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Trend analysis for rainfall in Delhi and Mumbai, India

Arun Rana · Cintia Bertacchi Uvo · Lars Bengtsson · P. Parth Sarthi

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Abstract Urbanisation has burdened cities with many problems associated with growth and the physical environment. Some of the urban locations in India are becoming increasingly vulnerable to natural hazards related to precipitation and flooding. Thus it becomes increasingly important to study the characteristics of these events and their physical explanation. This work studies rainfall trends in Delhi and Mumbai, the two biggest Metropolitan cities of Republic of India, during the period from 1951 to 2004. Precipitation data was studied on basis of months, seasons and years, and the total period divided in the two different time periods of 1951–1980 and 1981–2004 for detailed analysis. Long-term trends in rainfall were determined by Man-Kendall rank statistics and linear regression. Further this study seeks for an explanation for precipitation trends during monsoon period by different global climate phenomena. Principal component analysis and Singular value decomposition were used to find relation between southwest monsoon precipitation and global climatic phenomena using climatic indices. Most of the rainfall at both the stations was found out to be taking place in Southwest monsoon season. The analysis revealed great degree of variability in precipitation at both stations. There is insignificant decrease in long term southwest monsoon rainfall over Delhi and slight significant decreasing trends for long term southwest monsoon rainfall in Mumbai. Decrease in average maximum rainfall in a day was also indicated by statistical analysis for both stations. Southwest monsoon precipitation in Delhi was found directly related to Scandinavian Pattern and East Atlantic/West Russia and inversely related to Pacific Decadal Oscillation, whereas precipitation in Mumbai was found inversely related to Indian ocean dipole, El Niño-Southern Oscillation and East Atlantic Pattern.

Keywords Urbanization · India · Statistical analysis · Man-Kendall · Climate indices · Principal component analysis · Singular value decomposition

A. Rana (✉) · C. B. Uvo · L. Bengtsson
Department of Water Resources Engineering, LTH, Lund University, Box No. 118, 22100 Lund, Sweden
e-mail: Arun.Rana@tvrl.lth.se; arunranain@gmail.com

P. Parth Sarthi
Center for Environmental Sciences, Central University of Bihar, Camp Office: BIT Campus-Patna, P.O-B.V. College, Patna, Bihar 800014, India

1 Introduction

Urbanization has established a network of competitive urban centres that set the physical reference points for today's globalization. Some of the urban locations in India are becoming increasingly vulnerable to natural hazards related to weather and climate (De and Dandekar 2001). Global averaged precipitation is projected to increase, but both increases and decreases are expected at the regional and continental scales (IPCC 2001). Information about the trends of rainfall are important as it is closely related to the practical water relates issues in the region especially flood related problems. Thus it becomes increasingly important to study the trends in precipitation and their physical explanation.

Several studies have addressed the important issue of trends in rainfall in India since last century. For example, Guhathakurta and Rajeevan (2006) have shown that there is no long term trend in the southwest monsoon seasonal rainfall over the country, when about 60–90% of the annual rainfall over India is received (Joshi and Rajeevan 2006), but there are significant regional variations. Long term southwest monsoon/annual rainfall trends over India as a whole were previously studied by Pramanik and Jagannathan (1954), a pioneer work in organizing series of annual rainfalls over 80–100 years ending in 1950, found systematic variations over certain regions in addition to random fluctuations. These findings were later corroborated by Mooley and Parthasarathy (1984) and by Parthasarathy et al. (1993). Rao and Jagannathan (1963), Thapliyal and Kulshrestha (1991) and Srivatsava et al. (1992) analyzed the data organized by Pramanik and Jagannathan (1954) and reported no trends for an average time series, for all India, of southwest monsoon/annual rainfall. Regionally Pant and Borgaonkar (1984) did not find any trend in rainfall over the hilly region of Uttar Pradesh. No trends were reported over western Himalaya on seasonal and annual rainfall during the period 1893–1990 by Pant et al. 1999. Singh and Sontakke (1999) studied Post monsoon rainfall from 1871 to 1980: northwest India, 1844–1996; North Central India, 1842–1996; northeast India, 1829–1996; West Peninsular India, 1841–1996; East Peninsular India, 1848–1996; and South Peninsular India, 1813–1996 and concluded that these areas do not possess a significant long-term trend, and were weakly correlated.

Long term trends in annual rainfall on small spatial scale were reported; among others, by Koteswaram and Alvi (1969) over west coast of India, by Jagannathan and Bhalme (1973), during the monsoon season for each of the years 1901–1951 for a network of 105 stations over India; by Parthasarathy (1984) over two subdivisions viz. sub-Himalayan West Bengal and Sikkim and the Bihar Plains that showed decreasing trends in monsoon rainfall, and for the four subdivisions viz. Punjab, Konkan and Goa, West Madhya Pradesh and Telangana that showed increasing trends; by Chhabra et al. (1997) that indicated a decrease in the precipitation in hilly stations and an increase in the precipitation in the urbanized/industrialized cities; and by Naidu et al. (1999) on annual rainfall for 29 sub-divisions of India by using the rainfall series for a period of 124 years (1871–1994). Recently, Goswami et al. (2006) indicated significant positive trends in the frequency and the magnitude of extreme rain events and a significant negative trend in the frequency of moderate events over central India during the monsoon seasons from 1951 to 2000.

The relation between precipitations in India and global climate phenomena is well known, however their association to precipitation trends is not as well explored. Roy (2006) has indicated that the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO) have negative relationship with winter rainfall in almost all north and central parts of India whereas SST around the mainland have negative correlation with rainfall in peninsular India. Singh (2001) have also shown the negative relationship of pre-monsoon ENSO conditions to the amount of precipitation taking place in north-western and peninsular India. A major shift in total rainfall during recent years has been observed which shows that they might be following periodical cycles of PDO, ENSO and local SSTs, (Roy 2006). Joseph and Xavier (1999) have reported a strong decreasing trend in the monsoon depression frequency during last 100 years. Kumar and Dash (2001) showed that the decadal frequency of number of depressions was decreasing in recent years.

The present research is aimed at analyzing trends in precipitation in the cities of Delhi and Mumbai and seeks for physical explanation to trends during southwest monsoon season on global climate phenomena as expressed by climatic indices. We aim to investigate the long term trend in southwest monsoon rainfall and the possible effect of global climatic phenomena. Statistical linear methods are used for recognizing trends and their physical explanation. Delhi is located at 28°37′N 77°14′E, and lies in northern India whereas Mumbai is located at 18°58′30″N 72°49′33″E in south western part of India. This study has been divided into three sections. Section 2 deals with data used and methodology, Sect. 3 deals with results and discussion where we presented analysis of monthly precipitation, analysis of annual and decadal precipitation, of seasonal precipitation, of maximum daily precipitation per year and climate relation of trends, finally in Sect. 4 conclusions are outlined.

2 Data used and methodology

For this study, daily accumulated rainfall data was obtained from India Meteorological Department (IMD) and monthly climatic indices data were obtained from the National Weather Service, Climate Prediction Centre (NOAA). Data for Delhi, Mumbai and climatic indices including Scandinavian Oscillations (SCA), East Atlantic/West Russia (EA/WR), West Pacific (WP), North Atlantic Oscillations (NAO), East Pacific/North Pacific (EP/NP), Indian Ocean Dipole (IOD), El Niño- Southern-Oscillation (NINO 3.4), Pacific Decadal Oscillation (PDO), East Atlantic (EA) and Pacific/North American Oscillations (PNA) considered in the study are from 1951 to 2004.

From the basic daily rainfall data, monthly means, median, percentiles, seasonal totals, Standard Deviation (SD) and percentage contribution to annual rainfall were computed monthly and season-wise viz., Pre-monsoon (March–May), Southwest monsoon (June–September), Post-monsoon (October–November) and Winter (December–February). A linear trend line was added to the series for identifying the trends. The data was subjected to Mann–

Kendall test for trend analysis in different time periods from 1951 to 1980, 1981 to 2004 and also from 1951 to 2004 for all the seasons and annually so as to see changes in precipitation on decadal basis. The data was also analyzed for daily extreme/Maximum precipitation events per year.

The linear regression method is widely used to determine long-term trends seasonally, annually, and for daily maximum precipitation (e.g. Gadgil and Dhorde 2005, among many others). The non-parametric Mann–Kendall test, which is another popular statistical method used by contemporary climatologists (e.g. Gadgil and Dhorde 2005; Tomozeiu et al. 2006 and many others) is used here as a significance test. The major advantages of this test highlighted by Rio et al. (2005) are: (1) No assumptions about distribution are necessary and (2) it is directly applicable to climate data for a given month or season. The procedure of carrying out this statistical test is outlined by Mitchell et al. (1966).

Further, trends in total precipitation during the southwest monsoon (June–September) at these stations were compared to climatic indices/tele-connection patterns in seeking for a physical explanation to observed trends. Principal component analysis (PCA) and Singular value decomposition (Bretherton et al. 1992) were used to investigate such relationship. Both methods isolate important coupled modes of variability between time series of two different fields.

PCA, which maximizes variance explained by weighted sum of elements in two or more fields, was first proposed by Pearson (1902). It identifies linear transformations of the dataset that concentrate as much of the variance as possible into a small number of variables. First applications to meteorology were by Fukoka (1951), Lorenz (1956), Holmstrom (1963) and Obukhov (1960). The lucid exposition of PCA by Katzbach (1967) was instrumental in promoting the use of this technique in climate research. Katzbach (1967) pointed out that two or more field variables can be combined in the same PCA to document the relationship between the fields. It isolates the modes of variability observed in time series of different fields and gives their relationships in separate modes.

SVD is a fundamental matrix operation, a generalization of the diagonalization procedure that is performed in PCA to the matrices that are not squared or symmetric. SVD was first used in meteorological context by Prohaska (1976), later by Lanzante (1984) and Dymnikov and Filin (1985). As applied by Bretherton et al. (1992), SVD is performed to the cross-covariance matrix of two fields and isolates the linear combinations of variables within the fields that tend to be linearly related to one another by maximizing the covariance between them. Here SVD is applied to the cross-covariance matrix of the **s** (t, x) matrix of x climatic indices (called as predictant) at t years and the **z** (t, y) matrix composed by total monsoon precipitation in Delhi and Mumbai at t years, this might be called as predictor. All time series are standardized to zero mean and unit standard deviation prior of use in the SVD. The data time series **s** (t) and **z** (t) for each variable can be expanded in terms of a set of N vectors, called pattern (Bretherton et al. 1992). Here we try to estimate the predictor on basis of predictant.

$$s(t) \leftarrow \breve{s}(t) \equiv \sum_{k=1}^{N} a_k(t) p_k$$

$$z(t) \leftarrow \breve{z}(t) \equiv \sum_{k=1}^{N} b_k(t) q_k$$

The time series a_k (t) and b_k (t) are called expansion series; p_k and q_k are the patterns. The expansion coefficients are calculated as weighted linear combination of variables in data.

$$a_k(t) = \sum_{i=1}^{N_s} u_{ik} s_i(t) = u_k^T s(t)$$

$$b_k(t) = \sum_{j=1}^{N_z} u_{jk} z_i(t) = v_k^T z(t)$$

The vectors u_k and v_k are called weight vectors. Together, each pair of patterns, the corresponding pair of weight vectors and the pair of expansion coefficients defines a mode, which combines the variability observed in different fields. The variables in the **s** and **z** fields are subscripted by i and j, respectively, and individual modes by k. Further square covariance fractions were calculated to give the percentage of squared covariance fraction explained by predictor in the predictant field in particular mode. This can be used to compare the relative importance of particular mode in the expansion.

3 Results and discussion

3.1 Analysis of monthly precipitation

Rainfall characteristics of Delhi and Mumbai are represented in Fig. 1 in form of box plot and Tables 1, 2. The annual mean rainfall over Delhi and Mumbai from 1951 to 2004 is 715 and 2,142 mm with a standard deviation of 199 and 3,516 mm, respectively (Table 1). For Delhi, rainfall during August is the highest (234 mm) and contributes to 32% of annual rainfall (715 mm), followed by July (28%), September (16%) and June (8%) of the annual rainfall. Rainfall in November is the least (4 mm) and contributes only 0.6% to the annual rainfall. The coefficient of variation is highest during April (284%), followed by November (240%) and December (203%) and the least during the high rainfall months of July (57%) and August (57%). Rainfall during the southwest monsoon (June–September) contributes 85.9% of the annual rainfall. The contribution of pre-monsoon (March–May), post-monsoon (October–November) and winter rainfall (December–February) to annual rainfall is 5, 3 and 5% respectively. Whereas for Mumbai, rainfall during July is the highest (777 mm) and contributes to 36% of annual rainfall (2,142 mm), followed by June (23%), August (23%) and September (13%) of the annual rainfall, respectively. Rainfall during the southwest monsoon (June–September) contributes 96% of the annual rainfall. The contribution of pre-monsoon (March–May), post-monsoon (October–November) and winter rainfall (December–February) to annual rainfall is 0.8, 3 and 0.1%, respectively.

3.2 Analysis of annual and decadal precipitation

The mean annual rainfall over Delhi showed no significant declining trend during the entire study period (Fig. 2a). However, the annual rainfall in the period 1981–2004 showed a relative decrease when compared to 1951–1980 (Fig. 3a; Table 2). These results are corroborated by the Man-Kendall Test (Table 3). The mean annual rainfall over Mumbai showed a long term significant negative trend that is statistically significant at the 0.05 significance level (Fig. 2a). The negative trend in annual rainfall is statistically significant when considered the period of 1951–1980; however, the apparent positive trend during the 1981–2004 periods is not statistically significant (Fig. 3a). Mumbai also showed a significant negative trend for the southwest monsoon season (Fig. 3c). All trends in rainfall are tested for significance at 0.05 level using the Man-Kendall Test and test results is presented in Table 3.

3.3 Analysis of seasonal precipitation

For Delhi, Pre-monsoon (March–May) rainfall showed insignificant decreasing trend in both data periods (Fig. 3b). As it rains very little during this season, no conclusion can be drawn about the changed precipitation. Southwest monsoon (June–September) rainfall (676 mm) was higher from 1951 to 1980 against the long term mean (614 mm) while lower (536 mm) from 1981 to 2004. The increasing trend of precipitation was not significant during both data periods (Fig. 3c). Post-monsoon (October–November) rainfall depicts the same pattern as pre-monsoon rainfall with decreasing trends in both data periods (Fig. 3d). Winter (December–February) rainfall had an increasing trend during 1981–2004 and decreasing trend during 1951–1980, which is, however, not statistically significant (Fig. 3e).

Seasonal rainfall trends at Mumbai are significant in some seasons during data period of 1951–1980 and 1951–2004 (Table 3). Pre-monsoon (March–May) rainfall showed statistically insignificant increasing trend in both data periods (Fig. 3b). The increase was sharper during the later period of study. Southwest monsoon (June–September) rainfall was major part of rainfall in whole data period. There was a significant decreasing trend in rainfall during

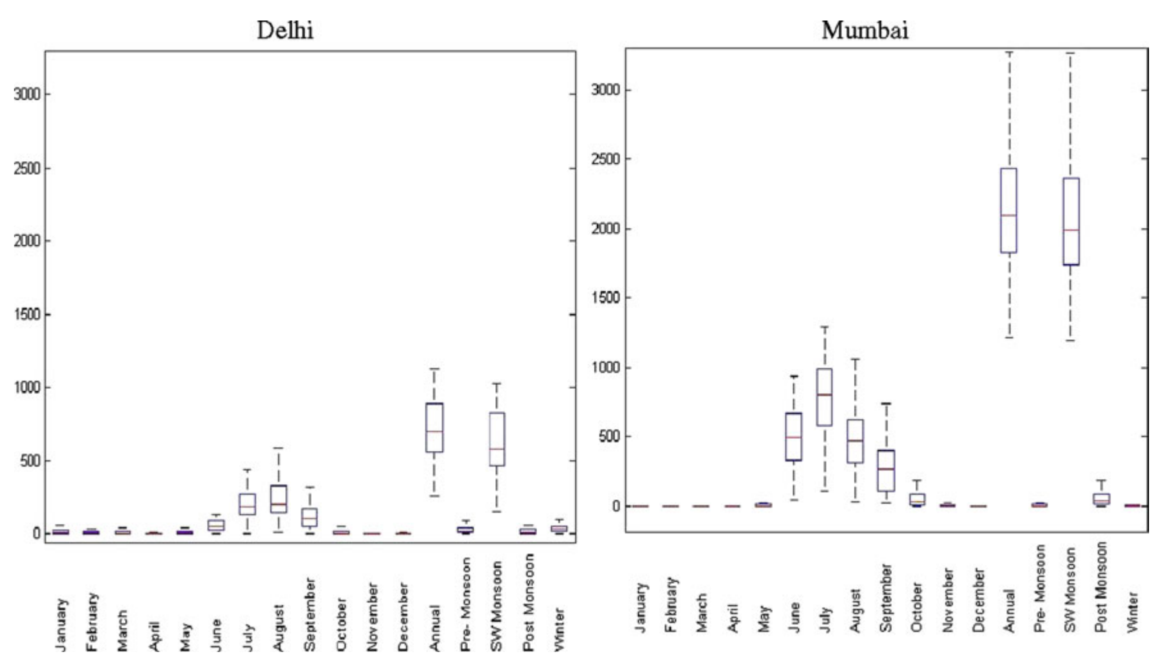


Fig. 1 Monthly and seasonal rainfall at Delhi and Mumbai during data period of 1951–2004

Table 1 Monthly (only those which contribute to % of annual rainfall) and seasonal rainfall at Delhi and Mumbai during data period of 1951–2004

Month	Delhi				Mumbai			
	Mean	SD	CV (%)	% to Annual	Mean	SD	CV (%)	% to Annual
June	58.1	40.3	69.4	8.1	504.1	218.6	43.4	23.5
July	204.7	117.1	57.2	28.6	777.5	269.3	34.6	36.3
August	234.5	135.6	57.8	32.8	493.5	247.5	50.2	23.0
September	116.9	89.4	76.5	16.3	282.3	200.0	70.8	13.2
Annual	715.5	199.6	27.9	100.0	2142	3516	164.2	100.0
Pre-monsoon	36.0	61.1	169.9	5.0	16.8	80.1	477.9	0.8
Southwest monsoon	614.2	493.3	80.3	85.9	2057	1170	56.9	96.0
Post monsoon	24.8	62.2	250.7	3.5	65.3	125.2	191.6	3.1
Winter	40.5	57.1	141.1	5.7	2.7	10.5	387.9	0.1

Table 2 Variation in seasonal rainfall at two stations during different data period of 1951–1980 and 1981–2004

Data period	Season	Delhi				Mumbai			
		Mean	SD	CV (%)	% to Annual	Mean	SD	CV (%)	% to Annual
1951–1980	Pre-monsoon	28.7	40.7	141.9	3.7	14.5	68.6	473.2	0.6
	Southwest monsoon	676.2	532	78.7	87.2	2232	1241	55.6	96.5
	Post monsoon	31.0	77.2	249.2	4.0	63.8	132	208.1	2.8
	Winter	39.5	26.1	66.1	5.1	2.8	11.7	422.1	0.1
	Annual	775.3	206	26.6	100.0	2314	3791	163.9	100.0
1981–2004	Pre-monsoon	45.1	79.0	175.2	7.0	19.6	93.0	474.3	1.0
	Southwest monsoon	536.8	430	80.2	83.8	1838	1041	56.7	95.4
	Post monsoon	17.0	34.6	203.1	2.7	67.2	116	173.1	3.5
	Winter	41.7	55.5	133.2	6.5	2.6	9.0	338.4	0.1
	Annual	640.6	166	25.9	100.0	1927	3133	162.5	100.0

the 1951–1980 periods and an insignificant increasing trend during 1981–2004 (Fig. 3). Also, the monsoon rainfall has decreased from 2,232 mm in 1951–1980 to 1,838 mm in 1981–2004. The decreasing trend during the 1951–2004 in monsoon rainfall is statistically significant at 0.05 levels. Post-monsoon (October–November) rainfall depicts decreasing trends in both data period with slight increase above the long-tem mean in 1981–2004 (Fig. 3d). Winter (December–February) rainfall had a slightly increasing tendency during both data periods, which is not statistically significant (Fig. 3e).

3.4 Analysis of maximum daily precipitation per year

The Mann–Kendall test was applied to determine possible trends on maximum precipitation in a day per year and results are depicted in Table 4. It can be inferred from Table 4 that maximum precipitation in a day per year presents a significant ($P = 0.013$) negative trend for Delhi during the period 1951–2004, in agreement with Fig. 3. In Mumbai, a significant ($P = 0.046$) negative trend is observed during 1951–1980 and ($P = 0.08$) during 1951–2004 (Fig. 4). Other detected trends were not statistically significant. Delhi and Mumbai generally have extreme precipitation events during southwest monsoon period which decrease, in number of occurrences, in the later data period.

3.5 Climatic relation of the trends

Monsoon rainfall data for Delhi and Mumbai were tested for relation against PDO, NINO3.4, IOD, EP/NP, NAO, WP, SCA, EA/WR, PNA and EA climatic indices using PCA and SVD. Average southwest monsoon rainfall (June–September) for both stations and average of climatic indices for the same season, for the whole data period, were used for analysis. PCA revealed a close relationship that is direct or inverse between some of these climatic indices

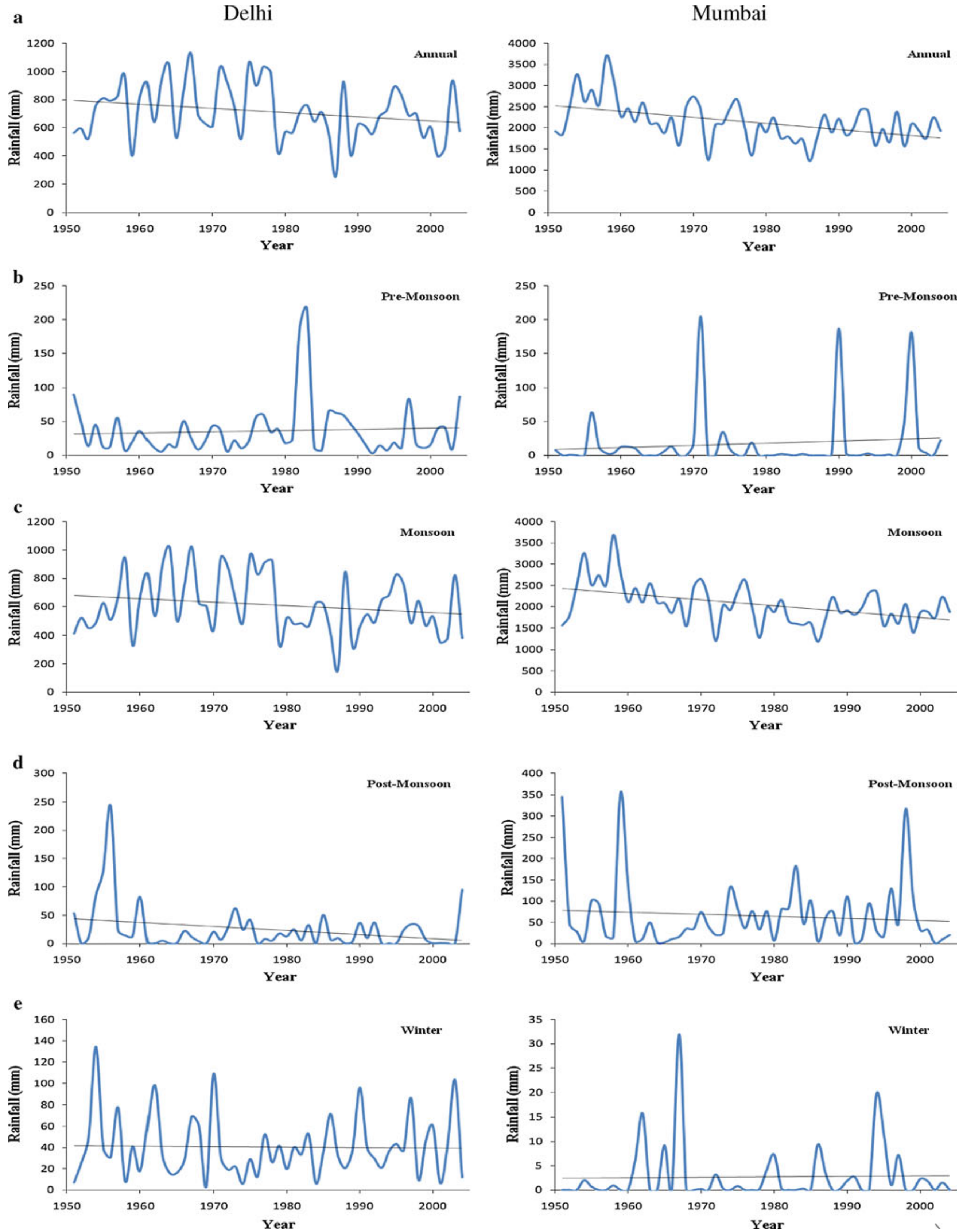


Fig. 2 Trends in seasonal and annual rainfall at the two stations during 1951–2004

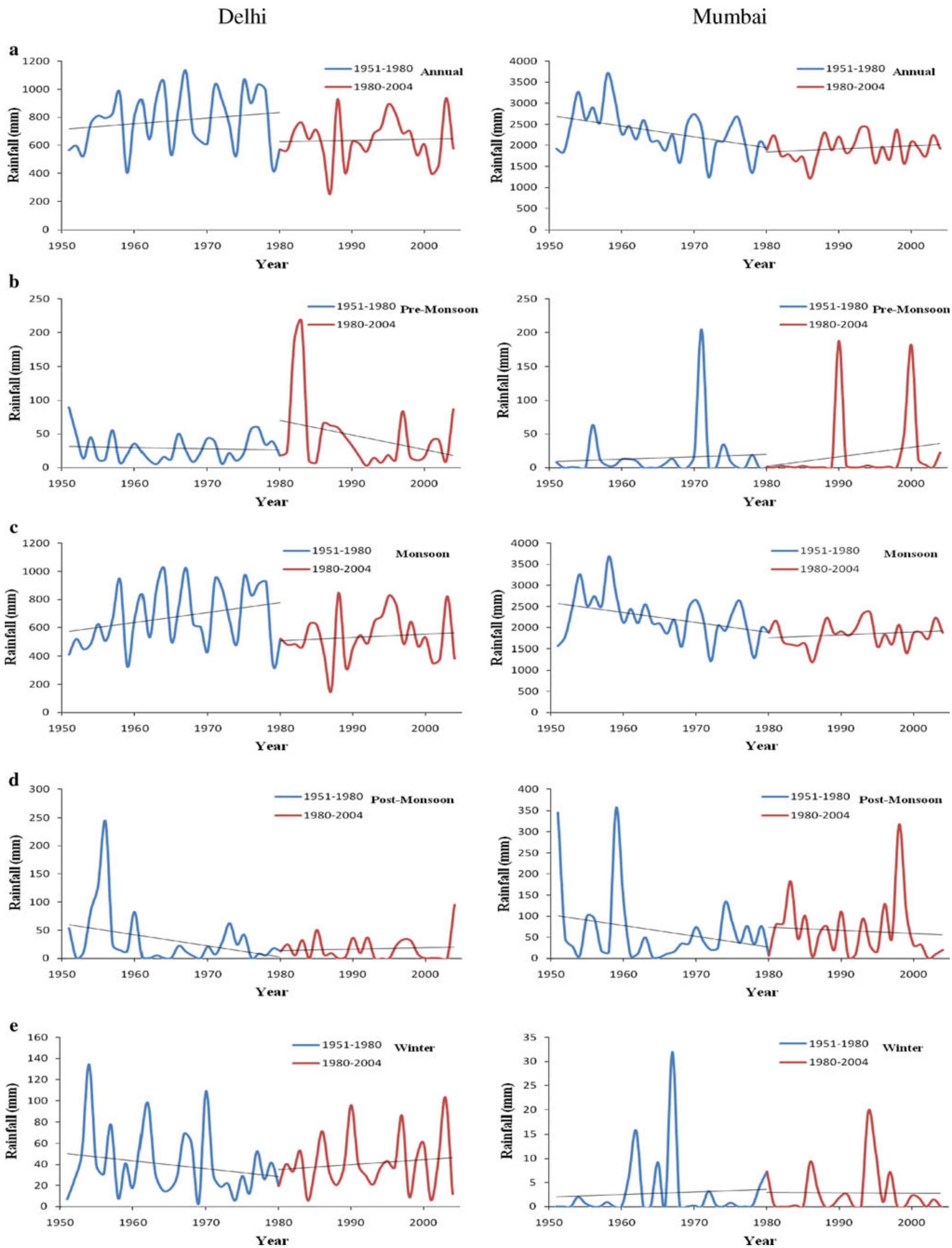


Fig. 3 Trends in seasonal and annual rainfall at the two stations during 1951–1980 and 1980–2004

Table 3 Man-Kendall statistics for annual and seasonal rainfall trends for the two stations

Data period	Season	Delhi		Mumbai	
		Z	*P*	*Z*	*P*
1951–1980	Pre-monsoon	0.0535	0.9573	−0.2855	0.7753
	Southwest monsoon	1.5700	0.1164	**−2.2123**	0.0269
	Post monsoon	−0.8385	0.4017	−0.0357	0.9715
	Winter	−0.7850	0.4325	1.0883	0.2765
	Annual	1.1775	0.2390	**−2.3907**	0.0168
1981–2004	Pre-monsoon	−1.0666	0.2862	1.6619	0.0965
	Southwest monsoon	0.1984	0.8427	1.0914	0.2751
	Post monsoon	−0.4961	0.6198	−1.2154	0.2242
	Winter	0.4217	0.6733	0.0744	0.9407
	Annual	−0.3225	0.7471	0.7193	0.4719
1951–2004	Pre-monsoon	0.0821	0.9346	−0.1343	0.8932
	Southwest monsoon	−1.3205	0.1867	**−3.2751**	0.0011
	Post monsoon	−1.3578	0.1745	0.0895	0.9287
	Winter	0.5222	0.6015	1.1265	0.2599
	Annual	−1.5070	0.1318	**−3.4765**	0.00050791

values in bold are statistically significant at the 0.05 level

Table 4 Man-Kendall statistics for maximum precipitation trends per year for the two stations and different time spans

Data period	Delhi		Mumbai	
	Z	*P*	*Z*	*P*
1951–1980	−0.5709	0.5681	**−1.9982**	0.0457
1981–2004	−0.9178	0.3587	1.4139	0.1574
1951–2004	**−2.4619**	0.0138	**−1.7457**	0.0809

values in bold are statistically significant at 0.05 level

and precipitation at these two stations. The first two modes of PCA are analyzed as they are the ones that can most easily be associated to physical phenomena. Figure 5 gives the PCA bi-plot and Fig. 6 reveals the time series of these first two modes of PCA with explained variance of 20.41 and 16.85%, respectively.

The precipitation events at the two cities are seen in isolation due to two main factors namely: the geographic location of the cities, and difference in precipitation variability. As suggested by Goswami et al. (2006) the whole of India cannot be taken as one unit to investigate the trends due to large variability. A PCA analysis (Fig. 5) further clarify the differences between precipitation variability in the two sites. Precipitation variability for Delhi is almost totally represented in the first PCA mode (Fig. 5) while the precipitation variability for Mumbai is almost equally represented by the first and the second PCA modes (x and y axis values). Considering that the modes are orthogonal, there is a large part of the precipitation variability that is diverse in the two regions and that deserves to be analysed separately.

As it can be observed from Fig. 5 that rainfall variability in Delhi is closely related to SCA, EA/WR and PDO as they are mostly represented in the first mode of the PCA. It can also be observed that it has a direct relation to SCA and EA/WR and inverse with PDO as it is directly opposite to variability of rainfall in Delhi in the first mode. The variability in precipitation for Mumbai can be associated inversely with NINO3.4, IOD and EA in the second mode of PCA in agreement with some previous findings (Roy 2006). It can also be observed the clear difference in precipitation variability in these two cities, as precipitation in Delhi is mainly represented in the first mode and that of Mumbai, in the second mode of PCA. The time series of the first PCA mode (Fig. 6a) shows the typical phase change presented in Delhi's precipitation during Southwest monsoon (Fig. 2c) as well as in the SCA, EA/WR and PDO time series (average values for the same season). Similar changes can be observed for Mumbai.

Figure 6a shows the time series of the first mode of PCA; climatic indices SCA, EA/WR and PDO (as in biplot for first mode) show a close relation to precipitation variability for Delhi as presented in Fig. 3c. Precipitation for

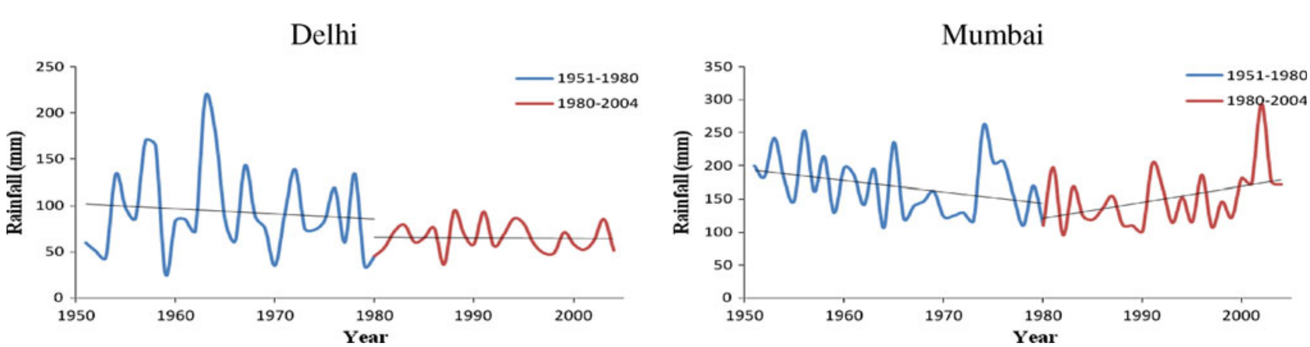


Fig. 4 Maximum daily rainfall per year at the two stations during 1951–1980, 1981–2004 and 1951–2004

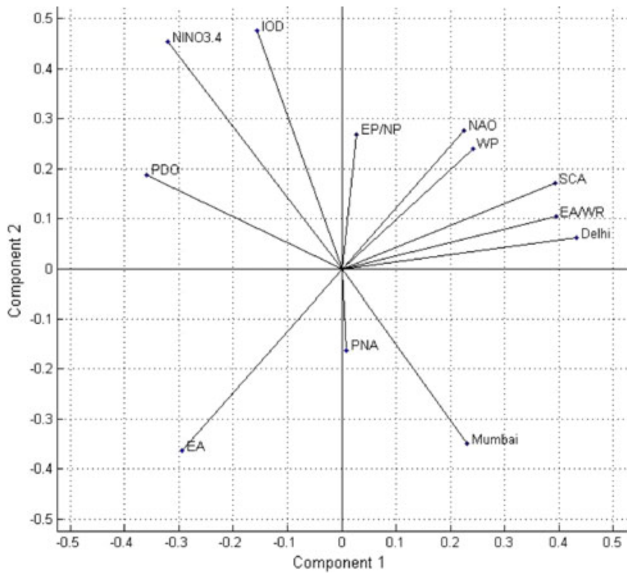
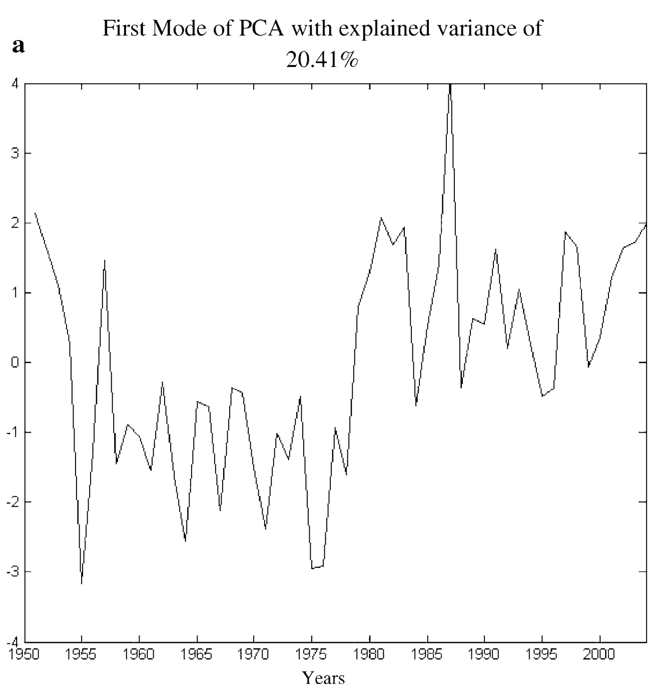


Fig. 5 Bi-Plot from the first four modes of PCA

Delhi in Southwest monsoon season follows the same trend as for the climatic indices. These climatic variables are changing phase of variability in around 25–30 years from starting data period i.e. 1975–1980 (climate shift phenomena) which is clearly indicated for southwest monsoon precipitation for Delhi (Fig. 3c) which is also changing phase in around that period. Also in Fig. 6b, that shows the time series of the second mode of PCA, a close relationship with precipitation for Mumbai is clear (in accordance to Fig. 3c). These indices are also experiencing climate shift phenomena around 1975–1980 as for the variability for Mumbai precipitation (Fig. 3c). The PCA analysis performed provides strong evidences of the relationship between monsoon precipitation at these stations and climatic phenomena and it clearly shows that monsoon precipitation in Delhi and Mumbai are mainly related to the variability of different climate phenomena. To further strengthen the findings of PCA we plot the standardised data for these stations against the standardised data of related climatic indices in Fig. 7. This is done for visual interpretation of the results and similar findings can be observed in the figure. Visually, the relationship between precipitation and climatic indices is very clear. It can be observed from the figure that for Delhi the precipitation is in direct relation to EA\WR and SCA and inversely related to PDO, when during the period 1975–1980 the climatic indices experience climate shift phenomena; the effect for the same can be easily observed on the precipitation in accordance to the relation. The same can be said for Mumbai's precipitation which is indirectly related to EA, IOD and NINO 3.4. The climate shift phenomenon is evident from the figure and has been documented by many authors namely Bainnes and Folland (2007); which has clear indications on the precipitation change during that period.

SVD was applied to the cross-covariance matrix between the average southwest monsoon precipitation per year (June to September) of Delhi and Mumbai and the average of climatic indices for the same season from 1951 to 2004. The two first modes of SVD were considered for



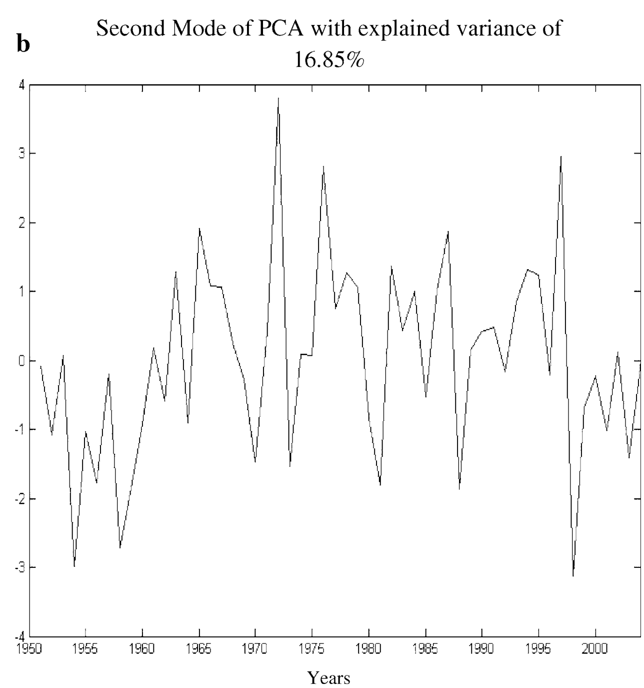


Fig. 6 Time series with explained variance in each mode of PCA analysis for monsoon rainfall and climatic indices

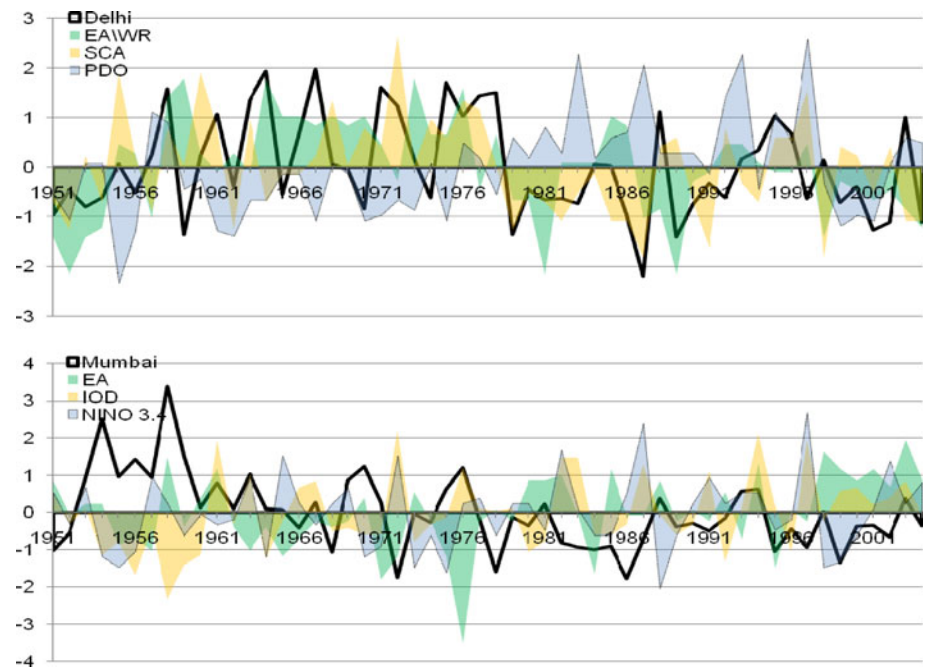


Fig. 7 Comparison of precipitation with related climatic indices

analysis as depicted in Fig. 8. It shows the time series of predictor and predictant over the period of time. They explain, respectively, 61% and 38% of the variance of the original data, which accounts for almost 99% of variability explained. So we can say that the variability in precipitation at these stations is mainly due to global climate phenomena and very less due to local factors as it accounts for 99% of it. Squared covariance fractions for these modes are 72.26 and 27.73%, respectively. Figure 8 depicts time series of the first two modes of the SVD. The correlation between the time series for each field in the first and second mode is 0.52 and 0.41, respectively.

Heterogeneous correlation table (Table 5) was examined to seeking the relationship between different climate indices with rainfall at the two stations. It can be observed from Fig. 8a, where first mode of SVD is depicted, that the predictand field (precipitation for both stations) is closely related to predictor field (climate indices). From Table 5 it is noticeable that the precipitation in both stations is positively related to EA/WR, SCA, and negatively related to

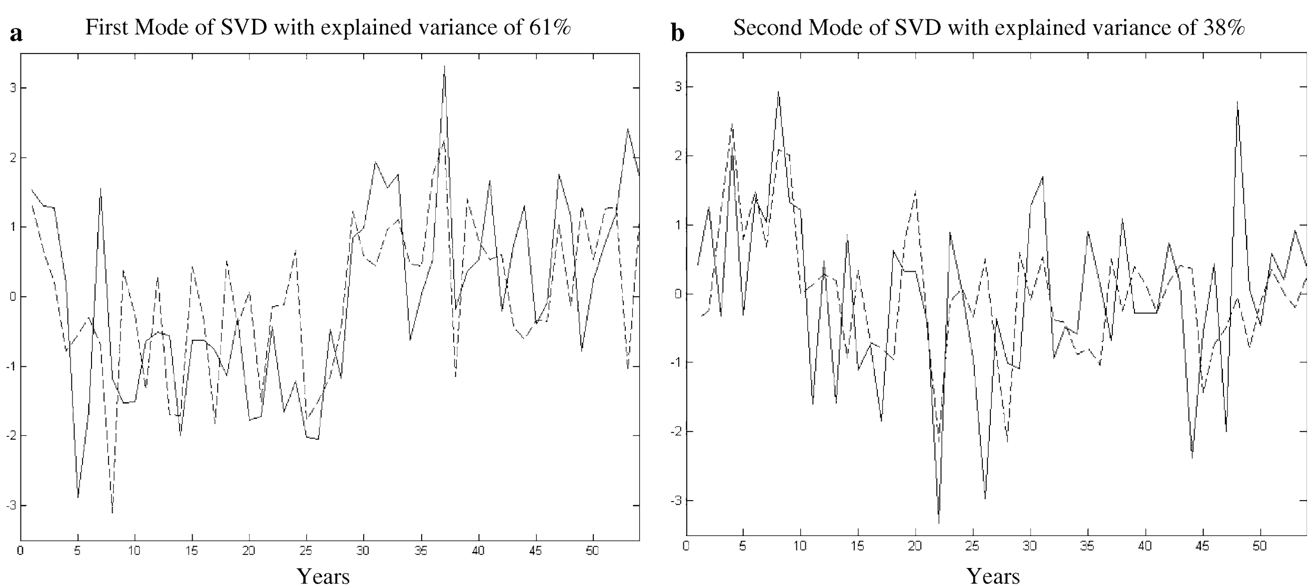


Fig. 8 Time series of predictor (monsoon rainfall) and predictant (climatic indices) in first two modes of SVD with correlation coefficients

Table 5 Heterogeneous correlation table of monsoon total rainfall and climatic indices

S. No.	Delhi	Mumbai	NAO	EA	WP	EP/NP	PNA	EA/WR	SCA	IOD	PDO	NINO3.4
Mode 1	**−0.49**	**−0.29**	0.01	0.20	−0.14	−0.05	−0.09	**−0.35**	**−0.34**	0.16	**0.25**	**0.33**
Mode 2	−0.19	**0.32**	**−0.23**	0.12	−0.12	−0.09	0.13	−0.05	−0.11	**−0.39**	0.00	−0.07

Values in bold are statistically significant at the 0.05 level

PDO and NINO3.4, of all the climatic indices, with Delhi having a dominating effect. The second mode in Table 5 evidences the negative relation of the precipitation in Mumbai with NINO3.4 and IOD.

The result of SVD confirms the relationship between precipitation and climatic variables in the global scenario accounting for most of variability observed in precipitation. There is marked effect of these variables in precipitation of these two cities and different variables have different effect on precipitation. Results from the SVD analysis strengthens and detailed the ones obtained from PCA.

These aspects of variability of precipitation with climatic phenomena are interesting to study the future models that can be developed for long term prediction of rainfall at these stations as the global climate phenomena seem to explain great part of variability in precipitation.

4 Conclusions

An important aspect of the present study is the variability of trends in precipitation that are observed at Delhi and Mumbai. The analysis revealed an insignificant decrease in southwest monsoon rainfall while increase in winter and pre-monsoon season over Delhi for the whole period. That suggests a tendency of a slight spread of the precipitation throughout the year during the period 1951–2004, however without statistical significance. For Mumbai, significant negative changes for long term rainfall were detected for different seasons and for the whole year in the 1951–2004 periods. Trends in southwest monsoon precipitation for both Delhi and Mumbai were shown to be related to the variability of climatic indices. Southwest monsoon precipitation at Delhi is related to SCA, EA/WR and PDO whereas at Mumbai is related to IOD, NINO 3.4 and EA. There is clear indication of decadal shift in precipitation pattern with climatic indices in these two cities.

In concern to daily rainfall, statistical analysis has revealed significant decrease in maximum daily rainfall per year at both the stations along with decrease in average maximum rainfall in a day. Most of the rainfall at both the stations was found to be taking place in southwest monsoon season with greater variability for Mumbai than Delhi. All trends identified in this work can be related to some findings by other authors namely Kumar et al. (1992) where they have found significant increasing trend in monsoon seasonal rainfall along the west coast, north Andhra Pradesh and northwest India while significant decreasing trends over east Madhya Pradesh and adjoining areas, north-east India and parts of Gujarat and Kerala. Similar studies have been done by Goswami et al. (2006) for trend analysis on different areas in India than Delhi and Mumbai.

These relationships might prove useful in prediction of rainfall for these urban centres that will prove handy in planning and management. Finally there is a need to incorporate climate variability in the planning and management of water resources of these cities. This study provides subsidies, which may be used for sensitivity analysis of water availability in Delhi and Mumbai. Although there are uncertainties about the magnitude and direction of future climate variation at various places, measures must be initiated to minimize the adverse impacts of these changes on society and resources.

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