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Using GADI index to determine the drought and the dry areas in Kerman province

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Abstract

Aridity as a spatial concept and drought as a temporal concept have always been studied in different aspects as two distinct categories. However, both concepts indicate anomalies from normal condition. Several indices have been introduced to examine each of these concepts using one or more hydrological cycle's components. Meanwhile, soil moisture and changes in its spatial and temporal variations can be considered as one of the most important factors in detecting the drought and determining the areas of drought. Due to difficulties including cost and time consuming measurements, soil moisture has not been used so far. In this study, the intensity and the persistence of drought in Kerman province were evaluated using soil moisture from the output of NASA Global Land Data Assimilation System (GLDAS). For this purpose, the new GLDAS based Aridity and Drought Index (GADI) was used, which realized the drought and aridity in each region simultaneously. The soil moisture time series in four soil layers were derived from NOAH land surface model for the years 1953 until 2017. GADI were employed to map aridity and drought conditions. The results showed that the severity of drought increased in lower soil layers. The low percentage of soil moisture in the lower layers indicates that lower layers had not been fed from rainfall as a result of sever evaporation losses. This also shows the existence of long-term droughts in these layers.

Keywords: Drought; Soil moisture; GADI index; Land surface model

1. Introduction

Rainfall deficit in an area is one of the main (but not the only) causes of drought in that area which can have an impact on agriculture, runoff and drinking water. Water supply, which is needed for agriculture has many economic effects and in long-term, a water crisis can cause many serious problems (Guha-Sapir *et al.*, 2004). Drought is a repetitive action that can happen not only in arid and semi-arid areas but also can be seen in many humid and semi-humid areas (Soleymani Sardoo *et al.*, 2010). Although it is expected that greenhouse gases change the effects of drought, but there is always a doubt about the effects of temperature, rainfall and the soil moisture on the degree of drought all over the world (Touma *et al.*, 2015).

Meteorological droughts can cause hydrologic and agricultural droughts. Lack of rainfall causes meteorological droughts; and if these last they can cause hydrologic and agricultural droughts (Nazaripour *et al.*, 2016). Such can threaten rural life because there are very little job opportunities except farming. The first step for having a better understanding of related hydrologic actions, social and economic processes (Pande *et al.*, 2012) and categorizing areas for the right action (Ghazanfari *et al.*, 2013) is the proper determination of the degree of drought (Pande *et al.*, 2010). Despite drought, aridity is a climatic feature that is mostly present in areas with low rainfall and it is one of the permanent characteristics of that weather (Atayi and Khaje Longi, 2013).

One of the most common methods in monitoring droughts is calculating drought indices (Nazaripour *et al.*, 2016). For determining the degree and the range of

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drought, many indices were made; with each having its own inputs and special conditions (Hanafi, 2013). Spatial and temporal development as well as the degree of drought will be determined by the use of these indices (Nazaripour *et al.*, 2016). Indices like Standard Precipitation Index (SPI), Z-Score Index (ZSI), Decile Precipitation Index (DPI) and Percent Normal Precipitation Index (PNPI) are indices based on the accessibility to the climatic data which choses weather variables as the input. However, Palmer Drought Severity Index (PDSI) and United Nations Environment Program (UNEP) aridity index, which are two common indices for drought and aridity, are somehow limited. PDSI index measures the local deviation of soil moisture from the amount of its long-term average (Palmer, 1956). This index shows the correlation of climate conditions in an area. This drought index is one algorithm based on soil moisture balance. The necessary components for this index are included such as average monthly or weekly air temperature, total rainfall, available water storage capacity and potential evaporation (Palmer, 1956). Therefore, PDSI index cannot be used for a cross comparison of two sites (Palmer, 1956). Two sites with a significant different soil moisture conditions may have the same PDSI values, so PDSI is most suitable for comparing site specific drought severities in different time periods. Also, this index is more suitable for agricultural impacts and is not very convenient for hydrologic droughts. The UNEP aridity index will provide a scale that compares different areas. This index is based on ratio of yearly evaporative demand to rainfall supply (UNEP, 1997). On the contrary to PDSI index, the UNEP index is not based on the soil moisture (Zhang *et al.*, 2009). Because land use and the available water storage capacity have a significant effect on the hydrologic cycle; an index with all hydrologic models' output can consider most of the aspects (Yang *et al.*, 2012).

Recently, Hydrological model outputs have been widely employed for monitoring drought and aridity. Niazi (2017) has shown that water and energy balance components, especially soil moisture in central Iran during 2000 to 2015 using Variable Infiltration Capacity (VIC) land surface model outputs has an acceptable accuracy. The outputs of soil moisture were used as the inputs for the drought index on the base of Palmer water balance (Palmer, 1956). Results have shown that VIC-PDSI index has the most correlation coefficient in comparison to other drought indices that are as 0.61 with

soil moisture data and 0.87 with the changes in groundwater level.

Mao *et al.* (2017) have used the VIC model and the Soil Moisture Anomaly Percentage Index (SMAPI) for determining drought and analysing the time and place specification of drought between 1956 and 2011. Results have shown that the VIC model and the simulated three layered daily soil moisture database can be replaced by the measured soil moisture.

Other similar studies have introduced drought indices based on the soil moisture resulted from hydrological models (Soud *et al.*, 2003; Kingtes *et al.*, 2011; Wang *et al.*, 2011; Shefild *et al.*, 2007; Shefild *et al.*, 2009). Hoberg *et al.* (2012) have made a drought model based on Gravity Recovery and Climate Experiment (GRACE) data. They indicated that standard drought indices provide little information about the soil moisture and ground level water in depth (Ghazanfari *et al.*, 2013).

Using the average of rainfall only considers meteorological drought whereas hydrologic and agricultural droughts later will happen in meteorological drought. On the other hand, using self-site data at each point reduces uncertainty of output for that site. In the literature, interpolation methods were used in areas between stations in order to generalize the results. This reduces drought zoning accuracy. Most of the used indices, which are used for analysing droughts, are completely useless for analysing aridity. Meanwhile, determining dry areas has a significant role in planning for water sources. Most researches have used only normal indices to study drought in Iran. These indices are generally measurable by using rainfall data. However, in most areas there may not be any rain gauge station or maybe its data is incomplete. Also aridity has been less analysed by researchers simultaneously with drought (Ghazanfari *et al.*, 2013).

Ghazanfari *et al.* (2013) have introduced a new index using soil moisture in different layers which can analyse aridity and drought at the same time. They have used GLDAS land surface models to extract soil moistures in different layers. Empirical Orthogonal Functions (EOF) were used to calculate GADI (GLDAS based Aridity and Drought Index) for global scale. Results from this study have shown that using this index can show areas that are changing to dry sites better than other indices (Ghazanfari *et al.*, 2013).

In this paper, GADI were employed to study drought and aridity condition in Kerman province. The main aim of this research was to determine different types of drought

(meteorological, hydrological and agricultural) from the availability of water in different soil layers. The novelty of this study is that GADI have not been used for drought assessment yet. The advantage of using GADI is to provide tools to analyse drought and aridity at the same time using site specific data. One of the inclusive features of this index in comparison to other indices is the possibility of simultaneous spatial and temporal comparison. Also by the use of soil moisture in different layers, this index can consider meteorological, agricultural and hydrologic droughts and can compare their delay time.

2. Materials and Methods

2.1. Study area

Kerman province is the biggest province in Iran, which is located in the south east of Iran and covers almost 11 % of the country. This province is located in 53° 26' to 59° 29' eastern longitudes and also in 25° 55' to 32° 00' northern altitudes. The climate of this province is mostly arid and semi-arid. The main rainfall in this province is about 145 mm, the average temperature is 16°C, the minimum and maximum altitude is 200m and 4465m above sea level respectively.

2.2. GADI index

The GLDAS based Aridity and Drought Index (GADI) was introduced by Ghazanfari *et al.* (2013) which can analyse drought and aridity simultaneously. This index uses data from soil moisture that is achieved by the global soil moisture land surface models.

For this index, analysing three GLDAS land surface models are used which include: VIC, MOSAIC and NOAH. One of the advantages of using this method is the updated soil moisture data that makes it available for all sites. The index shows that temporal dominant site specific soil moisture is less or more than the spatial dominant soil moisture of the whole area. Table 1 shows the values of GADI index based on different aridity and drought conditions.

This index was made out of periods of three decades from different sites of soil moisture with different land uses. For presenting a place model related to the condition of soil moisture, the Empirical Orthogonal Functions (EOFs) of the three VIC, MOSAIC and NOAH models have been measured.

If in the M stations and in the N periods the hydrologic variables (such as rainfall, temperature, soil moisture, etc.) were measured, a matrix with M columns and N rows can be drawn for each variable. Here, a matrix for soil moisture in each layer is considered. The mentioned matrix can be decomposed to its Eigen values and Eigen vectors. The first column of the Eigen values will be derived.

If the measured variable in station X in time of t showed with X_t; analysing of EOF is a method that decomposes it into temporal and spatial series.

The mean and the standard deviation can be measured by the following formulas:

$$x=1,2,3,\ldots,m$$
$$\overline{y_x} = \frac{\sum_{t=1}^{N} y_{x,t}}{N} \tag{1}$$

$$x=1,2,3,\ldots,m$$
$$S_x^2 = \frac{\sum_{t=1}^{N}(y_{x,t}-\overline{y_x})}{N-1} \tag{2}$$

Normal data was shown by $f_{x,t}$ and can be measured as follow:

$$f_{x.t} = \frac{y_{x,t}-\overline{y_x}}{S_x} \qquad t=1,2,3,\ldots,N$$
$$x=1,2,3,\ldots,m \tag{3}$$

If standard data was showed in a m*n matrix, it is as following:

$$F = \begin{bmatrix} f_{1,1} & \cdots & f_{1,N} \\ \vdots & & \vdots \\ f_{m,1} & \cdots & f_{m,N} \end{bmatrix} \tag{4}$$

Each matrix F contains m measured amount at n time. The correlated matrix is defined as R=FF^t. R is m*m matrix which includes r_{ij} elements that are defined as:

$$i=1,2,\ldots,m \qquad j=1,2,\ldots,m \qquad r_{i,j} =$$
$$\sum_{n=1}^{N} f_{i,n}f_{j,n} \tag{5}$$

R is a symmetric matrix and has M true positive amount. r_{ij} is the summation of the amount of variables in one station multiplied by other station in corresponding times.

2.3. NASA GLDAS

The aim of NASA GLDAS is to use satellite data and observational data from land surface to simulate land surface and its hydrologic relations. GLDAS includes NOAH, VIC, CLM and MOSAIC models (Rui *et al*, 2018). GLDAS

data has data forcing, one of them is completely adjusted with meteorological data and the other one is a mix of observational models and data. GLDAS data include the period from 1948 up-to-date. GLDAS data's spatial resolution is three

hours and its temporal resolution is 0.25 degrees. Monthly data will be produced out of the average of three hours data. Table 2 shows some of the main features of GLDAS data.

Table 1. The amount of GADI index based on site specific aridity and drought

Current situation	GADI
Arid areas in drought	0 to 0.03
Arid areas in normal conditions	0.03 to 0.06
Arid areas in wet condition	0.06 to 0.1
Semi-arid areas in drought	0.1 to 0.13
Semi-arid areas in normal conditions	0.13 to 0.16
Semi-arid areas in wet condition	0.16 to 0.2
Humid areas in drought	0.2 to 0.23
Humid areas in normal conditions	0.23 to 0.26
Humid areas in wet condition	0.26 to 0.3

Table 2. Main features of NASA GLDAS data (Rui and Beaudoing, 2018)

Contents	Outputs from NOAH and catchment land surface models
Format	Net CDF
Latitude extent	-60° to 90°
Longitude extent	-180° to 180°
Spatial resolution	1.0°, 0.25°
Temporal resolution	3-hourly, daily, and monthly

4.2. GADI index and data

NOAH (LSM) data has been used in this study. The data included soil moisture in 4 different depths (0-10 cm), (10-40 cm), (40-100 cm) and (100-200 cm) over 65 years (1953-2017). Therefore, except 2017 there were 48 pieces of data (12 months and 4 depths) and for 2017 there were 32 pieces of data (8 months and 4 depths). Soil moisture data was measured in kilogram per cubic meter, which has been converted to millimetre for each pixel based on the pixel area.

Information about Kerman province was extracted by shape file after categorizing data respectively as year, month, and the depth of soil moisture. Raster data from GLDAS outputs were converted to ASCII format to be used in MATLAB software for calculations. Each text file stood for one month of the year that included 238 numbers. From all 238 numbers, 139 of them had values for each pixel.

For each depth, all years and months were organized. Then all the text files were converted to a matrix by MATLAB software with the sizes of 139 by 776 (776 months and for each month there were 139 pixels). After that, each transposed of a matrix was multiplied to the related matrix and the result matrix's size was 139 by 139. Vector matrix was calculated for

each square matrix. The first column of vector matrix has 139 numbers, which was selected as the index moisture of each pixel. All 139 numbers were placed respectively in a text file. The text file was changed to raster format in ArcGIS software. This process was done for the first, the second and the third depths. The procedure was carried out for the average of first and second depths, the average of first, second and third depths and also for the average of all four depths. Then the maps for GADI index were extracted based on the depth. For determining the degree of drought during the last 5 years in different areas, all the calculations were repeated for the first 60 years. The numbers of corresponding Eigen vector were subtracted from Eigen vector in 65 years. Therefore, as a result minus negative numbers showed drought and positive numbers showed wet condition for each pixel.

3. Results

GADI index numbers for four different depths in Kerman province including 1 to 10 cm (Fig. 1A), 10 to 40 cm (Fig. 1B), 40 to 100 cm (Fig. 1C) and 100 to 200 cm (Fig. 1D) were calculated. Figure 1 shows the results for four different depths.
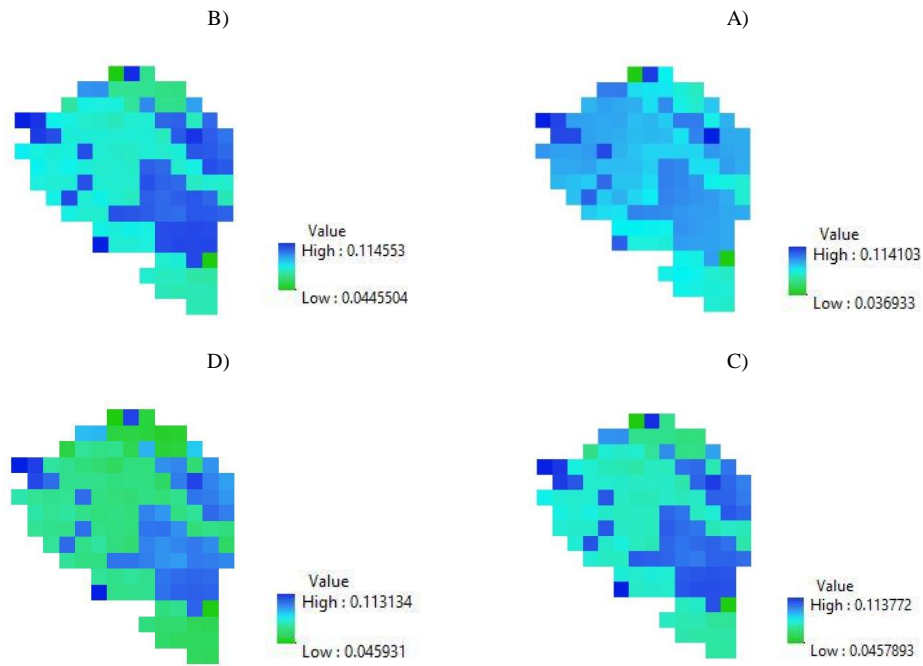
Fig. 1. GADI index values for Kerman province using 65 years of soil moisture content at depths of A) 0-10 cm, B) 10 to 40 cm, C) 40 to 100 cm, and D) 100 to 200 cm

The amount of GADI index for the first and second layers were between 0.04 and 0.11 and for third and fourth layer were between 0.05 and 0.11 as shown in the figures. The maximum amount of index for moisture was for the second layer and the minimum was for the first layer.

Also the average moisture for three depths was calculated based on different depths moisture. As a result, the average soil moisture was calculated for the depths 0 to 40 cm (first and second layer average, Fig. 2A), 0 to 100 (first, second and third layer average, Fig. 2B)

and also for 0 to 200 (fourth layer average, Fig. 2C). The map of GADI index for this average was shown in Fig 2.

GADI index amount for the first and second average layers' moisture were 0.4 to 0.11, while for third average layer it was 0.5 to 0.11. The maximum amount of index average moisture was for the second layer and the minimum was for the first layer. The difference map for corresponding Eigen vector for each pixel related to the first 60 years from all the years for all layers were measured (Fig. 3).
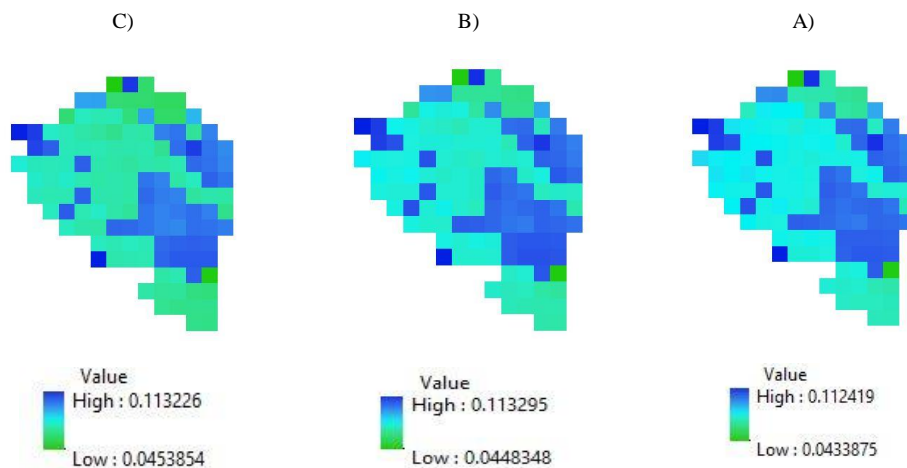

Fig. 2. GADI index values for Kerman province using 65 years of soil moisture content for the average depth of A) 0 to 40 cm, B) 0 to 100 cm, and C) 0 to 200 cm

With the use of this map, the degree of drought for each area based on the positive and negative amounts was calculated separately. As

a result, negative numbers showed the drought during the last 5 years and positive numbers showed the wet condition.
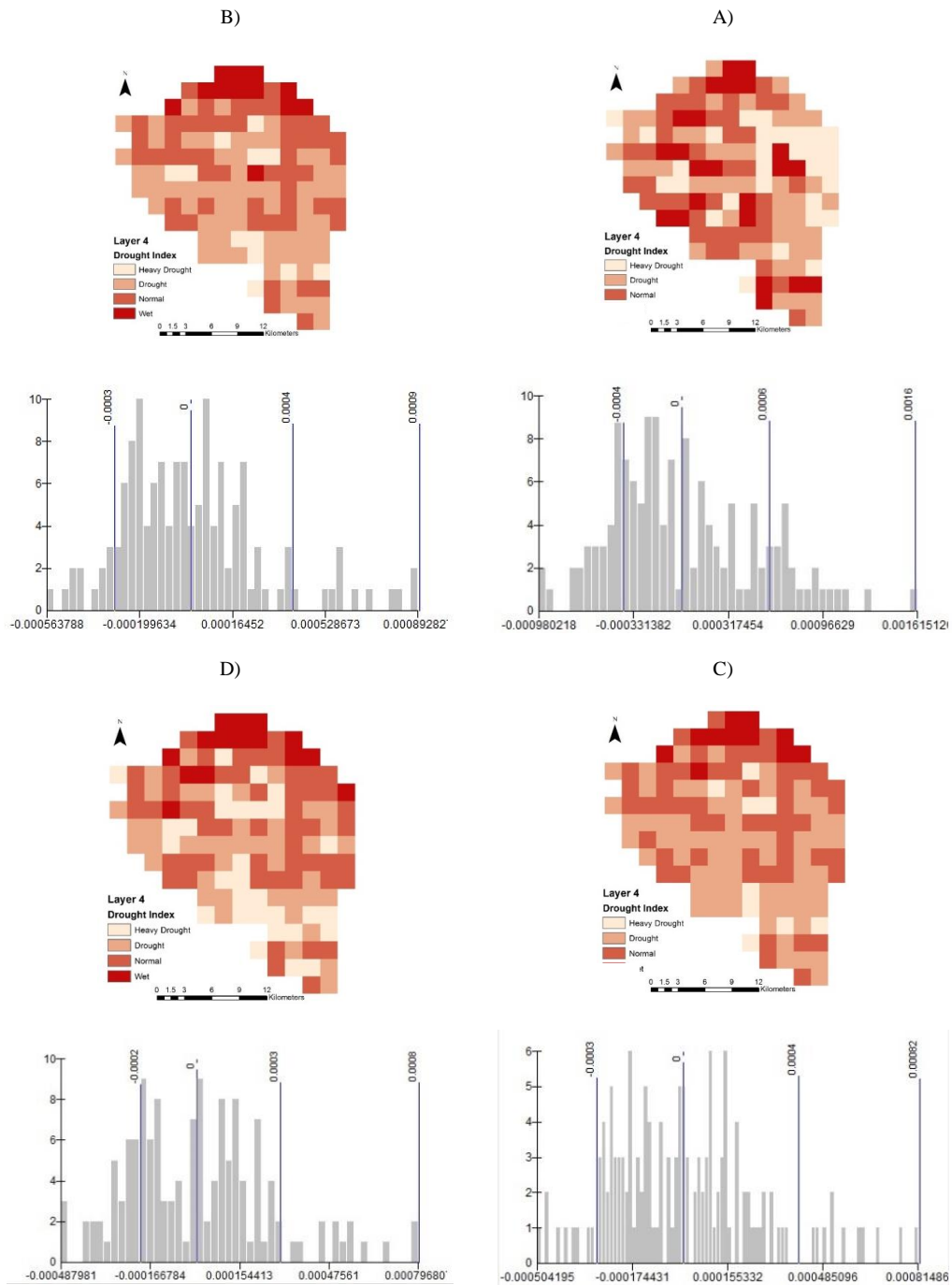

Fig. 3. Differences in values of the GADI index; Total years from the 60th year of primary and spatial dispersion. The percentage of different areas in terms of drought for Kerman province using soil moisture at depths of A) 0-10 cm, B) 10 to 40 cm, C) 40 to 100 cm and D) 100 to 200 cm

4. Discussion

Results have shown that based on the moisture in all layers and the amount of index (Table 1), Kerman province is arid and is in

drought (Figs. 1 and 2). Because all the numbers of the index in soil moisture are less than 11, the soil moisture of Kerman province is considered to be a dry region and also these numbers show drought in this province.

Additionally, results from GADI index show that underlying layers have faced more intense drought. It can be concluded that the first layer of the soil shows the degree of meteorological and hydrologic drought. The other layers based on their depth, show agricultural and economic drought. Since Kerman province is subject to heavy evaporation losses, it can be concluded that the index has shown true results. While evaporation losses prevent deep percolation, drought in the first layer in comparison to other layers has happened with less intensity (Fig. 1A). Fewer pixels with positive value in 2nd, 3rd and 4th layers have increased respectively. Therefore, the amount of moisture flux from the first layer to atmosphere (which has happened by evaporation) is more than downward moisture flux. This shows the importance of using soil moisture for determining aridity and drought. As saving water after rainfall is very important, in places which saving water is not possible, more rainfall can't change the drought situation.

Results revealed that the degree of drought has increased by depth in arid areas (Fig. 2). Fewer percentage of moisture in underlying layers in comparison to other upper layers shows that they haven't had enough rainfall. This also shows long term drought in this area.

As the moisture in the fourth layer is normally out of root zone, since the amount of soil moisture in this layer is less, it shows that rain loss in these areas is more than moisture penetration to these layers. On the other hand, results have shown that the degree of drought in dry areas (south and east) is more than other areas with more rainfall amount (Fig. 3). Drought is a statistical concept that shows lack of rainfall in accordance to long term average. Therefore, in arid areas where rainfall's standard deviation is less than humid regions, lack of rainfall on big scales causes more droughts.

Graph of pixels' percentage in different drought conditions for different layers indicates that in the second and third layers, most areas are in normal condition, and the percentage of areas exposed to drought and wet conditions are equal. However, conditions in the first and fourth layers are similar and their condition are more exposed to droughts. In the first, second, third and fourth layers, 23, 9, 6 and 23 percent of pixels are exposed to severe drought respectively. Accordingly, it can be noted that the drought of the first stage (meteorology) was much more severe than agricultural drought and the region has been able to control the drought severity of agriculture by maintaining the moisture content of the middle layer (root zone).

However, the presence of drought in the fourth layer indicates that there is not enough soil moisture to feed, which in the long run can have a devastating effect on water resources.

5. Conclusion

Results from this study indicate that looking at drought without considering aridity situation could make changes in the conclusion and increases uncertainty of results. Furthermore, looking at the lack of rainfall as the main factor to study drought may not show the real facts on water scarcity. Some places with good reservoir of moisture in lower soil layers may not be affected by decreasing rainfall amount. However, lack of soil moisture capacity may cause agricultural drought even while rainfall is taking place in the normal range. Therefore, a general sight to the hydrology cycle can help to monitor drought while the aridity situation is considered. This study shows that soil moisture in different layers from the global land surface model can be generalized to a good index based on EOF analysis. GADI, by employing Eigen values and Eigen vector concepts, provides a robust index to study temporal (which is drought concept) and spatial (which is aridity concept) concepts simultaneously.

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