compared to measured data in percentages. Negative percentages indicate that a lower VP value than the measured value has been figured out. 20,165 out of 26,868 data are located within the scope of ±5%. There exists 5667 monthly VP data calculated between ±5% and ±10%. There exists only 51 VP data calculated as higher than ±20% (lower for negative values). Based on the previously obtained results, it is concluded that Gill formula (Gill, 1982) performs high accuracy calculation of VP data measured in Turkey. As shown in Table 3, the percentage of the absolute error has been calculated as 3.569%.

Considering the distribution of the inaccurate calculations performed in percentages, and based on the statistical comparisons in general, it has been concluded that there is no drawback in using the computed S_h in the hydrometeorologic and the climatologic studies. Because the S_h values were computed with measured data, high accuracy could be expected regarding the measured S_h data to computed S_h data. Standard deviation of the error rates (4.529%) and the percentage of the absolute error (3.569%) and the other statistics in Table 4 and Table 5 supports that the Gill formula (Gill, 1982) computes S_h accurately.

Table 4
Error statistics of calculated VP data compared to measured data (%).

	%
Minimum error	0.00015
Maximum negative error	−35.013
Maximum positive error	29.751
Arithmetic mean	−1.259
Standard deviation	4.529
Arithmetic mean (absolute value)	3.569
Standard deviation (absolute value)	3.060

Table 5
Number of errors regarding the calculated VP data compared to measured data (%).

Error rate	Calculated number of *VP* data
<−20%	5
Between −20% and −10%	545
Between −10% and −5%	4357
Between −5% and 0%	12,075
Between 0% and 5%	8090
Between 5%and 10%	1310
Between 10% and 20%	440
>20%	46

3. Results

Fig. 2 shows the contour map of S_h correlations of Iğdır station with all stations. S_h shows high correlations with the stations close to Iğdır station as expected and the rate of correlation constantly declines towards the SAN, which is a hot region. The single point correlation graph of S_h data clearly shows the entrance of aridity through Syrian border and the progress of aridity into the inner regions of Anatolia.

The Iğdır station was selected to make one-point correlation map because it is located easternmost part of the Turkey and the distribution of correlations according to Iğdır station were smoother than the other stations. Choosing another station will not change the distribution of the correlations fundamentally.

Continental tropical airstreams from the Northern African and the Middle East/Arabian regions dominate particularly throughout summer by causing long lasting warm and dry conditions over Turkey, except in the Black Sea region and the continental northeastern part of the Anatolian Peninsula (Türkeş, 1998, 1999). This is coherent in Fig. 2 with aridity index (*AI*) map drawn in the study conducted by Türkeş (1999).

As understood from Fig. 2, the stations located at the Syrian border have the lowest values of correlation with S_h data considering Iğdır meteorological station and other stations. According to standardized precipitation index (SPI) method applied in the case of extreme aridity and modified SPI method introduced by Türkes and Tatlı (2009), the highest possibility of aridity has been found out at the Syrian border. The SPI is the number of Standard deviations that the observed value would deviate from the long-term average (or median) for a normally distributed random variable (Mckee et al., 1993).

3.1. Evaluating common and different aspects of arid zones found with AI, I_m and I_q in Turkey with respect to controls of physical geography

The geographical distribution of the aridity index map prepared by Türkeş (1999, 2010) is shown in Fig. 3. Dry land and humid land boundaries, however, may change, depending on the number of stations used and study period, and particularly because of high year to year variability in precipitation amounts and aridity conditions.

According to Fig. 3, dry sub-humid climatic conditions extend over most of continental Central Anatolia and South-eastern Anatolia, some parts of the Eastern Mediterranean, and the eastern

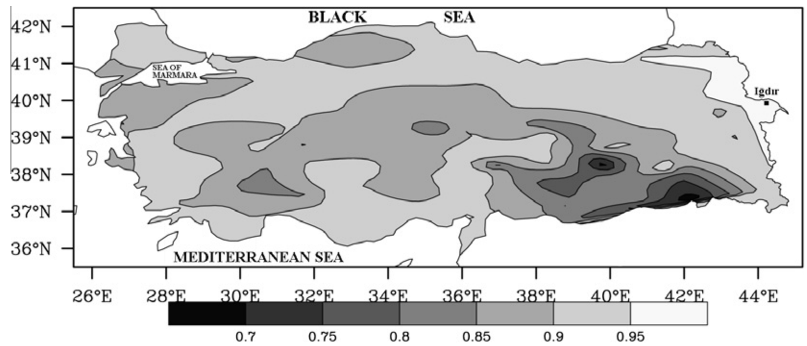

Fig. 2. The single point correlation graph of S_h considering Iğdır station.

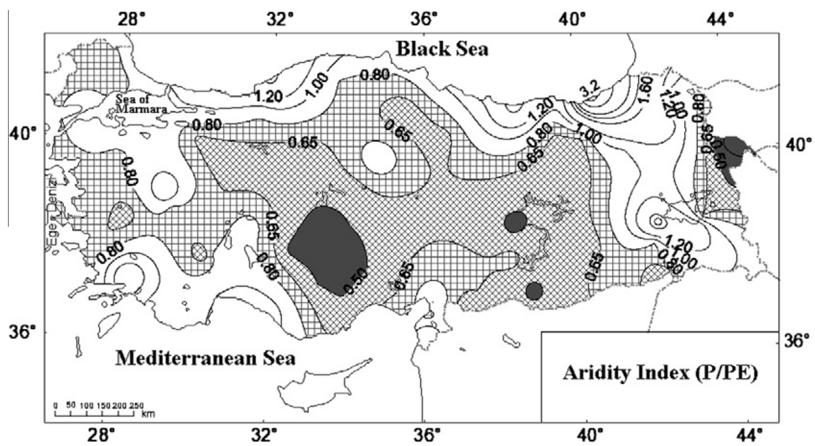

Fig. 3. Geographical distribution of aridity index (*AI*) values for 94 stations prepared by Türkeş (1999, 2010) in Turkey.

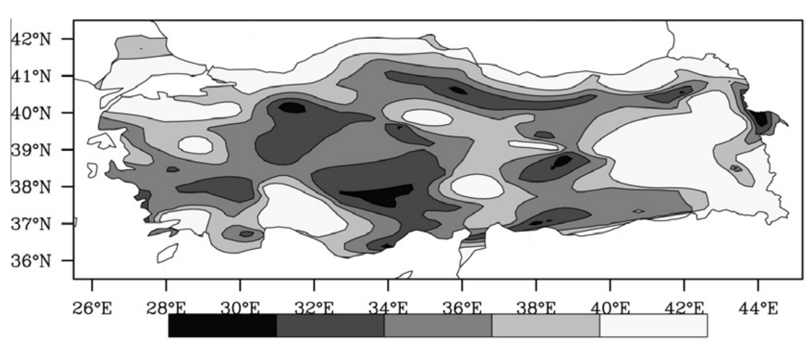

Fig. 4. Geographical distribution of aridity index (*AI*) values for 211 stations prepared by Romanenko (1961) model in Turkey.

and western parts of the Eastern Anatolia. Semi-arid climatic conditions are dominant only over the Konya Plain and the Iğdır district of Eastern Anatolia. Humid climatic conditions exist western part of Mediterranean, Marmara region and western part of Blacksea region. Very humid climatic conditions exist only in eastern part of the Blacksea region and southeastern part of Anatolia. With an aridity index value above 2, Rize and Hopa zones are identified as ‘‘very humid’’ and located in the eastern BLS.

There are many differences occurred in geographical distributions of *AI* between Fig. 3 and Fig. 4. It is considered that these differences were caused by the study period, number of stations and accuracy of the model applied for computing PET values. Fig. 3 was prepared with the data recorded between 1930–1993 by Türkeş (1999, 2010) and the Watbug program was used to calculate PET values. Generally, the entrance of aridity through the South Eastern Anatolia Region into Turkey and the distribution of the aridity values over Turkey ($AI < 0.8$) show similarity. However, in Fig. 4, semi-arid zones appear in northwestern part and northeastern of Anatolia shows discrepancies with Fig. 3. Besides, the humid and very humid zones between CAN and EAN region in Fig. 4 do not exist in Fig. 3. These humid and very humid zones between CAN and EAN region were not expected according to spatial distribution of vegetation formations over Turkey. The borders of the humid and very humid areas ($AI > 0.8$) are different in Fig. 3 and Fig. 4 especially in EAN region. The distribution of very large humid areas ($AI > 1$) was not an expected case in Fig. 4. It

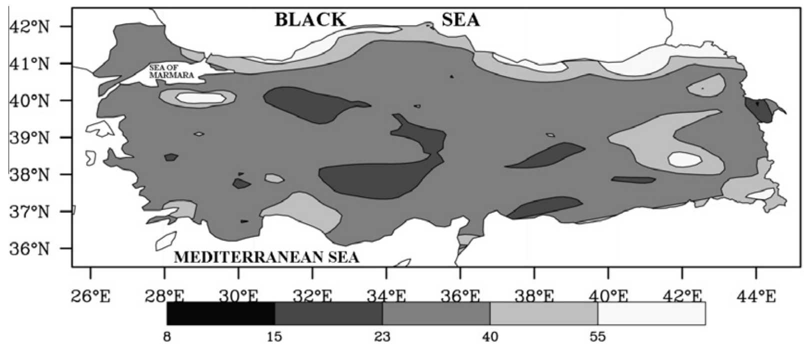

Fig. 5. Geographical distribution of I_m values for 211 stations in Turkey.

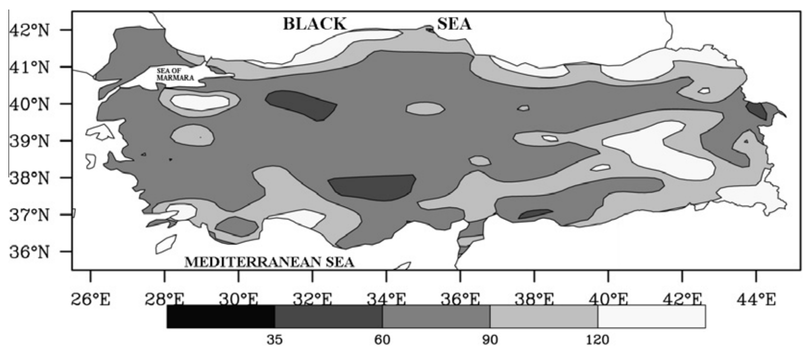

Fig. 6. Geographical distribution of I_q values for 211 stations in Turkey.

is considered that the PET values were underestimated by Romanenko (1961) model in EAN region. This underestimation problem was also observed in the MAR and western part of MED region in Fig. 4.

The aridity index map prepared according to Erinç aridity index values is shown in Fig. 5. In spite of 211 stations used to prepare the aridity index map, the distribution of aridity index values was not detailed as expected. According to Fig. 5, semi-humid climate conditions dominant over in a very large area of Turkey. Semi-arid climate conditions dominant in Konya plain, the Iğdır district of EAN and vicinity of Polatlı district of Northeastern part of CAN. Humid climatic conditions exist in Eastern part of the Blacksea region and southeastern part of Anatolia. It must be noted that humid and semi-arid climate conditions shows similarity in Fig. 3 and Fig. 5. The difference between Fig. 3 and Fig. 5 is the distribution of the semi-humid climate conditions.

The aridity index map prepared according to I_q index values is shown in Fig. 6. In summers, Polar front and maritime polar (mP) and continental polar (cP) air masses move towards the north and thus Turkey is affected by tropical air masses. In the CAN region, Taurus Mountains serve as a barrier against tropical air masses and prevent them to move into inner parts. Likewise, Taurus Mountains prevent polar air spreading over inner parts to move into the Mediterranean. CAN is among regions with the lowest precipitation. Konya plain is one of the most arid zones of Turkey with respect to climatologic aridity (Türkeş, 1999). This result is common in all aridity maps drawn with *AI*, I_m and I_q values.

3.1.1. Comparison of aridity index values in MED

Mediterranean climate shows real seasonal, humid and semi-humid subtropical characteristics while it has considerably rainy and warm winters; hot and dry summers (Türkeş, 1999). Summers are dry due to hot and dry air systems originating from Azores high and Basra low. Due to limited number of cyclonic activities low precipitation occurs in summers and springs. The effects of semi-humid and conditionally unstable Mediterranean air systems directly coming from the west decrease towards the east and these systems lose their effects at the transition point at the middle of western and eastern part of the MED (Türkeş et al., 2009). Furthermore, at this transition point, local impacts decrease in conjunction with large or synoptic scale weather types and thus these western and eastern parts of the MED are subject to different local impacts. These local impacts can be clearly seen in Fig. 3 and Fig. 6 which shows the distribution of *AI* and I_q values.

3.1.2. Comparison of aridity index values in BLS

The Black Sea region, which gets its name and characteristics from the adjacent sea, is like a strip extending along the north part of Anatolia. All seasons are rainy, summers are cool and winters are warm in the Black Sea climate. Orographic precipitation brought by Atlantic based moist and cold air currents (maritime polar) carried by air masses from the north and north-west prevails in Black Sea region (Türkeş et al., 2009). The Black Sea climate resembles in many aspects to temperate oceanic climate. Humid and very humid climate conditions are dominant in this region according to the distribution of *AI*, I_m and I_q values shown in Figs. 3–5, respectively. In this region, the aridity index values used in this study show similar distribution especially in Figs. 5 and 6.

3.1.3. Comparison of aridity index values in MAR

Marmara region has a distinctive climate due to variations in the characteristics of factors such as topography, altitude, relative position, exposure and vegetation. Due to its geographical position, Marmara region has the characteristics of a transition climate between Mediterranean and Black Sea climates. However, this region is generally under the influence of Mediterranean region. Though maximum precipitation falls in the winter season, the level of aridity in the summer season is not so high as compared to

Mediterranean regime. The direction of the prevailing wind is north–northeast due to pressure conditions. The cold air movements are frequently observed due to the effect of winds from Balkan Peninsula with cold weather. The moist air masses from Balkans leave their moisture over Balkan Mountains and bring a dry wind that lacks moisture. Semi-humid climate conditions are dominant in major part of MAR. This is coherent with the distribution of aridity index values in Figs. 3, 5 and 6.

3.1.4. Comparison of aridity index values in EAN

Summers are hot and dry whereas winters are cold and snowy. Long and snowy winters and short summers are typical characteristics of this region. High altitudes and the strengthening of high pressure conditions linked to cold and stable air masses constitute an obstacle to high precipitation in the region. Annual temperature differences are high. In this region, the distribution of *AI*, I_m and I_q show differences more than any regions in Turkey. According to Erinç Aridity index, the major part of EAN is semi-humid. Climate conditions may change rapidly by distance because of changes at topography at short distance. Therefore, existence of various climate types was expected in this region as in Fig. 3 and Fig. 6. Southeastern Taurus Mountains prevent very hot air masses from North Africa and Middle East – Arabia regions and the surface distribution of circulation-based effects of Asian summer Monsoon low into inner parts of EAN region. This effect can only be seen in the distribution of I_q values.

3.1.5. Comparison of aridity index values in SAN

The south part of Turkey, under direct effect of continental and very hot air masses over North Africa and Middle East – Arabia regions, is hotter and drier in summers as compared to the north part of Turkey (Türkeş, 1996). Semi-arid and semi-humid climatic conditions (summers are considerably hot and dry, winters are cold and rainy,) dominate over Southeastern Anatolia region. Large-scale frontal cyclones of Mediterranean origin are effective in this region and their impacts decrease towards to the northern east. High amount of mean annual total precipitation in this region confirms this. The effect of large-scale frontal cyclones can be seen in both distributions of *AI* and I_q values. Southeastern Taurus Mountains prevent polar air masses from East Anatolia to move into the inner parts. This effect can only be seen in the distribution of I_q values.

3.1.6. Comparison of aridity index values in AEG

Typical characteristics of Mediterranean climate are observed in AEG region. Mean low precipitation is the most important distinctive feature of this region as compared to MED. Upper atmospheric circulations and large scale pressure systems such as middle-latitude and Mediterranean cyclones of Atlantic origin and dynamically formed subtropical anti-cyclones originating from the Azores are the factors that bring precipitation. Semi-humid climate type is dominant in this region. Distribution of *AI* and I_q values shows similarity in this region. According to I_m values in Fig. 5, semi-humid climate type prevails in entire region which is not expected.

4. Summary and conclusion

Considering the distribution of the inaccurate calculations performed in percentages, and based on the statistical comparisons in general, it has been concluded that there is no drawback in using the computed S_h in the hydrometeorologic and the climatologic studies.

According to the single point correlation graph of S_h, the entrance of the aridity through South Eastern Anatolia Region into Turkey and the distribution of the aridity over Turkey have been shown. This result is related with the relationship between moisture availability at the surface (soil moisture) and in the atmosphere (specific humidity) which are moisture-balance components. In other words, this graph of S_h explains the relationship with S_h and aridity.

The results of the I_g and I_m aridity indexes are similar in terms of fundamental aspects. The differences between these two indexes appear in semi-humid and humid areas. According to I_m index, semi-humid climate type prevails in a very large area of Turkey. This result is illogical considering the controls of physical geography, degree of continentality, orographic factors and geomorphologic characteristics such as general air circulation, air masses and topography. It must be noted that I_m index is not valid for negative T_{max} values which limits the application of this index, especially in global scale.

There are many differences occurred in geographical distributions of *AI* prepared by Romanenko (1961) model applied in this study and prepared by Türkeş (1999, 2010). It is considered that the PET values were underestimated by Romanenko (1961) model in EAN region in the MAR region, western part of MED region and humid and very humid zones between CAN and EAN region. This underestimation problem was also observed in *AI* values computed with Türkeş (1999, 2010), because the humid and very humid areas ($AI > 0.8$) are larger than expected according to spatial distribution of vegetation formations over Turkey.

The distribution of *AI* and I_g values are similar in MED, BLS and partially in AEG and MAR. The difference between *AI* and I_g appear in SAN, upper SAN and western part of EAN. It is considered that, this significant difference is caused by approximately a two fold difference between the number of stations while preparing the *AI* and I_g map. Also, 94 stations used in *AI* map while 211 stations used in I_g map. Türkeş (1999) had also mentioned that, dry land and humid land boundaries, however, may change, depending on the number of stations used and study period, and particularly because of high year to year variability in precipitation amounts and aridity conditions.

The I_q index can be calculated with the precipitation, the mean temperature, the relative humidity and the local pressure which are the most readily available variables. Therefore, I_q can be easily applied globally and regionally with a very high number of meteorological stations. This is an important advantage while monitoring climate change. Due to lack of the measured PET data and difficulties of accurate estimation of PET or various input requirements to estimate PET, the *AI* defined by UNEP has not been widely and effectively used especially in developing countries.

Consequently, considering the controls of physical geography, land morphology, topography, geomorphologic characteristics, orography and based on graphical comparisons, there is no drawback in using the I_q aridity index. I_q index can be used globally and regionally for monitoring climate change and the distribution of aridity.

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