Recent trend in spatiotemporal variation of rainfall over India—an investigation into basin-scale rainfall fluctuations

NITYANAND SINGH, NEELIMA A. SONTAKKE, H. NARENDRA SINGH & AMIT KUMAR PANDEY
Indian Institute of Tropical Meteorology, Dr Homi Bhabha Road, Pashan, Pune 411 008, India
nsingh@tropmet.res.in

Abstract In recent years a new perspective has been added to India's hydrological and water resources research with the formulation of the Master Plan "Interbasin Water Transfer—Interlinking of Rivers of India". The issue of rainfall fluctuations over and across the country needs to be addressed amicably in the planning process of the programme. Using highly quality-controlled data from 316 widely distributed raingauge stations, spatiotemporal features of annual, seasonal and monthly rainfall for the whole of India and its 11 major and 31 (including west coast drainage) minor river basins are reported in this paper. Spatial features of the rainfall for the whole country were studied by examining expansion/contraction of rainfall zones under specified rainfall conditions over the period 1871–2001. Broadly, from around the 1940s, a westward shift, larger variability and declining tendency is seen in the rainfall over the country. To understand temporal features across the country, basin-scale area-averaged rainfall series (1813–2001) have been subjected to time series analysis. Basins in central India (Sabarmati, Mahi, Narmada, Tapi, Godavari and Mahanadi) have been experiencing reduced rainfall from about the 1960s, while in others—Indus from 1954, Ganga from 1993, Brahmaputra from 1988, Krishna from 1953 and Cauvery from 1929—there has been an upward trend in rainfall. The recent trend in rainfall across India is believed to be due to global warming; a possible mechanism is suggested.

Key words basin rainfall studies; global warming; India; instrumental period rainfall series; rainfall spatiotemporal variation; RS-GIS in hydrometeorology

INTRODUCTION

In recent years a new perspective has been added to hydrological investigations in India. The Government of India has launched the most ambitious Master Plan "Interbasin Water Transfer—Interlinking of Rivers of India" with a focused objective to utilize the country's water resources to the fullest extent practicable by transferring water from the basins with surplus to areas of deficit. One of the important issues to be addressed in the planning process of the programme is the impact of global warming on the rainfall fluctuation over the different river basins. The influence of global warming on rainfall variations over India is reported in numerous observational (Singh *et al.*, 1991, 1992) and modelling studies (Lal, 1994). Though considerable rainwater enters the Indian territory from the Himalayan area, the major hydrological activities and water resources of the country are due to *in situ* rainfall occurrences, mostly summer monsoon rainfall during June–September. Large-scale studies on Indian rainfall have generally used area-averaged monsoon rainfall series of the whole country and/or meteorological subdivisions. Spatial variations are completely ignored in area-averaged rainfall studies. Further, a comprehensive basin-specific rainfall study of the country does not seem to exist. The main objectives of the present study are:

- to understand the nature of interannual variations in the spatial distribution of annual, seasonal and monthly rainfall (or rainfall spatial variability) over the country;
- to document the chief features of the rainfall variations over 11 major and 31 minor river basins, based on the longest available instrumental series; and
- to investigate the impact of recent global warming on the rainfall of India, and describe the possible mechanism.

FEATURES OF LARGE-SCALE RAINFALL VARIATIONS

In studies on large-scale variability using area-averaged rainfall series, spatial features are completely ignored. In this paper spatial variability of annual, seasonal and monthly rainfall over India is studied using highly quality-controlled data from 316 widely distributed locations for the period 1871–2001. Rainfall data up to 1900 were obtained from Eliot (1902) and for the period 1901–2001 the data were copied from the records of the India Meteorological Department (IMD), Pune. A digitized map of India on "Albers Equal Area Projection with Two Standard Parallels, 15°N and 30°N" and 1:6M scale was utilized in a GIS environment (GeoMedia Professional 5.1) for the spatial analysis of the rainfall data. To understand spatial variation of annual rainfall, expansion/contraction of different moisture regions viz. arid (rainfall ≤ 560 mm), semiarid (561–1040 mm), dry subhumid (1041–1420 mm), moist subhumid (1421–1630 mm), humid (1631–2450 mm) and perhumid (≥ 2450 mm), was examined. A yearwise chart showing areas of the country under different moisture conditions was prepared using GIS. Though the chart is prepared for each year of the period 1871–2001, for brevity it is shown for the last five years (1997–2001) in Fig. 1, along with the long-term mean (normal) position of the moisture regions. Different moisture regions of the country show large and random variation from one year to another. The time series of the area of the country under different moisture conditions is presented in Fig. 2 for the full period (1871–2001). In the low-frequency mode fluctuations, notable features of the moisture regions are a spreading tendency in semiarid and dry subhumid regions from the early 1940s and a contracting tendency in arid, humid and perhumid regions.

Spatial variation of the seasonal and monthly rainfall was studied by examining interannual variation of an optimum number of four rainfall zones under different rainfall conditions viz. very dry (VD), dry (D), wet (W) and very wet (VW), identified on the mean rainfall chart of the particular period (season/month) of equal size (25%) area of the country. The criterion of rainfall was then applied to yearly rainfall spatial distribution and the area of the country under different rainfall conditions was obtained. A Rainfall Spatial Distribution Index (RSDI) is defined by lumping VD, D, W and VW areas in order to assess the rainfall situation (both in terms of amount and areal distribution) for the country as a whole. For a particular year, the RSDI is

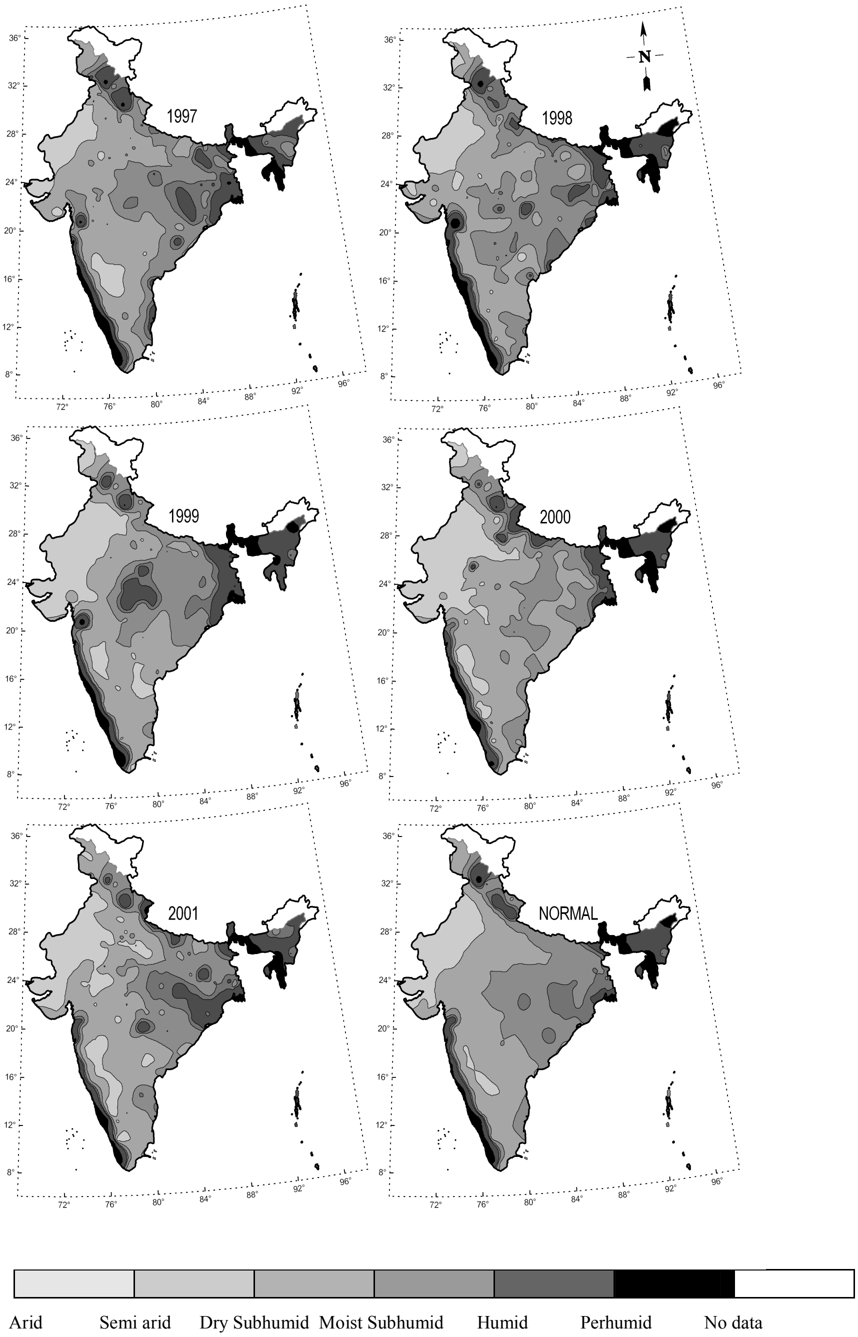

Fig. 1 A sample of spatial variations of moisture regions during 1996–2001 and their long-term mean position.

$$RSDI = \frac{1 \cdot a_{VD} + 2 \cdot a_D + 3 \cdot a_W + 4 \cdot a_{VW}}{A}$$

where a_{VD} denotes area of the country under very dry condition, a_D under dry, a_W under wet and a_{VW} under very wet condition, and A is the total geographical area of the country.

High RSDI value is indicative of enhanced rainfall over large areas, including dry areas and *vice versa*. In this short communication only recent trend of the RSDI

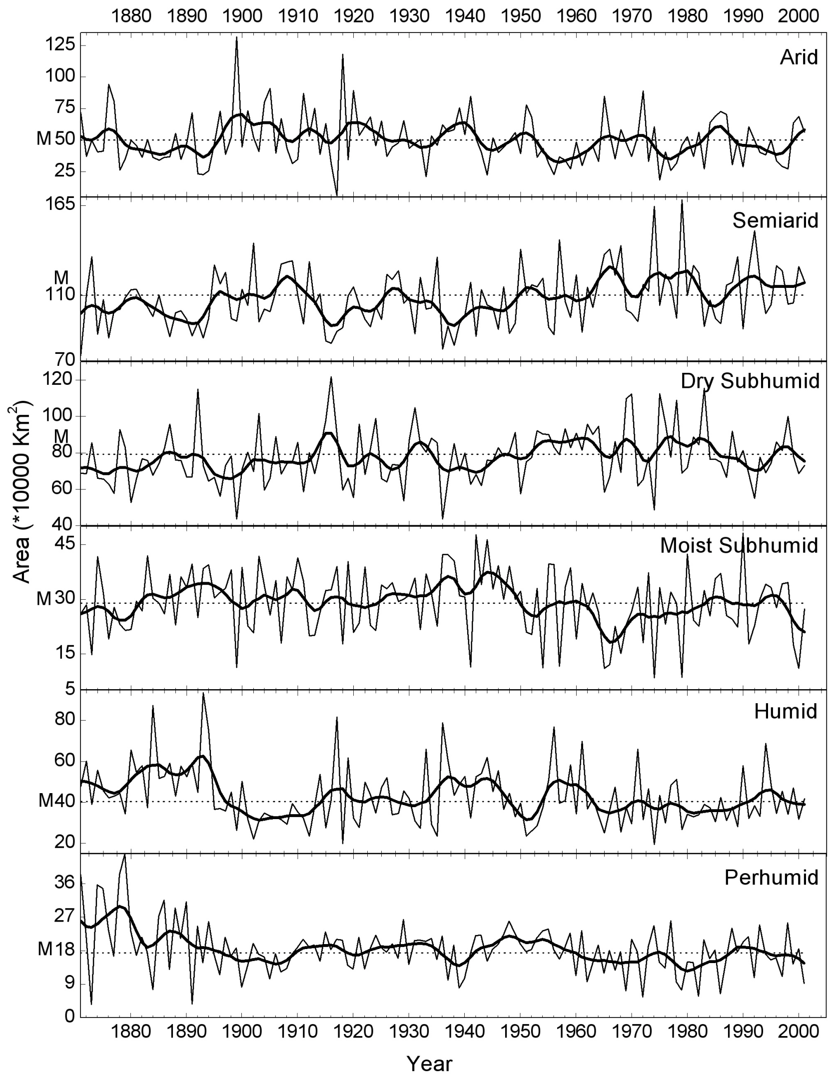

Fig. 2 Interannual variation (thin curve) in the area under different moisture conditions (arid, semiarid, dry subhumid, moist subhumid, humid and perhumid) during 1871–2001. The thick curve denotes the 9-point Gaussian low-pass filtered values with truncated end points.

fluctuation is discussed. Overall the winter and monsoon rainfall show decreasing trend from about 1940s and summer and post-monsoon increasing trend. On monthly scale January, February, March, July, August and September rainfall show decreasing trend and the remaining six months increasing trend.

LONGEST INSTRUMENTAL RAINFALL SERIES FOR MAJOR AND MINOR RIVER BASINS

The National Atlas and Thematic Mapping Organization (NATMO) of India has divided the country's drainage into 11 major basins, 30 minor basins and the West Coast Drainage. Four major basins—Mahi, Narmada, Sabarmati and Tapi—are

Table 1 Some important information about India's 30 minor basins: geographical area, starting year of rainfall data (ending year is 2001) and epochal pattern in the annual rainfall series.

Minor basins (area in km^2)	Start. year	Sequence of dry(D)/wet(W) epochs in the annual rainfall temporal pattern
Indus basin:		
Chenab (54 501)	1893	1893–1941 (D), 1942–1961 (W), 1962–1974 (D), 1975–2001(W)
Beas (18 866)	1857	1857–1900 (W), 1901–1921 (D), 1922–1978 (W), 1979–2001(D)
Sutlez (79 331)	1844	1844–1894 (W), 1895–1941 (D), 1942–2001 (W)
Ganga basin:		
Yamuna (112 695)	1844	1854–1894 (W), 1895–1941 (D), 1942–2001 (W)
Ramnganga (31 572)	1845	1845–1859 (W), 1860–1877 (D), 1878–1894 (W), 1895–1913 (D), 1914–1978 (W), 1979–2001 (D)
Gomati (77 152)	1860	1844–1884 (D), 1885–1900 (W), 1901–1920 (D), 1921–1961 (W), 1962–2001 (D)
Ghaghara (50 431)	1844	1844–1884 (D), 1885–1949 (W), 1950–1979 (D), 1980–2001(W)
Gandak (28 001)	1859	1849–1884 (D), 1885–1922 (W), 1923–1968 (D), 1969–2001(W)
Chambal (156 054)	1857	1856–1894 (W), 1895–1941 (D), 1942–1961 (W), 1962–2001(D)
Sind (28 634)	1860	1860–1894 (W), 1895–1954 (D), 1955–1988 (W), 1989–2001(D)
Betwa (44 479)	1860	1861–1894 (W), 1895–1930 (D), 1931–1961 (W), 1962–2001(D)
Ken (30 100)	1860	1845–1876 (W), 1877–1883 (D), 1884–1894 (W), 1895–1921 (D), 1922–1961 (W), 1962–2001 (D)
Tons (39 425)	1860	1845–1898 (W), 1899–1913 (D), 1914–1956 (W), 1957–2001(D)
Son (111 300)	1842	1842–1884 (D), 1885–1949 (W), 1950–2001 (D)
Damodar (64 753)	1829	1839–1871 (W), 1872–1896 (D), 1897–1955 (W), 1956–1967 (D), 1968–2001 (W)
Kasai (21 625)	1859	1859–1922 (W), 1923–1983 (D), 1984–2001 (W)
Brahmaputra basin:		
Surma (47 216)	1863	1863–1922 (D), 1923–1977 (W), 1978–2001 (D)
Godavari basin:		
Wainganga (65 899)	1861	1861–1913 (D), 1914–1949 (W), 1950–2001 (D)
Wardha (22 766)	1855	1855–1876 (D), 1877–1894 (W), 1895–1930 (D), 1931–1962 (W), 1963–2001 (D)
Godavari (143 213)	1861	1861–1895 (W), 1896–1930 (D), 1931–1963 (W), 1964–2001(D)
Indravati (46 605)	1871	1871–1897 (W), 1898–1909 (D), 1910–1963 (W), 1964–2001(D)
Krishna basin:		
Bhima (76 772)	1853	1842–1895 (W), 1896–1952 (D), 1953–2001 (W)
Krishna (141 466)	1841	1841–1952 (D), 1953–2001 (W)
Tungabhadra (77 412)	1837	1837–1876 (D), 1877–1903 (W), 1904–1952 (D), 1953–2001(W)
Independent minor basins:		
Suvarnarekha (32 647)	1859	1859–1900 (W), 1901–1939 (D), 1940–1952 (W), 1953–2001(D)
Brahmani (50 581)	1871	1871–1924 (D), 1925–1947 (W), 1948–2001 (D)
Luni (79 456)	1856	1856–1897 (W), 1898–1939 (D), 1940–2001 (W)
Penner (96 538)	1813	1813–1869 (D), 1870–1925 (W), 1926–1954 (D), 1955–2001(W)
Palar and Ponnaiyar (48 084)	1863	1863–1883 (D), 1884–1925 (W), 1926–1953 (D), 1954–1978 (W), 1979–1992(D), 1993–2001 (W)
Vagai (39 522)	1846	1855–1918 (D), 1919–1984 (W), 1985–2001 (D)

independent with no minor basin. The minor basins of the other major basins—Indus, Ganga, Brahmaputra, Godavari, Cauvery, Krishna and Mahanadi—are given in Table 1. The Luni basin is a minor basin in the Rajasthan Desert. The West Coast Drainage is a combined drainage system for 25 small rivers originating in the west coast Sahayadri range and discharging into the Arabian Sea. A detailed description of the physical features of the different basins is available in *India's Water Wealth* (Rao, 1975). For each of the major and minor river basins, the longest possible monthly, seasonal and annual rainfall series were prepared. Rainfall data for the network of all the 316 raingauges is available for the period 1901–2001. From this network the data for 314 stations extends back to 1900, for 312 to 1871, for 101 to 1861, for 57 to 1844, for 13 to 1842, for six to 1829, for two (Chennai and Mumbai) to 1817 and for the lone station Chennai to 1813. For a particular basin, the representative area-averaged series for the period 1901–2001 was prepared from the simple arithmetic mean of the gauges in the basin. The representative monthly, seasonal and annual series prior to 1901 were constructed by applying a theoretically vindicated objective method (Singh, 1994; Wigley *et al*., 1984) on lesser available observations—details of the construction are given in Sontakke & Singh (1996). A brief description of the major basins, the rainfall data and chief features of the annual rainfall fluctuations is given below. The longest annual rainfall series for major basins are given in Fig. 3.

Major river basins

Indus (area: 291 749 km^2; mean annual rainfall: 860.3 mm; longest available series: 1844–2001). The sequence of dry/wet epochs in the annual rainfall temporal pattern is: 1844–1894 wet, 1895–1953 dry and 1954–2001 wet.

Ganga (area: 860 884 km^2; mean annual rainfall: 1040.4 mm; longest available series: 1829–2001). The sequence of dry/wet epochs in the annual rainfall temporal pattern is: 1829–1853 dry, 1854–1894 wet, 1895–1913 dry, 1914–1964 wet, 1965–1992 dry and 1993–2001 wet.

Brahmaputra (area: 186 732 km^2; mean annual rainfall: 2238.7 mm; longest available series: 1848–2001). The sequence of dry/wet epochs in the annual rainfall temporal pattern is: 1848–1881 wet, 1882–1909 dry, 1910–1921 wet, 1922–1945 dry, 1946–1960 wet, 1961–1987 dry and 1988–2001 wet.

Godavari (area: 330 628 km^2; mean annual rainfall: 1068.3 mm; longest available series: 1826–2001). The sequence of dry/wet epochs in the annual rainfall temporal pattern is: 1861–1895 wet, 1896–1930 dry, 1931–1963 wet and 1964–2001 dry.

Krishna (area: 295 650 km^2; mean annual rainfall: 832.3 mm; longest available series: 1826–2001). The sequence of dry/wet epochs in the annual rainfall temporal pattern is: 1836–1873 dry, 1874–1903 wet, 1904–1952 dry and 1953–2001 wet.

Sabarmati (area: 36 688 km^2; mean annual rainfall: 742.8 mm; longest available series: 1843–2001). The sequence of dry/wet epochs in the annual rainfall temporal pattern is: 1861–1898 wet, 1899–1925 dry, 1926–1959 wet and 1960–2001 dry.

Mahi (area: 41 179 km^2; mean annual rainfall: 836.1 mm; longest available series: 1857–2001). The sequence of dry/wet epochs in the annual rainfall temporal pattern is: 1857–1898 wet, 1899–1940 dry, 1941–1963 wet and 1964–2001 dry.

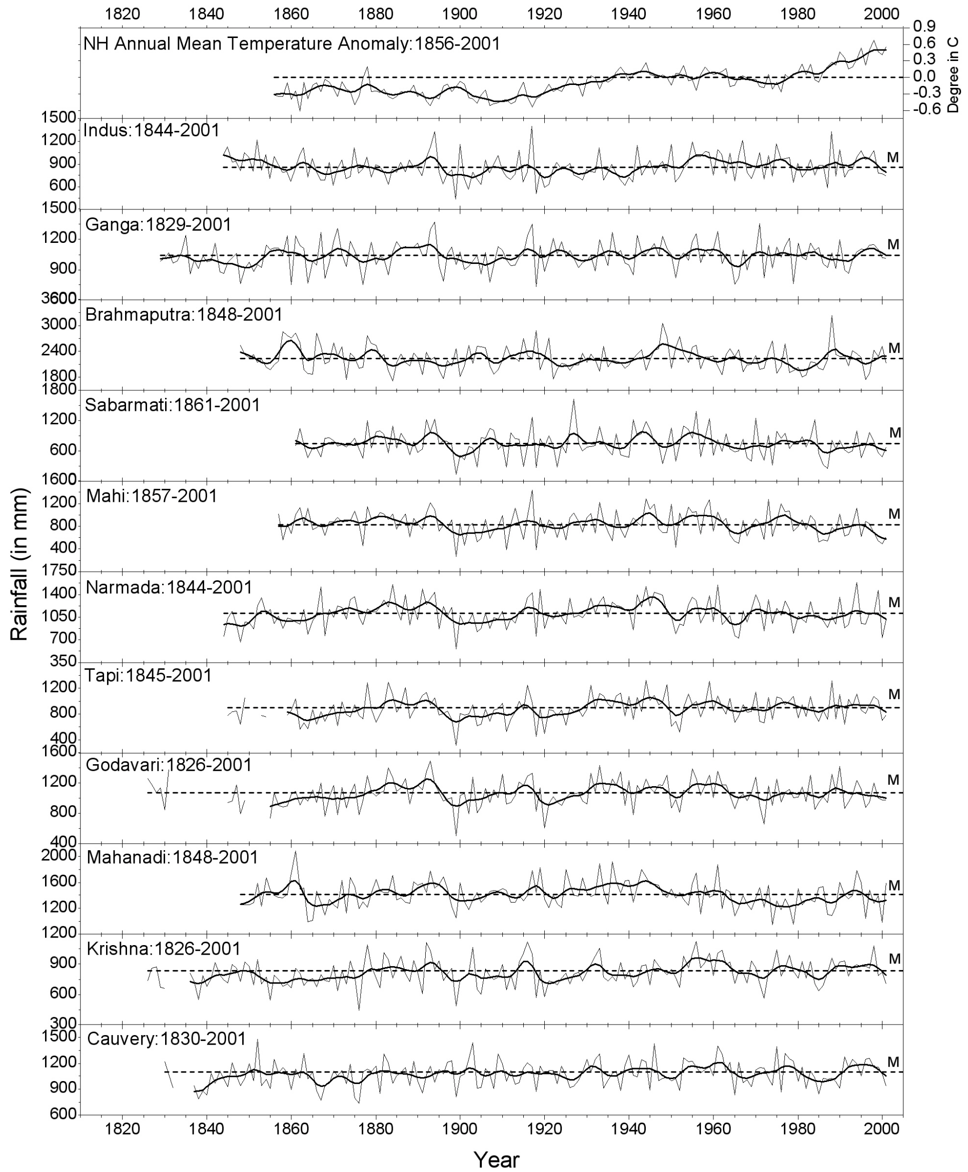

Fig. 3 Longest instrumental annual rainfall series of 11 major basins of India. Thin curve denotes actual values and thick curve 9-point Gaussian low-pass values.

Narmada (area: 94 562 km^2; mean annual rainfall: 1107.3 mm; longest available series: 1844–2001). The sequence of dry/wet epochs in the annual rainfall temporal pattern is: 1844–1868 dry, 1869–1894 wet, 1895–1913 dry, 1914–1949 wet and 1950–2001 dry.

Tapi (area: 65 041 km^2; mean annual rainfall: 894.4 mm; longest available series: 1844–2001). The sequence of dry/wet epochs in the annual rainfall temporal pattern is: 1859–1881 dry, 1882–1894 wet, 1895–1930 dry, 1931–1964 wet and 1965–2001 dry.

Mahanadi (area: 145 040 km^2; mean annual rainfall: 1410.4 mm; longest available series: 1848–2001). The sequence of dry/wet epochs in the annual rainfall temporal pattern is: 1848–1878 dry, 1879–1961 wet and 1962–2001 dry.

Cauvery (area: 91 691 km^2; mean annual rainfall: 1100.1 mm; longest available series: 1829–2001). The sequence of dry/wet epochs in the annual rainfall temporal pattern is: 1837–1928 dry and 1929–2001 wet.

West Coast Drainage (area: 117 962 km^2; mean annual rainfall: 2528.5 mm; longest available series: 1817–2001). The sequence of dry/wet epochs in the annual rainfall temporal pattern is: 1838–1911 dry, 1912–1964 wet and 1965–2001 dry.

In general, the recent annual rainfall fluctuations show a decreasing trend over basins in central India (Sabarmati, Mahi, Narmada, Tapi, Godavari and Mahanadi) since 1960 and an increasing trend over others—Indus from 1954, Ganga from 1993, Brahmaputra from 1988, Krishna from 1953 and Cauvery from 1929.

Minor river basins

The total geographical area, longest available rainfall sequence and epochal pattern in the annual rainfall fluctuation for minor basins are given in Table 1. The major dry/wet epochs in the annual rainfall series are consistent with the epochal pattern of the respective major basins.

Annual rainfall in India generally reflects the features of the monsoon rainfall fluctuation. Winter (January–February) rainfall is of some significance in extreme northern India and the southeast peninsula and summer (March–May) rainfall is of significance in northeastern India and the extreme southwest peninsula; however, post-monsoon (October–December) rainfall is of considerable significance in the southern peninsula (south of 15°N). A large variability in the characteristics of rainfall has been observed over the same basin in different seasons and months. Due to space limitations the details are not published here. In the following section, the impact of the recent warming tendency in the Northern Hemisphere on monsoon rainfall over different basins is discussed.

IMPACT OF GLOBAL WARMING ON RAINFALL VARIATIONS OVER DIFFERENT BASINS

Notable features of recent monsoon rainfall fluctuations over the major basins are a decreasing trend over the Sabarmati (from 1960), Mahi (from 1964), Narmada (from 1950), Tapi (from 1965), Godavari (from 1964) and Mahanadi (from 1962) basins, and an increasing trend over the Indus (from 1954), Ganga (from 1993), Brahmaputra (from 1988), Krishna (from 1953) and Cauvery (from 1929) basins. A linear trend fitted to the monthly surface air temperature anomaly (with respect to 1965–1980), kept in sequence over the period 1949–1998, indicated the highest increasing rate of 4°K (100 year)$^{-1}$ over the Manchurian area, centred near 100°E, 45°N, and a decreasing rate of –1.5°K (100 year)$^{-1}$ over the central Pacific, centred near 160°W, 30°N. While the warmer Eurasian landmass is favouring a more intense Arabian Sea branch monsoon, current and intense rainfall over the west coast and northwest India, there is suppression of deep moist convection over the Bay of Bengal. Intensification of the anticyclone over the central Pacific is suppressing cyclogenesis over the Bay of Bengal, as a consequence of which there is a decline in rainfall over the central parts of

India. From the 1970s to the present, the number of monsoon storms/depressions over the Bay of Bengal has declined from about six (June–September) to less than two. Similarly, the frequency of western disturbances has declined from 26 to six during the monsoon season (June–September) and from 33 to 15 during the pre-monsoon season (March–May) over the period 1970–2000 (Das *et al*., 2002).

Further, there are notable changes in the interannual fluctuation of important components of the monsoon circulation. The June–July–August sea-level pressure (SLP) showed a rising trend (period 1949–2003) at "Mascarene High" at the rate of 3.1 mb $(100\ \text{year})^{-1}$, at "Heat Low" area (northwest India–Pakistan) 5.7 mb $(100\ \text{year})^{-1}$, and at "head Bay of Bengal" 3.5 mb $(100\ \text{year})^{-1}$. Also, the pressure gradient between Mascarene High and Heat Low has been reducing at the rate of –2.7 mb $(100\ \text{year})^{-1}$ and between Mascarene High and Bay of Bengal at –0.59 mb $(100\ \text{year})^{-1}$ over the same period. These changes in the pressure field are indicative of weaker Indian summer monsoon circulation. But increasing trend in the geopotential height of the "Tibetian High" (200 hPa level) at the rate of 38.7 m $(100\ \text{year})^{-1}$ (period 1949–2003) shows some strengthening of the monsoon circulation. Because of these complex changes in the meteorological conditions over the monsoon regime, the relationship between NOAA OLR (Outgoing Longwave Radiation) and the rainfall across India is changing—while OLR is decreasing (or clouding is increasing) everywhere, rainfall across the country shows a mixture of increasing, decreasing and no trends. Increasing trend in clouding is perhaps due to a rising trend in surface air temperature (SAT) and sea-surface temperature (SST), but a decrease in rainfall over some parts of the country is due to reducing frequency of rain inducing disturbances. This paradigm needs to be thoroughly explored.

SUMMARY AND CONCLUSION

(a) Different moisture regions of the country show large and random spatial variation from one year to another. Since the 1940s, a shrinking tendency is seen in the area under arid, humid and perhumid conditions and spreading tendency in the area under semiarid, dry subhumid and moist subhumid conditions. Fluctuations of seasonal dry/wet zones indicated a decreasing trend in winter and monsoon rainfall since the early 1950s and an increasing trend in summer and post-monsoon rainfall. The net effect is a westward shift, more variable and declining rainfall over the country.

(b) Annual rainfall over major basins in central India (Sabarmati, Mahi, Narmada, Tapi, Godavari and Mahanadi) shows a decreasing trend since the 1960s, while in other basins it shows an increasing trend. The features of the minor basins are consistent with those of the major basins.

(c) Due to intensification of the monsoon circulation caused by a rising trend in surface air temperature over Eurasia, rainfall is increasing over northwest India, northeast India and the south peninsula. On the other hand, due to a decline in cyclogenesis over the Bay of Bengal caused by cooling of surface air over the central Pacific and strengthening of anticyclone there, rainfall over central India is decreasing. The effect of large-scale temperature changes on the rainfall over India is felt at different times of the year; the reason is not immediately known.

Acknowledgements The authors are extremely grateful to Dr G. B. Pant, Director of the Indian Institute of Tropical Meteorology for providing the facilities to pursue this study; to Dr K. Rupa Kumar, Head of the Climatology and Hydrometeorology Division for his keen interest and encouragement; and to the India Meteorological Department for all the rainfall data used.

REFERENCES

Das, M. R., Mukhopadhyay, Dandekar, M. M. & Kshirsagar, S. R. (2002) Pre-monsoon western disturbances in relation to monsoon rainfall, its advancement over NW India and their trends. *Current Sci.* **82**, 1320–1321.

Eliot, J. (1902) *Monthly and Annual Rainfall of 457 Stations in India to the End of 1900*. India Meteorological Department Memoirs, vol. XIV.

Lal, M. (1994) Water resurces of the south-east Asian region in a warmer atmosphere. *Adv. Atmos. Sci.* **11**, 239–246.

Rao, K. L. (1975) *India's Water Wealth—its Assessment, Uses and Projection.* Orient Longman Ltd, New Delhi, India.

Singh, N. (1994) Optimzing a network of raingauges over India to monitor summer monsoon rainfall variations. *Int. J. Climatol.* **14**, 61–70.

Singh, N., Mulye, S. S. & Pant, G. B. (1992) Some features of the arid area variations over India: 1871–1984. *Pure Appl. Geophys.* **138**, 135–150.

Singh, N., Pant, G. B. & Mulye, S. S. (1991) Distribution and long term features of the spatial variations of the moisture regions over India. *Int. J. Climatol.* **11**, 413–427.

Sontakke, N. A. & Singh, N. (1996) Longest instrumental regional and all-India summer monsoon rainfall series using optuimum observations: reconstruction and update. *The Holocene* **6**, 315–331.

Wigley, T. M. L., Briffa, K. R. & Jones, P. D. (1984) On the average value of correlated time series, with application in dendroclimatology and hydrometeology. *J. Clim. Appl. Met.* **23**, 201–213.