Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-642
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 17 January 2019

Hydrology and Earth System Sciences
Open Access
Discussions

Spatiotemporal Changes in Aridity of Pakistan during 1901-2016

Kamal Ahmed[1, 2], Shamsuddin Shahid[1], Xiaojun Wang[3, 4]*, Nadeem Nawaz[2], Najeebullah Khan[1]

[1]Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM), Johor Bahru, 81310, Malaysia
[2]Faculty of Water Resource Management, Lasbela University of Agriculture, Water and Marine Sciences, Balochistan, 90150, Pakistan
[3]State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute, Nanjing, 2100292, China
[4] Research Center for Climate Change, Ministry of Water Resources, Nanjing, 210029, China

Correspondence to: Xiao-Jun Wang (xjwang@nhri.cn)

Abstract. The changing characteristics of aridity over a larger spatiotemporal scale have gained interest in recent years due to climate change. The long-term (1901-2016) changes in spatiotemporal patterns of annual and seasonal aridity during two major crop growing seasons of Pakistan, Kharif and Rabi are evaluated in this study using gridded precipitation and potential evapotranspiration (PET) data. UNESCO aridity index was used to estimate aridity at each grid point for all the years between 1901 and 2016. The temporal changes in aridity and its associations with precipitation and PET are evaluated by implementing a moving window of 50-years data with 11-year interval. The modified Mann Kendall trend test is applied to estimate unidirectional change by eliminating the effect of natural variability of climate and the Pettitt's test is used to detect year of change in aridity. The results reveal that climate over 60% of Pakistan (mainly in southern parts) is arid. The spatial patterns of aridity trends show a strong influence of the changes in precipitation on aridity trend. The increasing trend in aridity is noticed in the southeast where precipitation is low during Kharif while a decreasing trend in Rabi season in the region which receives high precipitation due to western disturbances. The annual and Kharif aridity are found to decrease at a rate of 0.0001 to 0.0002 per year in northeast while Kharif and Rabi aridity are found to increase at some locations in the south at a rate of -0.0019 to -0.0001. The spatial patterns of aridity changes show a shift from arid to the semi-arid climate in annual and Kharif over a large area while a shift from arid to hyper-arid region during Rabi in a small area. The most of the significant changes in precipitation and aridity are observed in the years between 1971 and 1980. Overall, aridity is found to increase in 0.52%, 4.44%, and 0.52% area and decrease in 11.75%, 7.57%, and 9.66% area for annual, Rabi and Kharif seasons respectively during 1967-2016 relative to 1901-1950.

1 Introduction

More than 20% of the global population is living in arid regions under the threat of severe consequences of climate change, particularly due to increasing hydrological extremes (Alazard et al., 2015). The temporal variability and spatial distribution of precipitation and other hydrological phenomena have significantly changed with the increase in global temperature (Kousari et al., 2014). Changes in precipitation have triggered more hydrological extremes such as floods or droughts. The ecosystems of arid and semi-arid climates are sensitive to minor changes in climate (Ahmed et al., 2018). These regions are also characterized by very complex hydrological systems due to high variability in precipitation which often exhibit extreme behaviours, such as flash floods triggered by extreme precipitation and extended droughts due to prolonged dry spell (Buytaert et al., 2012). The droughts are projected to become more frequent and severe in arid regions due to an increase in aridity (Nam et al., 2015) as reported in Iran (Tabari et al., 2012), Serbia (Hrnjak et al., 2014), Turkey (Selek et al., 2018), Iraq (Şarlak and Agha, 2018), India (Ramarao et al., 2018) and China (Liu et al., 2018a) among others. Climate models projected an increase in the range of 11 to 23% by 2100 in global arid and semi-arid climate area which will expand aridification in different parts of the globe (Huang et al., 2016).

Pakistan located in South Asia has a complex terrain with limited water resources. Several attempts have been made to classify the aridity and climate of Pakistan based on different climate variables and methods (Bharuqha and Shanbhag, 1956;Oliver et al., 1978;Shamshad, 1988;Chaudhry and Rasul, 2004;Hussain and Lee, 2009;Zahid and Rasul, 2011;Sarfaraz, 2014;Sarfaraz et al., 2014;Haider and Adnan, 2014). Bharuqha and Shanbhag (1956) classified the climate of a station based on the fraction of precipitation to evaporation for the period 1926−1940. Oliver et al. (1978) applied clustering approach for climate classification using meteorological data from 53 stations. Chaudhry and Rasul (2004) used Thornthwaite's precipitation effectiveness index for estimation of annual and seasonal aridity for the period 1961-1990 using temperature data of 50 stations. Hussain and Lee (2009) classified the climate using factor and cluster analysis utilizing 26 years (1980-2006) rainfall and temperature records of 32 stations. Haider and Adnan (2014) estimated several aridity indices to classify the climate of Pakistan based on records of 54 stations for the period 1961-2009. Sarfaraz (2014) and Sarfaraz et al. (2014) used principal component analysis and Köppen classification respectively to classify the climate. Recently, Nabeel and Athar (2018) classified the climate based on wet and dry spell using 46 stations data ranging from 1976 to 2007. Even though several studies have been conducted for the classification of climate using aridity indices, no attempt has been made so far to assess the changing characteristics of arid climatology of Pakistan over a longer period.

In recent years, an increase in aridity is reported in Pakistan (Haider and Adnan, 2014). Several studies suggest rising temperature and changing precipitation due to global warming are the primary factors for increasing aridity. Recently, Pakistan experienced several temperature extremes in the form of scorching heatwaves that resulted in large fatalities. Additionally, prolonged spells of droughts due to lack of seasonal precipitation caused huge economic damages. The annual maximum temperature in the country is increasing at a rate of 0.17- 0.29 ℃/decade (Khan et al., 2018), while the precipitation is reported to increase in the north and decrease in the south at a rate of -4 to 4 mm/year in last fifty years (Ahmed et al., 2017). The variations in temperature and precipitation patterns are also reported in different climatic and cropping seasons (Iqbal et al., 2016). The rising temperature has intensified the evaporation which in turns has caused water losses from major water reservoirs and thus causing water scarcity. In this context, assessing the changing characteristics of precipitation and potential evapotranspiration (PET) over the manifold topography and climate of Pakistan is very important. As the characteristics of precipitation, PET and aridity changes with season and time, it is also imperative to evaluate their changing patterns for different time periods and seasons.

The main objective of the present study is to evaluate the changing characteristics of aridity based on precipitation and PET in annual and two distinct cropping seasons (Rabi and Kharif) of Pakistan. A number of aridity indices are available for the classification of aridity such as de Martonne aridity index (de Martonne, 1926), Thornthwaite aridity index (Thornthwaite, 1931), Erniç aridity index (Erinç, 1965), UNESCO aridity index (UNESCO, 1979). Among all the aridity indices, the UNESCO aridity index which considers the effect of precipitation and PET for the classification of climate is most widely used (Zarch et al., 2017). The long-term (1901-2016) gauge-based gridded precipitation and PET datasets is analyzed by implementing a moving window of 50-years data with 11-year interval. The modified Mann-Kendall trend (MMK) is used to evaluate the significance of changes estimated using Sen's slope estimator and the Pettitt's test is used to identify the year of change in aridity and climate. It is expected that the use of MMK test would provide the changes in aridity due to global warming by eliminating the effect of natural variability of climate. The procedures presented in this study can be used for the assessment of the changing characteristics of aridity and the identification of the factors that drives the changes which can help to understand possible shift in climatology of an area owing to climate change. The findings of the study can be helpful for Pakistan in planning adaptation measures and adjust cropping patterns to ensure sustainability in agriculture.

2 Study Area and Datasets

2.1 Description of the Study Area

Pakistan located in South Asia shares borders with India in the east, China in the north, Iran and Afghanistan in the west, and the long coastline with the Arabian Sea in the south (Fig.1). Around 80% of the land is characterized by arid to semi-arid climate where precipitation is less and temperature is high (Khatoon and Ali, 2004). The topography of the country varies widely from plain lands in the south to high mountainous ranges in the north. The large variations in topography from 0 to 8552 m above mean sea level causes a large variation of climate in the country.

Rabi and Kharif are the two major cropping seasons of Pakistan (Chaudhry and Rasul, 2004). The Rabi season commences in the month of November and finishes in May while the Kharif season starts in April and finishes in October (Nabeel and Athar, 2018). Both the seasons coincide with two major rainy seasons i.e. winter and monsoon. Rabi coincides with winter (December to March) when the moist wind from the Mediterranean Sea brings precipitation in the west and north of Pakistan (Hussain and Lee, 2014). On the other hand, Kharif coincides with monsoon (June to September) which brings moist wind from the Bay of Bengal and contributes 60% of total precipitation of the country (Sheikh, 2001). The agro-economy and the livelihood of farmers constituting 43% of total population of Pakistan significantly depend on winter and monsoon (Ahmed et al., 2018).

The precipitation in both seasons varies widely in time and space (Ullah et al., 2018b). The mean annual precipitation in Rabi is 119 mm/year and Kharif is 191 mm/year. The precipitation varies from 10 to 700 mm from the southwest to the north during Rabi and 11 to 900 mm from the southwest to the north near the foothills of Himalaya during Kharif. Most of the country receives precipitation less than < 100 mm in Rabi and < 190mm in Kharif (Ahmed et al., 2018).

The Rabi and Kharif have contrasting temperature due to their coincidence with winter and summer respectively (Ullah et al., 2018a). The annual average temperature is 14 ºC during Rabi and 26 ºC in Kharif (Khan et al., 2018). The average temperature in around 10% of the country (the northwest and far north) goes below zero during Rabi season while it goes above 30 °C in 45% of the area during Kharif. The overall temperature varies from -12 to 23 °C in Rabi and 1.9 to 33 °C in Kharif (Ahmed et al., 2018).

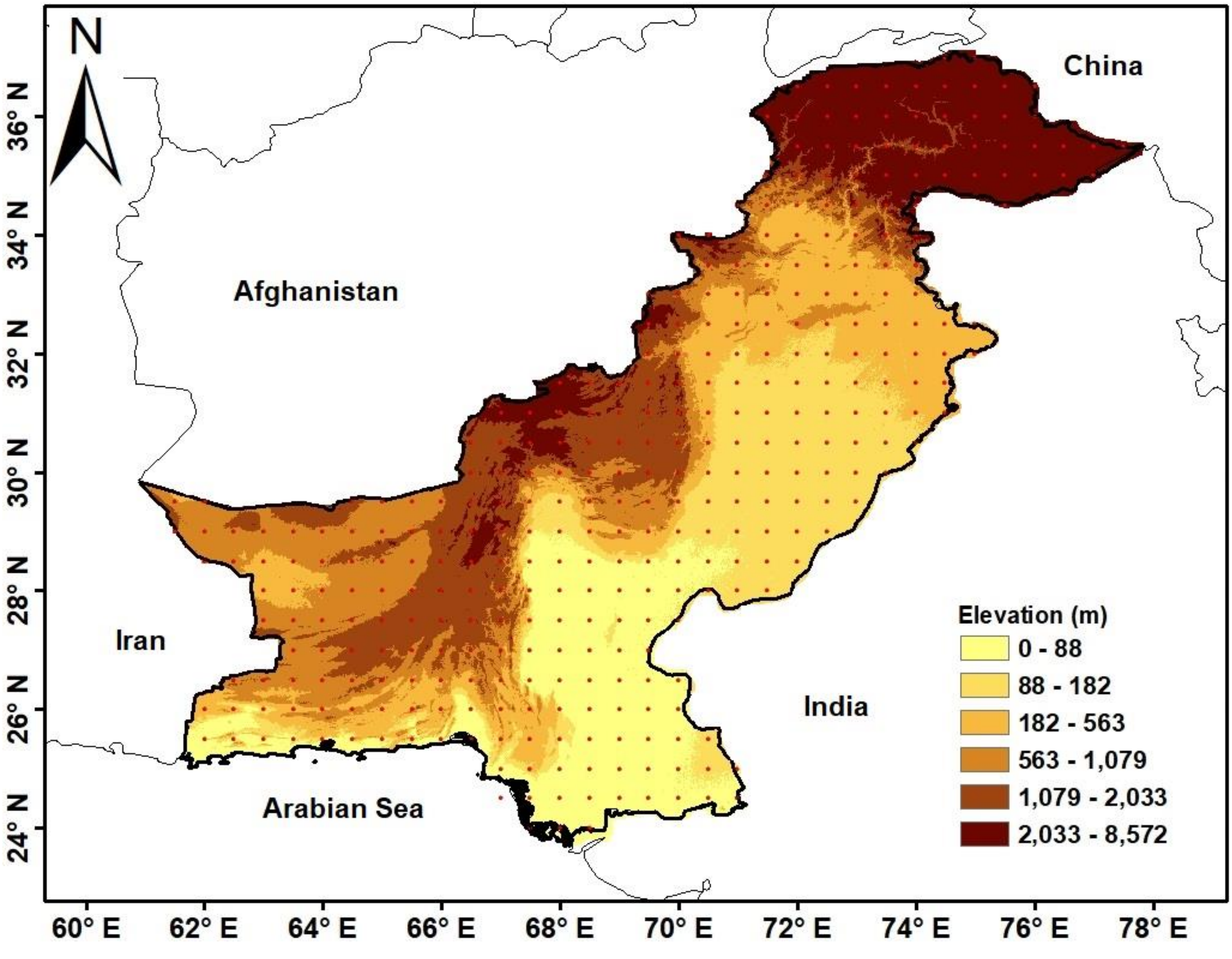

Figure 1. Geographic location and topography of Pakistan. The locations of precipitation and potential evapotranspiration data extraction are presented using dots.

2.2 Datasets

In The gauge-based gridded climate data are widely used as a proxy of observed precipitation and PET data around the world (Shiru et al., 2018). Over the last two decades, a number of gauge-based gridded datasets has been developed and applied for different purposes (Li et al., 2014). Among them, the datasets of Global Precipitation Climatology Centre (GPCC) (Schneider et al., 2013) (dwd.de/EN/ourservices/gpcc/gpcc.html) and Climatic Research Unit (CRU) (Harris et al., 2014) of the East Anglia University (crudata.uea.ac.uk) are the most popular due to their spatial and temporal continuity (Kishore et al., 2015). Thus, GPCC precipitation and CRU PET data are used in the present study. The GPCC and CRU data have a number of advantages that made the products superior to others. Both the datasets are developed by considering relatively a large number of in-situ data (Schneider et al., 2014;Harris et al., 2014). Besides, these datasets are available at high spatial resolution ($0.5^{o} \times 0.5^{o}$) and longer period (1901 to 2016) that helps better understand of the changes in climate (Spinoni et al., 2014). Furthermore, an extensive quality control procedure was followed during the development of GPCC and CRU data which has made them more reliable compared to other products (Sun et al., 2014). Additionally, robust interpolation technique was used in development of GPCC (Spheremap spatial interpolation) and CRU (Thin plate smoothing splines interpolation) (Becker et al., 2013;New et al., 2002). Several studies revealed better agreement of GPCC and CRU data with station records of Pakistan (Adnan and Ullah, 2015;Asmat et al., 2017). The precipitation and PET data are extracted from 350 grid points for the period 1901-2016 to cover the entire Pakistan.

3 Methodology

3.1 Aridity Index

Aridity index (AI) is often used to quantify the long-term climatic conditions of an area (Ashraf et al., 2014). A number of definitions of aridity can be found in literature which are derived using different climate variables like precipitation, temperature and PET (Zarch et al., 2017). Among them, the AI definition of UNESCO (1979) as a ratio of precipitation to PET is most widely used (UNEP, 1992). The precipitation and PET data are averaged for a year or a season to estimate AI. The AI categorized climate of an area into five classes, hyper-arid ($AI<0.03$), arid ($0.03\leq AI<0.20$), semi-arid ($0.20\leq AI<0.50$), sub-humid ($0.50\leq AI<0.75$) and humid ($AI\geq 0.75$).

Various methods are available in the literature to estimate PET. Among them, the Thornthwaite (Thornthwaite, 1948) and Penman-Monteith (Monteith, 1965) methods are most widely used. The Penman-Monteith method is adopted in UNESCO (1979) while the Thornthwaite method is adopted in UNEP (1992) for defining aridity. Thornthwaite method is preferred over the Penman-Monteith method in data scare regions (Zarch et al., 2015). However, Penman-Monteith method provides better estimation \ compared to other approaches (Tukimat et al., 2012). Thus, CRU PET data estimated using Penman-Monteith method is used in the present study.

3.2 Sen's Slope Estimator

Sen's slope estimator (Sen, 1968) is a non-parametric method which is widely used for robust estimation of change over a period (Yue et al., 2002;Khan et al., 2018). In this method, the rate of change in data between two consecutive times is first estimated for the whole series. The median of all the consecutive changes in data series is then determined to show the rate of change for the whole period.

3.3 Modified Mann-Kendall (MMK) Test

In MMK test (Hamed, 2008), the significance in the trend is first computed by applying classical MK test. The MMK test is performed only if there is any significant trend, otherwise it considers no trend in data series. In case of significant trend, the data series is de-trended and ranked (R_i) to estimate the equivalent normal variants of rank,

$$Z_i = \phi^{-1}\left(\frac{R_i}{n+1}\right) \tag{1}$$

where, n is the number of data in series, and ϕ^{-1} is the inverse standard normal distribution function. A correlation matrix is then derived to assess self-similarity or the Hurst coefficient (H) (Koutsoyiannis, 2003):

$$C_n(H) = \left[\rho_{|j-i|}\right], \qquad for\ i = 1{:}n;\ j = 1{:}n \tag{2}$$

$$\rho_l = \frac{1}{2}\left(|l+1|^{2H} - 2|l|^{2H} + |l-1|^{2H}\right) \tag{3}$$

where ρ_l represents lag l autocorrelation of provided H, which is obtained using the maximum log-likelihood method. The variance of classical MK statistics (S) is calculated if H is found significant,

$$V(S)^{H'} = \sum_{i<j} \cdot \sum_{k<l} \frac{2}{\pi} \sin^{-1}\left(\frac{\rho|j-i| - \rho|i-l| - \rho|j-k| + \rho|i-k|}{\sqrt{(2-2\rho|i-j|)(2-2\rho|k-l|)}}\right) \tag{4}$$

Where, $V(S)^H$ is used to represent the biased estimate of variance S. The bias can be removed using a correction factor, which is a function of H,

$$V(S)^H = V(S)^{H'} \times B \tag{5}$$

Finally, Z statistics is used to compute the significance as,

$$Z = \begin{cases} \dfrac{V(S)^H - 1}{\sqrt{Var\ (V(S)^H)}} & when\ V(S)^H > 0 \\ 0 & when\ V(S)^H = 0 \\ \dfrac{V(S)^H - 1}{\sqrt{Var\ (V(S)^H)}} & \text{when}\ V(S)^H < 0 \end{cases} \tag{6}$$

3.4 Pettitt Test

The point of change in time series is detected using Pettitt test (Pettitt, 1979). This nonparametric test is adopted from Mann-Whitney test which allows identification of the point at which any significant shift occurred in time series. The shift is detected in the year *m* when the estimated value of Pettitt test statistic (X_E) exceeds the critical value:

$$X_E = \max_{1 \le d \le n} |X_d| \quad (7)$$

where, X_d is Mann-Whitney statistic and can be calculated for a series of *n* point as:

$$X_d = 2\sum_{i=1}^{d} r_i - d(n+1) \quad (8)$$

where, *d* can have a value from 1 to *n*, and r_i is the rank of i_{th} observation.

4 Result

4.1 Spatial patterns of Precipitation and PET

The spatial patterns in annual and seasonal precipitation and PET from the mean of 1901 to 2016 are shown in Figure 2. Precipitation values are grouped in seven classes using natural break algorithm available in ArcGIS 10.3 to show the spatial distribution. Figure 2a shows that mean annual precipitation vary from 38 mm in the south to 2390 mm in the north of Pakistan. The annual average precipitation in the north ranges from 1278 to 2390 mm while it ranges between 38 and 158 in the southwest and some areas in the southeast. The precipitation in Rabi is found to vary between 10 and 773 mm and Kharif between 4 and 1971 mm. Rabi season coincides with the winter precipitation which enters Pakistan from western sides while Kharif season coincides with the monsoon that mostly enters from the northeastern sides of Pakistan. The occurrence of both precipitation phenomena can be clearly seen in Figure 2b and c. The precipitation is high in the west during Rabi and low during Kharif. Overall, the average annual and seasonal precipitations are high in north, low in the southeast during Rabi and in the southwest during Kharif.

Figure 2d depicts the spatial distribution of average annual PET. The PET is relatively high in the south and low in the north. The southwestern and southeastern corners showed the highest PET ranging from 2100 to 2529 mm. Like the annual, the PET in Rabi (Figure 2e) and Kharif (Figure 2f) show more or less similar distributions. In Rabi, it is found to vary between 168 and 843 mm while in the range of 497 to 1790 mm during Kharif. Relatively lower PET in Rabi indicates the influence of winter (low temperature) while higher PET in Kharif is due to its coincidence with summer when temperature is normally high in most of the country.

Hydrology and Earth System Sciences
Open Access
Discussions

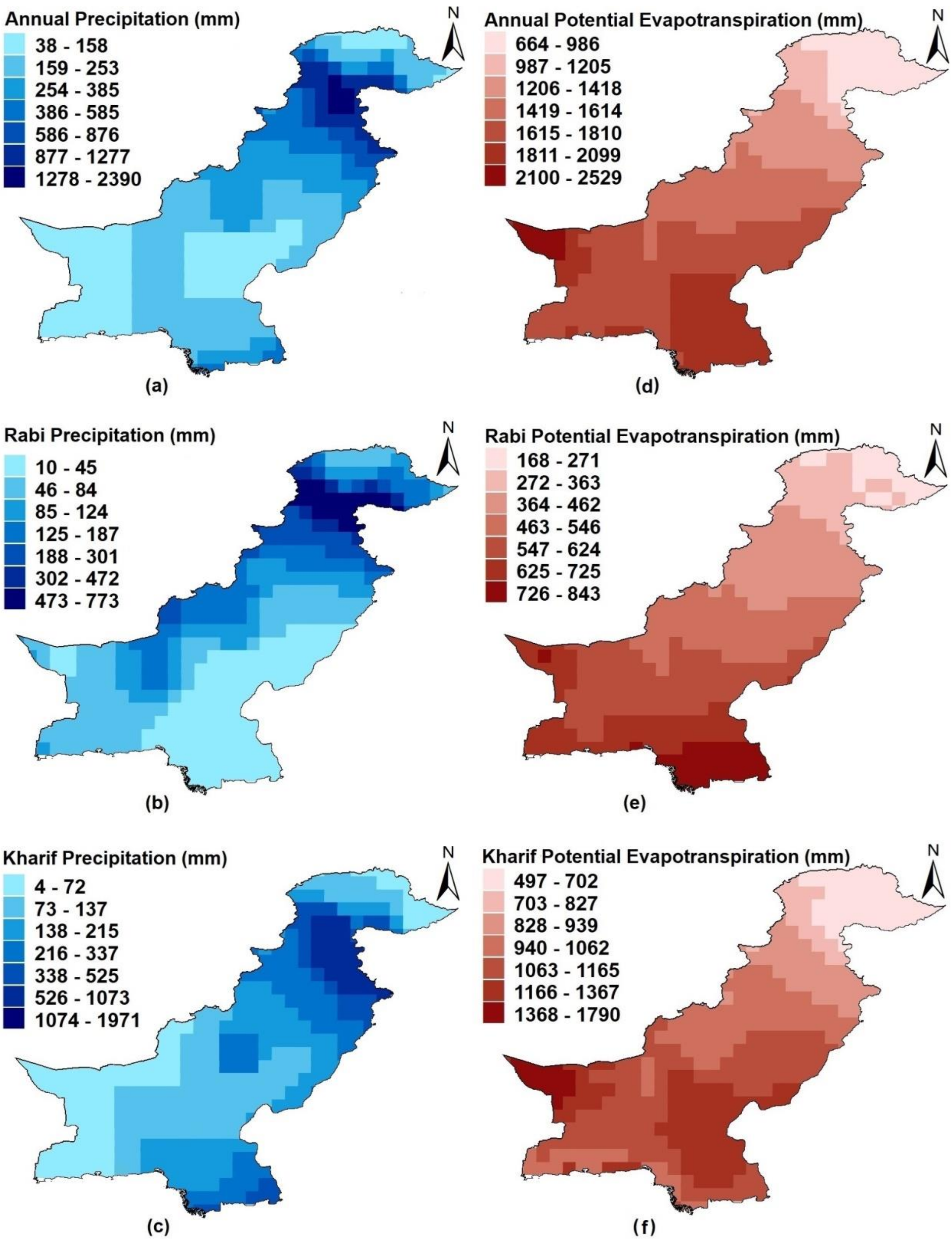

Figure 2. Spatial patterns of (a) annual, (b) Rabi and (c) Kharif precipitation; and (d) annual, (e) Rabi and (f) Kharif potential evapotranspiration in Pakistan

4.2 Spatial Pattern of Annual and Seasonal Aridity

The AI values are classified as hyper-arid, arid, semi-arid, sub-humid and humid based on UNESCO classification to show the spatial distribution of annual and seasonal aridity in Pakistan (Figure 3). The annual aridity over Pakistan for the period 1901-2016 (Figure 3a) reveals an arid climate in most part of the country (61%) followed by semi-arid (21%) and humid (11%). Arid climate covers a larger area in the south and in a small area at the top north. The sub-humid and humid climate dominates near the foothills of Himalaya where precipitation is high. On the other side, the climate in a small area (2%) in the southwest is found hyper arid where PET is high and precipitation is very low.

Figure 3b shows the spatial patterns of aridity during Rabi. Cold winds bring precipitation from the Mediterranean Sea during Rabi season which enters the country from the southwest and therefore, aridity in Rabi is notably less in the southwest. The percentage of area belongs to semi-arid, sub-humid and humid climate increases during Rabi which indicates decrease in aridity over a major portion of the country. However, area belongs to hyper-aridity climate (9%) increases in the southeast during Rabi. Besides, the aridity in the top north reduces and the humid climate zone near the foothills of Himalaya increases.

Spatial distribution of aridity during Kharif is presented in Figure 3c. The most of the country is characterized by arid climate (59%) followed by semi-arid (20%) and hyper-arid (9%). The area belongs to hyper-aridity climate in the southwest increases during Kharif due to the lack of precipitation in the west during this season. On the other hand, aridity reduces in the southeast due to monsoon precipitation. The area in the top north and near the foothills of Himalaya which are characterized by semi-arid also reduces which could be owing to an increase in PET.

Overall, figures showed that climate in more than 70% of the country are arid to semi-arid. The aridity varies with season due to the occurrences and dominance of precipitation is different in different seasons. In general, southern region of the country is characterized by arid climate and the northern region is predominantly sub-humid to humid.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-642
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 17 January 2019

Hydrology and Earth System Sciences
Open Access
Discussions

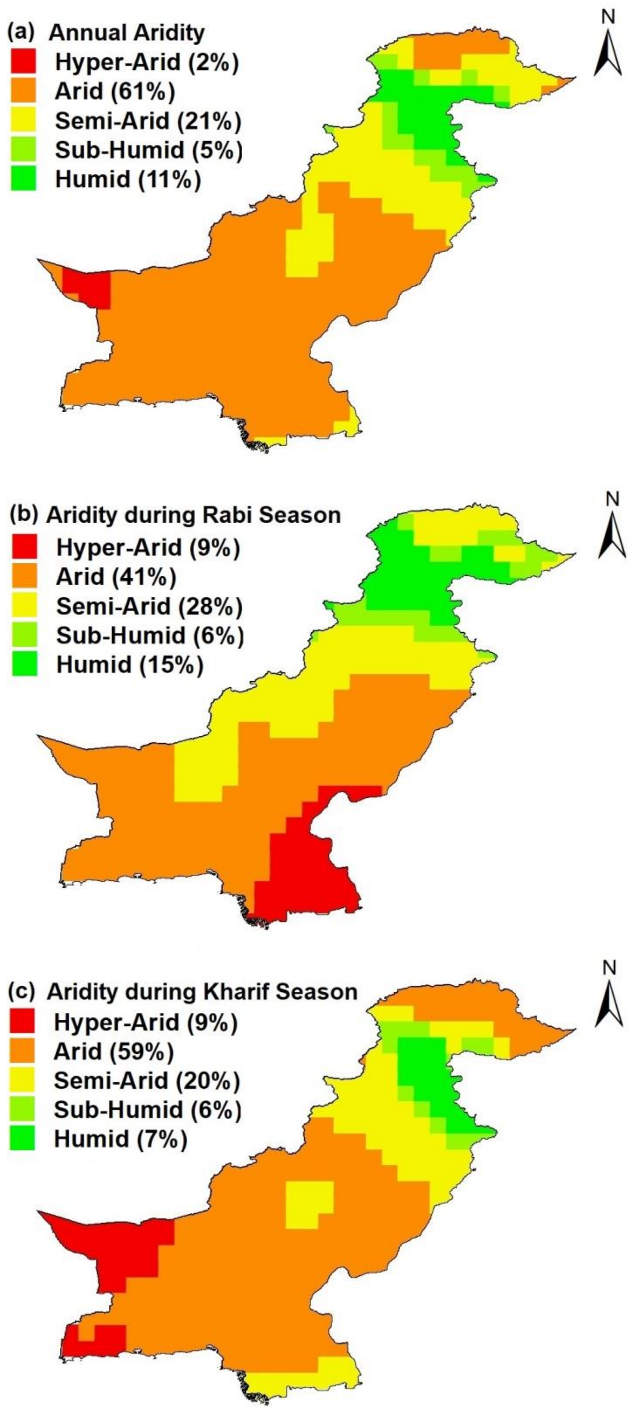

Figure 3. Spatial patterns of aridity for (a) annual (b) Rabi and (c) Kharif in Pakistan

4.3 Spatial Pattern in the Trends of Precipitation and PET

The Sen's slopes estimated for annual and seasonal precipitation and PET at 350 grid points of Pakistan are presented in Figure 4a. The plus (+) and minus (-) signs are used to designate the increase and decrease in trends respectively estimated using MMK test at 95% level of confidence. Figure 4a shows that annual precipitation is increasing in a small area in the northeast and at a few points in the far north, while it is decreasing at a few points in the south and three locations near the foothills of Himalaya. It is worth to mention that precipitation is decreasing at few locations near the foothills of the Himalaya where precipitation is highest in Pakistan (Figure 2a).

Figure 4b shows the spatial patterns in the trend of Rabi precipitation. The precipitation during Rabi is found to increase at a location in the north and at two grid points in the east while decrease at two locations in the south. The Kharif precipitation (Figure 4c) is found to increase in the east and decrease in the southwest. Besides, decreasing Kharif precipitation is noticed at five grid points near the foothills of Himalaya. Overall, the spatial patterns in annual and Kharif precipitation trends are found very similar.

The spatial distributions of trends in annual PET are shown in Figure 4d. The annual PET in Pakistan is increasing in the southeast corner and decreasing at a few grids scattered in the center and northeastern parts where precipitation is usually high and temperature is low. The PET in Rabi (Figure 4e) is found to increase at a few locations in the southeast and the southwest, while the PET in Kharif (Figure 4f) is found to decrease over a large area in the north.

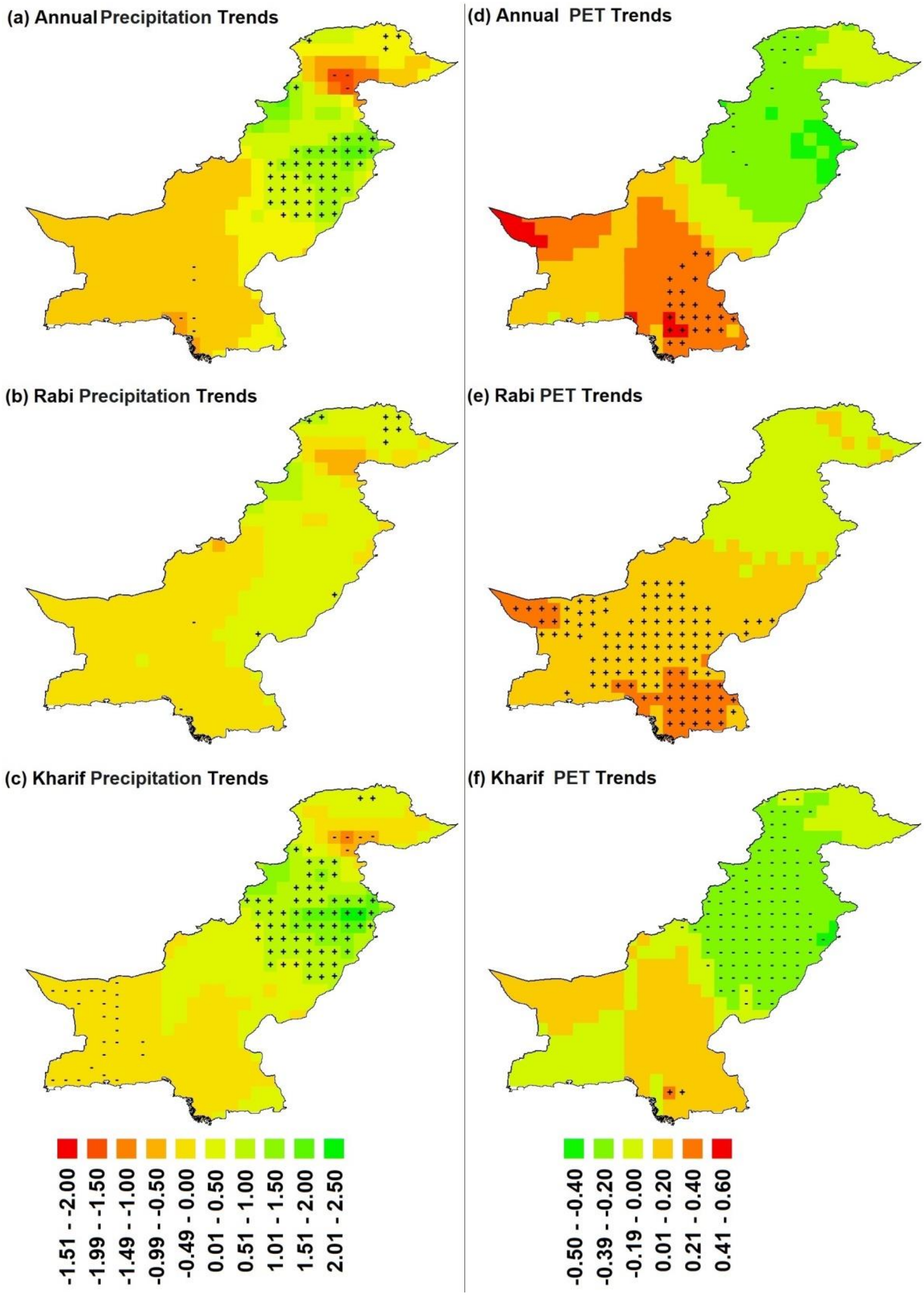

Figure 4. Spatial patterns in the trends of annual (a, d), Rabi (b, e) and Kharif (c, f) precipitation and PET in Pakistan

4.4 Spatial Pattern in the Trends of Annual and Seasonal Aridity

The estimated Sen's slopes of aridity are divided into five classes ranging from -0.0039 to 0.0060 to show the spatial distribution of aridity trends (Figure 5). The mean annual aridity is found to reduce in a large area in the northeast and increase only at four grid points in the south. The aridity trends in Rabi (Figure 5b) shows increases in the southwest, at two grid points in the center and at a single grid point in the south. Decreases in aridity during Rabi are also observed at a few grid points in the northeast and the north. The aridity trend in Kharif (Figure 5c) is found to follow similar patterns of annual aridity trend. Increase in aridity is noticed in a major area in northeast and at a few grid points in the north while decrease at few locations in the southwest and southern corner of the country. Overall, the results reveal a decrease in aridity in a major portion in the northeast and increase at few locations in the southeast.

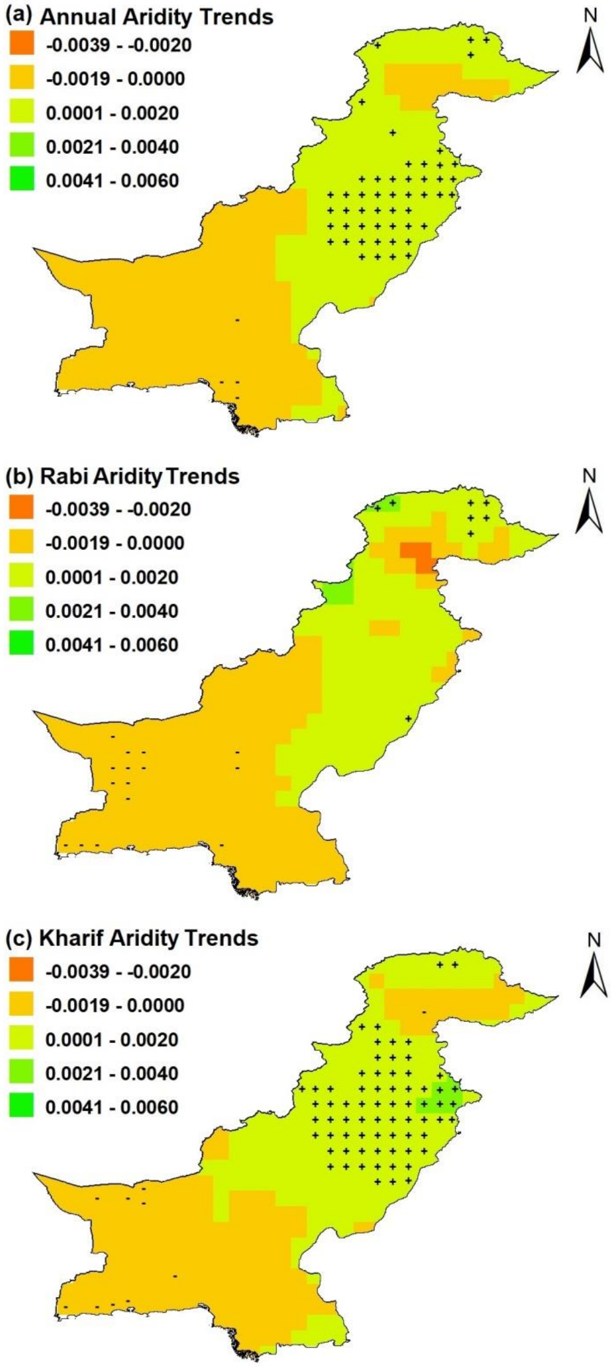

Figure 5. Spatial patterns in the trends of (a) annual (b) Rabi and (c) Kharif aridity in Pakistan

4.5 Time-varying Trends in Areal Extent of Aridity

A moving window of 50-years data with 11-year interval over the period 1901-2016 is used to assess the time-varying trends in aridity, precipitation and PET. The major purpose was to understand the influence of precipitation and PET on aridity in different periods. The obtained results are presented in Figure 6 and 7. The figures showed higher influence of precipitation on aridity compared to temperature. For instance, reduction in precipitation at 80 grid points triggered an increase in aridity at 77 grid points in 1923-1972. On the other side, a decrease in PET at 150 grid points resulted in a reduction of aridity over 40 grid points in 1934-1983. Similar results are also noticed for Rabi and Kharif seasons (Figure 7). Therefore, it can be remarked that the changes in precipitation have a higher impact compared to PET in determining the aridity of Pakistan.

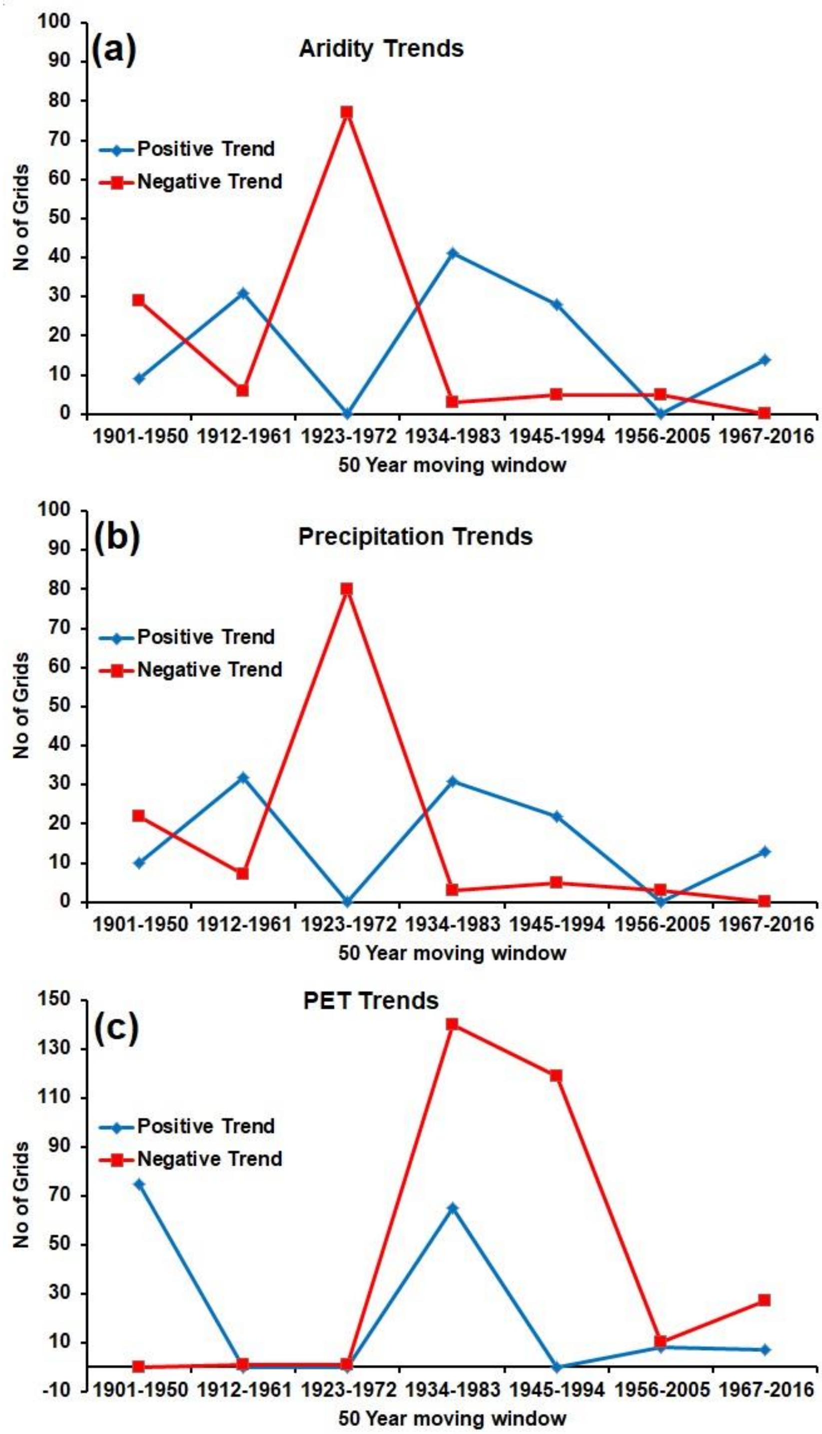

Figure 6. Number of grids where annual aridity, precipitation and PET are changed during different time periods

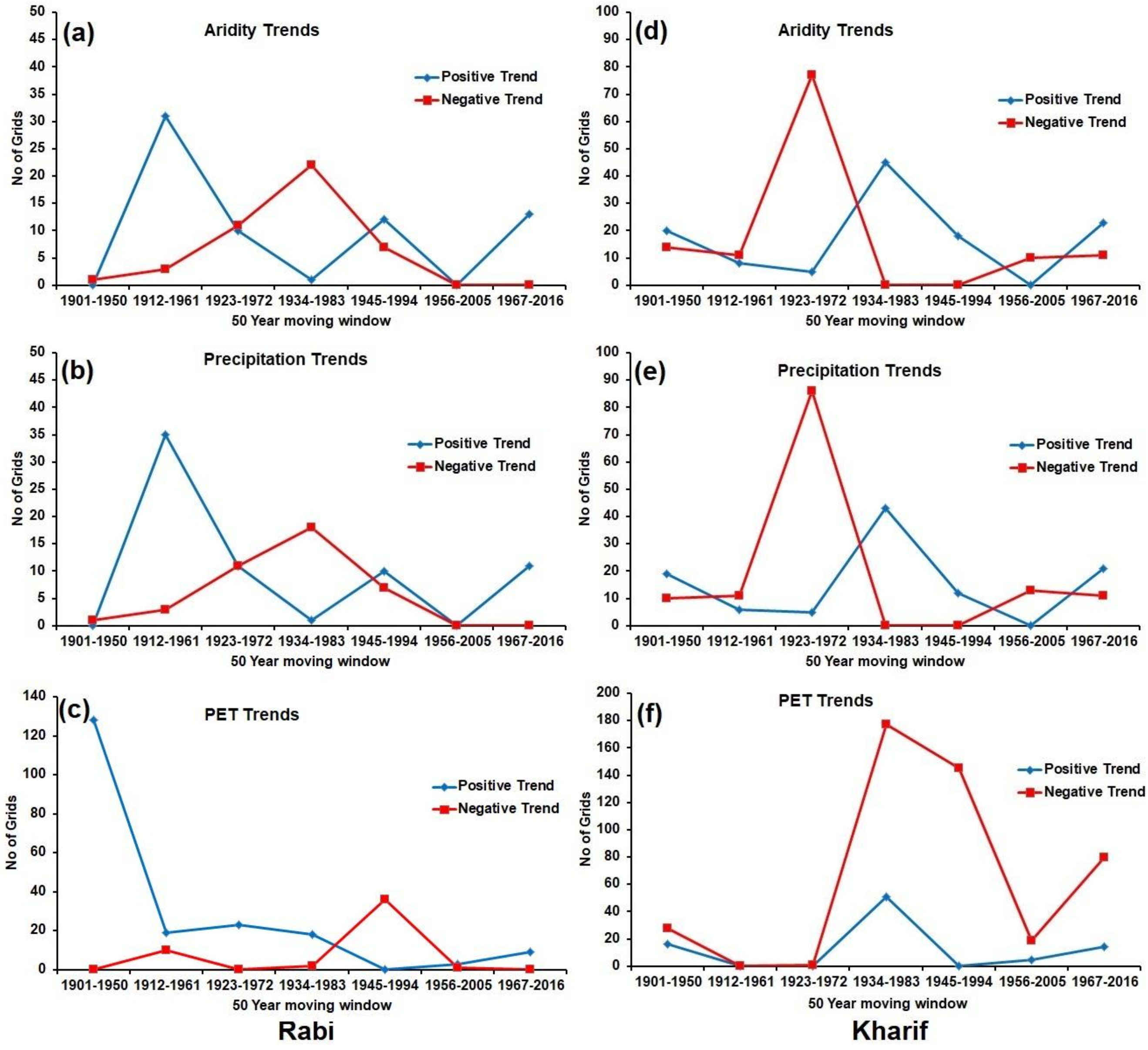

Figure 7. Number of grids where Rabi and Kharif seasons aridity, precipitation and PET are changed during different time periods

5

4.6 The Shift in Aridity

The spatial pattern in the shift of aridity from one class to another is estimated by comparing the aridity maps of early period (1901-1950) and late period (1967 to 2016). The obtained results are presented in Figure 8. The shifting of aridity from one to another class are illustrated using different colours while white colour represent no shift in aridity class. Annual climate in a large area is found to shift from arid to semi-arid (Figure 8a). A shift from semi-arid to sub-humid climate is also observed at a few grid points near the foothills of Himalaya. On the other side, the climate at two grid points in southwest is found to shift from semi-arid to arid.

Relatively more changes in aridity during Rabi (Figure 8b) compared to annual is observed. A large area in the southeast has changed from arid to hyper-arid. Climate at some grid points in the center and the southwest are also found to change from semi-arid to arid. Besides, sub-humid climate at a grid point in the north is found to become humid. Climate at several points are also changed from hyper-arid to arid in the southeast and arid to semi-arid at different locations in north. The spatial pattern of the shift of climate in Kharif (Figure 8c) reveals a change in arid climate to semi-arid climate in central region and hyper-arid to arid at a grid point in the southwest corner while the climate at a grid point in the southeast corner is shifted from semi-arid to arid.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-642
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 17 January 2019

Hydrology and Earth System Sciences
Open Access
Discussions

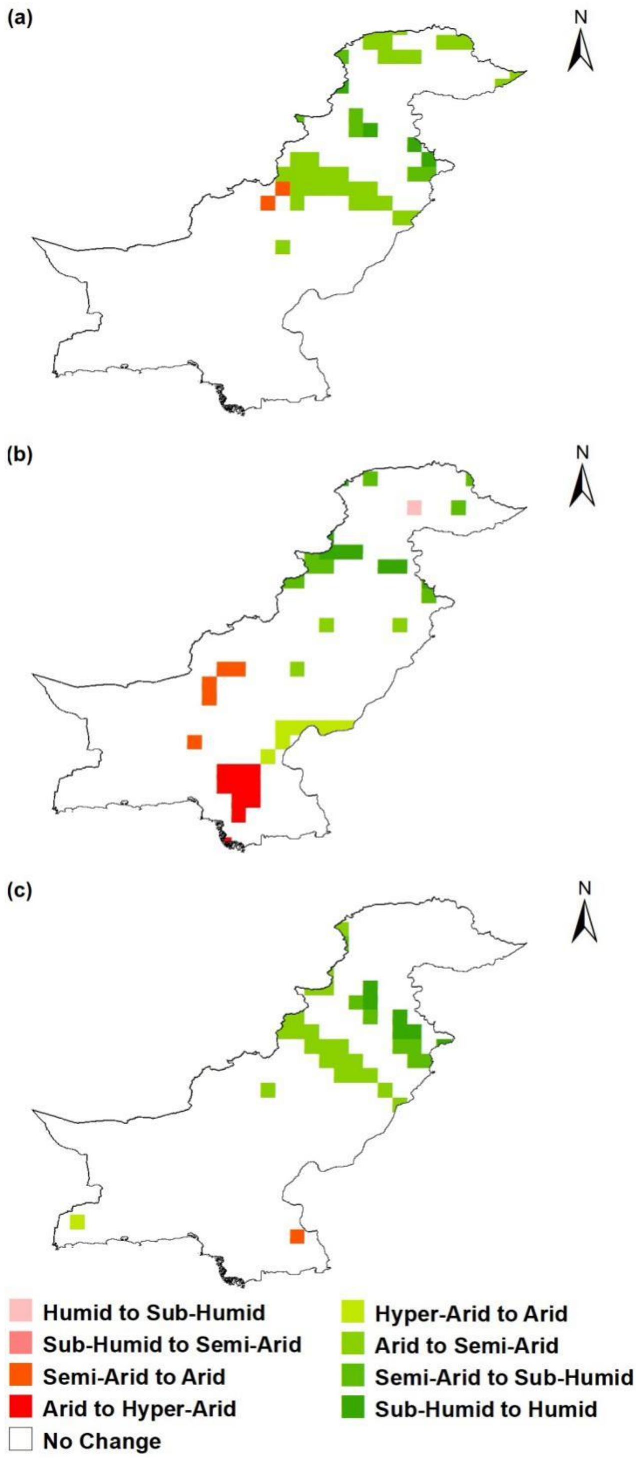

Figure 8. Changes in the spatial patterns of aridity between 1901-1950 and 1967-2016

The percentage of changes in different aridity classes are shown in Table 1. No shift in aridity class is observed in more than 85% of the area. There are both positive shift (more arid to less arid class) and negative shift (less arid to more arid class). However, positive shifts are found relatively more compared to negative shifts.

The highest positive shift is found from arid to semi-arid climate (9.14% of total area for annual and 5.48% for Kharif) while 2.61% area is noticed to shift from semi-arid to sub-humid climate during Rabi season. On the other hand, negative shift in only 0.52% and 0.27% areas are noticed for annual and Kharif and relatively in a higher area (2.61%) for Rabi.

Table 1. Percentage of area shifted from one to another aridity class between the periods 1901-1950 and 1967 to 2016.

Class Changes	Annual	Rabi	Kharif
H → SH	0.00	0.26	0.00
SH → SA	0.00	0.26	0.26
SA → A	0.52	1.31	0.27
A → HA	0.00	2.61	0.00
NC	87.73	87.99	89.82
AA → A	0.00	2.09	0.78
A → SA	9.14	0.78	5.47
SA → SH	1.57	2.61	1.83
SH → H	1.04	2.09	1.57
Increase in Aridity	0.52	4.44	0.52
Decrease in Aridity	11.75	7.57	9.66

H: Humid; SH: Sub-Humid; SA: Semi-Arid; A: Arid; HA: Hyper-Arid; NC: No change

4.7 Detection of Change Point in Climate

The areal averages of aridity, precipitation and PET of different aridity classes are used to detect the year of their changes using Pettitt's test. The significant changes detected in different years are presented using bold letters in Table 2. The most of the changes in aridity and precipitation are detected between 1971 and 1980 while the change point for PET is found to vary although it showed more significant changes compared to aridity and precipitation.

It is important to note that the changes (years) detected for aridity and precipitation are same for all seasons. For example, change point of both aridity and precipitation in hyper-arid region is 1983. The results again suggest that the influence of precipitation is higher on aridity compared with PET.

Table 2. The year of change in aridity, precipitation and PET in different climatic regions of Pakistan. The bold number in the table represents significant change

Season	Class	Aridity	Precipitation	PET
Annual	Hyper-Arid	1983	1983	**1957**
	Arid	1974	1974	1967
	Semi-Arid	**1974**	**1974**	**1974**
	Sub-Humid	**1971**	**1971**	**1963**
	Humid	1997	1997	**1974**
Rabi	Hyper-Arid	1975	1975	**1940**
	Arid	1961	1961	**1939**
	Semi-Arid	1978	1978	1939
	Sub-Humid	1980	1980	1974
	Humid	1977	1978	1974
Kharif	Hyper-Arid	1948	1948	**1965**
	Arid	1974	1974	**1948**
	Semi-Arid	**1974**	**1974**	**1954**
	Sub-Humid	1952	1952	**1963**
	Humid	1952	1952	**1954**

5 Discussions

The changes in aridity depends on the changes of different climatic variables. The present study found precipitation as the most dominating factor to drive the changes in aridity in Pakistan. A number of literatures are available on the changes in aridity in neighboring country of Pakistan namely, India, China and Iran. The influence of different climatic variables is examined in those studies to identify the driving factors of aridity changes. Ramarao et al. (2018) assessed the changing pattern of aridity in the semi-arid regions of India during 1951–2005 and reported increase in semi-aridity in the last decade due to the reduction in precipitation and escalation of PET. Ramachandran et al. (2015) assessed the changing behaviour of aridity in the East Coast of South India using regional climate models and RCP4.5 scenario. They reported aridity would increase with the increase in temperature and lowering of precipitation, however, rising temperature have more influence on the aridity in the East Coast of South India. Gao et al. (2015) evaluated the relationship of aridity with PET, precipitation, temperature, sunshine duration, wind speed and diurnal temperature range over the Tibetan Plateau and found precipitation as the most dominating factor that contribute to the aridity. Liu et al. (2018b) assessed the individual contribution of different variables including precipitation, temperature, wind speed, sunshine duration, and total solar radiation on aridity of China for the period 1961-2006 and showed that the contribution of different variables on aridity varies from region to region, but precipitation is the most dominating factor in most of the regions. Tabari and Talaee (2013) reported increasing PET and decreasing precipitation are the cause of increasing aridity in Iran. Most recently, Araghi et al. (2018) also identified increasing temperature and decreasing precipitation due to global warming as the major cause of increasing aridity in Iran. These studies indicate different climate variables as the major driver of aridity in the region. The present study reveals changes in precipitation are the major cause of the changes in aridity in Pakistan.

Pakistan receives precipitation from the monsoon originated in the Bay of Bengal and the western disturbances originated from the Mediterranean Sea. Monsoon contributes a large quantity to annual precipitation as compared to winter rainfall (Sheikh et al., 2009). Therefore, the geographical distribution of annual precipitation is found more or less same with the monsoon. Several studies such as, Ahmed et al. (2017) claimed that climate change has altered monsoon precipitation in the form of more precipitation in the north and at a few places in the southeast of Pakistan. Similar pattern in annual and Kharif precipitation trends has been observed in the present study. The aridity has decreased in the area where precipitation has increased. The PET is found to increase significantly in a big area in the southeast but its impact is not significant for annual aridity. Like monsoon, increase in winter precipitation in a big area has been reported (Ahmed et al., 2017). The aridity during Rabi season is found to follow the same pattern of Rabi precipitation. However, a mismatch in rainfall and aridity trends is found in the southwest. This is due to a large increase in PET in the region. Khan et al. (2018) reported a rapid rise in temperature in the southwest which has probably increased PET and aridity in the area. This indicates that both the changes in precipitation and PET have impacts on the changes in aridity in Pakistan. However, precipitation has much higher influence on aridity of Pakistan compared to PET.

The aridity is found to increase and decrease in different regions and seasons with the changes in precipitation and PET. Overall, it is found to decrease in 11.75%, 7.57%, and 9.66% areas and increase in 0.52%, 4.44%, and 0.52% areas for annual, Rabi and Kharif respectively. It is important to mention that a large area has shown less aridity in recent years particularly in the semi-arid or sub-humid regions which means more area become wetter in the recent years. However, some areas in arid region are found to become drier. This indicates that few dry regions are becoming drier and a large relatively wet area is becoming wetter. A similar finding has been reported by Liu et al. (2018b) in neighboring China.

The changes in temporal patterns of aridity reveal that the major shift in aridity and rainfall is occurred between 1971 and 1980. Global atmospheric moisture amount is found to increase after 1973 (Ross and Elliott, 2001). An increase in precipitation in many regions of the world is observed due to the increase in global moisture content (Trenberth, 1998). The present study suggests that precipitation of Pakistan has also changed during 1971-1980 which may be due to the increase in global atmospheric moisture after 1973. This has caused a shift in precipitation and aridity in Pakistan

6. Conclusions

The long-term changes (1901-2016) in annual and seasonal aridity in Pakistan and its causes are analyzed in this paper. Gauge-based gridded precipitation and PET data are used to show the spatial and temporal patterns of the changes in aridity over the diverse climate of the country. Following conclusions are drawn based on the findings: (1) The precipitation is high in the north and low in the southeast and southwest during both Rabi and Kharif seasons while the PET is low in the north due to cold climate and high in south due to high temperature. (2) The most part of the country is characterized by arid climate except the northern region near the foothills of Himalaya which is characterized by sub-humid to the humid climate. However, the aridity of the country is found to vary for different seasons due to the spatial pattern of precipitation occurrence in the corresponding season. (3) The annual precipitation of Pakistan is increasing in the northeast, while the Kharif precipitation is decreasing over a large area in the east and the Rabi precipitation is increasing at a few grid points in the north. The decreasing trends in annual and seasonal precipitation are mostly observed in the southern parts of the country. (4) The increases in annual and Rabi PET are noticed in the southeast corner while decrease in Kharif PET over a large area in the north. (5) The aridity for annual and Kharif show a decrease over a large in the northeast and an increase over few points in the south while the aridity in Rabi is found to increase in the southwest. (6) The time-varying trends in aridity reveals that the influence of precipitation is high on the aridity compared with PET. Increase in precipitation in the southeast has reduced the aridity to some extent in the region. Even though the increasing temperature has triggered an increase in PET but its influence is found less on aridity. (7) The changes in spatial patterns of aridity shows that the climate in a large area has shifted from arid to semi-arid for annual and Kharif while a small area from arid to hyper-arid in Rabi. (8) The highest shift in arid climatology is observed between arid to semi-arid. About 9.1% area is found to shift from arid to semi-arid climate between the periods 1901-1950 and 1967 to 2016. (9) Significant shift in aridity and precipitation in most of the climatic regions of Pakistan is found between 1971-1980.

The present study suggests that the relative influence of precipitation and temperature on aridity determines its trends in the context of climate change. Aridity may decrease due to a small increase in precipitation in the regions where precipitation has much higher influence on aridity; the gridded data used in this may cause uncertainty in estimation of aridity and its trends. Other gridded data can be used in future to assess the uncertainty in the trends of aridity estimated in this study. Besides, different aridity assessment methods can be used to compare the results.

Acknowledgement

This work is supported by the Young Top-Notch Talent Support Program of National High-level Talents Special Support Plan and Professional Development Research University (PDRU) grant no. Q.J130000.21A2.04E10 of Universiti Teknologi Malaysia.

References

Adnan, S., and Ullah, K.: Characterization of drought and its assessment over Sindh, Pakistan during 1951–2010, Journal of Meteorological Research, 29, 837-857, 2015.

Ahmed, K., Shahid, S., Chung, E.-S., Ismail, T., and Wang, X.-J.: Spatial distribution of secular trends in annual and seasonal precipitation over Pakistan, Clim. Res., 74, 95-107, 2017.

Ahmed, K., Shahid, S., and Nawaz, N.: Impacts of climate variability and change on seasonal drought characteristics of Pakistan, Atmospheric Research, 214, 364-374, 10.1016/j.atmosres.2018.08.020, 2018.

Alazard, M., Leduc, C., Travi, Y., Boulet, G., and Ben Salem, A.: Estimating evaporation in semi-arid areas facing data scarcity: Example of the El Haouareb dam (Merguellil catchment, Central Tunisia), Journal of Hydrology: Regional Studies, 3, 265-284, http://dx.doi.org/10.1016/j.ejrh.2014.11.007, 2015.

Araghi, A., Martinez, C. J., Adamowski, J., and Olesen, J. E.: Spatiotemporal variations of aridity in Iran using high-resolution gridded data, International Journal of Climatology, 38, 2701-2717, doi:10.1002/joc.5454, 2018.

Ashraf, B., Yazdani, R., Mousavi-Baygi, M., and Bannayan, M.: Investigation of temporal and spatial climate variability and aridity of Iran, Theoretical and Applied Climatology, 118, 35-46, 2014.

Asmat, U., Athar, H., Nabeel, A., and Latif, M.: An AOGCM based assessment of interseasonal variability in Pakistan, Climate Dynamics, 1-25, 2017.

Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Schamm, K., Schneider, U., and Ziese, M.: A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901-present, Earth System Science Data, 5, 71-99, 2013.

Bharuqha, F., and Shanbhag, G.: Classification of the vegetation of India, Pakistan and Burma according to effective precipitation, In other words, 10, 9, 1956.

Buytaert, W., Friesen, J., Liebe, J., and Ludwig, R.: Assessment and management of water resources in developing, semi-arid and arid regions, Water Resour. Manage., 26, 841-844, 2012.

Chaudhry, Q., and Rasul, G.: Agro-climatic classification of Pakistan, Science Vision, 9, 59-66, 2004.

de Martonne, E.: Areisme et indice d'aridite, comptes rendus de L'Academie des Sciences de Paris. 182: 1393-1 398, English: Regions of Interior Basin Drainage. Geogr. Rev, 17, 397-414, 1926.

Gao, Y., Li, X., Leung, L. R., Chen, D., and Xu, J.: Aridity changes in the Tibetan Plateau in a warming climate, Environmental Research Letters, 10, 034013, 2015.

Haider, S., and Adnan, S.: Classification and assessment of aridity over Pakistan provinces (1960-2009), International Journal of Environment, 3, 24-35, 2014.

Hamed, K. H.: Trend detection in hydrologic data: The Mann–Kendall trend test under the scaling hypothesis, Journal of Hydrology, 349, 350-363, https://doi.org/10.1016/j.jhydrol.2007.11.009, 2008.

Harris, I., Jones, P. D., Osborn, T. J., and Lister, D. H.: Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset, International Journal of Climatology, 34, 623-642, 10.1002/joc.3711, 2014.

Hrnjak, I., Lukić, T., Gavrilov, M. B., Marković, S. B., Unkašević, M., and Tošić, I.: Aridity in Vojvodina, Serbia, Theoretical and applied climatology, 115, 323-332, 2014.

Huang, J., Yu, H., Guan, X., Wang, G., and Guo, R.: Accelerated dryland expansion under climate change, Nature Climate Change, 6, 166, 2016.

Hussain, M. S., and Lee, S.: A classification of rainfall regions in Pakistan, Journal of the Korean Geographical Society, 44, 605-623, 2009.

Hussain, M. S., and Lee, S.: Long-term variability and changes of the precipitation regime in Pakistan, Asia-Pacific Journal of Atmospheric Sciences, 50, 271-282, 2014.

Iqbal, M. A., Penas, A., Cano-Ortiz, A., Kersebaum, K. C., Herrero, L., and del Río, S.: Analysis of recent changes in maximum and minimum temperatures in Pakistan, Atmospheric Research, 168, 234-249, http://dx.doi.org/10.1016/j.atmosres.2015.09.016, 2016.

Khan, N., Shahid, S., Ismail, T. b., and Wang, X.-J.: Spatial distribution of unidirectional trends in temperature and temperature extremes in Pakistan, Theoretical and Applied Climatology, 10.1007/s00704-018-2520-7, 2018.

Khatoon, S., and Ali, Q.: Biodiversity of the semi-arid and arid regions of Pakistan: Status, threats, and conservation measures, Annals of Arid Zone, 43, 277, 2004.

Kishore, P., Jyothi, S., Basha, G., Rao, S. V. B., Rajeevan, M., Velicogna, I., and Sutterley, T. C.: Precipitation climatology over India: validation with observations and reanalysis datasets and spatial trends, Climate Dynamics, 46, 541-556, 10.1007/s00382-015-2597-y, 2015.

Kousari, M., Dastorani, M., Niazi, Y., Soheili, E., Hayatzadeh, M., and Chezgi, J.: Trend Detection of Drought in Arid and Semi-Arid Regions of Iran Based on Implementation of Reconnaissance Drought Index (RDI) and Application of Non-Parametrical Statistical Method, Water Resour. Manage., 28, 1857-1872, 10.1007/s11269-014-0558-6, 2014.

Koutsoyiannis, D.: Climate change, the Hurst phenomenon, and hydrological statistics, Hydrological Sciences Journal, 48, 3-24, 2003.

Li, L., Xu, C.-Y., Zhang, Z., and Jain, S. K.: Validation of a new meteorological forcing data in analysis of spatial and temporal variability of precipitation in India, Stochastic environmental research and risk assessment, 28, 239-252, 2014.

Liu, C., Huang, W., Feng, S., Chen, J., and Zhou, A.: Spatiotemporal variations of aridity in China during 1961–2015: decomposition and attribution, Science Bulletin, 63, 1187-1199, 2018a.

Liu, L., Wang, Y., You, N., Liang, Z., Qin, D., and Li, S.: Changes in aridity and its driving factors in China during 1961–2016, International Journal of Climatology, 0, doi:10.1002/joc.5781, 2018b.

Monteith, J. L.: Evaporation and environment, Symp. Soc. Exp. Biol, 1965, 4,

Nabeel, A., and Athar, H.: Classification of precipitation regimes in Pakistan using wet and dry spells, International Journal of Climatology, 38, 2462-2477, 2018.

Nam, W.-H., Hayes, M. J., Svoboda, M. D., Tadesse, T., and Wilhite, D. A.: Drought hazard assessment in the context of climate change for South Korea, Agric. Water Manage., 160, 106-117, 10.1016/j.agwat.2015.06.029, 2015.

New, M., Lister, D., Hulme, M., and Makin, I.: A high-resolution data set of surface climate over global land areas, Clim. Res., 21, 1-25, 2002.

Oliver, J., Siddiqi, A., and Goward, S.: Spatial patterns of climate and irrigation in Pakistan: A multivariate statistical approach, Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie B, 25, 345-357, 1978.

Pettitt, A.: A non-parametric approach to the change-point problem, Applied statistics, 126-135, 1979.

Ramachandran, A., Praveen, D., Jaganathan, R., and Palanivelu, K.: Projected and observed aridity and climate change in the east coast of South India under RCP 4.5, The Scientific World Journal, 2015, 2015.

Ramarao, M., Sanjay, J., Krishnan, R., Mujumdar, M., Bazaz, A., and Revi, A.: On observed aridity changes over the semiarid regions of India in a warming climate, Theoretical and Applied Climatology, 1-10, 2018.

Ross, R. J., and Elliott, W. P.: Radiosonde-based Northern Hemisphere tropospheric water vapor trends, J. Clim., 14, 1602-1612, 2001.

Sarfaraz, S.: The sub-regional classification of Pakistan's winter precipitation based on principal components analysis, Pakistan Journal of Meteorology Vol, 10, 2014.

Sarfaraz, S., Arsalan, M. H., and Fatima, H.: Regionalizing the climate of Pakistan using Köppen classification system, Pakistan Geogr Rev, 69, 111-132, 2014.

Şarlak, N., and Agha, O. M. M.: Spatial and temporal variations of aridity indices in Iraq, Theoretical and Applied Climatology, 133, 89-99, 2018.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Ziese, M., and Rudolf, B.: GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle, Theoretical and Applied Climatology, 115, 15-40, 10.1007/s00704-013-0860-x, 2013.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Ziese, M., and Rudolf, B.: GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle, Theoretical and Applied Climatology, 115, 15-40, 2014.

Selek, B., Tuncok, I. K., and Selek, Z.: Changes in climate zones across Turkey, Journal of Water and Climate Change, 9, 178-195, 2018.

Sen, P. K.: Estimates of the regression coefficient based on Kendall's tau, Journal of the American Statistical Association, 63, 1379-1389, 1968.

Shamshad, K. M.: The meteorology of Pakistan: climate and weather of Pakistan, Royal Book Company, 1988.

Sheikh, M., Manzoor, N., and Khan, A.: Climate Profile and Past Climate Changes in Pakistan. Global Change Impact Studies Centre (GCISC), Islamabad Research Report: GCISC-RR-01, 2009.

Sheikh, M. M.: Drought management and prevention in Pakistan, COMSATS 1st meeting on water resources in the south: present scenario and future prospects, Islamabad, 2001, 1-2, Shiru, M. S., Shahid, S., Alias, N., and Chung, E.-S.: Trend Analysis of Droughts during Crop Growing Seasons of Nigeria, Sustainability, 10, 871, 2018.

Spinoni, J., Naumann, G., Carrao, H., Barbosa, P., and Vogt, J.: World drought frequency, duration, and severity for 1951-2010, International Journal of Climatology, 34, 2792-2804, 10.1002/joc.3875, 2014.

Sun, Q., Miao, C., Duan, Q., Kong, D., Ye, A., Di, Z., and Gong, W.: Would the 'real'observed dataset stand up? A critical examination of eight observed gridded climate datasets for China, Environmental Research Letters, 9, 015001, 2014.

Tabari, H., Abghari, H., and Hosseinzadeh Talaee, P.: Temporal trends and spatial characteristics of drought and rainfall in arid and semiarid regions of Iran, Hydrological Processes, 26, 3351-3361, 2012.

Tabari, H., and Talaee, P. H.: Moisture index for Iran: spatial and temporal analyses, Global Planet. Change, 100, 11-19, 2013.

Thornthwaite, C. W.: The climates of North America: according to a new classification, Geographical review, 21, 633-655, 1931.

Thornthwaite, C. W.: An approach toward a rational classification of climate, Geographical review, 38, 55-94, 1948.

Trenberth, K. E.: Atmospheric Moisture Residence Times and Cycling: Implications for Rainfall Rates and Climate Change, Clim. Change, 39, 667-694, 10.1023/a:1005319109110, 1998.

Tukimat, N. N. A., Harun, S., and Shahid, S.: Comparison of different methods in estimating potential evapotranspiration at Muda Irrigation Scheme of Malaysia, Journal of Agriculture and Rural Development in the Tropics and Subtropics (JARTS), 113, 77-85, 2012.

Ullah, S., You, Q., Ali, A., Ullah, W., Jan, M. A., Zhang, Y., Xie, W., and Xie, X.: Observed changes in maximum and minimum temperatures over China-Pakistan economic corridor during 1980–2016, Atmospheric Research, 2018a.

Ullah, S., You, Q., Ullah, W., and Ali, A.: Observed changes in precipitation in China-Pakistan economic corridor during 1980–2016, Atmospheric Research, 210, 1-14, 2018b.

UNEP: World atlas of desertification. Edward Arnold. London, 1992.

UNESCO: Map of the world distribution of arid regions, UNESCO Paris, 1979.

Yue, S., Pilon, P., and Cavadias, G.: Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series, Journal of hydrology, 259, 254-271, 2002.

Zahid, M., and Rasul, G.: Thermal classification of Pakistan, Atmospheric and Climate Sciences, 1, 206, 2011.

Zarch, M. A. A., Sivakumar, B., and Sharma, A.: Assessment of global aridity change, Journal of Hydrology, 520, 300-313, 2015.

Zarch, M. A. A., Sivakumar, B., Malekinezhad, H., and Sharma, A.: Future aridity under conditions of global climate change, Journal of Hydrology, 554, 451-469, 2017.