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Relationship between drought and solar irradiation variables

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Abstract:

Drought prediction for in many regions of the world has critical importance for strategic planning agriculture and water management. The occurrence of droughts cannot be predicted with certainty and thus must be treated as random variables. It is the main purpose of this paper to develop a new concept of drought features assessments based on triple drought related hydrometeorological and meteorological variables, namely, rainfall, solar irradiation and sunshine duration. Equal standard rainfall lines are drawn as a map with two reference variables as solar irradiation and sunshine duration. These are referred to as the triple graphical method (TGM) approach. It furnishes rich features of drought behaviour variation based on the rainfall, solar irradiation and sunshine duration. This analysis and the solar irradiation estimation method are applied to seven climatologically different stations in the Republic of Turkey for the monthly data period 1982–1991. The linear relations between drought and the variables of the Angström equation are found between 55% and 94% without Trabzon. Drought and Angström equation parameters are estimated by the proposed methodology. Relations between monthly drought and Angström equation variables are presented by the triple solar-drought graphical method. TGM provides information about the drought occurrences for different combinations of solar irradiation and sunshine duration. TGM graphs help to identify not only precipitation surplus (wet spells) or deficits (dry spells droughts) but also their variations with two more meteorological variables as solar irradiation and sunshine duration.

KEY WORDS drought; triple graphical method (TGM); Z-score; Angström equation; solar irradiation; sunshine duration; dry and wet season

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INTRODUCTION

Droughts are among the most significant natural hazards that might damage human life and property under different meteorological and environmental conditions. It is not easily possible to identify the initiation of drought because its occurrence starts as a creeping phenomenon, which is felt after some major and quantifiable effects. Droughts are water deficit related phenomena and their continuation for extended periods leads to water shortages in demand meeting, agricultural food deterioration concerning quantity and quality aspects, social disruptions in addition to economically undesirable consequences.

According to recently researches, Folland *et al.*, 2002; drought forecasting will be significant since global temperature increases have become pronounced after the 1970s and have been attributed to human-induced climate changes arising primarily from increased greenhouse gases (Karl and Trenberth, 2003). Higher temperatures increase the water-holding capacity of the atmosphere and thus increase potential evapotranspiration. The increased risk of drought duration, severity, and extent is a direct consequence, and the theoretical expectations are being realized by Nicholls (2004) and Dai *et al.* (1998, 2004). Drought analysis has concentrated on point analysis, which yields the temporal variations at a specific site only. The first classical approach has been the evaluation of the instantaneously low values in an observed hydrologic sequence recorded at a single site (Gumbel, 1963). This method gives information on the instantaneous maximum value of drought magnitude only, without any elaboration of either its duration or areal extent. The first objective definitions of hydrologic point drought and applications have been reported by various researchers (Yevjevich, 1967; Bayazit and Sen, 1977; Sen, 1980; Sirdas and Sen, 2001).

The Office of Technology Assessment (OTA, 1993) presented their results that the direct impacts of climate change on water resources will be hidden beneath natural climate variability. With a warmer climate, droughts and floods could become more frequent, severe, and longer lasting. The potential increase in these hazards is a great concern given the stresses being placed on water resources and the high costs resulting from recent hazards. Understanding interannual to interdecadal variations in continental drought is important for improved water resource planning and management. The 1988 drought and accompanying heat waves over the mid-western US caused around $39 billion in damages and contributed to increased heat-related mortality rates (Riebsame *et al.*, 1991; Trenberth and Branstator, 1992). Droughts and floods are extreme climate events that percentage-wise are likely to change more rapidly than the mean climate. Since droughts and floods are among the world's costliest natural disasters and affect a very large number of people

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each year, it is important to monitor them and understand and perhaps predict their variability as being presented by Wilhite (2000). The potential for large increases in these extreme climate events under global warming is of particular concern (Trenberth *et al.*, 2003, 2004). However, Wilhite (2000) and Keyantash and Dracup (2002) showed that the precise quantification of droughts and wet spells is difficult because there are many different definitions for these extreme events (e.g. meteorological, hydrological, and agricultural droughts); and the criteria for determining the start and end of a drought or wet spell also vary along with historical records of direct measurements of the dryness and wetness of the ground, such as soil moisture content. In order to monitor droughts and wet spells and to study their variability, numerous specialized indices have been devised using readily available data such as precipitation and temperature (Heim, 2000; Keyantash and Dracup, 2002; Dai *et al.*, 2004).

In addition, for spatio-timely drought monitoring the drought indices are used commonly. Standard precipitation index (SPI) is one of the latest indices suggested by McKee *et al.* (1993). SPI is suggested and designed to quantify the precipitation deficit for multiple time scales. These time scales reflect the impact of drought on availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short time scale, while ground water, stream flow, and reservoir storage reflect the longer term precipitation anomalies. The classification system is normalized so that wetter and drier climates can be represented in the same way (McKee *et al.*, 1993). The criteria for a 'drought event' for any of the time scales are also defined by McKee *et al.* (1995). A deficit occurs when the SPI is continuously negative. The accumulated magnitude of deficits is referred to as drought magnitude, and it is the positive sum of the SPI for all the months within a drought event (Sirdas and Sen, 2003).

So far, there is not a single definition of drought or drought index that has been suitable for all interests and purposes. A wide variety of definitions have been mentioned by Wilhite and Glantz (1985). Perhaps, the main lack in such a common definition arises from the fact that there are several kinds of information needed for drought monitoring. Hence, in addition to precipitation, runoff, soil moisture, weather relative humidity, evaporation, temperature, solar irradiation, sunshine duration etc., variables are also necessary as basic information. Most of the studies are concentrated on the precipitation shortages as drought implications because precipitation is the most singly significant input variable for many water related activities such as water supply, ground water and reservoir storages, soil moisture, snow pack and stream flow. The simplest methodology of temporal drought assessment is the Z-score method, which is used to quantify the precipitation deficit for several time scales and is explained later. However, the Z-score for a given averaging period of time is physically the difference of precipitation from the mean divided by the standard deviation. In fact, this is tantamount to the standardization procedure in the statistics literature where a time series is standardized by subtracting from each element, the arithmetic average of the series and then these differences are divided by the standard deviation of the same time series.

DATA AND OBSERVATIONS

The Republic of Turkey extends for 1650 km from west to east, which takes the form of an irregular rectangle with sides that are multi-curved. It lies meridionally between 36 °N and 42 °N latitudes and approximately between 26 °E and 45 °E longitudes (Figure 1). A small part of the country, Turkish Thrace, west of the Bosporus, is located geographically in Europe. The rest of the country, Anatolia or Asia Minor, is in Asia. The Black Sea from the north, the Marmara and the Aegean seas from the west and the Mediterranean Sea from the south enclose Anatolia. Various mountains form the eastern

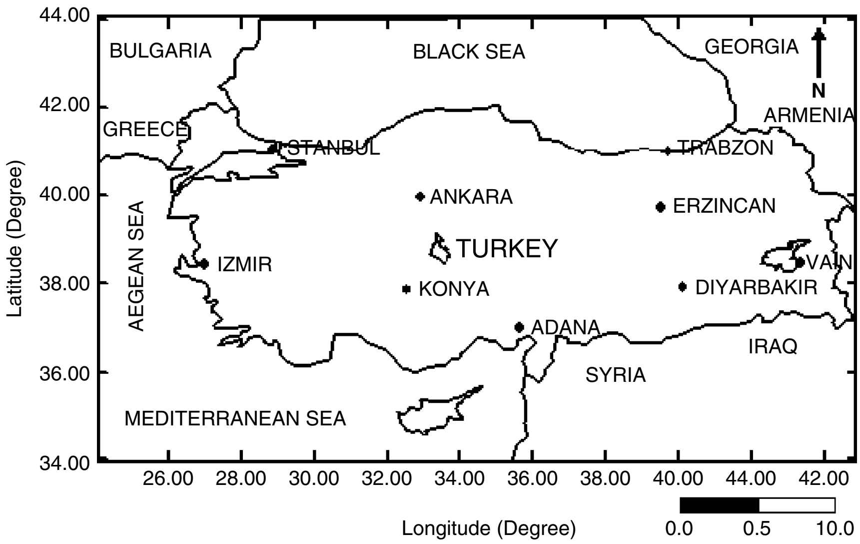

Figure 1. Location map of Turkey

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boundary of Turkey. The influence of the surrounding seas is, however, restricted by the prevailing pressure patterns and the mountainous ranges so that aridity and continentally characterizes most parts of the country (Taha *et al.*, 1981; Kadioglu, 2000).

Turkey's diverse regions have different climates because of irregular topography. Taurus Mountains are close to the coast and rain clouds cannot penetrate to the interior part of the country. Rain clouds drop most of their water on the coastal area. As rain clouds, which have no significant capability to produce rain, pass over the mountains and reach central Anatolia. In the eastern region of Anatolia, the elevation of mountains exceeds 2500–3000 m. Northern Black Sea Mountains and Caucasian Mountain hold the rain clouds, and therefore the area is affected by the continental climate with long and very cold winter. Minimum temperatures of $-30\,^{\circ}$C to $-38\,^{\circ}$C are observed in the mountainous areas in the east, and snow may lie on the ground 120 days of the year. Winters are bitterly cold with frequent, heavy snowfall. Summers are hot and dry, with temperatures above $30\,^{\circ}$C. Spring and autumn are generally mild, but during both seasons sudden hot and cold spells frequently occur in the region giving annual precipitation averages about 500–600 mm with actual amounts determined by elevation. The Aegean and Mediterranean coasts have cool, rainy winters and hot, moderately dry summers. The wettest regions are the Black Sea coast which receives the greatest amount of rainfall. The north-eastern part of that receives 2400 mm annually and is the only region of Turkey that receives rainfall throughout the year. The driest regions are the Konya, Diyarbakir and Sanliurfa, where annual rainfall frequently is less than 200 mm (Sirdas, 2002).

The Z-score, Angström and triple graphical method (TGM) methodologies, which are described in the next section, are presented for the seven cities of Turkey. The monthly data of precipitation, sunshine duration and solar irradiation data are available from 1982 to 1991. The selected stations are representatives of different parts of Turkey (Figure 1).

METHODS

Z-Score

The Z-score for an item indicates how far and in what direction that item deviates from its distribution's mean, expressed in units of its distribution's standard deviation. The mathematics of the SPI transformation are such that if every item in a distribution is converted to its Z-score, the transformed scores will necessarily have a mean of zero and a standard deviation of one (Wu *et al.*, 2001). The Z-score transformation is especially useful when seeking to compare the relative standings of items from distributions with different means and/or different standard deviations. Firstly, the Z-score method used is simply the standardization of a given monthly precipitation time series, X_i such as $X_1, X_2, \ldots, X_n$. The standardized monthly precipitation (SMP) series, x_i is defined as:

$$x_i = \frac{X_i - \overline{X}}{S_x} \tag{1}$$

where $\overline{X}$ is the arithmetic mean and S_x is the standard deviation of the series. The Z-score is defined theoretically as the sub-areas under a normal (Gaussian) probability distribution function. It has many advantages over other drought indices, which require more than two variables such as the Palmer approach. It needs consideration of only two parameters, the arithmetic mean and the standard deviation. Table I shows the Z-score categories, which are used for SMP series. As an example various drought characteristics are shown in Figure 2. In addition, the SMP is commonly used for the identification of various drought characteristics such as the duration, magnitude, and intensity at different standard truncation levels. The basic formulations are given for these drought features and their applications are presented for Diyarbakir, Konya, Erzincan, İstanbul, Trabzon, Izmir and Adana precipitation records in different locations of Turkey. The relationships between the drought intensity and solar irradiation variables are provided in the form of scatter diagrams with the best straight-line fits. As a result of this study, general characteristics of meteorological drought are discussed for Turkey. The SMP time series is used for the triple drought-solar graphical method estimation part.

Linear Angström equation

The solar irradiation and sunshine duration records both of them depend on the combined effects of astronomical and meteorological events. The astronomical effects on the solar energy variables are deterministically calculable by mathematical expressions depending on the average distance and declination angle of the sun, longitude and latitude of the site and seasons of the year (Angström, 1924). The meteorological events direct effects on the solar energy calculations introduce random behaviours. For these reasons solar irradiation and sunshine duration variables have randomness in their temporal and spatial evolutions.

Table I. Z-Score categories

SMP values	Category	Abbreviation
0 to −0·99	Mild drought	MID
−1·00 to −1·49	Moderate drought	MOD
1·50 to −1·99	Severe drought	SED
< − 2·00	Extreme drought	EXD

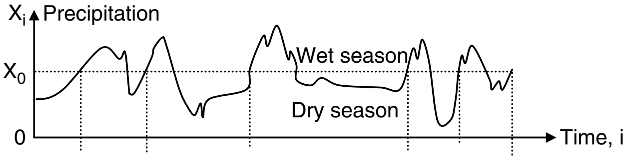

Figure 2. Schematic representation of wet and dry spells

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The first systematic proposal was in the form of a linear expression as suggested by Angström (1924). His formula has been used in practical applications for many years to estimate the daily, monthly and annual global solar irradiation, H, from the comparatively simple measurements of sunshine duration, S, according to:

$$\frac{H}{H_0} = a + b\frac{S}{S_0} \tag{2}$$

where H_0 and S_0 are the astronomical daily global irradiation received on a horizontal surface at the ground level and sunshine duration, respectively, and a and b are model parameters. The ratios of meteorological solar energy variables to their astronomical counterparts H/H_0 and S/S_0 assume values between zero and one in a random manner depending on the cloud cover and atmospheric turbidity of the period concerned. In practice, the measurement of S is comparatively easier and more economical than that of H, and therefore, many researches have proposed various statistical expressions in order to estimate the latter from the former. As explained earlier, although H and S vary temporally in a random manner, H_0 and S_0 have deterministic values and the question is whether the model parameters a and b also vary temporally and randomly at a given station. In most applications so far in the literature, a and b are considered as constants for the time period used in the application of Equation (2).

Angström's linear model relates global radiation to sunshine duration by ignoring other meteorological factors such as the rainfall, relative humidity, maximum temperature, air quality, latitude, elevation above mean sea level, etc. The effects of other meteorological variables appear as deviations from the straight line fit on a scatter diagram. In order to cover these errors to a certain extent, it is necessary to assume that the model coefficients are not constants, but random variables that change with the other meteorological data (Sahin and Sen, 1998). However, many researchers have considered additional meteorological factors to the equation of Angström for the purpose of increasing the accuracy in the coefficients estimate (Swartman and Ogunlade, 1967; Rietveld, 1978; Soler, 1986, 1990; Sen *et al*., 2001). Although each one of these studies refined the coefficient estimates, these studies all depend on the average parameter values obtained by the least squares method, and therefore, there are still remaining errors although smaller than in the Angström's model. Since the drought is accumulative consequences of continuous sunshine duration spells and low precipitation occurrences in addition to high solar irradiation rates, it is combined in a single graph in this paper by considering the SMP series with the Angström equation representing validation and sunshine duration variability's. In this manner temperature and humidity effects are represented by the solar irradiation and precipitation variables in drought descriptions.

The view taken in this paper is that the linear regression technique, which yields the average coefficient values, is not sufficient to represent the whole variability of the meteorological factors, and still better interpretations with monthly variations should be considered from the scatter diagram.

Triple graphical method (TGM)

The three dimensions variations can be visualized using Cartesian coordinate systems through contour maps. Normally maps are regarded as the variation of a variable by location variables that are either longitudes and latitudes or easting and northings (Isaaks and Srivastava, 1989; Cressie, 1993; Kitanidis, 1997). For this reason, it is possible to estimate the concerned (mapped) variable value for a known couple of location variables. In addition, if someone wants to forecast the present drought situations from temperature and humidity records, it is recommended that the two previous records replace the two location variables; this mapping method is suggested by the doctoral thesis of Sirdas (2002). Furthermore, Sahin and Sirdas (2002) and Altunkaynak *et al*. (2003) have applied this method in order to predict different meteorological and hydrometeorological conditions. Using this method the current value of a variable can be mapped, based on two preceding values of the same variable. First of all previous to mapping is to determine the empirical semi-variogram (SV) which guides the theoretical model that will be employed in the classical Kriging model. Thus different theoretical SV models such as linear, power, spherical and Gaussian types have been tried for the best fit and, in the end; the Gaussian SV was the best match to the experimental SV tendency. Among SV models the Gaussian type is the most appropriate in precipitation, solar duration, irradiation and the properties of a fixed Gaussian SV model. For this purpose, the empirical SV is selected parabolic. The scatter of SV versus distance is shown in Figure 3. Such a mapping technique is referred to hereafter as TGM. Even though for mapping Davis (1986) has suggested the application of various simple regional methods such as opposite distance, opposite distance squares, etc., which regards the geometrical pattern of the scatter points only without the use of a third variable. In this paper, preparation of the TGM is based on the classical Kriging technique to estimate drought using solar irradiation and solar duration. The structure of a TGM necessitates three variables, two of which are mentioned as independent variables [predictors: standardized solar irradiation (SSI) and standardized sunshine duration (SSD)] and comprise the basic scatter diagram. The third is the dependent variable [standardized monthly precipitation (SMP)], which has its calculated values added to each scatter point. Matheron (1963) presented that the equal value lines are built by the Kriging methodology concept, which is also referred to as geostatistics. In addition, Journel and Huijbregts (1978), Isaaks and Srivastava (1989) and Cressie (1993), respectively, explained the facts of geostatistical methods for earth sciences applications. These methods take into consideration the effective role of the measured values of a regional variable at a set of irregular sites. First, in this

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research, the locations of asymmetrical sites establish the scatter points of two independent variables. Second, in the scatter diagram attached to its points are the values of the dependent variable, which is then mapped by conventional Kriging methodology. Third, the resulting map comes out in the appearance of contour lines covering the complete variability areas of the two independent variables. The TGM diagram preparing such a map helps to predict the value of the mapped variable given the values of the independent variables.

RESULTS

Relationship between drought and solar variables

In dry seasons, solar radiation and sunshine duration increase to the highest degree and in wet seasons solar irradiation and sunshine duration have the lowest values. In dry (drought) times, sunshine duration plays an effective role and is controlled by these severe natural events. At cloudy sky, sunshine duration is low and rainfall may occur. However, at high clear sky condition, sunshine duration is highest and generally, there is not any important amount of rainfall. If dry periods continue over several seasons, drought will occur. Solar irradiation and sunshine duration ratios can be standardized using the Z-score method that is described earlier as follows:

$$\mathrm{SSI}_i = \frac{(H/H_0)_i - (H/H_0)_{\mathrm{mean}}}{\mathrm{Standarddeviation}_{(H/H_0)}} \tag{3}$$

and

$$\mathrm{SSD}_i = \frac{(S/S_0)_i - (S/S_0)_{\mathrm{mean}}}{\mathrm{Standarddeviation}_{(S/S_0)}} \tag{4}$$

As mentioned earlier, there are physical relations between sunshine duration and solar irradiation with precipitation. These physically rules can be written as follows:

(1) IF sunshine duration SSD is lower than mean value, in other words IF SSD values are less than zero and SMP value as are higher than zero, THEN wet climatic conditions occur,
(2) IF SSD and SMP values are greater than zero, THEN moderate wet climatic conditions are effective,
(3) IF SSD values are higher than zero and SMP values are less than zero, THEN severe drought conditions occur, and
(4) lastly, IF SSD and SMP values are less than zero, THEN moderate drought conditions occur.

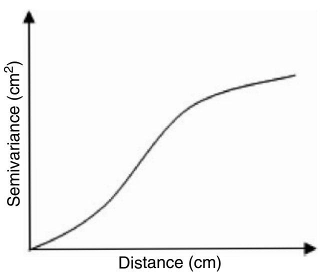

Figure 3. Theoretical parabolic semi-variogram

These rules can be used for a fuzzy logic inference system as suggested by Zadeh (1968). Besides, these situations and classification are presented graphically in Figure 4. These rules can be written in the same manner for SSI values as shown in Figure 4. In Figures 5–10 the specific drought–solar graphs are shown for the different stations. In Figures 5–10 dots represent individual monthly averages for the period 1982–1991.

In Diyarbakır two different climatic conditions prevail very distinctive as wet and dry spells. Few months of wet conditions and several months of severe drought conditions are observed according to Figure 5(a). This high linearity observed in the SSI values is almost as strong in the SSD values (Figure 5b). In addition, it can be seen that solar-drought linear ships are conserved for both standardized solar variables (Figure 5). The SSI and SSD values obtain from meteorological observation. The linear relationship equations between SSI (or SSD) and SMP present information to estimate wet and dry conditions from Cartesian coordinates.

At some stations where continental, dry climatic conditions are effective, linear relations exist between drought and solar variables for Konya as shown in Figures 6. At this station, points are scattered within regions of I, II, and III drought-solar conditions as indicated in Figure 4. Konya is the large crop storage of Turkey; it is affected by severe drought conditions, which decrease yield significantly. Therefore, drought forecast carries an immense importance for agriculture.

Dry, continental climatic conditions are also effective in the Erzincan region where a high non-linear relationship is observed between SMP and SSD values. Especially, 3 months moderate wet conditions are observed and this situation indicates the change from linear to non-linear relation (Figure 7a). In contrast to the SSD values, there is a low linear relationship between SMP and SSI values (Figure 7b).

Istanbul, where both continental and maritime climatic effects can be observed, is located in the north-western part of Turkey. It is the largest city in Turkey with a huge drinking water demand. Some severe droughts were observed between 1980 and 1993 and as a consequence, very serious drinking water shortages occurred. Another high non-linear relationship between SMP and SSD values is noticed for Istanbul station. In contrast

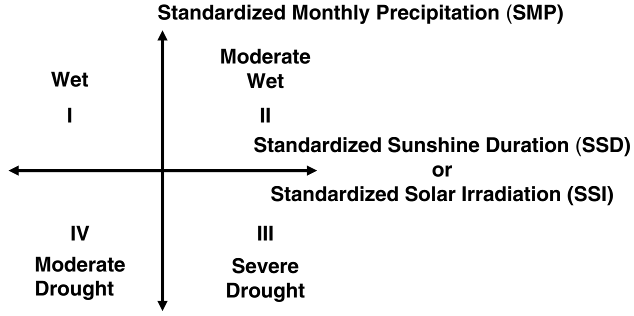

Figure 4. General drought-solar classification between SMP and SSD or SSI. The x-axis defines SSD (or SSI) and the y-axis defines SMP

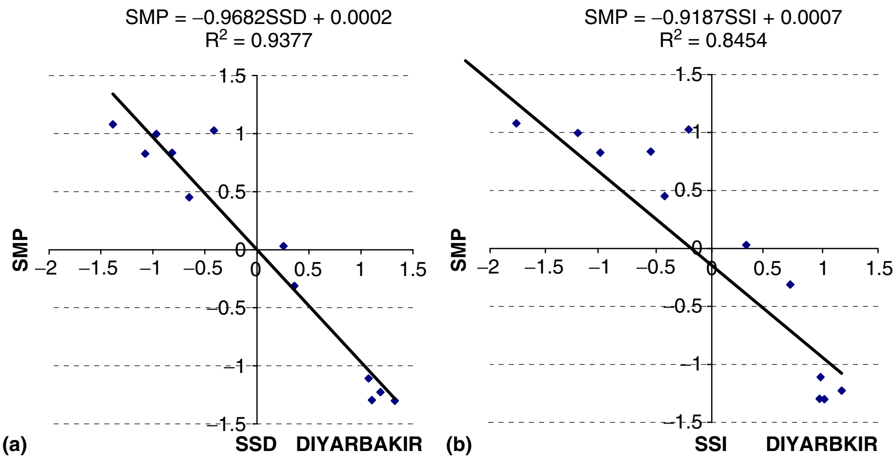

Figure 5. Relation between 5 years average SMP and solar variables (a) SSD and (b) SSI for annual from January to December for Diyarbakır

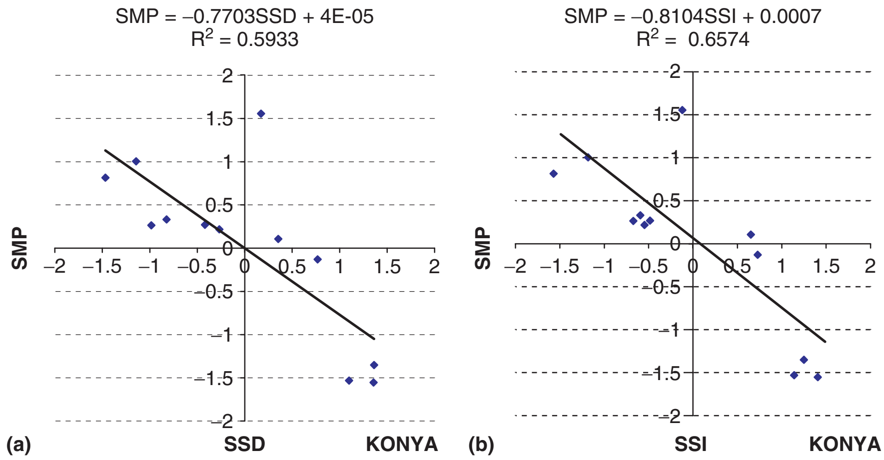

Figure 6. Relation between 5 years average SMP and solar variables (a) SSD and (b) SSI for annual from January to December for Konya

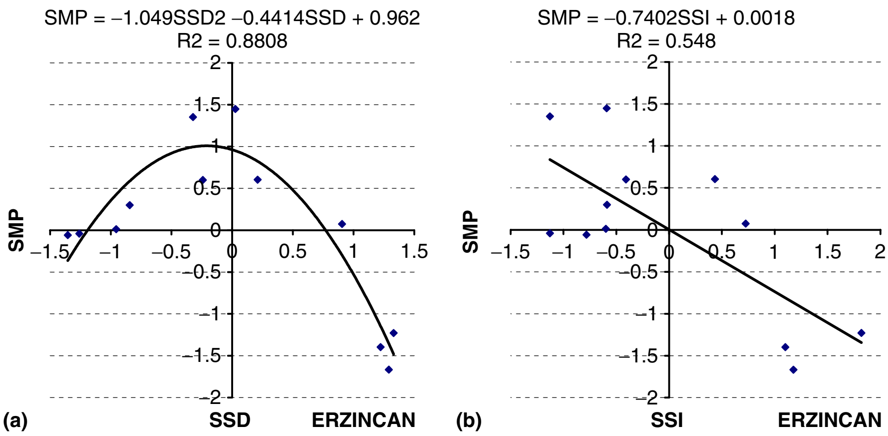

Figure 7. Relation between 5 years average SMP and solar variables (a) SSD and (b) SSI for annual from January to December for Erzincan

to Erzincan, 1 month moderate drought, 6 months wet and 5 months severe drought conditions are observed in Figure 8(a). There is a linear relation between SSI and SMP values. This means that, drought intensity can be calculated easily from SMP and SSI relationships function (Figure 8b).

Trabzon is located in the north-eastern region of Turkey is under the influence of maritime climatic conditions. It is also the second heaviest rainy city in Turkey. The rainfall continues to trough four seasons. Generally, the sky is covered with cloud, which blocks solar duration and sunshine irradiation. Therefore, it is not possible to find a relationship between SMP and SSD values (Figure 9a). Figure 9(a) is similar to Figure 7(a) and both have SMP and SSD values that are scattered all around the graph (such as in the general solar-drought

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classification graph in Figure 4). In other words, severe drought conditions could not be observed clearly at this station, but the other three conditions can be observed (Figure 9).

Adana lies in the southern part with its typical Mediterranean climatic features where winters are relatively short with cool periods but summer seasons have high temperature, solar irradiation and relative humidity. Here, in Figure 10 scatter diagrams show a high linear relationship between SMP and SSD (or SSI). Besides, 12 months are scattered for two conditions which are wet and severe drought.

Triple solar-drought graphics

The main purpose of this graphical approach is to combine three different but related variables and examine their common behaviour on two-dimensional domains on the basis of contour maps; details are explained earlier. In addition, linear model relations between two variables are derived. In this study, least square and Kriging methods are used for different goals. First, the least-square method is used to find a linear equation, and then third variable SMP values are taken into account as a base map for the Kriging approach (Sahin and Sirdas, 2002). This approach reveals not only some climatic variations but can also be used to estimate drought intensity depending on sunshine duration and solar irradiation values. Some solar engineering variables such as the parameters in the Angström equation can also be estimated. Figures 11–17 show triple solar-drought graphics, which reveal how changing drought conditions, depend on sunshine duration (S/S_0) and solar irradiation values (H/H_0). Besides the straight line represents the linear Angström equation and its a and b parameters. If one of the measured variables is known, then the other variable can be found easily by using the a and b parameters. As seen from this graphical approach, two different usage areas and three variables can be discussed and evaluated easily.

Diyarbakır is located in the far south-eastern part of Turkey as a semi-arid region with high solar energy potential and high drought intensity. Therefore, the method of this paper can be used efficiently for both applications. Generally, high intensity drought occurs at this station except at low levels of sunshine duration in Figure 11. However, some low level sunshine

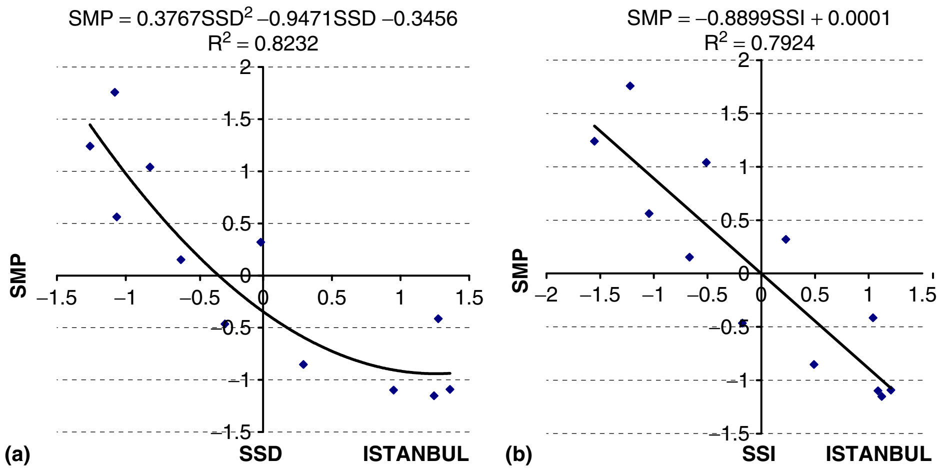

Figure 8. Relation between 5 years average SMP and solar variables (a) SSD and (b) SSI for annual from January to December for İstanbul

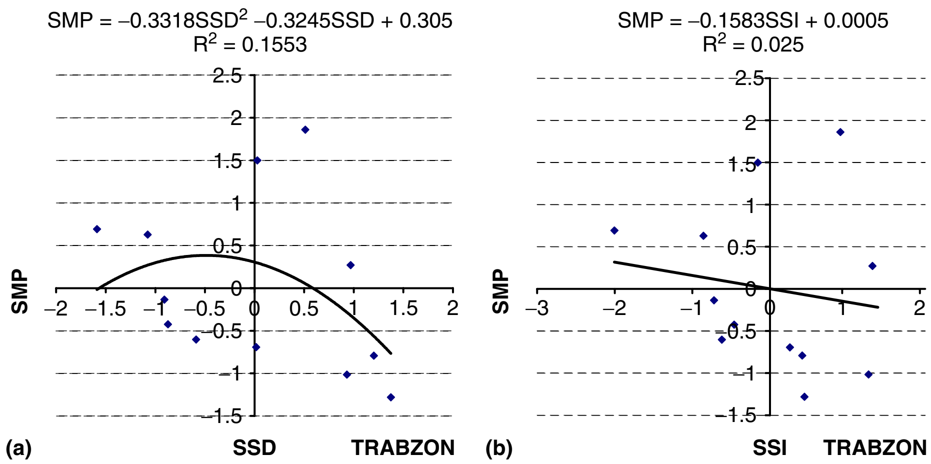

Figure 9. Relation between 5 years average SMP and solar variables (a) SSD and (b) SSI for annual from January to December for Trabzon

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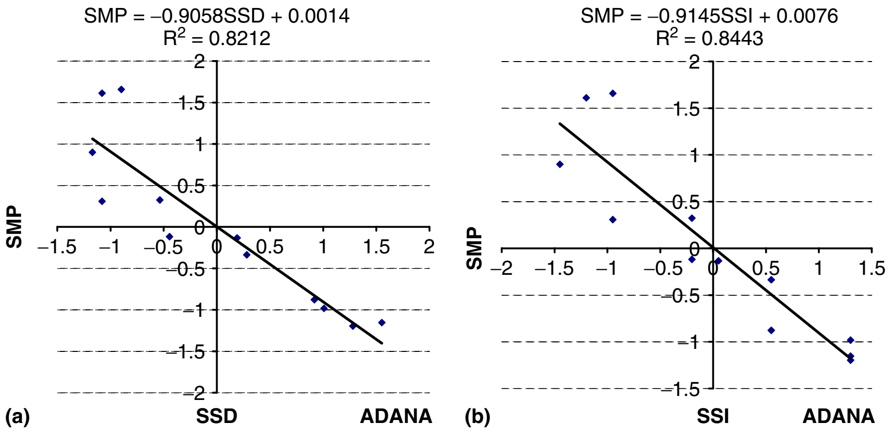

Figure 10. Relation between 5 years average SMP and solar variables (a) SSD and (b) SSI for annual from January to December for Adana

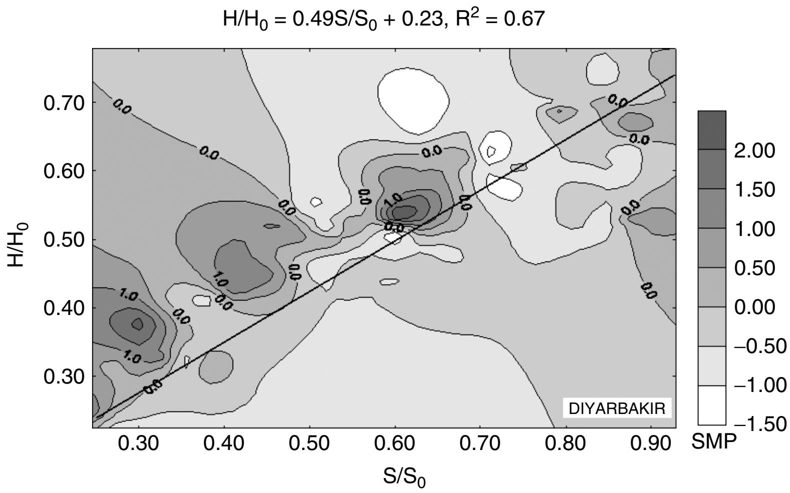

Figure 11. Triple solar-drought graphical approach among H/H_0 (solar irradiation), S/S_0 (sunshine duration) and SMP for the period 1982–1991 for Diyarbakır

duration combined with low-level solar irradiation ratio gives rise to drought occurrence. This situation means that rain shortages can occur in winter seasons too. Figure 11 shows while the solar duration is bigger than 0·50, Diyarbakir city might be affected by severe drought conditions.

In the central part of Turkey, continental climate prevails and topographic conditions affect the rainfall occurrences mostly. Konya, which is located in central Anatolia, has a high but flat plateau surrounded by mountains in the north, south and west directions. The largest lowland is located in this region. Thus, area climatic effects will be very high especially in the summer months. Normally in this semi-arid region, moderate and severe droughts have occurred in the past. Due to the marked continentally of this region, rainfall shortage is observed during the years, and the standard deviations of SMP also take high absolute values. As seen from Figure 12, severe drought values occur. Commonly moderate drought values are seen at high-level sunshine duration and solar irradiation ratios. There is an interesting situation that occurs at low-level sunshine duration in this station. In general, at low-level sunshine duration, wet season is present, but in Konya, some dry seasons occur. Approximately, sunshine duration ratio alone is not sufficient for an explanation of drought intensity at this station. Angström equation parameters are evaluated at this station as well. Usually, in summer solar collectors are used for water heating at this region. Consequently, solar energy variables (sunshine duration and solar irradiation) take a very important role for solar energy calculations and design parameters (Figure 12).

In Figure 13, Erzincan is located in the eastern part of Turkey where continental climatic conditions are dominant. Winters are cold and dry, summers are hot, autumns and springs are rainy. Generally, severe drought conditions are observed between 0·50–0·75 S/S_0 and 0·55–0·70 H/H_0 values. Because of the dry winter climatic conditions, maximum rainy seasons occur between 0·1–0·5 S/S_0 and 0·4–0·6 H/H_0 values (Figure 13).

İstanbul station lies in the north-western part of Turkey, which is characterized by modified Mediterranean type of climate with influences from the Black Sea maritime and Balkan continental effects. As a result, winters are cold and summer seasons are rather warm with long hours of sunshine duration and high relative humidity. In Figure 14 extreme drought has several periods at different times for Istanbul. Moderate drought values are seen at highest sunshine duration and solar irradiation ratio levels. At medium level, mild drought can be seen. At low level of sunshine duration and solar irradiation ratios, there are no negative SMP values. In other words, at these conditions wet periods occur. The same figure can be used for estimation of sunshine duration or solar irradiation.

Trabzon station along the eastern Black Sea region is under the influence of humidity laden with air mass movements from the north-western directions over Eastern Europe with high relative humidity but shorter

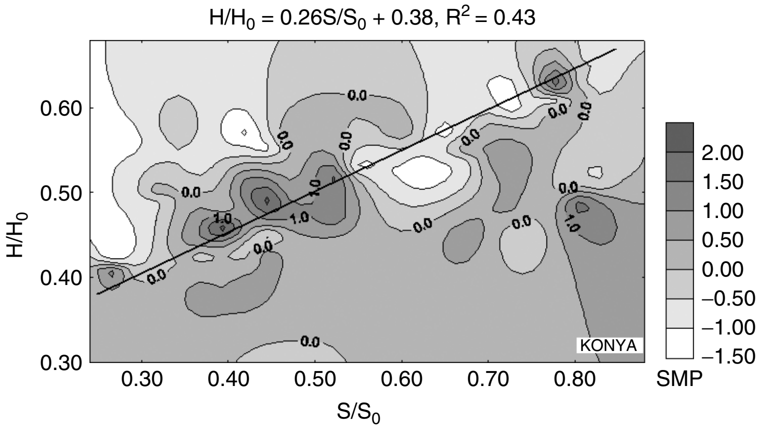

Figure 12. Triple solar-drought graphical approach among H/H_0 (solar irradiation), S/S_0 (sunshine duration) and SMP for the period 1982–1991 for Konya

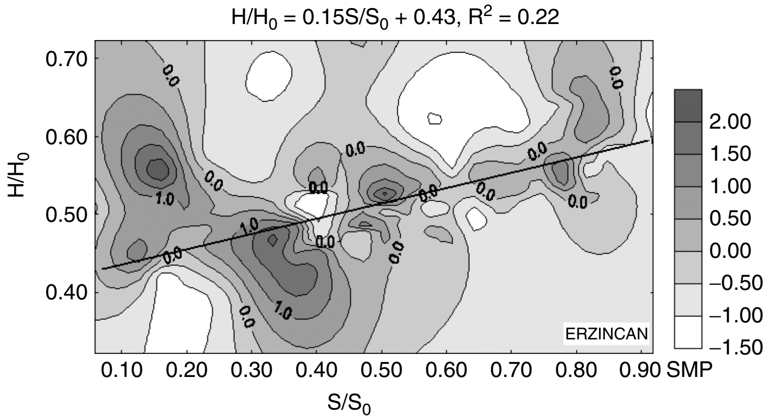

Figure 13. Triple solar-drought graphical approach among H/H_0 (solar irradiation), S/S_0 (sunshine duration) and SMP for the period 1982–1991 for Erzincan

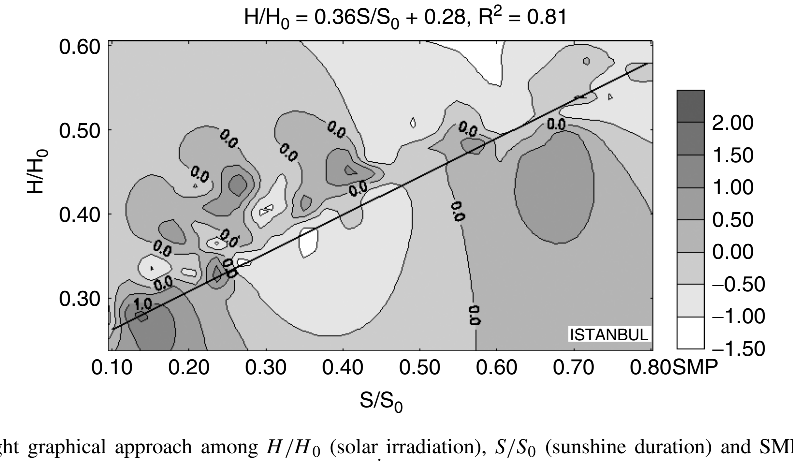

Figure 14. Triple solar-drought graphical approach among H/H_0 (solar irradiation), S/S_0 (sunshine duration) and SMP for the period 1982–1991 for İstanbul

sunshine duration spells. In almost all months, rainy days can be observed frequently and moderate maritime conditions are effective in this region. The triple diagram of Trabzon is shown in Figure 15 where there are mixture of islands of drought and wet regions. Such a pattern indicates unstable air and weather conditions in the region and the predictability of dry spells is rather difficult due to its chaotic occurrences. The highest wet condition at this station is observed at 0·43 S/S_0 and 0·4 H/H_0 values. Besides, high wet season values with low level H/H_0 and S/S_0 values are observed at this station. This map is a good example for the drought multiple graphical approach. If sunshine duration and solar irradiation have low values, then continuously wet season occurs with the exception of one or two times (Figure 15).

İzmir is located in the western part of Turkey at the coast of the Aegean Sea. In winter, moderate and rainy climatic conditions and in summer, hot climatic conditions occur. In the summer months, high amounts of moist air are brought in and most of the time, moderate wet conditions occur at this station when S/S_0 ratio values are lower than 0·6, and also when S/S_0 ratio values are higher than 0·6, the moderate and severe droughts are observed. At some high S/S_0 and H/H_0 values, moderate wet weather occurs. This situation can be explained by summer moist air conditions. High solar irradiation and sunshine duration values are observed at 0·9 S/S_0 and 0·7 H/H_0 values in Izmir (see Figure 16). Thus, solar energy estimation takes a very important role in this region.

Like Izmir, Adana is affected by sea climatic conditions. Adana is located in the southern part of Turkey that is usually known as windy. Synoptic systems originating from the Island low-pressure system in the winter months are less effective here than in the western part of Turkey. Therefore, contrary to other coastal regions, the Mediterranean Sea effects generally occur. As seen in Figure 17 moderate, severe and extreme droughts occur at high-level sunshine duration and almost high solar irradiation values. Solar irradiation ratios are higher than sunshine duration in this area. Drought values occur with high-level and low sunshine durations. Adana is known as the highest solar energy potential city in the southern part of Turkey. Nearly every day of the year, water can be solar-heated, and solar power plants can effectively work in the Mediterranean areas (Figure 17).

DISCUSSIONS

Droughts are extreme hydrological events, which may adversely affect the social, economical, cultural, and

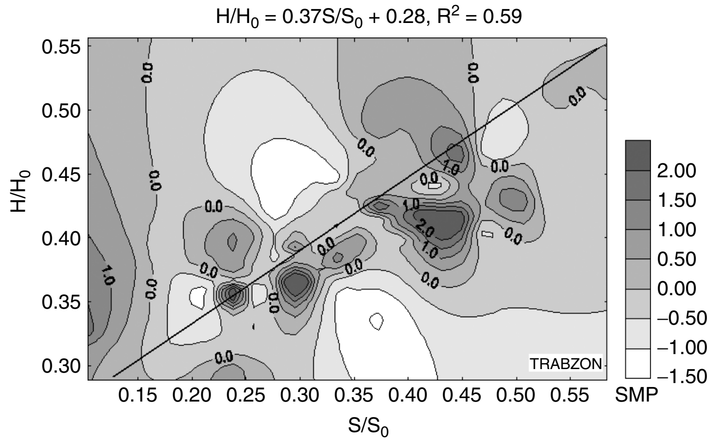

Figure 15. Triple solar-drought graphical approach among H/H_0 (solar irradiation), S/S_0 (sunshine duration) and SMP for the period 1982–1991 for Trabzon

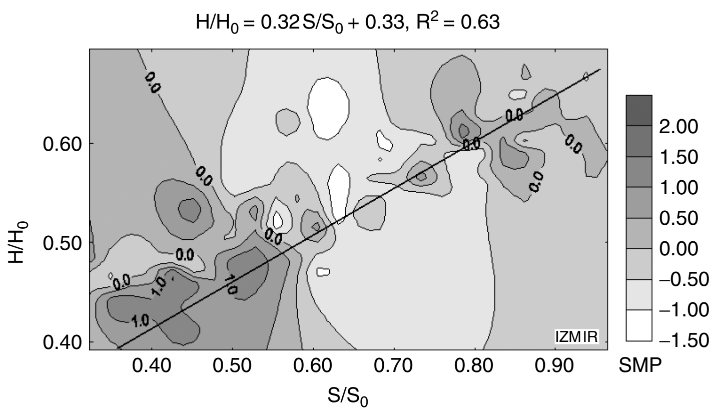

Figure 16. Triple solar-drought graphical approach among H/H_0 (solar irradiation), S/S_0 (sunshine duration) and SMP for the period 1982–1991 for İzmir

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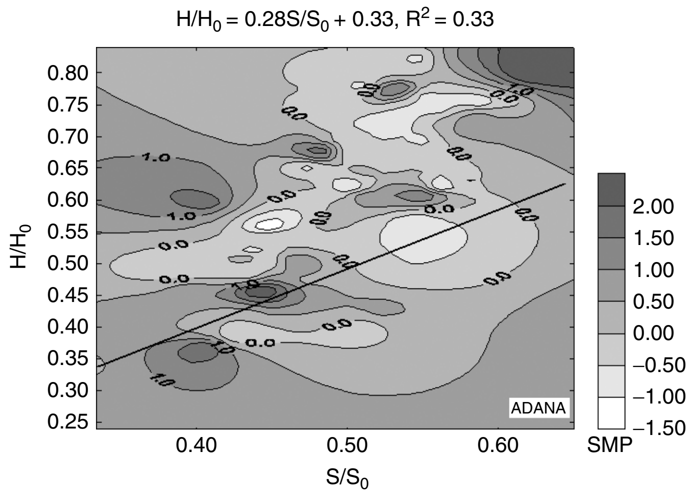

Figure 17. Triple solar-drought graphical approach among H/H_0 (solar irradiation), S/S_0 (sunshine duration) and SMP for the period 1982–1991 for Adana

political and other functions of a region during dry periods. Therefore, it is necessary to develop methods of prediction such as deterministic stochastic techniques based on the available past experiences on environmental conditions. Drought occurrence is rather complex since it depends on various interactions of many hydrological and meteorological phenomena such as rainfall, runoff, evaporation, solar irradiation, cloud cover, sunshine duration, infiltration, and surface, ground water storages and surface roughness. It is very difficult to predict drought before it takes place because it is a result of multi-scale complex processes. It starts slowly such as a few years ago and then affects gradually atmosphere processes and land. Droughts can be monitored using satellite observational systems and climatological indices but these indices can have some disadvantages because of assumptions used in their derivation. In this paper, the TGM includes a relationship with three variables which are sunshine duration, solar irradiation, and precipitation. These variables can be obtained easily which makes the present work unique. As a result drought prediction can be achieved from using the TGM graphs.

It should be noted that cloud processes are very complex and therefore precipitation processes can be related to meteorological processes in many different scales. For example liquid water content (LWC) versus temperature relationship studied by Gultepe and Isaac (1997) suggested that it decreases with height for the stratiform clouds. In fact, precipitation is related to availability of moisture in the atmosphere and surface conditions. In the same work although they did not have detailed observations, LWC decreased with increasing temperature, suggesting that global warming may be related to the decrease of LWC within the clouds to some degree. This suggests that detailed regional climate models should be used to better understand drought processes.

In addition, precipitation based drought description has been extended to the triple-variable technique that also includes solar irradiation and sunshine duration time series. It is possible to find a precipitation-solar irradiation-sunshine duration descriptor at a site using SMP contour lines based on solar irradiation and sunshine duration data. Then, such contours can be prepared for any base precipitation value but in this paper average precipitation value is taken as the truncation level.

The TGM provide information about the drought occurrences for different combinations of solar irradiation and sunshine duration. First, triple variable drought descriptors help to identify not only precipitation surplus (wet spells) or deficits (dry spells droughts) but also their variations with two more meteorological variables e.g. solar irradiation and sunshine duration. Second, the TGM approach provides not only some climatic variables but also allows the estimation of some solar engineering variables in the Angström equation. If sunshine duration ratio is known and using *a* and *b* parameters at Angström equation solar irradiation (H/H_0) ratio can be evaluated easily. In contrast to this, when solar irradiation ratio is known then sunshine duration can be evaluated by defined parameters. By using solar irradiation and sunshine duration ratios, drought magnitude can be estimated with the triple solar-drought graphical approach. This approach as explained before; can also be used also for drought intensity estimation.

CONCLUSIONS

The new drought estimation method that is proposed to combine three different variables on a two-dimensional domain Cartesian coordinate system is the TGM approach. It is shown that all variables are directly related to each other and there are physically and statistically meaningful relationships among these variables. Basic formulations are given between the variables of the Angström equation and drought variables, and their applications are presented for Diyarbakır, Konya, Adana, Izmir, Erzincan, İstanbul and Trabzon. The precipitation,

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sunshine duration and solar irradiation records in different parts of Turkey have been used for depicting the relationships between Angström variables and drought in the form of contour maps with the best linear Angström equation straight-line fits. It has been demonstrated that high level sunshine duration and solar irradiation ratios correspond to moderate, severe and extreme drought levels. At medium level, sunshine duration and solar irradiations ratios imply moderate drought values. Wet seasons occur at low-level Angström variables values.

Herein, the basics concern is with the precipitation based droughts, but in addition to precipitation time series closely related other two time series records are considered. These are, namely, solar irradiation and sunshine duration. It is a well-known fact that temperature or better evaporation, humidity, solar irradiation and sunshine duration are also among drought descriptor variables. Simultaneous consideration of precipitation, solar irradiation and sunshine duration presents a mean for drought assessment provided that their interrelationships are described on a Cartesian coordinate system. The best way of achieving such an interrelationship is through the visualization of precipitation values as mathematically dependent and solar irradiation and sunshine duration as independent variables. This gives rise to a different drought evaluation technique apart from the temporal and/or spatial methodology. This is in a way consideration of precipitation variability related to solar irradiation and sunshine duration (Sahin and Sırdaş, 2002). There are many benefits from such a triple-variable drought graph some of which can be given as:

(a) the variation of precipitation can be depicted according to solar irradiation and sunshine duration,
(b) it is possible to depict the locations of precipitation deficits on the basis of solar irradiation and sunshine duration ranges,
(c) one can construct arithmetic average and standard deviation variations of precipitation on the basis of solar irradiation and sunshine duration,
(d) for any given value of sunshine duration, it is possible to identify the precipitation variation with solar irradiation,
(e) likewise, precipitation variation with sunshine irradiation can be obtained for any given value of sunshine duration,
(f) regions of maximum precipitation can be enclosed and this gives rise to domains of solar irradiation and sunshine duration for maximum precipitation occurrences; these regions are representatives of water surpluses,
(g) likewise minimum precipitation occurrences can be located from triple-variable drought graphs, and accordingly, solar irradiation and sunshine duration ranges can be determined for such situations; these occurrences in the triple-variable drought graphs indicate actual precipitation deficits and hence drought concentration locations,
(h) it is possible to estimate the precipitation amounts for a given pair of solar irradiation and sunshine duration values; in this manner, one can also estimate drought spells and amounts,
(i) it is also possible to see the variation of drought variation with solar irradiation (sunshine duration) for a given level of sunshine duration (solar irradiation).

The influence of other meteorological variables on drought can also be studied by the TGM approach. This method also enhances the detailed identification of droughts, which is important especially for semi-arid and arid regions.

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