Arab J Geosci (2017) 10: 319
DOI 10.1007/s12517-017-3096-8

ORIGINAL PAPER

Statistical analysis of rainfall trends over Damodar River basin, India

Shonam Sharma[1] · **Amal Krishna Saha**[1]

Received: 19 October 2016 / Accepted: 5 July 2017 / Published online: 27 July 2017

Abstract This paper is intended to compute long-term spatiotemporal variability of precipitation on annual and seasonal scale of Damodar River Basin over the period of 113 years (1901–2013). The lag-1 autocorrelation coefficient was applied to check serial dependence in the dataset. After this, non-parametric Mann Kendall and modified Mann Kendall test were used to identify trends and the Theil-Sen's slope method to estimate magnitude of trend line. Sequential Mann Kendall test was also applied to detect the potential turning point. Results found significant decreasing precipitation trend in annual and monsoon season over the basin except the southeastern part. The maximum decrease was found for annual and monsoon season at the northwestern part while minimum at the northeastern region. The sequential Mann Kendall test identified several non-significant as well as significant turning points for seasonal and annual rainfall at most of the locations.

Keywords Mann Kendall test · Sequential Mann Kendall test · Precipitation trends · Spatiotemporal · Climate change

Introduction

The event of precipitation is a result of a complex natural process that varies significantly on both temporal and spatial scale (Bohnenstengel et al. 2011). It is one of the most important climatic variables often studied by researchers to understand its changing patterns. The variable nature of precipitation makes it a highly challenging issue for the water resource planners and also agricultural planners. Climate change studies reported an increasing average global temperature trends; however, the average precipitation showed an increasing trend on a global scale while both increasing as well as decreasing trend at local or regional scale (McCarthy 2001). Also, the rise in sea surface temperature (SST) has a significant effect on the increasing rainfall (Trenberth 2011)**.** It is predicted that climate change will affect more adversely the poorer countries. So, the problem of water scarcity as well as food security faced by those very nations will be more pronounced in the future. The agricultural and water sector of the Asia-Pacific region have been already substantially affected by the variable precipitation pattern.

Worldwide, a number studies of precipitation patterns revealed significant decrease in precipitation over Saudi Arabia (Almazroui et al. 2012), Sicily island (Italy) (Cannarozzo et al. 2006), Italy (Buffoni et al. 1999), Kenya (Kipkorir 2002), northeastern part of Brazil (da Silva 2004), Russia (Peterson et al. 2002), and northeast and north China (Zhai and Pan 2003). On the other hand, an increase in precipitation was reported over the Netherlands (Daniels et al. 2014), Changjiang Valley, and the southeastern coast of China (Hu et al. 2003; Zhai and Pan 2003), western coasts of the Philippines (Cruz et al. 2013), New York of USA (Burns et al. 2007), and Mexico (Méndez González et al. 2008).

In India, regional-level studies revealed a significant decreasing trend of precipitation over Madhya Pradesh (Duhan and Pandey 2013; Kundu et al. 2015), Chattisgarh (Meshram et al. 2016), downstream areas of Gomti river basin (Abeysingha et al. 2014), Wainganga Basin (Taxak et al. 2014), while insignificant decrease in rainfall was found over Cauvery river basin (Sushant et al. 2015). However, significant increasing precipitation trend was reported over the Sindh river basin (Madhya Pradesh) (Gajbhiye et al. 2015; Gajbhiye

✉ Shonam Sharma
Sharma23shonam@gmail.com

[1] Indian Institute of Technology (Indian School of Mines), Dhanbad 826004, Jharkhand, India

et al. 2016), upstream area of Gomti river basin (Abeysingha et al. 2014), Haryana (Darshana 2012).

Study area

Damodar River originates in the hills of the Chottanagpur Plateau of the Palamau district of Jharkhand (Fig. 1). The Usri, the Barakar, and the Kasai are the tributaries of Damodar River that drains the basin. It is a sub-basin of Ganga basin that lies between 84°35′ to 88°20′ east longitudes and 21°44′ to 24°25′ north latitudes of India. It covers a drainage area of 41,965.49 sq. and have a length of 575 km. It is bounded on the north by Central India hills, in the south and east by the Eastern Ghats, and in the west by Maikala hill range. The climate of the basin characterized by hot and humid summers with moderate winters.

Data collection

The British Atmospheric Data Center (BADC) is the designated data center that provides global grid datasets of climatic variables. For the present study, CRU TS 3.23 monthly precipitation data at 0.5° × 0.5° grid (1901–2013) was downloaded from Centre of Environmental Data Archival (http://badc.nerc.ac.uk). Eighteen grid points of CRU TS 3. 23 dataset cover the whole Damodar basin which is shown in Fig. 1. The annual and monsoon data series was then prepared by adding all the month's data as annual and monsoon includes precipitations from June–September.

In this study, therefore, an attempt has been made to determine the rainfall climatology over the Damodar River Basin (DRB). The aim of the present study is to identify spatiotemporal variability in precipitation along with the turning point in annual and monsoon season precipitation for a period of 113 years (1901–2013). To analyze spatially the changes in rainfall behavior, the Sen's slope value of each grid was interpolated using inverse distance weighted (IDW) interpolation in the ArcGIS environment version 10 for the period 1901–2013.

Methodology

Autocorrelation

Autocorrelation is also known as the serial correlation or lagged correlation. It is used to check serial dependence between the data. The lag-1 autocorrelation coefficient is the simple correlation coefficient of the first observations $N-1$, x_t, $t = 1,2,3 \ldots\ldots\ldots\ldots N-1$ and the next observations, x_{t+1}, $t = 2, 3, \ldots N$. The first-order correlation coefficient (r_1) between x_t and x_{t+1} can be calculated first and then its significance is tested against the null hypothesis following Anderson formula (1941).

If the value of r_1 lie outside the confidence interval (95%), the data are assumed to be serially correlated; otherwise, the sample data are considered to be serially independent.

Mann-Kendall trend test

The Mann-Kendall test is a non-parametric test that was used for the analysis of time series data of rainfall trend in the present study. It is frequently used for the detection of significant trend in hydrologic data series (Patra et al. 2012). The

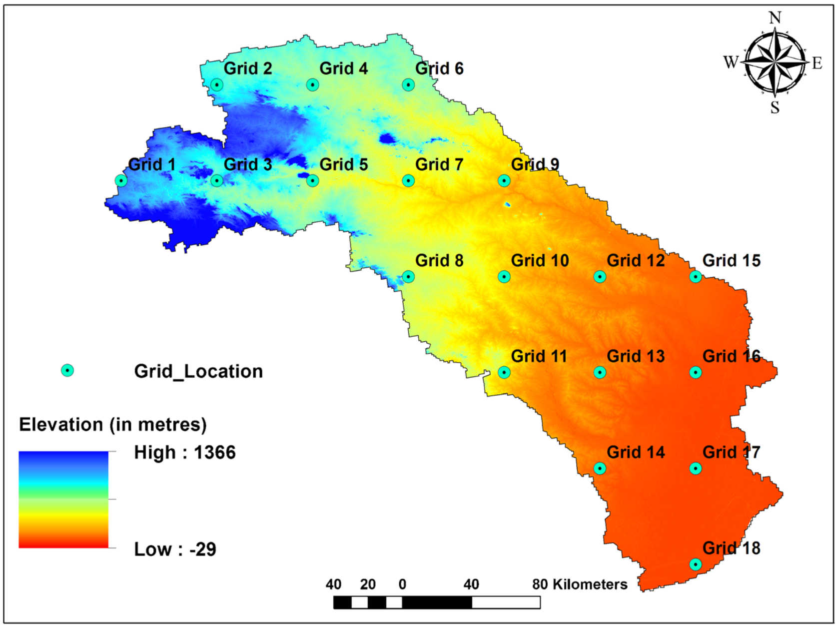

Fig. 1 Damodar River Basin area showing grid locations along with DEM

MK test, S statistics for a series $X_{1,}\ X_2$ …………………X_n can be given by

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(X_j - X_i\right)$$

where X_i is ranked from $i = 1, 2 \ldots n - 1$ and X_j ranked from $j = i + 1$, 2, and n is the length of thedataset.

$$Sgn(\vartheta) = \begin{cases} 1\ldots.if\ \vartheta > 0 \\ 0\ldots if\ \vartheta = 0 \\ -1\ldots.if\ \vartheta < 0 \end{cases}$$

The value of S whether negative or positive displays either increasing or decreasing trend. For the sample size $n \geq 8$, variance of the Mann-Kendall statistics is given by

$$Var(S) = \frac{\left[n(n-1)(2n+1) - \sum_t t(t-1)(2t+5)\right]}{18}$$

where t_i is the number of ties present up to sample i.

The standardized MK test statistics (Z_{mk}) can be estimated by the following given formula:

$$Z_{mk} = \begin{cases} \dfrac{S-1}{\sqrt{V(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sqrt{V(S)}} & if\ S < 0 \end{cases}$$

The Z_{mk} follows a standard normal distribution and if its value is positive, it signifies an upward trend and if negative, it signifies a decreasing trend. If the value of Z_{mk} is greater than $Z_{\acute{\alpha}/2}$, it is considered as significant trend (where $\acute{\alpha}$ is significance level) and the null hypothesis is rejected.

Theil-Sen's slope method

In addition to trend identification, the magnitude of the drift was also computed by the Sen's slope (β) method, which was suggested by Sen (1968). This is a non-parametric method (Sen, 1968) by which slope of N pairs of data points is estimated. It quantifies the linear median (50th percentile) concentration changes with time and is used to determine the magnitude of the trend line. A positive value of Sen's slope indicates an "upward (increasing) trend" and a negative value suggests a "downward (decreasing) trend" in the time series.

Modified Mann-Kendall

Modified Mann-Kendall (MMK) has been applied to detect trend in serially correlated data. In this method, the significant values of ρk (autocorrelation coefficient) are used to estimate variance correction factor$^{n}/_{n_s^*}$, as the variance of S is undervalued when data are positively auto-correlated.

$$\frac{n}{n_s^*} = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{K=1}^{n-1} (n-k)(n-k-1)(n-k-2)_{\rho k}$$

The revised variance is calculated by the given formula:

$$V^*(S) = V(S) \times \frac{n}{n_s^*}$$

where $V(S)$ is the same as it was computed in the Mann-Kendall method.

Sequential Mann-Kendall

Sneyres (1990) introduced the sequential Mann-Kendall test to detect abrupt potential turning points in long-term data. This test involves the computation of two series: one is progressive and another one is retrogressive. When the two series cross each other and deviate beyond the confidence limit of 95%, then that point will be a statistically significant turning point. It is computed by comparing the values of xj annual mean time series ($j = 1,\ldots,n$) with xi, ($i = 1,\ldots,j - 1$) (Nasri and Modarres 2009). At the time of comparison, the cases where $xj > xi$ is counted and denoted by nj.

Then, test statistic t is computed by using following equation:

$$t_{j=}\sum_{1}^{j} n_j$$

The mean and variance of the test statistic are

$$E(t) = \frac{n(n-1)}{4}$$

and

$$Var\left(t_j\right) = [j(j-1)(2j+5)]\Big/72$$

The sequential values of the statistic $u(t)$ are then calculated as

$$u(t) = \frac{t_j - E(t)}{\sqrt{Var\left(t_j\right)}}$$

The values of *u'(t) retrogressive series* are computed similarly, but starting from end of the series.

Results and discussion

In the present paper, rainfall trend analysis has been done in order to study the variability of rainfall over the basin. This is the first attempt to give a full picture of the spatial and temporal rainfall trend analysis covering Damodar basin. Damodar River basin covers a variety of topographic features like in the northwest; it covers the plateau region while on the southeast region, it is bounded by sea. These different topographic features result into different climatic conditions over the basin. Thus, the understanding of rainfall variability is essential for water resource management, proper agricultural activities so that accurate valuation of supplementary water requirements can be done.

Lag-1 autocorrelation at 1, 5, and 10% significance level was applied to both the annual and monsoon season data whose results are shown in Table 1. Results of autocorrelation found the presence of lag-1 autocorrelation in Grid 1, Grid 2, Grid 3, Grid 4, Grid 13, Grid 14 and Grid 16 for annual series and during the monsoon season in Grid 1, Grid 2, Grid 3, Grid 4, Grid 5, Grid 6, and Grid 16. The Modified Mann-Kendall test (Hamed and Rao 1998) was applied to the serially correlated data and for the rest data, Mann-Kendall trend test (Mann 1945) applied (Table 1).

MK statistics results indicated a significant decreasing trend annually at almost all the grid points (at 1, 5, and 10% significance level) except grids 14, 16, 17, and 18 which showed an insignificant increasing trend. The amount of the decreasing trends in annual precipitation ranged between 0.56 mm per year (Grid 13) and 2.43 mm per year (Grid 2) while, the increasing trends in annual rainfall ranged between 0.32 mm per year (Grid 14) and 1.78 mm per year (Grid 2). This shows a decline in rainfall in the northwestern region of the basin while an increment in rainfall over the southeastern region. The southeastern region of basin is near to sea coast and influence of sea may be responsible for insignificant rise of rainfall in that region. The spatial distribution of trend magnitude (mm/year) for annual rainfall is shown in Fig. 2. The Mann-Kendall test revealed a negative trend in annual rainfall, but it does not count for the identification of shift point. Hence, sequential Mann-Kendall test was applied to see if there were any abrupt changes.

The results of sequential Mann-Kendall indicating significant and first turning point were displayed for both annual and monsoon season data in Table 2. Results of sequential Mann Kendall (Fig. 3) showed declining trend in almost all the grid points for annual rainfall except for grid 14, 16, 17, and 18 which showed a periodic fluctuation with an increasing trend .

In India, monsoon is associated with El Niño Southern Oscillation (ENSO). During El Niño, weaker monsoon prevails in India as it causes suppression of the trade winds which are responsible for bringing monsoon. Krishnamurthy and Goswami (2000) observed that the inter-decadal decrease in monsoon rainfall occurred due to the El Niño. Another possible cause of the decreasing monsoon rainfall trend may be the rapid warming in the Indian Ocean. Warming of Indian Ocean potentially weakens the land-sea thermal difference that reduces the rainfall over parts of South Asia (Roxy et al. 2015). Stephenson and Kumar (2001) found weakening of the monsoon circulation using results from the recent atmospheric general circulation experiments for Asian summer monsoon. The conclusion drawn from a number of

Table 1 Trend analysis (Mann-Kendall z statistics and Sen's slope (Q) value) and percent change of annual and seasonal precipitation (1901–2013)

Time series	Annual			Monsoon		
	Test Z	Q	% Change	Test Z	Q	% Change
Grid1	−2.82**	−2.23	−20.46	−2.50*	−1.83	−19.82
Grid2	−4.23***	−2.43	−23.39	−3.38***	−2.12	−24.00
Grid3	−3.53**	−2.31	−19.98	−2.84**	−1.96	−20.11
Grid4	−3.63***	−2.41	−22.78	−4.55***	−2.26	−25.21
Grid5	−3.40***	−2.19	−18.78	−3.42**	−2.03	−20.76
Grid6	−3.49***	−2.27	−20.93	−5.08***	−2.16	−23.61
Grid7	−3.33***	−2.15	−18.49	−3.25**	−1.96	−20.16
Grid8	−2.72**	−1.64	−13.77	−2.66**	−1.58	−16.14
Grid9	−3.02**	−2.01	−16.90	−3.08**	−1.89	−19.25
Grid10	−2.60**	−1.62	−13.49	−2.72**	−1.60	−16.57
Grid11	−1.96	−1.27	−9.92	−2.31*	−1.38	−13.52
Grid12	−1.76	−1.01	−8.26	−2.09*	−1.25	−13.10
Grid13	−0.62	−0.56	−4.39	−1.11	−0.60	−5.97
Grid14	0.69	0.32	2.31	0.25	0.14	1.29
Grid15	−0.56	−0.35	−2.86	−1.03	−0.54	−5.54
Grid16	0.67	0.33	2.57	0.26	0.05	0.49
Grid17	1.90	1.36	9.61	1.61	0.91	8.43
Grid18	2.41*	1.78	11.75	1.93+	1.16	10.23

***$\alpha = 0.001$ level of significance; **$\alpha = 0.01$ level of significance; *$\alpha = 0.05$ level of significance; +$\alpha = 0.1$ level of significance

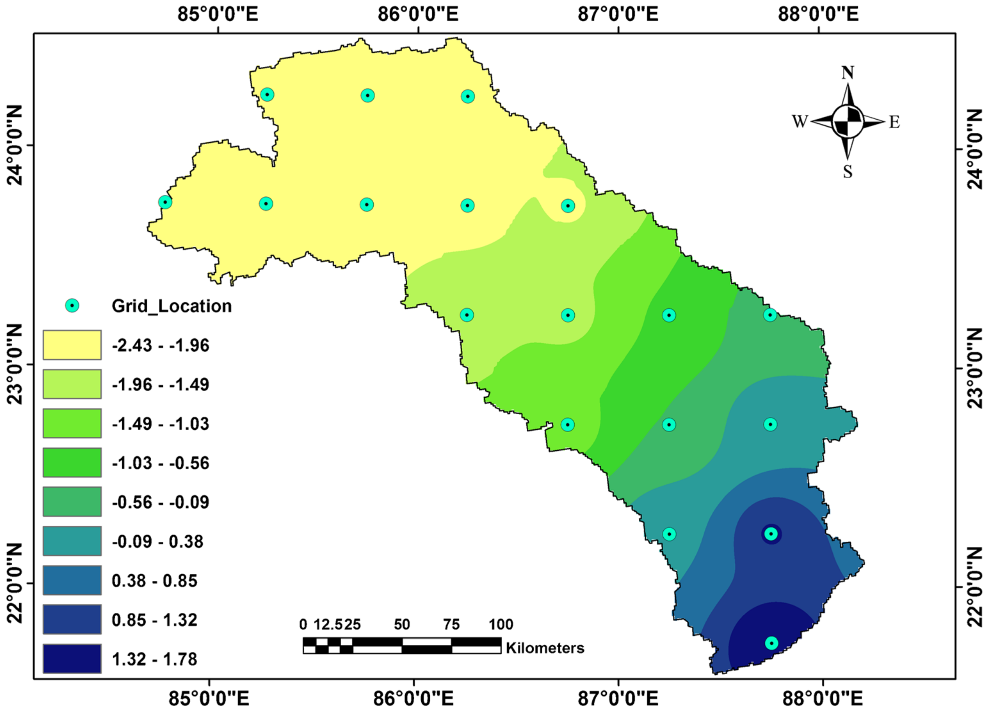

Fig. 2 Spatial distribution of Sen's slope value (mm/year) for the annual rainfall

studies has also indicated decreasing rainfall in Asia (Dash et al. 2007; Goswami et al. 2006; Khan et al. 2000; Lal 2003; Min et al. 2003; Mirza 2002; Shrestha et al. 2000; Sinha Ray and Srivastava 1999). Many researchers found decrease in South Asian monsoon rainfall (Loo et al. 2015; Roxy et al. 2015; Schewe and Levermann 2012; Sinha et al. 2015). Plausible explanation of the reduction in rainfall over South Asia has been given by Roxy et al. (2015) who reported that increased SST over Indian Ocean potentially weakens the land-sea thermal difference that reduces the rainfall over parts of South Asia.

It can be seen from the results that for most of the grid points, the significant turning point was found in between

Table 2 Significant change points by sequential Mann-Kendall test over Damodar basin

Time Series	Annual		Monsoon	
	First turning point	Significant turning points	First turning point	Significant turning points
Grid1	1944	1944	1944	1944
Grid2	1949	1949	1978	1998
Grid3	1945	1945	1946	1946,1999
Grid4	1949	1949	1953	1996
Grid5	1946	1946	1947	1947
Grid6	1946	1946, 1994	1950	1950, 1996
Grid7	1946	1946, 1993	1946	1946, 1944
Grid8	1944	1944	1943	1943, 1998
Grid9	1944	1944	1945	1945, 1996
Grid10	1944	1944	1944	1944
Grid11	1916	1916, 1919, 1943	1943	–
Grid12	1915	1915, 1926	1943	–
Grid13	1909	–	1922	–
Grid14	1906	–	1905	–
Grid15	1909	–	1920	–
Grid16	1907	–	1906	–
Grid17	1967	–	1905	–
Grid18	1906	1906	1906	–

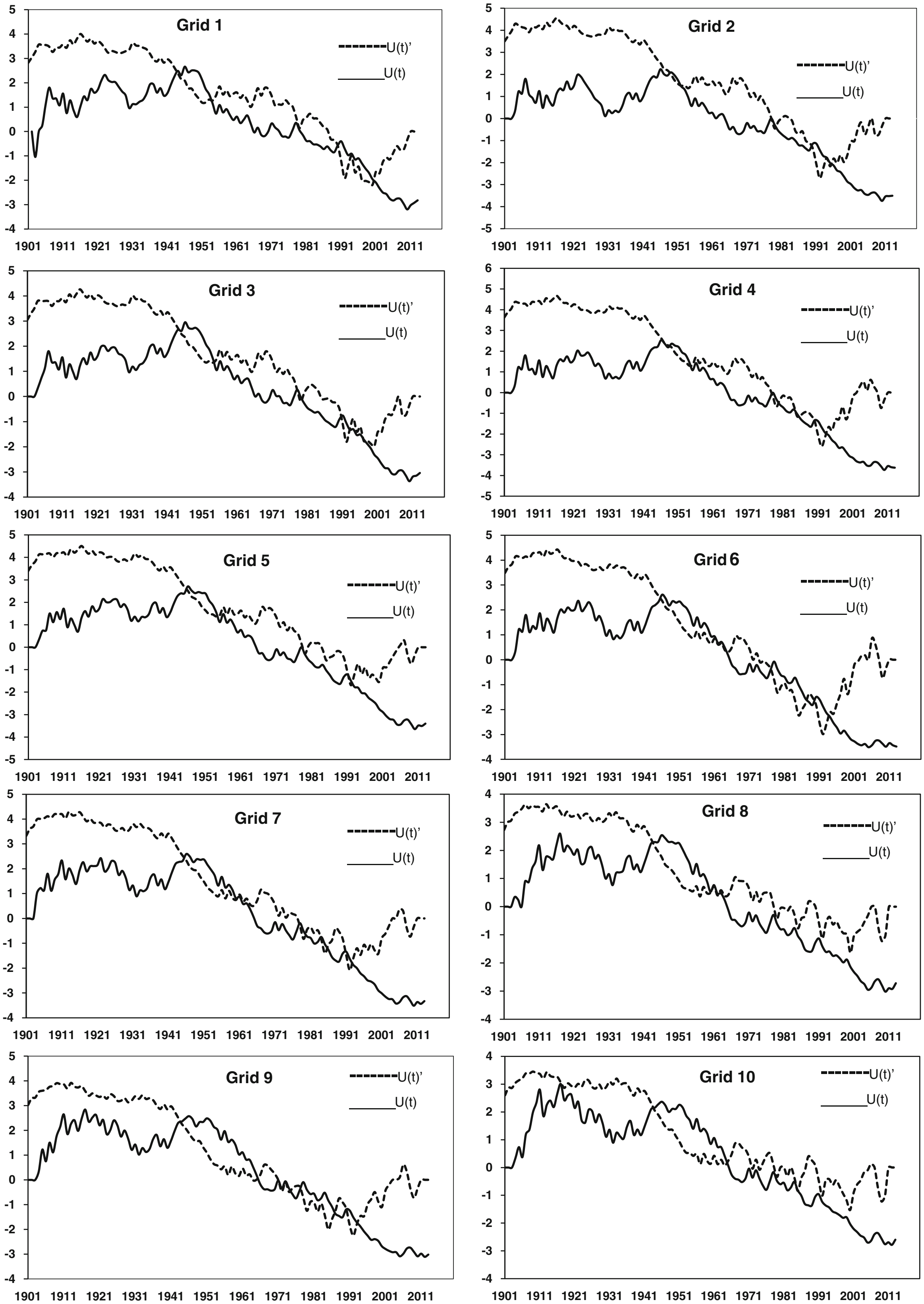

Fig. 3 Sequential Mann-Kendall test rank statistics for annual rainfall over all the grid locations

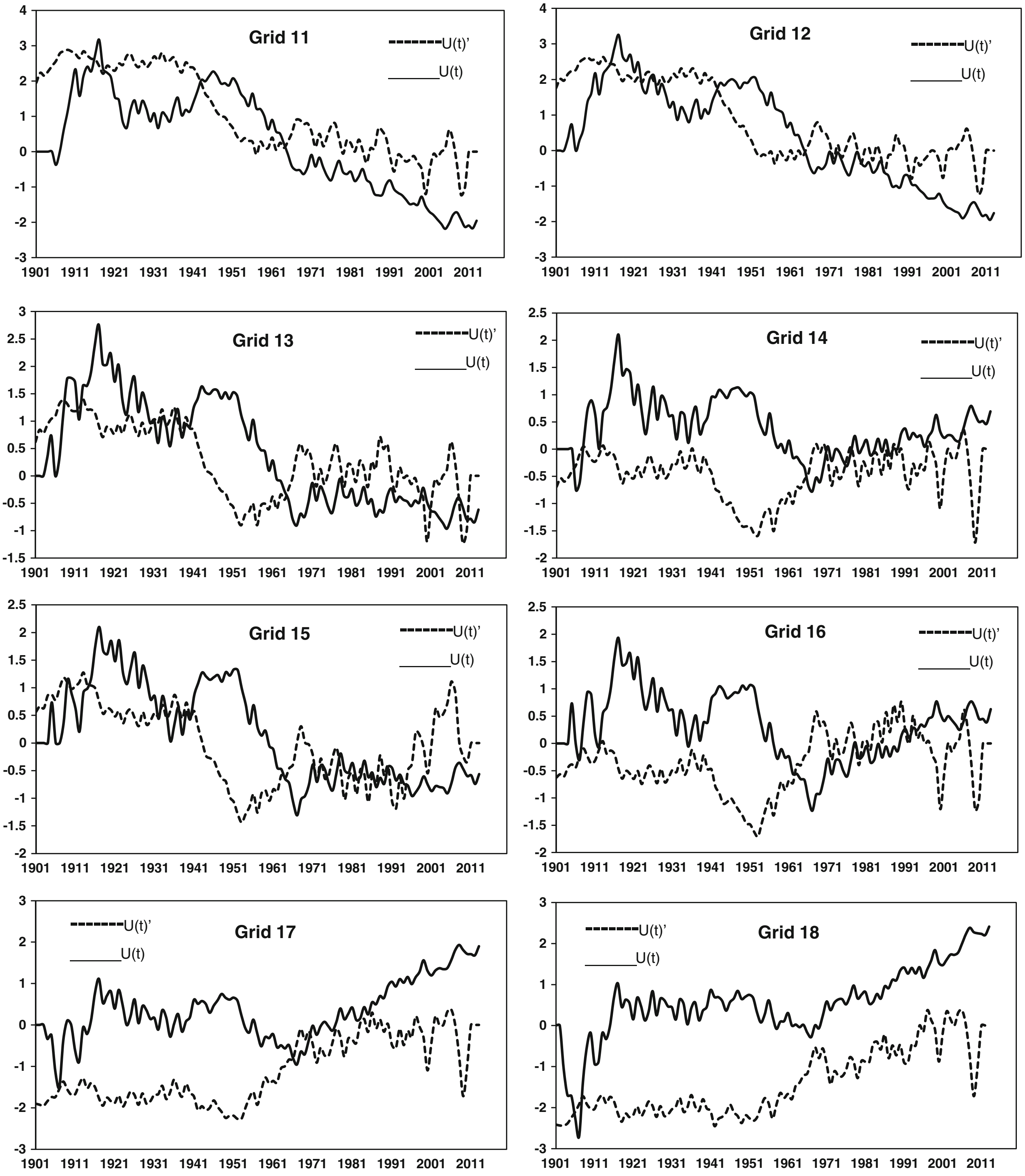

Fig. 3 (continued)

1940 and 1950. Grids 17 and 18 showed an increasing trend as depicted from *u(t)* statistics. The *u(t)* statistics displayed an upward change after 1909 till present in grid 18. Successive increasing and decreasing trend was found for grids 14, 15, and 16.

From Fig. 2, it can be concluded that for Grid 1, two significant turning points were clearly identified, i.e., 1944 and 2000. Grid 2 also showed two significant turning points that are 1997 and 1949. On the other hand, Grid 11 showed three significant turning points that are 1916, 1919, and 1943. 1944 was the most important turning point in the study as it was found significant for grids 1, 8, 9, and 10. No turning point was found for grids 13, 14, 15, 16, and 17.

The results of MK and MMK showed a significant decreasing trend for monsoon rainfall for all the grids except grids 14, 16, 17, and 18. Positive trend were not significant except for grid 18.The amount of the decreasing trends in monsoon precipitation ranged between 0.54 mm per year (grid 15) and 2.26 mm per year (grid 4). However, the increasing trends in rainfall during monsoon ranged between 0.05 mm per year (grid 16) and 1.16 mm per year (grid 18) (Fig. 4).

The *u(t)* statistics depicted a decreasing trend of monsoon rainfall for grid 1 to grid 15 (Fig. 5). High periodic fluctuations in monsoon rainfall were found for grids 14 and 16. For grid 17 and grid 18, an increasing trend in monsoon rainfall was observed. No turning point was found for grids 11, 13, 14, 15, 16, 17, and 18. It can be seen from the results that for most of the grid points, the significant turning point was found in between 1940 and 1950 and 1990 and 2000.

Results of trend analysis showed a declining as well as episodic fluctuation of rainfall trend in most of the cases. The declining trend in rainfall is in agreement with other studies who also found decrement in annual as well as monsoon rainfall over the Wainganga basin (Taxak et al. 2014**)**, Sindh river basin (Gajbhiye et al. 2016), Chhattisgarh (Meshram et al. 2016), Yamuna River basin (Rai et al. 2010), Seonath River basin (Chakraborty et al. 2013), and Madhya Pradesh (Duhan and Pandey 2013; Kundu et al. 2015) which are in different parts of India. However, the present study is in contradiction with the results of trend analysis found over Haryana (Darshana 2012), Haridwar (Pranuthi et al. 2014), Gangetic West Bengal, western Uttar Pradesh, Jammu and Kashmir, Konkan and Goa, Madhya Maharashtra, Rayalaseema, coastal Andhra Pradesh, and north Interior Karnataka (Guhathakurta and Rajeevan 2008) which showed the increasing precipitation trend.

Percent change was also computed for both annual and monsoon season rainfall data. For annual precipitation, the percentage change found more than 10% in 11 grids while for monsoon season, it was found more than 10% in 13 grids. The maximum negative percent change was found at grid 2 (−23.39) while minimum at grid 13 (−4.39) for annual series. Also, for monsoon season, the maximum negative percent change was found at grid 2 (−24) while minimum at grid 13 (−0.60).

The results showed temporal variability in rainfall trend which shows that the location, topography, altitude, and regional climate along with climate change have a complex relationship which results into these contradictory outcomes from one location to another location.

The most probable causes associated with the fluctuation in rainfall include the following reasons.

- Weakening of the global monsoon circulation (Duan and Yao 2003)
- Reduction in strength of tropical easterly Jet Stream, which are important for the formation of monsoon depression (Naidu et al. 2011; Rao et al. 2004; Sathiyamoorthy 2005)
- Rise in global temperature as a result of global warming leads to an uneven distribution of rainfall (Rao et al. 2001).

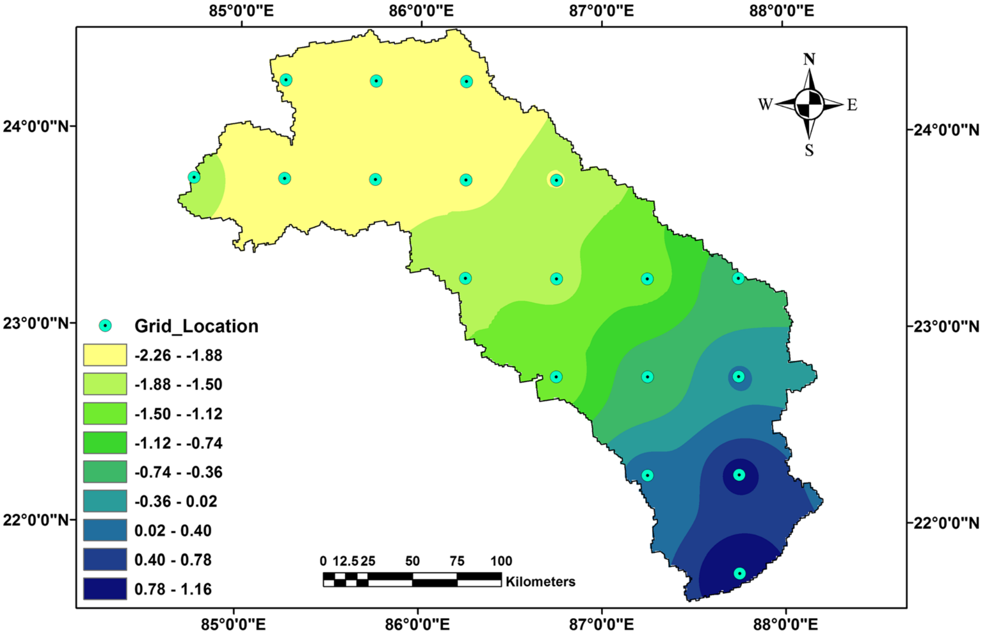

Fig. 4 Spatial distribution of Sen's slope value (mm/year) for the annual rainfall

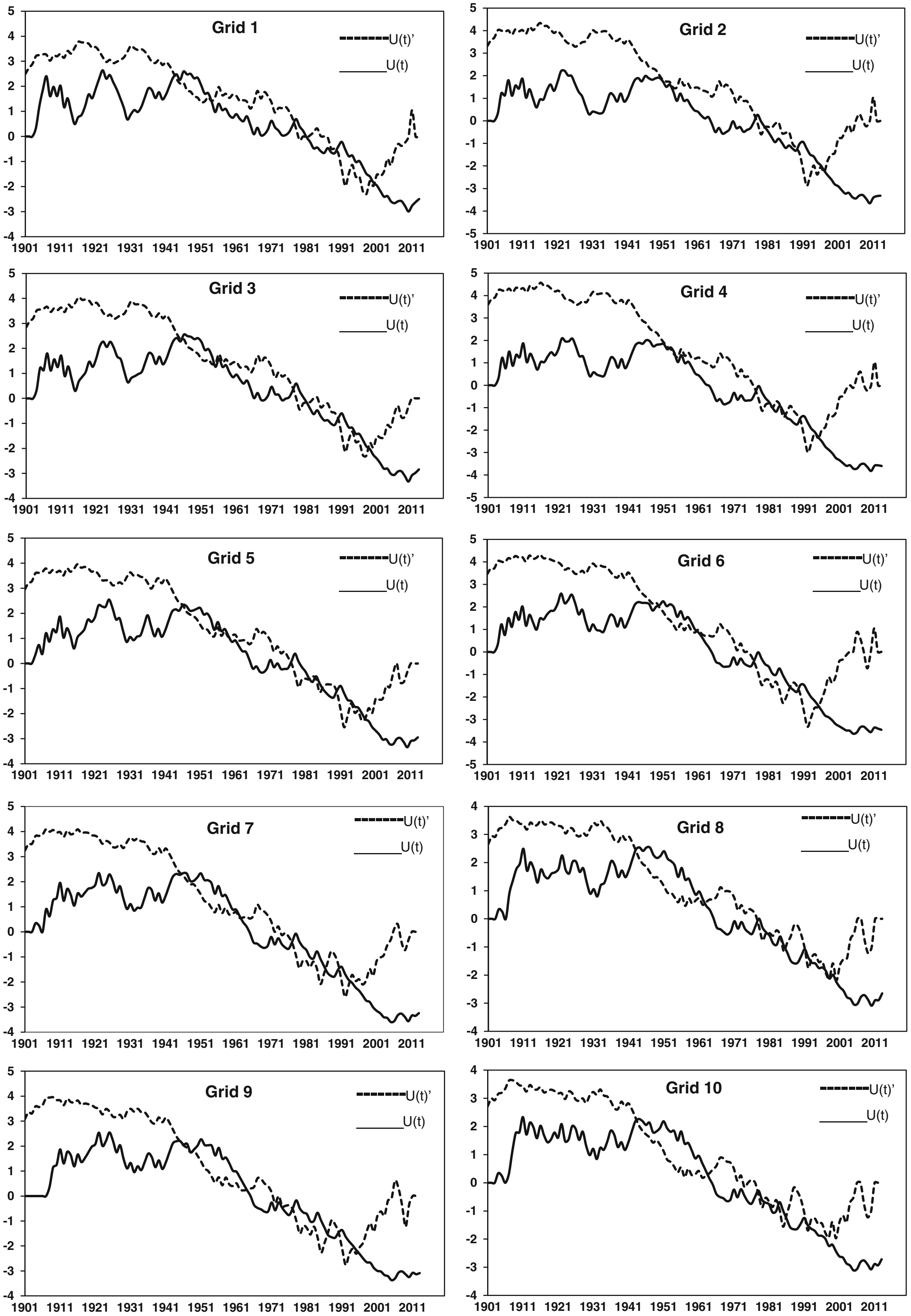

Fig. 5 Sequential Mann-Kendall test rank statistics for monsoon rainfall over the all the grid locations

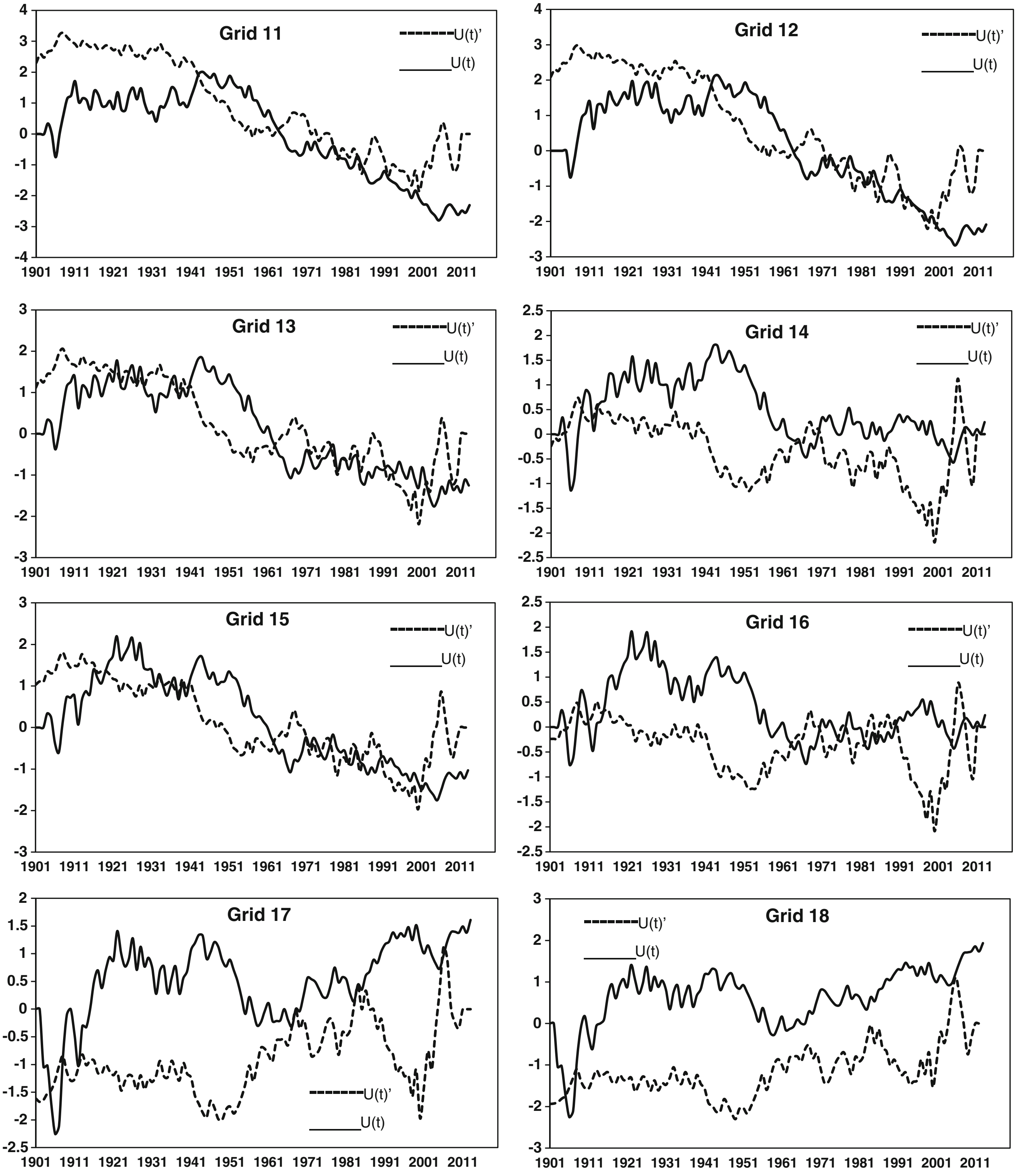

Fig. 5 (continued)

- Reduction in forest cover (Gupta et al. 2005; Nair et al. 2003)
- Rising aerosol content due to anthropogenic activities (Ramanathan et al. 2005; Sarkar and Kafatos 2004)

Increased temperature has direct influence on moisture holding capacity of air as it is positively correlated with it; hence, it may result in more extreme and intense rainfall with a decrease in rainy days keeping rainfall stable during the considered time span (Trenberth 1998). Kumar et al. (1987) also reported that the warming in the Indian temperature mainly resulted from increasing temperatures up to the late 1950s, after which temperature remained nearly stable over India.

Conclusion

The present study involves the analysis of annual and monsoon rainfall trend for the entire Damodar basin over the period 1901–2013, covering 18 grid points. The significant decreasing trend in precipitation were found over the basin annually as well as for monsoon season for most of the grid locations. In the annual series, the decline in magnitude of trend varies from 0.56 mm per year (grid 13) to 2.43 mm per year (grid 2). During monsoon season rainfall, the magnitude of the declining trend varies from 0.54 mm per year (grid 15) to 2.26 mm per year (grid 4).

The results of sequential Mann-Kendall test revealed the decreasing trend with periodic fluctuations in almost all the grid points for both annual and monsoon series. The results of the present study revealed that the declining trend of rainfall can have impacts on water resources and agriculture of the area. So, the water policy makers and agriculture planners have to adapt water conservation strategies along with this agriculture practitioners moving to crops or breeds requiring less water.

From the study, it is concluded that annual and monsoon precipitation is decreased significantly in DRB during the period 1901–2013. The decreasing trend in seasonal rainfall will have a more pronounced effect on agricultural activities that may affect the growth phase of the kharif crops (May–October) in the basin. There is a need to integrate the changing climate in the planning and management of water resources of the state. As the Damodar basin covers some areas of Jharkhand, where the agriculture is totally dependent on rainfall, the agriculture planners should actively incorporate some strategies to avoid the water stress condition.

On the basis of the results found in the present study, the future scope including the study of land use cover changes, temperature trends along with population and aerosol trends will be helpful in determining the probable reasons of decrement of rainfall.

References

Abeysingha N, Singh M, Sehgal V, Khanna M, Pathak H (2014) Analysis of rainfall and temperature trends in Gomti River Basin. J Agric Phys 14:56–66

Almazroui M, Islam MN, Jones PD, Athar H, Rahman MA (2012) Recent climate change in the Arabian peninsula: seasonal rainfall and temperature climatology of Saudi Arabia for 1979–2009. Atmos Res 111:29–45. doi:10.1016/j.Atmosres.2012.02.013

Bohnenstengel SI, Schlünzen K, Beyrich F (2011) Representativity of in situ precipitation measurements—a case study for the LITFASS area in North-Eastern Germany. Journal of Hydrology 400:387–395

Buffoni L, Maugeri M, Nanni T (1999) Precipitation in Italy from 1833 to 1996. Theor Appl Climatol 63:33–40

Burns DA, Klaus J, McHale MR (2007) Recent climate trends and implications for water resources in the Catskill Mountain region, New York, USA. J Hydrol 336:155–170

Cannarozzo M, Noto LV, Viola F (2006) Spatial distribution of rainfall trends in Sicily (1921–2000). Phys Chem Earth A/B/C 31:1201–1211. doi:10.1016/j.pce.2006.03.022

Chakraborty S, Pandey R, Chaube U, Mishra S (2013) Trend and variability analysis of rainfall series at Seonath River basin, Chhattisgarh (India). J Appl Sci Eng Res 2:425–434

Cruz FT, Narisma GT, Villafuerte Ii MQ, Cheng Chua KU, Olaguera LM (2013) A climatological analysis of the southwest monsoon rainfall in the Philippines. Atmos Res 122:609–616. doi:10.1016/j.atmosres.2012.06.010

da Silva VPR (2004) On climate variability in Northeast of Brazil. J Arid Environ 58:575–596

Daniels E, Lenderink G, Hutjes R, Holtslag A (2014) Spatial precipitation patterns and trends in The Netherlands during 1951–2009. Int J Climatol 34:1773–1784

Darshana PA (2012) Long-term trends in rainfall pattern over Haryana, India. Int J Res Chem Environ 2:283–292

Dash S, Jenamani R, Kalsi S, Panda S (2007) Some evidence of climate change in twentieth-century India. Climatic Change 85:299–321

Duan K, Yao T (2003) Monsoon variability in the Himalayas under the condition of global warming (SCI)

Duhan D, Pandey A (2013) Statistical analysis of long term spatial and temporal trends of precipitation during 1901–2002 at Madhya Pradesh, India. Atmos Res 122:136–149

Gajbhiye S, Meshram C, Mirabbasi R, Sharma S (2015) Trend analysis of rainfall time series for Sindh river basin in India. Theor Appl Climatol 1–16

Gajbhiye S, Meshram C, Singh SK, Srivastava PK, Islam T (2016) Precipitation trend analysis of Sindh River basin, India, from 102-year record (1901–2002). Atmos Sci Lett 17:71–77

Goswami BN, Venugopal V, Sengupta D, Madhusoodanan M, Xavier PK (2006) Increasing trend of extreme rain events over India in a warming environment. Science 314:1442–1445

Guhathakurta P, Rajeevan M (2008) Trends in the rainfall pattern over India International. J Climatol 28:1453–1470

Gupta A, Thapliyal P, Pal P, Joshi P (2005) Impact of deforestation on Indian monsoon—a GCM sensitivity study. J Ind Geophys Union 9:97–104

Hamed KH, Rao AR (1998) A modified Mann-Kendall trend test for autocorrelated data. J Hydrol 204:182–196

Hu ZZ, Yang S, Wu R (2003) Long-term climate variations in China and global warming signals. J Geophys Res Atmos 108

Khan TMA, Singh O, Rahman MS (2000) Recent sea level and sea surface temperature trends along the Bangladesh coast in relation to the frequency of intense cyclones. Marine Geodesy 23:103–116

Kipkorir E (2002) Analysis of rainfall climate on the Njemps flats, Baringo District, Kenya. J Arid Environ 50:445–458

Krishnamurthy V, Goswami B (2000) Indian monsoon-ENSO relationship on interdecadal timescale. J Clime 13:579–595

Kumar KR, Hingane L, Murty BVR (1987) Variation of tropospheric temperatures over India dining 1944-85. J Clim Appl Meteorol 26:304–314

Kundu S, Khare D, Mondal A, Mishra P (2015) Analysis of spatial and temporal variation in rainfall trend of Madhya Pradesh, India (1901–2011). Environ Earth Sci 73:8197–8216

Lal M (2003) Global climate change: India's monsoon and its variability. J Environ Stud Policy 6:1

Loo YY, Billa L, Singh A (2015) Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. Geosci Front 6:817–823

Mann H (1945) Non-parametric tests against trend. Econmetrica 13:245–259

McCarthy JJ (2001) Climate change 2001: impacts, adaptation, and vulnerability: contribution of working group II to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press

Méndez González J, Návar Cháidez JdJ, González Ontiveros V (2008) Análisis de tendencias de precipitación (1920–2004) en México. Investigaciones Geográficas 65:38–55

Meshram SG, Singh VP, Meshram C (2016) Long-term trend and variability of precipitation in Chhattisgarh State, India Theoretical and Applied Climatology:1–16

Min SK, Kwon WT, Park E, Choi Y (2003) Spatial and temporal comparisons of droughts over Korea with East Asia International. J Climatol 23:223–233

Mirza MMQ (2002) Global warming and changes in the probability of occurrence of floods in Bangladesh and implications. Glob Environ Chang 12:127–138

Naidu C, Krishna KM, Rao SR, Kumar OB, Durgalakshmi K, Ramakrishna S (2011) Variations of Indian summer monsoon rainfall induce the weakening of easterly jet stream in the warming environment? Glob Planet Chang 75:21–30

Nair US, Lawton RO, Welch RM, Pielke RA (2003) Impact of land use on Costa Rican tropical montane cloud forests: Sensitivity of cumulus cloud field characteristics to lowland deforestation. J Geophys Res Atmos:108

Nasri M, Modarres R (2009) Dry spell trend analysis of Isfahan Province, Iran. International J Climatol 29:1430–1438

Patra JP, Mishra A, Singh R, Raghuwanshi N (2012) Detecting rainfall trends in twentieth century (1871–2006) over Orissa state, India. Clim chang 111:801–817

Peterson BJ et al (2002) Increasing river discharge to the Arctic. Ocean Sci 298:2171–2173

Pranuthi G, Dubey S, Tripathi S, Chandniha S (2014) Trend and change point detection of precipitation in urbanizing Districts of Uttarakhand in India Indian. J Sci Technol 7:1573–1582

Rai R, Upadhyay A, Ojha C (2010) Temporal variability of climatic parameters of Yamuna River basin: spatial analysis of persistence, trend and periodicity. Open Hydrol J 4:184–210

Ramanathan V et al (2005) Atmospheric brown clouds: impacts on south Asian climate and hydrological cycle. Proc Natl Acad Sci U. S. A. 102:5326–5333

Rao B, Rao D, Rao VB (2004) Decreasing trend in the strength of Tropical Easterly Jet during the Asian summer monsoon season and the number of tropical cyclonic systems over Bay of Bengal. Geophys Res Lett 31

Rao DB, Naidu C, Rao BS (2001) Trends and fluctuations of the cyclonic systems over North Indian Ocean. Mausam 52:37–46

Roxy MK, Ritika K, Terray P, Murtugudde R, Ashok K, Goswami B (2015) Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient. Nat Commun 6

Sarkar S, Kafatos M (2004) Interannual variability of vegetation over the Indian sub-continent and its relation to the different meteorological parameters. Remote Sens Environ 90:268–280

Sathiyamoorthy V (2005) Large scale reduction in the size of the Tropical Easterly Jet. Geophys Res Lett 32

Schewe J, Levermann A (2012) A statistically predictive model for future monsoon failure in India. Environ Res Lett 7:044023

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63:1379–1389

Shrestha AB, Wake CP, Dibb JE, Mayewski PA (2000) Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. Int J Climatol 20:317–327

Sinha A et al. (2015) Trends and oscillations in the Indian summer monsoon rainfall over the last two millennia Nat Commun 6

Sinha Ray K, Srivastava A (1999) Is there any change in extreme events like droughts and heavy rainfall INTROPMET-97, IIT New Delhi: 2–5

Sneyres R (1990) Technical note no. 143 on the statistical analysis of time series of observation World Meteorological Organization, Geneva, Switzerland

Stephenson DB, Kumar KR (2001) Searching for a fingerprint of global warming in the Asian summer monsoon. Mausam 52:213–220

Sushant S, Balasubramani K, Kumaraswamy K (2015) Spatio-temporal analysis of rainfall distribution and variability in the twentieth century, over the Cauvery Basin, South India. In: Environmental Management of River Basin Ecosystems. Springer, pp 21–41

Taxak AK, Murumkar AR, Arya DS (2014) Long term spatial and temporal rainfall trends and homogeneity analysis in Wainganga basin, Central India. Weather and Climate Extremes 4:50–61. doi:10.1016/j.wace.2014.04.005

Trenberth KE (1998) Atmospheric moisture residence times and cycling: implications for rainfall rates and climate change. Clim Chang 39:667–694

Trenberth KE (2011) Changes in precipitation with climate change. Clim Res 47:123–138

Zhai P, Pan X (2003) Trends in temperature extremes during 1951–1999 in China. Geophys Res Lett 30