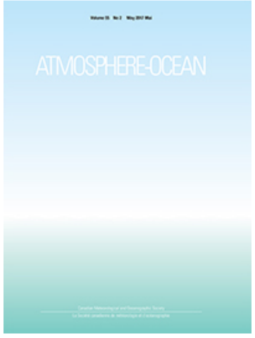

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Long-Term Rainfall Variability in the Eastern Gangetic Plain in Relation to Global Temperature Change

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ABSTRACT *India's annual weather cycle consists mainly of wet and dry periods with monsoonal rains being one of the significant wet periods that shows strong spatiotemporal variability. This study includes the climatological characteristics, fluctuation features, and periodic cycles of annual, seasonal, and monthly rainfall of seven river basins across the eastern Gangetic Plain (EGP) using the longest possible instrumental area-averaged monthly rainfall series (1829–2012). Understanding the relationships between these parameters and global tropospheric temperature changes and El Niño and La Niña climatic signals is also attempted.*

Climatologically, mean annual rainfall in the EGP varies from 1070.5 mm in the Tons River basin to 1508.6 mm in the Subarnarekha River basin. The highest rainfall in the EGP occurs during monsoon (1188 mm). The annual rainfall in all river basins and monsoon rainfall in four river basins is normally distributed. Annual and monsoonal rainfall in the Brahmani and Son River basins show a significant decreasing long-term trend. Over the last 20 years, annual rainfall in all river basins and monsoonal rainfall in five river basins show a decreasing trend. The power spectra for all rainfall series are characterized by consistent significant wavelength peaks at 3–5 years, 10–20 years, 40 years, and more than 80 years. Short-term fluctuations with a period less than 10 years is the major contributor to total variance in annual and/or monsoon rainfall (77.6%), followed by decadal variations with a period of 10–30 years (13.1%) and a long-term trend with a period greater than 30 years (9.3%).Temperature and thickness gradients from the Tibet–Himalaya–Karakoram–Hindu Kush highlands to eight strong highs show a significant correlation with rainfall during the onset and withdrawal phases of summer monsoon in the EGP.

RÉSUMÉ *[Traduit par la rédaction] Le cycle météorologique annuel de l'Inde se compose principalement de périodes sèches et de périodes humides. Les pluies de la mousson représentent une période particulièrement humide, qui montre de grandes variabilités spatiale et temporelle. Cette étude porte sur les caractéristiques climatologiques, les fluctuations et les cycles périodiques annuels, saisonniers et mensuels de la pluie, pour sept bassins fluviaux de la région est de la plaine du Gange. Elle se fonde sur les séries temporelles les plus longues possible de quantité de pluie mensuelle (moyenne spatiale), de 1829 à 2012. Nous tentons aussi de comprendre les liens qui existent entre ces paramètres, l'évolution mondiale de la température dans la troposphère, et le signal climatique que produisent El Niño et La Niña.*

Les moyennes annuelles de quantité de pluie sur l'est de la plaine du Gange varient de 1070,5 mm dans le bassin de la rivière Tons à 1508,6 mm dans le bassin du fleuve Subarnarekha. La quantité de pluie la plus élevée sur l'est de la plaine du Gange survient durant la mousson (1188 mm). La quantité annuelle de pluie pour tous les bassins fluviaux et la quantité de pluie de mousson pour quatre de ces bassins possèdent une distribution normale. Les quantités de pluie annuelles et de la mousson dans les bassins des rivières Brahmani et Son affichent une tendance à la baisse considérable, sur une longue période. Au cours des 20 dernières années, les quantités de pluie annuelles de tous les bassins fluviaux et les quantités de pluie de la mousson de cinq de ces bassins ont diminué. Le spectre de puissance calculé pour chaque série de quantités de pluie se caractérise par des pics importants aux longueurs d'onde de 3 à 5 ans, de 10 à 20 ans, de 40 ans et de plus de 80 ans. Les fluctuations courtes, avec une période de moins de 10 ans, contribuent majoritairement à la variance totale des quantités de pluie annuelles ou de mousson (77,6%); viennent ensuite les variations décennales, avec une période de 10 à 30 ans (13,1%); puis les tendances à long terme, qui possèdent une période supérieure à 30 ans (9,3%). Les gradients de températures et d'épaisseurs qu'ont produits huit anticyclones intenses sur le plateau tibétain et l'Aire Hindu Kush-Himalaya montrent une corrélation significative avec les quantités de pluie qui tombent durant les phases initiale et finale de la mousson d'été, sur la région est de la plaine du Gange.

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KEYWORDS rainfall variability; power spectra; global temperature change; river basin; climate change

1 Introduction

Heterogeneous changes in global tropospheric temperatures over the last few decades have been observed to make spatio-temporal changes in global rainfall distribution. Potential climate change and its impacts on rainfall distribution pose a threat to water resources throughout the world. The Intergovernmental Panel on Climate Change (IPCC, 2013) concluded that climate change would have the following impacts on freshwater resources: (i) by the middle of the twenty-first century, annual average river runoff and water availability are projected to increase by 10–40% at high latitudes and in some wet tropical areas and decrease by 10–30% in some dry regions at mid-latitudes and in the dry tropics, some of which are presently water-stressed areas; (ii) drought-affected or water-stressed areas will likely increase in extent; (iii) heavy precipitation events are very likely to increase in frequency and intensity thus augmenting flood risks; and (iv) water supplies stored in glaciers and snow cover are projected to decline during the course of the twenty-first century, reducing water availability in the regions supplied by meltwater from major mountain ranges, where more than one-sixth of the world's population currently lives.

For India, rainfall is a seasonal phenomenon. Development and management of water resources is of great importance because rainfall occurs for a short period of time (four months) over the country. As reported by the IPCC, the Indian subcontinent will be adversely affected by enhanced climate variation, rising temperature, and substantial reduction in summer rainfall with water stress in some areas by 2020 (Cruz et al., 2007). Annual, seasonal, and monthly rainfall across India shows strong spatiotemporal variation and large departures from normal. Many of the studies show an overall decreasing trend in monsoonal rainfall over a major part of the country (Kulkarni, 2012; Mooley & Parthasarathy, 1984; Rao & Jagannathan, 1963; Thapliyal & Kulshrestha, 1991, and many more). Kumar, Pant, Parthasarathy, and Sontakke (1992) reported a significant decreasing trend in monsoonal rainfall over Madhya Pradesh and near eastern India. Guhathakurta and Rajeevan (2008) found a decreasing trend in rainfall for all sub-divisions in winter except for Jharkhand. During recent global warming, monsoon activity has been found to be somewhat subdued—monsoon rainfall decreased by 2.4% during the 1979–2009 period compared with the 1949–1978 period (Ranade, Singh, Singh, & Sontakke, 2008; Sontakke, N. A., Singh, N., & Singh, H. N., 2008; Sontakke, N. A., Singh, H. N., & Singh, N., 2008). Many studies have related the decreasing trend in seasonal rainfall, especially over central India, to a number of factors including black carbon, sulphate aerosols (Bollasina, Ming, & Ramaswamy, 2011; Chung & Ramanathan, 2007), land use changes (Niyogi, Kishtawal, Tripathi, & Govindaraju, 2010), and sea surface temperature (SST) rise over the Indo-Pacific warm pool (Annamalai, Hafner, Sooraj, & Pillai, 2013). Dash, Kulkarni, Mohanty, and Prasad (2009) showed that the number of monsoon break days over India has increased. A decline in the number of monsoon depressions was found by Krishnamurthy and Ajayamohan, Merryfield, and Kharin (2010). An increasing trend in heavy rains (IPCC, 2007) also attracted the attention of many researchers. This increasing trend, especially in isolated extreme precipitation events across the country, has interested many researchers (Goswami, Venugopal, Sengupta, Madhusoodanan, & Xavier, 2006; Krishnamurthy, Lall, & Kwon, 2009; Pattanaik & Rajeevan, 2010; Rajeevan, Bhate, & Jaswal, 2008; Sen Roy & Balling, 2009 and many more). Ranade and Singh (2014) studied seven types of large-scale spatiotemporal extreme rain events (EREs) across India and found that the number of 1- to 5-day isolated EREs showed a highly significant increasing trend; however, 1- to 25-day EREs have not shown a significant long-term trend since 1951.

The Indo-Gangetic Plain (IGP) of India (geographical area ~600,000 km^2) is one of the largest fertile plains in the world formed by the river systems dominated by three main rivers, the Indus, Ganges, and Brahmaputra, encompassing most of northern and eastern India. The IGP is known for its topography, soil, rivers, surface, and groundwater. But it is also famous for its fluctuating weather. Its annual weather cycle is dominated by extremes of heat and cold, as well as rain. It is also one of the most sensitive parts of the country with respect to monsoon performance. Historical records show that whenever drought conditions existed, the part of the country most affected was the IGP. Good rainfall activity over this region is mainly a result of active summer monsoon circulation, frequent formation of rain-producing weather systems in nearby seas, and secondary disturbances formed in an active monsoon trough region. During boreal summer, the Intertropical Convergence Zone (ITCZ) shifts from the equatorial Indian Ocean and western Pacific to 30°–35°N latitude. The southeasterly trade winds, after crossing the equator, flow via the Arabian Sea, the Bay of Bengal, then take a meandering course over the IGP and the Indo-China peninsula before converging over the northwest India-Pakistan-Afghanistan sector and the eastern Tibet–Yangtze river area of central China. Different types of rain-producing weather systems such as circulation systems (low pressure area, cyclone, depression, etc.), linear systems (trough, convergence zone, squall line, etc.), and wave disturbances (easterly and westerly waves) develop in the monsoon flows and affect the IGP from June through September. Singh and Sontakke (2002) documented the longest period of instrumented fluctuations in rainfall amounts from 1829 to 1999 across the IGP. They found that summer monsoon rainfall over the western IGP had an increasing trend (170 mm per 100 years, significant at the 1% level) from 1900, while from 1939 rainfall in the central

IGP had a decreasing trend (5 mm per 100 years, not significant). In the eastern IGP they found a decreasing trend (50 mm per 100 years, not significant) from 1900 to 1984 and an increasing trend (480 mm per 100 years, not significant) from 1984 to 1999.

Northeastern central India, basically the states of Bihar, Orissa, and West Bengal, are often caught by rain-producing weather systems formed over the Bay of Bengal. These areas are also vulnerable to lightning activity associated with thunderstorms during the pre-monsoon and summer monsoon season. This area is expected to be highly prone to the consequences of climate change because of its geo-ecological fragility, strategic location, trans-boundary river basins, and inherent socio-economic instabilities. Against the background of recent global tropospheric warming and projected climate change scenarios it is important to study the long-term variability and fluctuation features of rainfall in river basins across the eastern Gangetic Plain (EGP). Understanding long-term basin-scale rainfall variability is of concern for water resource management of basin areas. Very few attempts have been made to understand these long-term basin-scale rainfall variations. Ranade et al. (2008) have studied climatological and fluctuation features of parameters of the hydrological wet season in 11 major and 36 minor river basins in India. They did not find any significant long-term trends in wet season parameters for any basin, but they did notice a declining tendency in wet season rainfall in some of the major basins of the EGP.

Keeping in mind recent changes in global surface temperature, monsoon circulation pattern, and occurrence of EREs, the aim of the present study is to understand the nature of the variability of basin-scale rainfall across the EGP using the longest instrumental rainfall dataset and to determine the causal factors of the dominant modes of its variability. It is expected that the results from this study will be useful for water resource management and hydrological modelling across the EGP region. The three main objectives of the study are as follows:

1. To document the climatological characteristics and fluctuation features of annual, seasonal, and monthly rainfall series across the EGP using the longest possible instrumental area-averaged monthly rainfall series.
2. To determine the relative strengths of the periodic cycles in all rainfall sequences.
3. To understand the relationship between global tropospheric temperature changes and monsoon rainfall of the EGP, as well as between different climatic signals and monsoon rainfall of the EGP.

2 Physical description of river basins and dataset used

The geographical area of the EGP is 79°30′–89°02′E and 19° 20′– 25°35′N (Fig. 1) and contains seven river basins (Subarnarekha, Brahmani, Kasai, Damodar, Son, Tons, and Mahanadi). The Subarnarekha River is one of the longest east flowing interstate rivers and drains a total catchment area of 32,647 km^2. It originates near the Chota Nagpur plateau of Jharkhand and flows into the Bay of Bengal after a distance of 395 km. Four rain-gauge stations were selected to prepare the longest area-averaged rainfall series for the Subarnarekha River. The Brahmani River is another of India's east flowing rivers, with a total length of 800 km. It has an interstate river basin with a total drainage area of 50,581 km^2. The Kasai River has the smallest river basin in the EGP area. It lies in the eastern state of West Bengal. Damodar River has a drainage area of 64,753 km^2 and originates in the Palamau Hills of Chota Nagpur. The Son River is the largest of the

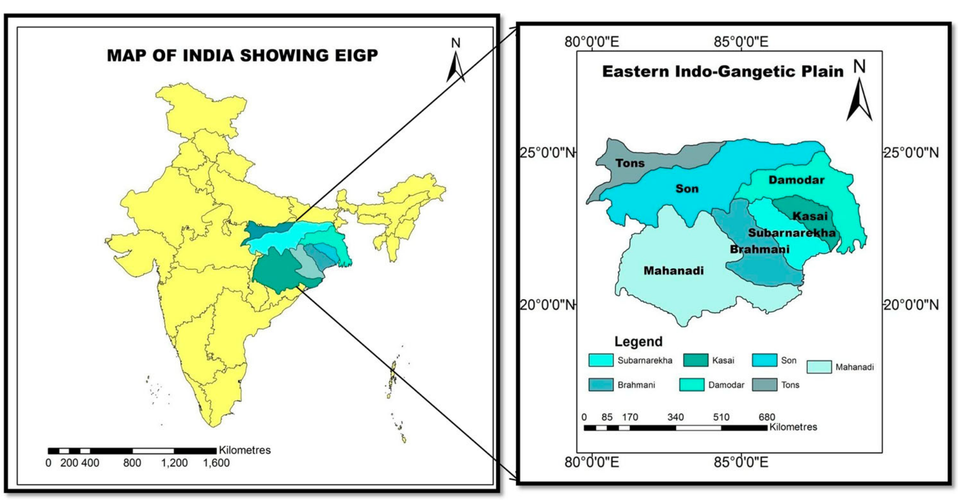

Fig. 1 Location of the EGP and seven river basins across the EGP.

southern tributaries of the Ganges River. It is 784 km long and is one of the largest river basins in India with a drainage area of 111,300 km^2. The Tons River basin is 264 km long, and five rain-gauge stations within the basin were used for this study. The Mahanadi River has the largest river basin in the EGP with a drainage area of 145,040 km^2. It is one of the major interstate rivers and originates in Chhattisgarh and drains Orissa, Jharkhand, as well as part of Maharashtra. Eleven rain-gauge stations within the Mahanadi River basin were used for the development of the longest rainfall series. A detailed description of the physical features of the river basins and the rainfall data availability are given in Table 1. The table gives (i) the geographical and/or drainage area; (ii) the length of the river; (iii) the number of rain-gauge stations in operation since 1901; (iv) the start year of the longest period of rainfall data; and (v) the mean annual and seasonal rainfall in seven basins and the EGP area.

The longest instrumental area-averaged monthly rainfall series for seven river basins (Sontakke, N. A., Singh, N., & Singh, H. N., 2008; Sontakke & Singh, 1996) across the EGP are used in this study. Monthly rainfall series for the EGP region was prepared by calculating the area average of the rainfall for seven river basins. Data from a well-distributed network of 316 rain-gauge stations, acquired from the India Meteorological Department (IMD), were used to develop the longest instrumental monthly basin rainfall from 1901 to 2006. For the earliest years (prior to 1901) data were reconstructed with a fewer number of observations using an established objective method. Details of the empirical procedure to construct the representative rainfall series backward are given in Sontakke and Singh (1996) and Sontakke, N. A., Singh, N., and Singh, H. N. (2008). The number of rain-gauge stations in each river basin varies from 3 to 11. Overall, 46 rain-gauge stations were available during the 1829–2006 period in the EGP. The length of the data series is different for each of the basins based on the availability of station data. The longest series is for the Damodar River basin (1829–2006) and the shortest is for the Brahmani River basin (1871–2006). Missing observations in the continuous data series are replaced with estimates using the ratio method (Rainbird, 1967), which uses the nearest available observation as a reference value. The number of estimated values is less than 2% of the total number of monthly rainfall records.

The monthly rainfall series for each river basin during monsoon season (June, July, August, and September (JJAS)) is extended (up to 2012) using gridded rainfall data. The National Centre for Medium Range Weather Forecasting merged satellite-gauge (NMSG) daily rainfall product at a latitude–longitude resolution of 1°×1° during the 1998–2012 period is available only for monsoon months across the Indian monsoon region (0°–40°N, 60°–100°E) (Mitra, Bohra, Rajeevan, & Krishnamurti, 2009). It uses three-hourly Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) estimates, accumulated for 24 hours and IMD rain-gauge observations. The monthly rainfall series of each river basin was prepared using an area-averaging method. In order to maintain homogeneity, the extended series (2007–2012) was further corrected by applying a simple ratio method. The nine-year period from 1998 to 2006 was used as the calibration period for the calculation of the ratio.

Because rainfall for individual months shows limited regularity in the interannual time series, annual and seasonal (premonsoon (March to May), monsoon (June through September), post-monsoon (October to December), and winter (January and February)) rainfall series were developed for each river basin and the EGP in order to show regularity in the temporal variation of the rainfall series. It is important to note that the June through September monthly rainfall and monsoon season rainfall are available up to 2012 whereas the other series are only available up to 2006. All rainfall

TABLE 1. Physiographic features and rainfall statistics for seven river basins across the EGP.

Basin Name	Drainage Area (km^2)	Length of River (km)	No. of Rain Gauges Since 1901	Longest Period Of Rainfall Data (start year)	Mean Seasonal Rainfall (mm) (±SD): Annual (up to 2006)	Monsoon (up to 2012)	Pre-Monsoon (up to 2006)	Post-Monsoon (up to 2006)	Winter (up to 2006)	Percentage Contribution of Monsoon Rainfall to Annual Total
Subarnarekha	32,647	395	4	1859	1508.6 (205.3)	1144.4 (167.1)	163.8 (71.9)	150.3 (96.5)	52.16 (41.4)	75.8
Brahmani	50,581	800	3	1871	1440.6 (203.2)	1138.3 (179.4)	124.2 (61.4)	126.4 (79.0)	48.5 (47.0)	79.0
Kasai	21,625	465	3	1859	1444.7 (230.4)	1115.9 (190.0)	163.5 (74.4)	118.10 (76.4)	47.8 (48.9)	77.2
Damodar	64,753	541	11	1829	1468.8 (207.6)	1121.8 (169.5)	180.5 (71.8)	129.8 (77.4)	41.47 (32.7)	76.3
Son	111,300	784	9	1842	1210.8 (176.2)	1045.47 (155.8)	54.2 (33.9)	68.6 (52.1)	44.6 (29.8)	86.3
Tons	39,425	264	5	1860	1070.5 (216.8)	946.5 (198.9)	26.58 (22.7)	53.1 (64.0)	44.3 (34.9)	88.4
Mahanadi	145,040	587	11	1848	1415.2 (207.2)	1183.3 (186.9)	80.1 (44.9)	108.4 (64.3)	38.0 (30.0)	83.61
EGP	465,371	–	46	1871	1368 (111.3)	1104.7 (110.9)	112.5 (45.2)	139.4 (28.2)	46.0 (30.5)	80.75

series were tested for their homogeneity, randomness, trend, and periodicity.

In order to understand the effect of global temperature change on rainfall in the EGP, monthly temperature, and geopotential height at standard isobaric levels (1000–150 hPa) available across the globe at 2.5° resolution from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al., 1996) and SST anomalies in the Niño 3.4 region (5° N–5°S, 120°–170°W) were also used.

3 Results and discussion

a *Climatological and fluctuation features of annual, seasonal, and monthly rainfall*

The basic statistics (e.g., mean and standard deviation (SD)) are calculated for the annual, seasonal, and monthly rainfall series for seven river basins and the EGP area given in Table 1. Climatological features show that mean annual rainfall in the EGP area varies from 1070.5 mm (±216.8 mm) in the Tons River basin to 1508.6 mm (±205.3 mm) in the Subarnarekha River basin. The mean rainfall during monsoon season varies from 946.5 mm (±198.9 mm) in the Tons River basin to 1183.3 mm (±186.9 mm) in the Mahanadi River basin, the largest basin in the EGP area. The highest pre-monsoon rainfall occurs in the Damodar River basin (180.5±71.8 mm) while the highest rainfall during post-monsoon occurs in the Subarnarekha River basin (150.3 ±96.5 mm). The highest monthly rainfall in the EGP area occurs in the month of July (338.5 mm). The coefficient of variation is about 13–21% for annual and monsoonal rains. It indicates that the probability of zero rainfall in the seasonal series is negligible. Monsoon rainfall across the EGP contributes approximately 81% to the annual total, thus appears to be a major contributor to annual rainfall.

Following the descriptive statistical characteristics, the nature of the frequency distribution for each time series was also studied by employing a Chi-sqared test and Fisher's G-test (Rao, 1952). The non-Gaussian distribution in the annual, seasonal, and monthly rainfall at the 5% and 1% level of significance (l.o.s.) across the EGP is shown in Fig. 2. The distribution of annual rainfall across the EGP appears to be Gaussian while winter rainfall is significantly different from normal at the 1% l.o.s. The monsoon rainfall in most of the river basins also demonstrates a Gaussian distribution except for the Damodar, Kasai, and Brahmani River basins, which have a non-Gaussian distribution at the 5% l.o.s. Pre-monsoon rainfall is significantly different from the normal distribution except for the Kasai and Subarnarekha River basins (Gaussian distributions), while the post-monsoon rainfall shows mixed patterns of distribution. It appears that the annual, seasonal, as well as monthly rainfall for June and September for the Subarnarekha River basin are normally distributed. Rainfall in the Damodar River basin also shows normal annual and July distributions.

To understand any long-term trends in the annual, seasonal, and monthly rainfall series, actual and filtered values are plotted for the entire available record as a first approach (Fig. 3). Figures 3 and 4 show the actual and 9-point Gaussian low-pass filtered values of annual and monsoonal rainfall for seven river basins and the EGP, respectively. A critical visual examination of the series reveals that, in general, over the

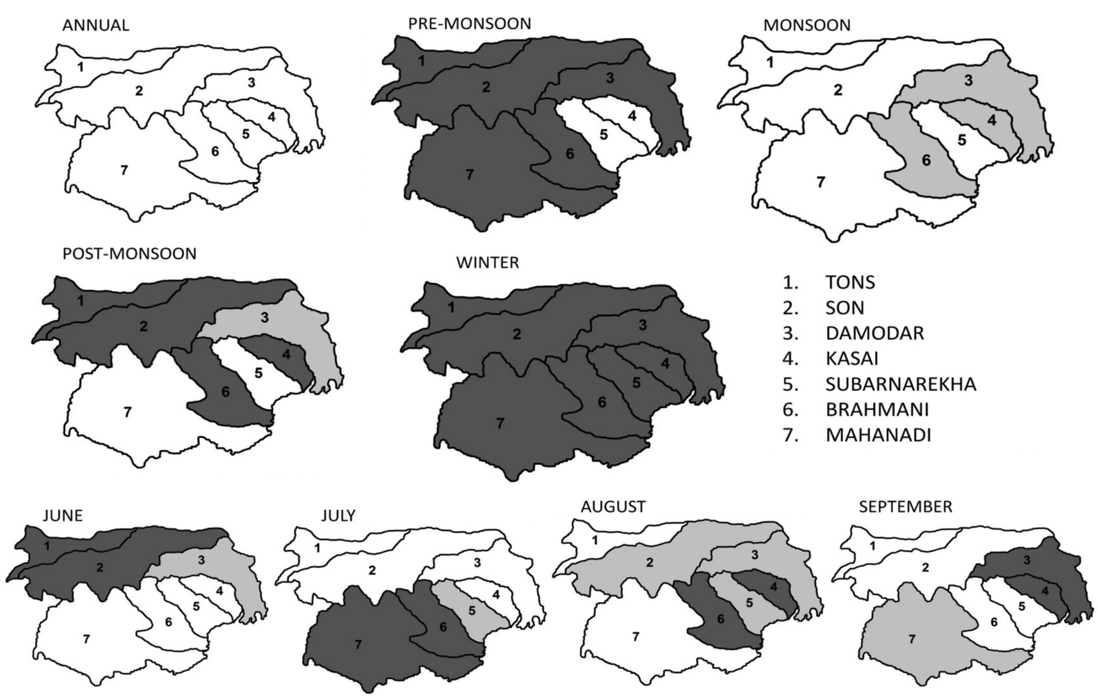

Fig. 2 Distribution pattern for annual, seasonal, and monthly rainfall of river basins across the EGP (dark grey indicates l.o.s. at 1% and light grey indicates l.o.s. at 5%. White indicates that the series is normally distributed).

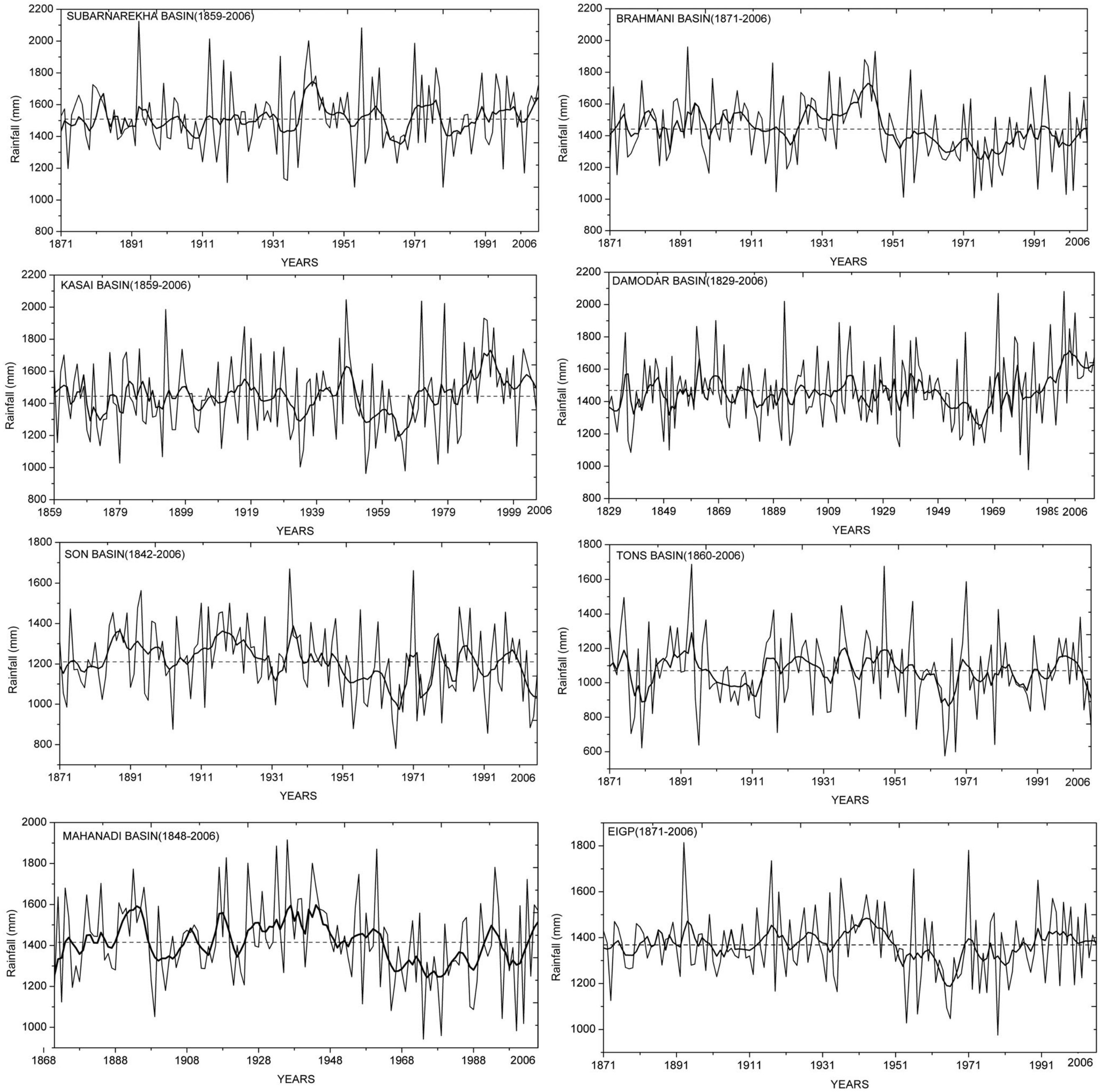

Fig. 3 Interannual variations in annual rainfall of seven river basins across the EGP. (The thin line represents actual values, and the thick line represents the 9-point Gaussian low-pass filtered values.)

period of available records, rainfall amounts showed two to three different trends including increasing, decreasing, and stable. Annual rainfall in the Damodar River basin from 1970 onwards has an increasing trend (Fig. 3), which is above the mean, whereas in the case of the Brahmani River basin the situation is the reverse, showing a decreasing trend for annual rainfall (below the mean). Similar results are found for the monsoon rainfall because the major contributor to annual rainfall is monsoon rainfall (Fig. 4). Therefore, visual examination of the rainfall series provides a preliminary understanding of the patterns and processes. To understand the significance of the long-term trend in a quantitative manner, two statistical tests (least-squares linear trend test and the Mann-Kendall test for randomness against trend (hereafter, MK test; WMO, 1966) are performed on the time series. The results are shown in Fig. 5. These tests do not suggest a significant long-term trend in pre-monsoon, post-monsoon, or winter rainfall in river basins across the EGP. However, monsoonal rainfall does show a significant decreasing long-term trend (at 5% l.o.s) for the Son and Brahmani River basins. Annual rainfall for the Son and Brahmani River basins also shows a significant decreasing long-term trend at the 5% l.o.s. Monthly rainfall in

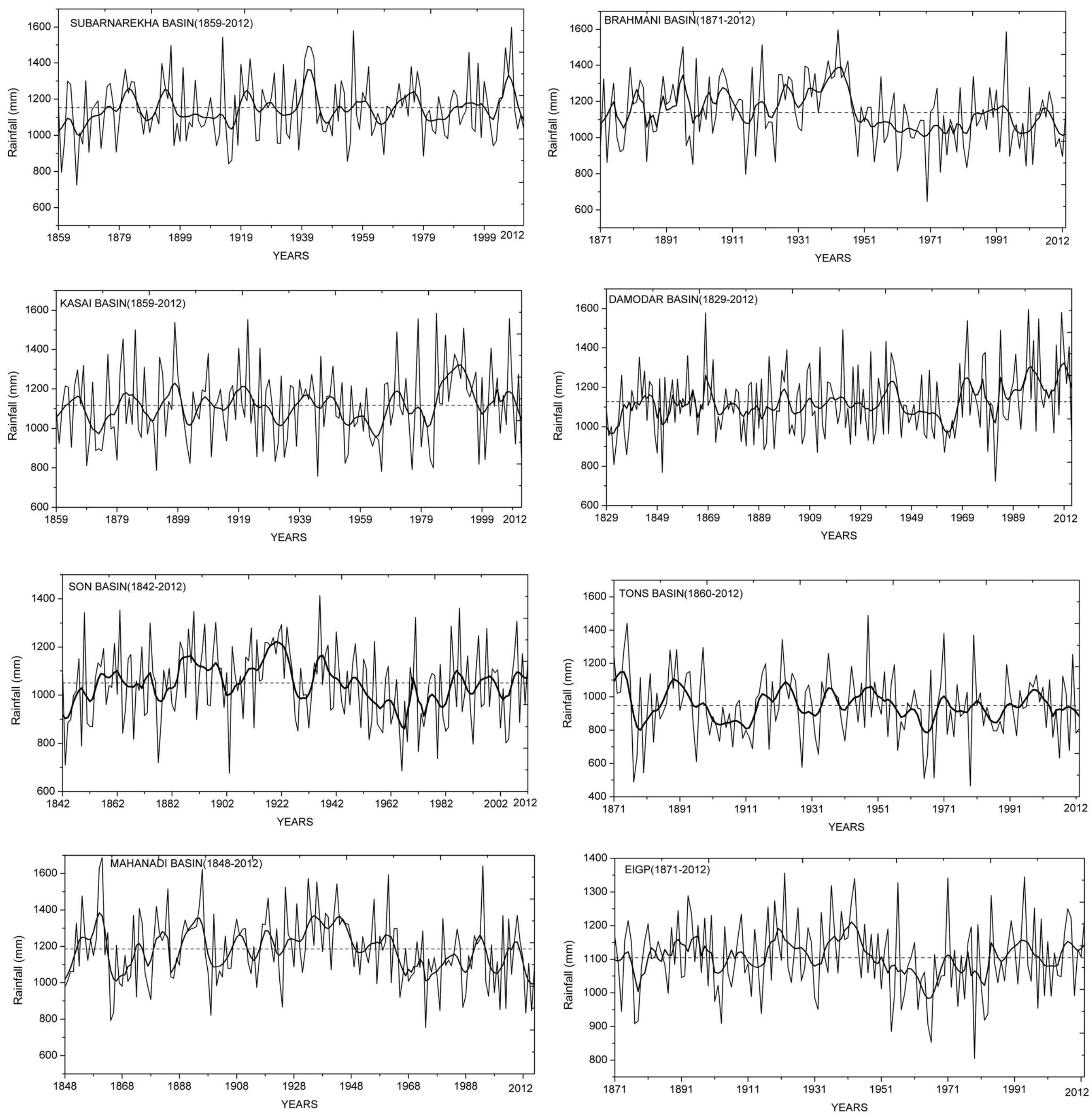

Fig. 4 Interannual variations in monsoon rainfall across the EGP. (The thin line represents actual values, and the thick line represents the 9-point Gaussian low-pass filtered values.)

most of the river basins does not show a significant trend; however, June rainfall in the Mahanadi and Damodar River basins, July rainfall in the Tons and Brahmani River basins, and August rainfall in the Kasai River basin show a significant decrease as suggested by the statistical tests.

In order to understand trends in rainfall amounts under global warming in recent years, fluctuations in basin rainfall are reported in the following two ways:

(i) change in the mean of the recent 30-year period (1977–2006) compared with previous years (prior to 1977) and

(ii) change in the mean of the recent 20-year period (1987–2006) compared with previous years (prior to 1987).

A Student's *t*-test was applied to each of 88 time series (11×8) for the difference between the means of two sub-periods, and the Wilcoxon–Mann–Whitney rank-sum test was used for two independent samples (Wilks, 1996). Analysis of the most recent 30 years shows that annual and monsoonal rainfall does not show any significant trend. However, in the last 20 years, a significant decrease (at 5% l.o.s) has been seen in the annual rainfall in all basins (Fig. 6). But

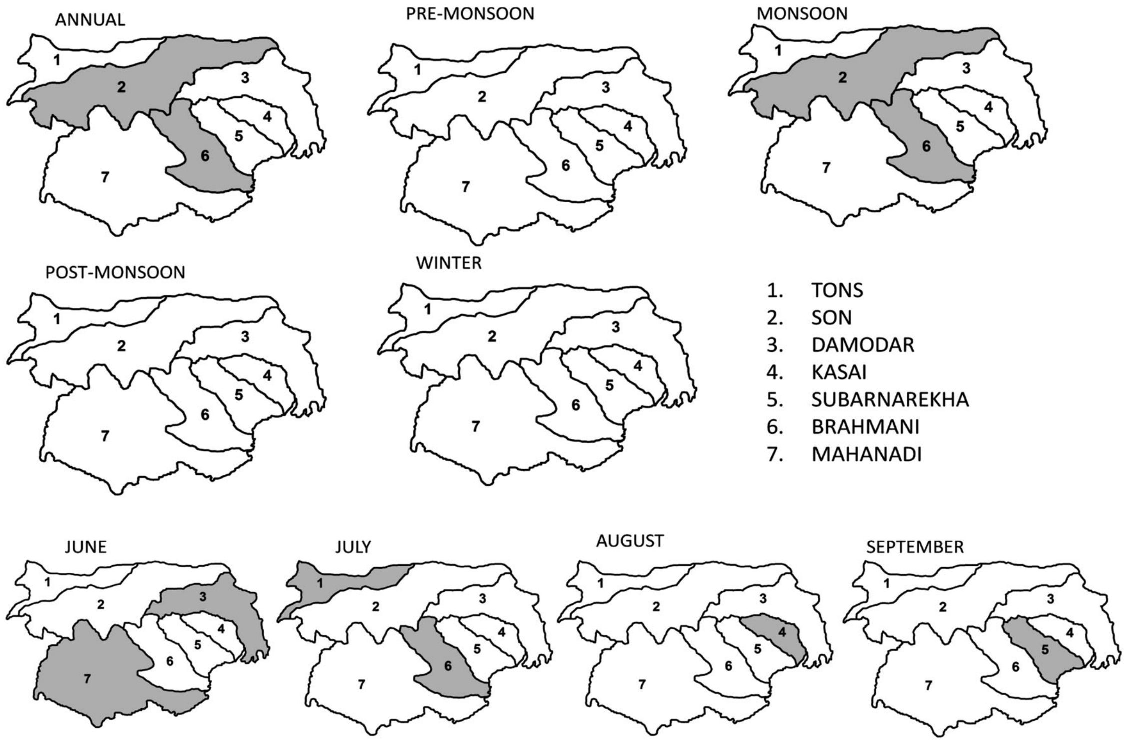

Fig. 5 Long-term trends in annual, seasonal, and monthly rainfall in seven river basins across the EGP (light grey indicates 5% l.o.s. and white indicates no change).

pre-monsoonal, monsoonal, and winter rainfall in the Mahanadi River basin, monsoonal and winter rainfall in the Subarnarekha River basin, and post-monsoonal rainfall in the Tons River and Brahmani River basins do not show a significant trend over the last 20 years. In the monthly rainfall series, the June rainfall in the Subarnarekha River basin shows a significant decrease at 1% l.o.s. July rainfall (except for the Tons and Mahanadi River basins), August rainfall (except for the

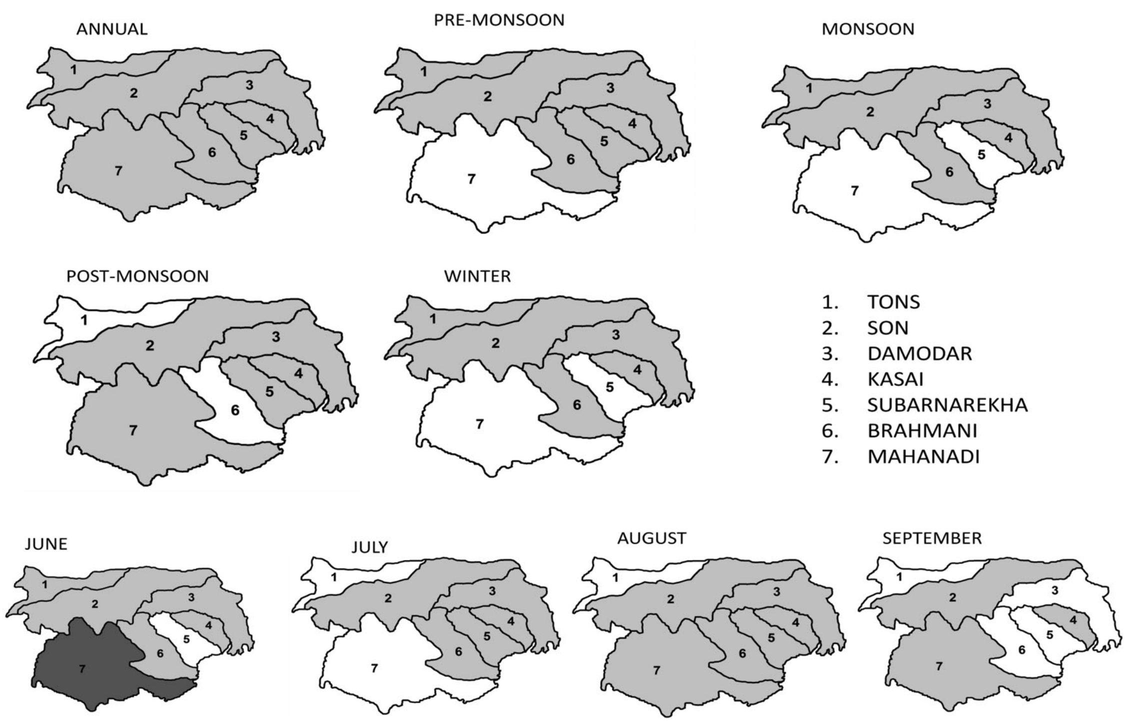

Fig. 6 Fluctuations in annual, seasonal, and monthly rainfall in seven river basins across the EGP over the last 20 years. (Dark grey and light grey indicate the 1% and 5% l.o.s., respectively, and white indicates no change.)

Tons River basin), and September rainfall (except for the Tons, Damodar, Subarnarekha, and Brahmani River basins) show a significant decrease (5% l.o.s.) over the last 30 years. Broadly speaking, a spatially coherent significant long-term trend for the last 30 years is not seen across the EGP. However, persistent negative trends are spread across the seven river basins. These trends can be attributed to changes in physical parameters (frequency, intensity, and duration) of weather systems formed in the Bay of Bengal and the monsoon trough region. Jadhav and Munot (2009) showed that, for the country as whole, there has been a significant decrease in the number and duration of depressions; however, the number of low pressure areas has significantly increased since the publication of the 2009 study. Significant negative trends in most of the rainfall series in recent years may also be related to the overall decreasing trend in mean annual rainfall across the IGP. Sontakke, N. A., Singh, H. N., and Singh, N. (2008b) reported that mean annual rainfall over the country during the 1965–2006 period was lower by 4.23% than during the 1931–1964 period.

b *Periodic cycles in rainfall series*

The characteristics of basin rainfall fluctuations show that a significant long-term trend does not exist in any of the rainfall series under consideration. Interannual variations of various rainfall periods (annual, seasonal, and monthly) are dominated by natural variability. This variability is a mixture of various regular and irregular oscillations. Some of the variations are periodic in nature; some are random, and some are due to non-linear feedback processes between different climatic elements. Harmonic analysis was used to understand the relative strengths of periodic cycles in the interannual rainfall series.

In harmonic analysis, time series are transformed into a finite number of sine and cosine waveforms after removing the annual cycle. The amplitudes (Fourier coefficients) of the sine and cosine waves are calculated depending upon whether the record length N is even or odd. The variance contained or power of each harmonic (linear combination of sine and cosine waves) is determined from the Fourier coefficients. The detailed mathematical expressions for the calculation of Fourier coefficients and respective variances (power) are given in Singh, Baek, and Kwon (2002). The power spectrum displaying the normalized spectral density (percentage of variance) against wavelength for annual rainfall series is shown in Fig. 7, while the same is show in Fig. 8 for monsoon rainfall. Significance limits are drawn at the 5%, 1%, and 0.1% l.o.s. (Schickedanz & Bowen, 1977).

Power spectrum analysis results indicated strong regularity in the annual and monsoonal rainfall in all basins. The significant peaks (5% l.o.s.) in the spectrum at 3–5 years and 10–20 years can be seen in all annual and monsoonal rainfall series for the basins. Peaks at 10–20 years (1% l.o.s.) are observed in the annual rainfall in the of the Subarnarekha, Mahanadi, Kasai, and EGP river basins and monsoonal rainfall (0.1% l.o.s.) in the Subarnarekha and Mahanadi river basins (Fig. 7). The monsoonal rainfall in Tons river basin shows a 30-year peak (0.1% l.o.s.). An 80-year cycle is observed in the annual and monsoonal rainfall in the Kasai River basin. These are a measure of persistence and can be related to the secular long-term trends. The largest cycle is more than 80 years, which is found in selected rainfall series (e.g., annual and monsoonal rainfall of the Son and Mahanadi River basins and the EGP). Peaks at 3–5 years and 10–20 years are considered as the dominant short-term fluctuations or seasonal variations, which occur periodically in the interannual variability. These fluctuations can be attributed to the variations in the date of occurrence, intensity, and duration of rain-producing weather systems formed in the Bay of Bengal and the eastern part of the monsoon trough. The El Niño–Southern Oscillation (ENSO) period is three to five years, which is further studied in relation to the periodic cycles found in the rainfall series. Similar spectra have also been generated for the remaining rainfall series (pre- and post-monsoon, winter, and May to October). Winter rainfall in the Tons River basin and post-monsoon rainfall in the EGP also shows a 40-year cycle. The pre-monsoon season in the Subarnarekha, Kasai, and Damodar River basins, as well as in the EGP, shows a cycle longer than 80 years. Significant peaks at greater than 80 years are difficult to attribute to a long-term trend or to a very long cycle because wavelengths greater than 80 years consist of only one cycle.

When the stability of significant peaks is compared for different basins, then it is observed that major significant peaks in the range of 3–5 years, 10–20 years, and more than 40 years are quite consistent in seven river basins across the EGP. In order to obtain a robust picture of the distribution of variance in these wavelength ranges, the waves are combined in three bands: (i) waves with a periodicity less than 10 years; (ii) waves with a periodicity of 10–30 years; and (iii) waves with a periodicity of more than 30 years. The combined percentage of variance explained by these three wavelength bands for all seasonal, annual, and monsoonal month's rain is given in Fig. 9. Figure 9 clearly indicates that the largest contribution to the variance is from short-term variability followed by decadal and long-term variability in the monsoonal rainfall in all river basins. Short-term variability ranges from 70.6% (in the Brahmani River basin) to 82.5% (in the Subarnarekha River basin) for the monsoon season. The decadal variability in the monsoon season is between 9.5% (Brahmani River basin) and 16.4% (Mahanadi River basin) and the long-term variability carries variance from 3.9% (Subarnarekha River basin) to 19.9% (Brahmani River basin). During August the decadal variability is higher than the long-term in all river basins except the Son River basin. The contribution of long-term variability to the variance is higher for the Brahmani and Mahanadi River basins and the EGP than for the other basins (Fig. 9). It seems that, the combined variances explained by the wave band with a wavelength less than 10 years is the manifestation of the contribution from short-term variability, that of 10–30 years is from decadal variability, and that greater than 30 years is

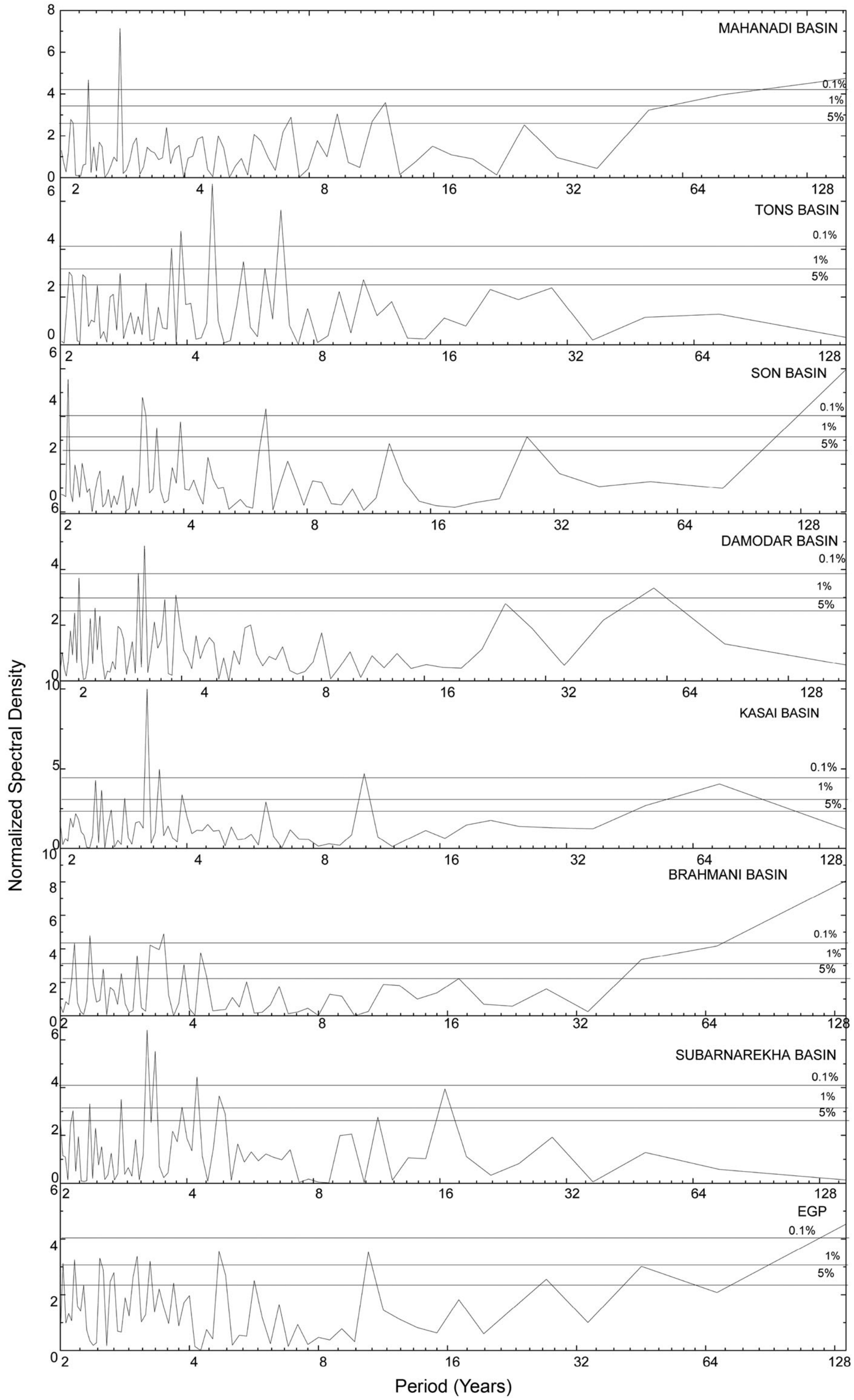

Fig. 7 Normalized spectral density of annual rainfall in seven river basins across the EGP.

from long-term variability. The distribution of variances from annual rains are similar to those for the monsoon rains because it is well known that monsoon rains are the major contributor to annual rainfall in the Indian subcontinent. The results for other seasonal and monthly rainfall are also more or less similar to that of monsoon rains.

Harmonic analysis clearly indicates that the rainfall variability (Fig. 9) of seven river basins in the EGP is mostly dominated by short-term fluctuations. Jadhav and Munot (2009) have shown that, since 1961, the number and duration of deep depressions are decreasing at the rate of 1.5–6 days per 10 years; however, the duration and number of low pressure

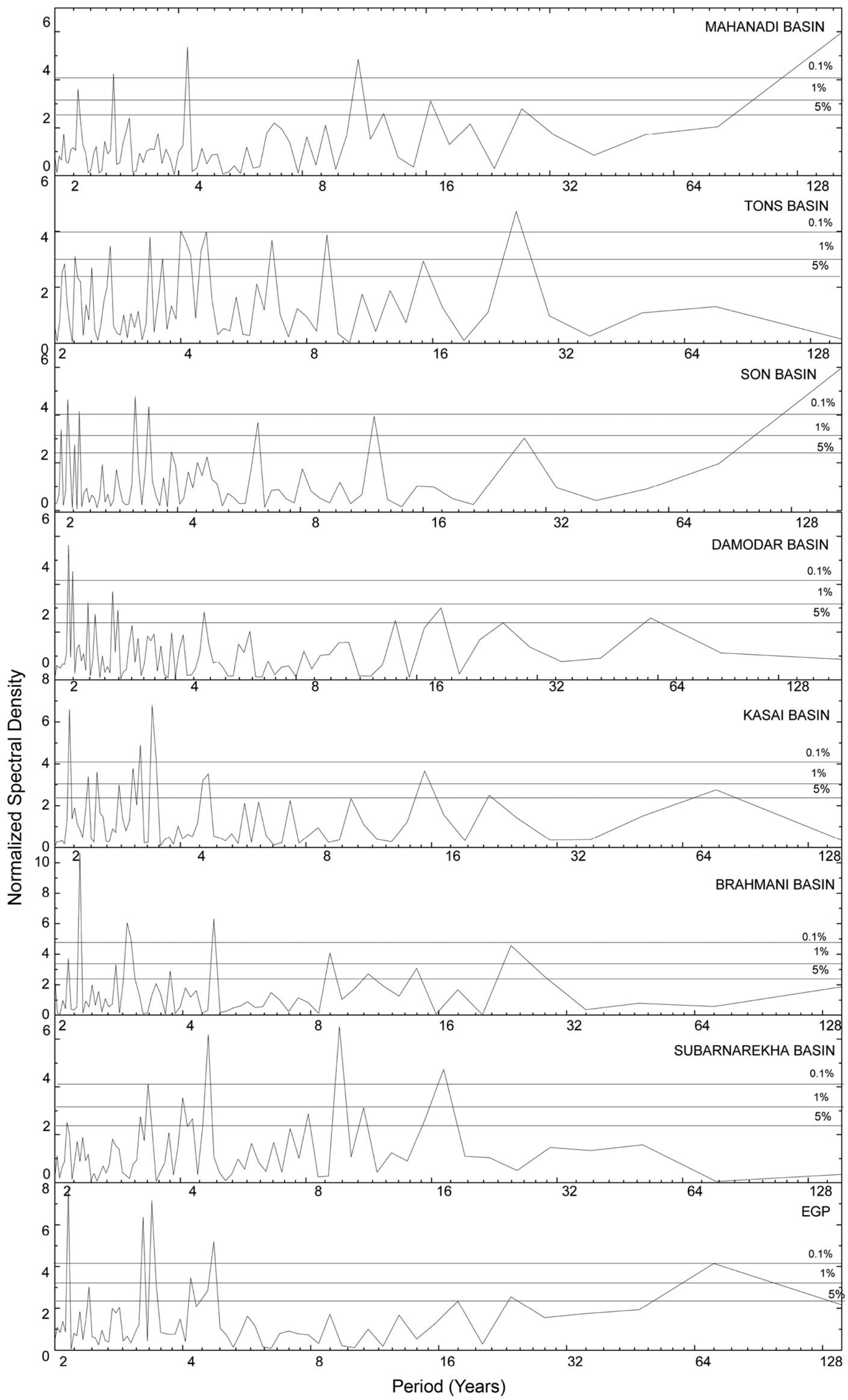

Fig. 8 Normalized spectral density of monsoon rainfall in seven river basins across the EGP.

areas (less deep) are increasing at the rate of 1.4–8 days per 10 years. Decadal variability seems to be related to different climatic signals across the globe. Detailed investigations have revealed that global tropospheric temperatures are rising around the globe. Long-term changes are the manifestation of asymmetry in tropospheric warming around the globe. The results of these studies can be utilized for the extrapolation of monsoonal rainfall for planning and management of water resources under global warming scenarios.

c *Effect of global tropospheric temperature changes on EGP rainfall*

About 79.0% of the annual rainfall across EGP river basins occurs during the summer monsoon season (JJAS) each

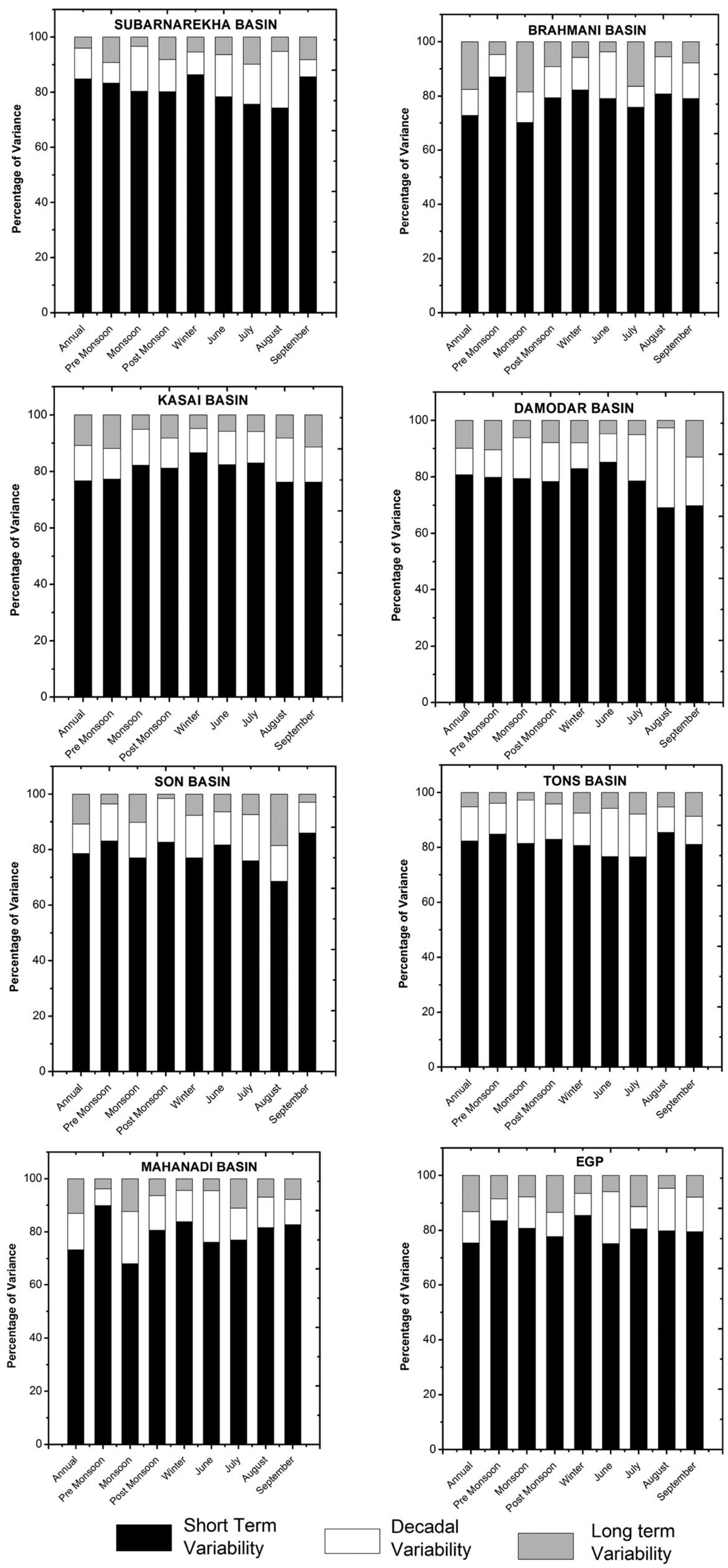

Fig. 9 Distribution of percentage of variation in short-term, decadal, and long-term variability of annual, seasonal, and monthly rainfall in the river basins in the EGP.

year. It is understood that the Indian summer monsoon is a regularly occurring tropical phenomenon though affected greatly by tropical–extra-tropical interactions and also by extra-tropical weather phenomena. Spatiotemporal variability of this thermally driven system depends on the intensity, location, and depth of various general, monsoonal, and regional circulation features around the globe. In this study, we have examined whether tropospheric temperature changes in different parts of the globe that modify the general, monsoonal, and regional circulation features can influence monsoonal rainfall in the EGP basins.

We performed a correlation analysis of rainfall in the EGP with the temperature and geopotential thickness of the areas averaged over the globe (0°–360°, 90°S–90°N), the northern hemisphere (NH: 0°–360°, 0°–90°N), the southern hemisphere (SH: 0°–360°, 0°–90°S), the extra-tropical NH (ExNH: 0°–360°, 30°–60°N), the extra-tropical SH (ExSH: 0°–360°, 30°–60°S), the North Pole (NP: 0°–360°, 75°–90°N), and the South Pole (SP: 0°–360°, 75°–90°S). The correlation coefficients (CCs) between the annual, seasonal, and monthly rainfall in individual river basins and tropospheric temperatures over different parts of the globe stated above are not significant. So, composite analysis was carried out in order to understand the effect of extreme temperature conditions on rainfall variability. Extreme warm years (temperature > mean + 1 SD) and extreme cold years (temperature < mean −1 SD) were selected from the 1951–2012 period. The difference between mean rainfall amounts of warm and cold years is tested for its significance using a Student's *t*-test. Similar analysis was carried out for geopotential thicknesses of the areas stated above. The results show that tropospheric temperature and geopotential thickness of the ExNH shows significant (5% l.o.s.) difference in the amount of JJAS rainfall in the EGP. The warmest and thickest is the ExNH; the wettest is the EGP area.

The Tibet–Himalaya–Karakoram–Hindu-Kush highlands (THIKHIHILs) is located in the middle of the eastern ExNH. It has a contiguous landmass in the west and north, which is a higher altitude heat source, and water bodies on the east and south during boreal summer. It has been seen that the tropospheric temperature (thickness) during JJAS over Tibet is −8.8°C (14,251.1 m), which is warmer (thicker) than the troposphere over the entire globe by 10.0°C (483.8 m). It is warmer (thicker) than over the NH by 6.2°C (284.5 m), the SH by 13.8°C (682.3 m), the ExNH by 9.4°C (461.2 m), the ExSH by 22.0°C (1134.5 m), the NP by 16.5°C (785.2 m), and the SP by 41.7°C (2076.0 m). The presence of a hotter troposphere over the THIKHIHILs than over other parts of the globe is an essential condition for the occurrence of the summer monsoon circulation. This area experiences the strongest tropospheric upwelling, forming the Tibetan anticyclone in the upper troposphere, and outflows from the anticyclone are scattered in all directions, subsiding over eight strong highs across the globe: the North Pacific (NPAC), South Pacific (SPAC), Australian (AUSH), Mascarene/Southern Indian Ocean high (SIOH), Azores/North Atlantic high (NAL), South Atlantic high (SAL), North polar high (NPH), and South polar high (SPH). The divergence from the lower layers of the strong highs returns through a large variety of meandering courses into the low pressure system over the Middle East and over the China–Mongolia sector forming different types of convergence (line, circular, meander, eddies, head-on-collision, orographic effect, and channellized flow). These produce frequent rain across the Asia–Pacific region. This boreal summer, large-scale atmospheric circulation is popularly known as the Asian monsoon circulation. The THIKHIHILS play a major role in determining the intensity and location of this circulation.

It has been seen that the temperature and thickness of the THIKHIHILS was well correlated with the all-India summer monsoon rainfall during the 1951–2012 period (CC=0.51 and 0.59, respectively, both significant at the 0.1% l.o.s. (Ranade, Singh, & Singh, 2010)). In order to understand the role of tropospheric warming over THIKHIHILS (25°–35°N, 40°–77°E) in summer rainfall in the EGP, correlation analysis was performed between tropospheric temperature and tropospheric thickness and monthly summer rainfall across the EGP. The CC for the summer season for temperature and thickness is 0.32 and 0.35, respectively, both significant at the 5% l.o.s as shown in Table 2. The highest correlations (CC=0.57 and 0.59, respectively, significant at the 5% l.o.s.) are observed for June rainfall in the EGP followed by the September rainfall (CC=0.46 and 0.47, respectively, significant at the 5% l.o.s.). It shows that the rainfall during the onset and withdrawal months of the Asian monsoon circulation of the EGP (June and September) are better correlated with temperature over THIKHIHILS. However, in August, rainfall in the EGP is not well correlated with THIKHIHILS. August is the month when the Asian monsoon circulation is well established over India, and the position of the Tibetan anticyclone is slightly shifted westward or sometimes breaks into two cores (westward and eastward positions). In the establishment phase of the Asian summer monsoon circulation, various convergence zones develop in the monsoon flow, which are controlled by large-scale flow, as well topography, moisture convergence, and local effects. Ranade et al. (2010) showed that seventeen of these types of convergence areas developed across the Asia–Pacific region during boreal summer. Line-cum-eddy convergence formed across the IGP is the major source of frequent rain across the EGP. It is formed between the monsoon flow from the Arabian Sea and northwesterlies from the Azores High. Small-scale eddies are formed in this combined flow, which is popularly known as the monsoon trough. Synoptic-scale weather systems formed in the Bay of Bengal also align with this convergence zone and produce heavy rains across the IGP, especially the EGP because of its proximity to the Bay of Bengal. It seems that, August rainfall in the EGP is mainly controlled by synoptic-scale weather disturbances formed in the Bay of Bengal and secondary local-scale eddies in the monsoon trough region rather than large-scale monsoon flow.

As stated earlier, all eight high pressure areas across the globe take part in the Asian monsoon circulation. Intensity of this monsoon circulation depends upon the temperature and thickness gradients between the THIKHIHILS and other pressure cells. The steeper the gradient, the stronger the outflow and the more intense the monsoon circulation. In this study, we have shown that the relationship between temperature gradient and thickness from the THIKHIHILLS to eight strong highs is one of the determining factors of the performance of a monsoon across the EGP. Table 3 shows the CCs between JJAS rainfall in the EGP and the temperature gradient from THIKHIHILLS to eight strong highs (SIOH: 60°–100°E, 25°–5°S; AUSH: 100°–160°E, 25°–5°S; NPAC: 150°E–130° W, 10°–40°N; SPAC: 90°–160°W, 25°–5°S; NAL: 80°–20° W,10°–40°N; SAL: 30°–10°E, 25°–5°S; NPH: 0°–360°, 75°–90°N; SPH: 0°–360°, 75°–90°S). Based on the data from the 1951–2012 period, the correlation of rainfall in the EGP during JJAS and the tropospheric temperature gradient from different subtropical highs varies from 0.34 to 0.43, significant at the 5% l.o.s. The temperature gradients from the NPH and SPH are not well correlated seasonally, but good correlation is observed in the monthly rainfall. It should be noted that the June and September rainfall in the EGP is very well correlated with the temperature gradients of all the strong highs. The correlation for June varies from 0.65 for SIOH to 0.42 for SPH and that of September from 0.45 for AUSH to 0.31 for NAL. A similar exercise is repeated for the geopotential thickness gradient from THIKHIHILS to eight strong highs and EGP rainfall (Table 4). The results are well matched with that for temperature gradient. The CCs significant at the 5% l.o.s. vary between 0.40 and 0.30 for the JJAS rainfall and 0.62 to 0.33 for the June rainfall.

d *Influence of ENSO on monsoon rainfall across the EGP*

It is well known that the climatic indices for the tropical Pacific Ocean also affect the interannual variability of the Indian summer monsoon rainfall. El Niño and La Niña are the most effective climatic signals for the Indian summer monsoon. Many authors have documented the relationship between the Indian summer monsoon rainfall and ENSO (Parthsarthy & Pant, 1985; Sikka, 1980; Webster & Yang, 1992 and many more). Recently, it was found that there are two types of ENSO mechanisms, the central Pacific ENSO and the eastern Pacific ENSO. The relationship between monsoon rainfall and Niño 3 and Niño 4 is analyzed separately. In this study, we have examined the effect of extremes of El Niño and La Niña on the amount of rainfall in the EGP during the summer monsoon season.

Table 5a shows that the Niño 3.4 SST indices during December, January, and February (DJF) have a significant (5% l.o.s.) negative correlation with monsoon rainfall in the Subarnarekha and Damodar river basins and that the Niño 3.4 SST index during JJAS has a significant (5% l.o.s) negative correlation with monsoon rainfall in the Tons River basin. Table 5b shows that monsoon rainfall in the Tons River basin is negatively correlated with all three Niño SST indices during November, December, and January (NDJ) at the 5% l.o.s. A significant relationship does not exist for other basins across the EGP. In order to obtain quantitative information about the effect of these climatic signals, a composite analysis was performed for ten extreme El Niño years and ten extreme La Niña years. The difference in the rainfall amount between an extreme El Niño year and an extreme La Niña year is given in Table 5a. Significant differences (5% l.o.s) are observed in the rainfall amounts in the Subarnarekha River basin (92.2 mm), the Tons River basin (220.4 mm), and the Mahanadi River basin (156.1 mm). Differences are also observed for other basins, but the results are not significant. For the EGP area, the difference in rainfall amount is 84.3 mm but is not statistically significant. In essence, composite analysis shows that during extreme El Niño years, rainfall in the EGP decreases significantly, by 8.3%, compared with extreme La Niña years.

4 Conclusions

Climatological characteristics, fluctuation features, and periodic cycles of annual, seasonal, and monthly rainfall series for seven river basins across the EGP were studied, using

TABLE 2. Correlation between tropspheric temperature and thickness for the THIKIHILLS and monsoon rainfall in the EGP.

Variables	Correlation Coefficient				
	June	July	August	September	JJAS
Tropospheric Temperature	0.57*	0.33*	−0.03	0.46*	0.32*
Tropospheric thickness	0.59*	0.30*	0.02	0.47*	0.35*

* indicates 5% l.o.s.

TABLE 3. The CCs for the relationship between monsoon rainfall in the EGP and temperature gradient from TIKHIHILLS to all high pressure areas across the globe.

High Pressure Areas	Correlation Coefficient				
	June	July	August	September	JJAS
SIOH	0.65*	0.18	0.14	0.42*	0.41*
AUSH	0.57*	0.17	0.13	0.45*	0.37*
NPAC	0.61*	0.33*	0.08	0.39*	0.43*
SPAC	0.63*	0.22	0.05	0.39*	0.39*
NAL	0.49*	0.32*	0.17	0.31*	0.39*
SAL	0.56*	0.17	0.04	0.37*	0.34*
NPH	0.47*	0.19	0.12	0.24	0.06
SPH	0.42*	−0.17	−0.03	0.11	−0.01

* indicates 5% l.o.s.

TABLE 4. The CCs for the relationship between monsoon rainfall in the EGP and thickness gradient from the TIKHIHILLS to all high pressure areas.

High Pressure Areas	Correlation Coefficient				
	June	July	August	September	JJAS
SIOH	0.62*	0.20	0.03	0.42*	0.34*
AUSH	0.55*	0.20	0.09	0.39*	0.40*
NPAC	0.59*	0.35*	0.00	0.38*	0.37*
SPAC	0.61*	0.25	−0.02	0.39*	0.34*
NAL	0.50*	0.32*	0.11	0.27	0.35*
SAL	0.53*	0.20	−0.02	0.36*	0.30*
NPH	0.48*	0.20	0.09	0.18	0.02
SPH	0.33*	−0.21	−0.05	0.04	0.09

* indicates 5% l.o.s.

TABLE 5a. Correlation between the Niño 3.4 SST index and monsoon (JJAS) rainfall in the EGP and the composite difference between mosnoon rainfall during El Niño and La Niña years of seven river basins.

	Correlation with JJAS rainfall		Composite difference in JJAS rainfall		
River Basins	El Niño index during JJAS	El Niño index during DJF	El Niño years	La Niña Years	Difference
Subarnarekha	0.13	−0.27*	1189.588	1097.409	92.14*
Brahmani	0.04	0.03	1060.929	1020.798	40.13
Kasai	0.08	0.11	1063.427	1128.565	65.10
Damodar	0.12	−0.24*	1162.579	1092.223	70.35
Son	−0.05	−0.11	1012.368	965.1309	47.23
Tons	−0.33*	0.14	1030.874	810.4062	220.43*
Mahanadi	−0.11	0.16	1176.638	1020.514	156.124*
EIGP	−0.13	−0.10	1101.966	1017.611	84.35

* indicates 5% l.o.s.

TABLE 5b. Correlation between Niño 3.4, Niño 3, and Niño 4 SST indices and monsoon (JJAS) rainfall in the EGP.

	Correlation of Niño Index (NDJ) with JJAS Rainfall		
River Basins	El Niño index (3.4)	El Niño index (3)	El Niño index (4)
Subarnarekha	−0.03	−0.03	−0.08
Brahmani	0.07	0.00	0.17
Kasai	0.10	0.03	0.20
Damodar	−0.12	−0.12	−0.04
Son	−0.02	−0.02	0.03
Tons	−0.26*	−0.25*	−0.27*
Mahanadi	0.01	−0.04	0.05
EIGP	−0.07	−0.09	0.02

* indicates 5% l.o.s.

the longest possible instrumental area-averaged monthly rainfall series. The effect of asymmetric changes in global tropospheric temperature on the EGP rainfall was also documented in detail. The main findings of the study follow:

1. The mean annual rainfall across the EGP varies from 1070.5 mm (±216.8 mm) in the Tons River basin to 1508.6 mm (±205.2 mm) in the Subarnarekha River basin, and the monsoon rainfall varies from 946.5 mm (±198.6 mm) in the Tons River basin to 1188.6 mm (±186 mm) in the Mahanadi River basin.
2. The annual rainfall in all river basins and the monsoonal rainfall in the Tons, Son, Mahanadi, and Subarnarekha River basins are normally distributed, whereas the distribution of the pre-monsoon and winter rainfall differs significantly from normal.
3. A significant long-term trend is not seen in the pre-monsoon, post-monsoon, or winter rainfall in all river basins; however, a significant decrease is seen in the annual and monsoon rainfall in the Brahmani and Son River basins.
4. During the past 30 years, neither annual nor monsoon rainfall showed any spatially coherent significant long-term trends; however, a significant decrease was noticed in the annual rainfall in all river basins and in the monsoonal rainfall in the Tons, Son, Damodar, Brahmani, and Kasai River basins during the past 20 years.
5. The power spectra of rainfall across the EGP were characterized by consistent, significant peaks at 3–5 years, 10–20 years, 40 years, and greater than 80 years.
6. Short-term fluctuations with a period less than 10 years are the major contributor to the total variance in annual rainfall (77.6%), followed by decadal variations with a period of 10–30 years (13.1%), and long-term trend with a period greater than 30 years (9.3%). Similar results were obtained for monsoon rainfall.
7. Temperature (thickness) of ExNH and their gradients from the THIKHIHILS to eight strong highs play an important role in rainfall in all river basins, especially during the onset and withdrawal phases of monsoon.
8. There is a significant decrease in rainfall in the EGP during extreme El Niño years (8.3%) but not during extreme La Niña years.

Against a backdrop of asymmetric global warming and a gradual decrease in rainfall over India, the results of the present longest river basin rainfall studies across the EGP can provide valuable information to water resource forecasters and planners, as well as management.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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