International Conference "Water, Environment, Energy and Society" (WEES–2009)
New Delhi, 12–16 January 2009

On Variability of Wet Season over Major River Basins of India

Nityanand Singh[1], A.A. Ranade, H.N. Singh and N.A. Sontakke
Indian Institute of Tropical Meteorology
Dr. Homi Bhabha Road, Pune - 411 008, INDIA
E-mail: [1]nsingh@tropmet.res.in

ABSTRACT : Longest possible instrumental area-averaged monthly, seasonal (winter JF, summer MAM, monsoon JJAS and post-monsoon OND) and annual rainfall series have been developed for each of the 11 major river basins and the West Coast Drainage System (WCDS) of India using highly quality-controlled data from well spread network of 316 raingauges. For the period 1901–2005 with complete data of all stations the area-averaged series has been prepared from simple arithmetic mean of the gauges in the particular basin, and for period prior to 1901 (sometimes going back to 1813) with lesser observations the series is constructed by applying established objective method. For different basins the starting year of rainfall data is as (ending year is always 2005): *The Indus* 1844; *The Ganga* 1829; *The Brahmaputra* 1848; *The Sabarmati* 1861; *The Mahi* 1857; *The Narmada* 1844; *The Tapi* 1859; *The Godavari* 1826; *The Krishna* 1826; *The Mahanadi* 1848; *The Cauvery* 1829 and *The WCDS* 1838. Fluctuation characteristics of the annual rainfall over different basins are briefly described.

In tropical monsoonal climate understanding regional variability of the wet (or rainy) season is as important as the variability of rainfall, very little attempt is made to study the later compared to former. The present study intends to document climatology, as well as fluctuation characteristics of the parameters of wet season (starting date, ending date and duration) over major basins of the country using longest available rainfall sequences.

INTRODUCTION

In recent years a new perspective has been added to hydrological investigations of India with the launch of the most ambitious Master Plan *'Interbasin Water Transfer –Interlinking of Rivers of India'*. The plan is intended to utilize the country's water resources to the fullest extent practicable by transferring water from the surplus basin to deficit areas. One of the important issues to be addressed amicably in the planning process of the program is the impact of global changes, particularly global warming, on the rainfall fluctuation over different basins across the country. Basin-scale characteristics of rainfall and wet season are expected to provide vital information to this plan.

Surrounded between the parallels of 8° 4′ 28″ N and 37° 17′ 53″ N, and between the meridians of 68° 7′ 53″ E and 97° 24′ 47″ E a beehive-shaped India occupies geographical area of 3,287,263 sq. km. (including territorial sea) on the southern plank of the Asian landmass. The contiguous land area of the country is 3,188,111 sq. km; its north-south length is about 3,214 km and east-west breadth about 2,933 km. The land frontier is 15,200 km and the coastline 7516.5 km. Andaman and Nicobar Islands in the Bay of Bengal and Lakshadweep in the Arabian Sea are parts of India. On the west of the country are Pakistan and Afghanistan, on the east Bangladesh and Burma, on the north Sinkiang province of China, Tibet, Nepal and Bhutan, and on the south Sri Lanka separated by a narrow channel of sea formed by the Palk Strait and the Gulf of Mannar.

With three large watersheds, the Himalayas, the Vindhyas and the Western Ghats, the country is drained by 11 major and 43 minor rivers and numerous rivulets. Thirty four of the 43 minor basins are the sub-basins of five major basins—the Indus 5 (*Jhelum, Chenab, Ravi, Beas and Satluj*), the Ganga 13 (*Yamuna, Ramganga, Gomati, Ghaghara, Gandak, Kosi, Mahananda, Chambal, Sind, Betwa, Ken, Tons and Son*), the Brahmaputra 8 (*Tista (or Teesta,) Kameng, Subansiri, Dihang, Dibang, Luhit, Dhansiri and Brahmaputra*), the Godavari 5 (*Wainganga, Wardha, Penganga, Godavari and Indravati*) and the Krishna 3 (*Bhima, Krishna and Tungabhadra*). The other nine minor basins are Luni, Surma, Kasai, Damodar, Suvarnarekha, Brahmani, Penner, Palar & Ponnaiyar and Vaigai. The Sabarmati, the Mahi, the Narmada, the Tapi, the Mahanadi and the Cauvery are the major basins without any distinct minor basin. Besides this in the West Coast Drainage system there are 25 small rivers that originate in the Sahayadri range (Western Ghats) and discharge into the Arabian Sea (NATMO, 1996; Rao, 1975).

[1]Conference speaker

Climate of the Indian subcontinent is dominated by the Indian Ocean southwest monsoon. Derived from the Arabic word 'Mausim' (or 'season of winds') the monsoon refers to system of winds that changes direction drastically from winter to summer season. During boreal summer outflows from the southern hemisphere Mascarene High pressure area into a bowl-shaped area of low pressure (monsoon trough) over Indo-Gangetic Plains are concentrated into a jet pattern, often called as a monsoon jet, monsoon surge, a low-level jet, or a cross-equatorial jet. Moisture laden onshore monsoon winds are about three miles thick. The rising air along the monsoon trough diverges out of an upper-tropospheric (Tibetan) anticyclone along an upper-level jet-like (easterly) flow. The monsoon trough is typically associated with low-level convergence, cyclonic vorticity and cloudiness. Though monsoon is basic factor rainfall at a particular location is a function of thickness of monsoon currents, convergence processes, regional geography and orography. Rainfall shows large temporal variation at the same location. To understand physical and dynamical causes of rainfall occurrences and their spatio-temporal variation is one of the main problems of the Indian meteorologists. High quality-controlled, spatially detailed, long period rainfall data is vital for monsoon studies.

Annual rainfall is less than 100 mm over parts of Ladakh (Jammu & Kashmir State) and Jaisalmer district (Rajasthan State) and less than 400 mm over central peninsula but it is between 1000 mm and 3207.8 mm (Dharamsala [Upper] station, Kangra District), between 1000 mm and 1788.4 mm (Bhanupratappur station, Bastar District) over central highlands and eastern plateau, between 1000 mm and 11405.8 mm (Mawsynram station, East Khasi Hills District) over northeast, and between 1000 mm and 7445.7 mm (Amboli station, Ratnagiri District) over Sahayadri range. The mean annual rainfall of the whole country is 1165.9 mm of which 0.7% occurs during winter, 9.0% during summer, 77.4% during monsoon and 12.9% during post-monsoon. Maximum temperature exceeds 50°C in extreme northwest India, 47.5°C over Indo-Gangetic plains and central highlands, 40°C over northeast, 45–47.5°C along east coast and 37.5–40°C along west coast. Lowest recorded minimum temperature is less than –2.5°C over Thar Desert, Punjab and Haryana and it increases to 17.5°C in the east, southeast and southwards. Annual potential evapotranspiration varies from about 1000 mm in the extreme northeast and western Himalaya to more than 2000 mm in the extreme northwest. C. Warren Thornthwaite's type climatic classification of the country can be done using mean annual rainfall alone as: less than 560 m m arid, 560–1040 mm semiarid, 1040–1420 mm dry subhumid, 1420–1630 mm moist subhumid, 1630–2450 mm humid and greater than 2450 mm perhumid (Singh, 1984 and Singh *et al.,* 1991 a). Twelve percent area of the country is arid, 37% semiarid, 28% dry subhumid, 9% moist subhumid, 9% humid and 5% perhumid. In other words, 77% area with annual rainfall less than 1420 mm is dry (evapotranspiration more than rainfall) and 33% with rainfall more than 1420 mm is wet (rainfall more than evapotranspiration).

Due to large variation in intensity and frequency of rain-inducing disturbances (western disturbances, thunderstorms, monsoon/cyclonic storms/depressions, monsoon troughs etc.) and summer monsoon and post monsoon circulations over different parts of the country rainfall occurrences exhibit large spatial variability. Hence areal representation of the area averaged rainfall series for the whole country is weak (Singh *et al.*, 1991 b). The National Atlas & Thematic Mapping Organization (NATMO, 1996) has published a map of India 'Drainage' on '*Conical Equal Area Projection with two Standard Parallels*' projection system and 1:6 M scale showing boundary of major and other basins (Figure 1). For the present report classification of the country's river systems into major and minor basins by K.L. Rao (1975) is adopted. Longest possible monthly, seasonal and annual rainfall series have been developed for 11 major basins, the West Coast Drainage System (WCDS) as well as the whole country.

In tropical monsoonal climate understanding basin-scale variability of wet (or rainy season) is as important as the variability of rainfall, very little attempt is made to study the former compared to later. Identification of wet season in the annual weather cycle is the crucial issue of the problem. Earlier attempts have been made to depicting the climatological summer monsoon (or rainy) season across the Asian monsoon region (Tao and Chen, 1987; Tanaka, 1992; Lau and Yang, 1997; Wang, 1994; Wang and LinHo, 2002 and many others). Ananthakrishnan and Soman (1988) however identified year-wise (1980) onset date of southwest monsoon over Kerala (India) by applying an objective criterion to raingauge observations and studied variation and distribution characteristics of the onset date. It is not known whether the criterion can be applied in reverse order to obtain the withdrawal date. Further, this information is limited to Kerala. Singh (1986) has

Fig. 1: Boundary of different river basins across the country. Dots denote location of 316 rain-gauge stations

applied an objective criterion '*continuous period with each of the monthly rainfall greater than 50 mm*' to obtain start and cessation dates of normal rainy (or wet) season at stations across India. The main objective of the present study is to apply this criterion to inter-annual area-averaged monthly rainfall data to document climatology and fluctuation characteristics of the parameters of wet season (starting date, ending date and duration) over different river basins of India using longest available instrumental observations.

RAINFALL DATA USED

Instrumental monthly rainfall records from a well spread network of 316 raingauges (Figure 1) from earliest available year up to 2005 is used in this study. For all the 316 stations data is available for the period 1901–2005. Prior to 1901 number of available stations from this network decreases back in time—for 314 raingauges the data extend back to 1900, for 312 back to 1871, for 196 back to 1870, for 101 back to 1861, for 80 back to 1860, for 70 back to 1851, for 60 back to 1846, for 57 back to 1844, for 13 back to 1842, for 6 back to 1829, for 4 (Chennai, Mumbai, Pune and Nagpur) back to 1826, for 2 (Chennai and Mumbai) back to 1817 and for sole station Chennai back to 1813. Missing observation in the continuous data sequence has been filled by the ratio method (Rainbird, 1967) using nearest available observation as reference value. Number of filled values is less than 2% of the total number of monthly rainfall records. Data upto 1900 is obtained from the India Meteorological Department (IMD) publication '*Monthly and Annual Rainfall of 457 Stations in India to the End of 1900*' (Eliot, 1902), and for the 1901–2005 period from the National Data Center and Hydrology Section of the IMD, Pune. An account of this dataset is described by Mooley and Parthasarathy (1984).

Blanford (1886) checked the reliability of data then available by applying two types of tests. First, he compared the averaged and variation of the earlier years at any given station with those of the last 10–12 years, during which much more care and attention had been given to rainfall registration. Second, he compared the variation in corresponding years and months between neighbouring stations situated under approximately similar conditions. Records which failed to satisfy either of the above tests were rejected. He concluded that selected data were 'free from any serious error'. In his attempt to compile and publish rainfall data for all the gauges over British India upto 1900 AD, Eliot (1902) also checked them thoroughly, but he did not mention the method employed. Regarding reliability of rainfall data of the Indian region, Walker (1910) had stated that 'long established observatories like Madras (Chennai), Bombay (Mumbai) and Calcutta (Kolkata) which have rainfall records available for earlier periods in the nineteenth century are trustworthy'.

THE METHODS—DEVELOPMENT OF LONGEST RAINFALL SEQUENCE

The instrumental period area-averaged rainfall series is prepared in two parts, (i) simple arithmetic mean for the period with all available observations from the selected network and (ii) construction by applying established objective method for the period with lesser available observations. The complete process is described step by step for the Indus basin. Rainfall observation in the Indus basin started in 1844. In 1845 number of gauges increased to 2 which continued up to 1951, increased to 3 in 1952, increased to 5 during 1853–54, decreased to 4 during 1855–56, increased to 6 in 1857, to 7 during 1858–59, to 8 during 1860–1861, to 9 during 1862–68, to 10 during 1860–70, to 16 during 1871–1900 and to 19 during 1901 and remained so since then. For creation of longest area-averaged annual rainfall series for the basin the computational steps are as (Singh, 1994; Sontakke and Singh, 1996; Wigley *et al.,* 1984),

1. Prepare the representative area-averaged annual rainfall series for the period 1901–2005 from simple arithmetic mean of observations from all the 19 raingauges in the basin; (As indicated annual rainfall data of only 16 raingauges from the 19-gauge network extends back to 1900, and the representative mean.)
2. Prepare the mean annual rainfall series of the 16 raingauges for the period 1901–2005;
3. Estimate the linear regression ($Y = a + bX$) of 19-gauge mean series $\{Yi\}$ on the 16-gauge mean series $\{Xi\}$ based on data of the period 1901–2000; (All constructions in this report have been done with respect to the '*reference period*' 1901–2000.)

   Theoretically derived mathematical expression for the correlation ($R_{m,M}$) between *M*-gauge mean rainfall series and m-gauge mean series (m is a subset of M) is given by (Wigley *et al.,* 1984),

$$R_{m,M} = \frac{1}{m\,s(m)} \sum_{i=1}^{m} s_i r_{i,M} \quad \ldots (1)$$

   In the present example M is 19 and m is 16; $s(m)$ is the standard deviation of the 16-gauge (here $m = 16$) mean series; s_i is the standard deviation of each of the 16 series; $r_{i,M}$ the correlation coefficient between each of the 16 gauge series and the *M*-gauge mean series. The correlation coefficient directly calculated between 10-gauge mean series (Y_i) and the 16-gauge mean series (X_i) was equal to the $r_{i,M}$.
4. Substitute the mean rainfall of 16 gauges available during 1900 in the regression and estimate the representative mean annual rainfall for the basin for the year 1900;
5. Inflate the variance of the estimated rainfall amount of the year 1900 by dividing its departure from long term mean by correlation coefficient (r) between 19-gauge mean series (1901–2000) and the corresponding 16-gauge mean series (Klein *et al.,* 1959), and get the constructed mean annual rainfall of the Indus basin for the year 1900;
6. Repeat the above process to estimate the rainfall of each of the four seasons (winter JF, summer MAM, monsoon JJAS and post-monsoon OND) for the year 1900;
7. Check if total of the estimated four seasonal rainfalls is equal to the estimated annual rainfall amount;
8. For any variation between the two figures proportionately increase/decrease the seasonal rainfall amounts to get their finally constructed amounts; and
9. Estimate the monthly rainfalls in a similar, compare them with corresponding constructed seasonal rainfall amount, and get the constructed monthly rainfalls after suitable correction for the year 1900.
10. Take up the year 1899 and repeat the above process sequentially.
11. Then take the year 1898, 1897 and so on till 1844.

Theoretical details of the construction method are given in Wigley *et al.* (1984). For pre—1901 period, the construction is retained if CC between all the gauges mean series and limited available gauges mean series based on the period 1901–2000 is significant at 5% level and above otherwise rejected. In the absence of anything this instrumental data might provide vital information. The rainfall series for the basin could be developed for the period 1844–2005. Similarly, longest rainfall series have been constructed for the other major basins.

DEFINITION OF THE WET SEASON

Annual weather cycle at stations across India can be divided into two periods, dry and wet. The wet period is also referred to as wet season, rainy season or wet period. Since the terminology 'rainy season' is generally used for summer monsoon season we will use the general term 'wet season' irrespective of the system brought the rainfall. Besides summer monsoon season during June through September, rainfall over northwestern India occurs due to western disturbances, over northeastern India due to thunderstorms during Mar–May, over extreme southwest due to thunderstorms in March–May and due to northeast monsoon during October-December, and over southeast mostly due to northeast monsoon. While some parts of the country experience reliable rainfall before and after the summer monsoon period, others experience rainfall during peak period of the summer monsoon season, July–August. There are large variations in the wet season (starting date, ending date and duration) across the country, and over the same place from one year to another. In an earlier study, the normal duration of wet season at a station is identified as the continuous period with monthly rainfall greater than 50 mm (Singh, 1986). Over southwest peninsula and the northeastern India the wet season starts around 28th March and northwestern India around 28th July. Over most parts of the country, the starting date progressively shifts between these two extremes. The wet season over the southwest peninsula and northeast India starts much before the onset of the southwest monsoon due to heavy and reliable rainfall activities associated with thunderstorms. The late start over northwestern part is because of lesser rainfall activities of the onset phase of the southwest monsoon over the region. Due to rain-shadow effect for the southwest monsoon, the extreme southeast peninsula gets reliable rainfall only during post-monsoon (or northeast monsoon) season and the date varies between 15th August and 10th October, from north to south. Being the area outside the monsoon regime, Jammu and Kashmir gets rainfall from extra tropical systems like western disturbances and trough in the westerlies. The season over the region starts between 20th December and the 1st week of January. The cessation date is especially more coherent, organized and progressively shifting from northwest to southeast. The extreme dates are 10th August for northwestern India and 10th January for southeastern peninsula. For Jammu and Kashmir, the cessation date is 10th May. Consequently there is large variation in the duration of the wet season over different parts of the country, about 20 days over northwestern India to exceeding 240 days over southwestern peninsula.

In the present study the criterion 'continuous period with each of the monthly rainfall greater than 50 mm' is applied to yearly monthly rainfall data of 11 major river basins, the west coast drainage system and the whole country. In the first month of the continuous period the starting date of the actual wet season is determined by linear interpolation up to which, from the beginning of the month, 50 mm rainfall is expected. And the ending date is determined in the last month of the period so that between the linearly-interpolated date and the end of the month 50 mm rainfall is expected to occur. Experiences suggest that occurrence probability of zero elements in the monthly rainfall sequence whose mean is greater than 50 mm is almost nil. So in the wet season one can expect some rainfall during every month. This report provides documentation of statistics, distribution and fluctuation of starting date, ending date and duration of the wet season over each of the river basins.

Limitation of the application of the criterion should be borne in mind. The criterion cannot be applied to interannual data of individual stations, particularly in arid and semiarid regions in which in large number of years monthly rainfall may not exceed the threshold of 50 mm. The criterion is however found applicable for area-averaged monthly rainfall data of different spatial units' viz. states, meteorological subdivisions, physiographic regions and hydrologic river basins.

FEATURES OF LONGEST ANNUAL RAINFALL SEQUENCE AND WET SEASON OF DIFFERENT BASINS

The basins are arranged from north to northwest to northeast to south. The West Coast Drainage System is given thereafter. In the end, description about the whole country longest rainfall series is given as general information. The annual Potential Evapotranspiration (PE) reported here is obtained from simple arithmetic mean of the stations in the particular basin. The normal monthly and annual PE at stations across India is given in Rao *et al.* (1971).

The Indus Major Basin (drainage area: 291,749 km^2; annual Potential Evapotranspiration (PE): 1390.4 mm; mean annual rainfall: 860.3 mm—winter 10.5%, summer 11.5%, monsoon 72.1% and post-monsoon 5.9% and annual rainy days: 41.6). The Indus rises in the Tibet near the Mansarovar Lake at an elevation of 5,180 m, passes through northern Kashmir and Gilgit, enters Pakistan and emerges out of the hills near Attock. The major tributaries are the Kabul, the Swat and the Kurram from the west and the Jhelum, the Chenab, the Ravi, the Beas and the Satluj from the east. Earliest rainfall record for Sirsa and Ferozepur is available from 1844. Data for all the 19 raingauge stations of the selected network is available from 1901 onwards. Monthly, seasonal and annual rainfall series for the period 1901–2005 have been prepared from simple arithmetic mean of rainfall of the 19 stations, and for the period 1844–1900 the different series have been constructed by applying the objective technique on lesser available observations discussed in the preceding section. Hence the rainfall sequence for the Indus River System is developed for the period 1844–2005. The major epochs in annual rainfall fluctuation are: 1844–1894 wet, 1895–1953 dry and 1954–2003 wet.

The time series plots of the wet season parameters are shown in Figure 2(a). The mean ($\pm 1\sigma$ days) of the parameters are: starting date—27 June (±11), ending date—9 Sept (±12) and the duration—75 days (±16). According to g-statistic test (Rao, 1967) the distribution of starting date and duration is normal while ending date suffers from mild kurtosis. The fluctuation of different parameters is homogeneous and random as suggested by Mann-Kendall rank test for randomness against trend (WMO, 1966). In fact, fluctuation of different parameters over all the basins under investigation is homogeneous and random. This may be noted and will not be repeated for individual cases any more. The wet seasons contribute 67% to the annual total.

The Ganga Major Basin (drainage area: 860,884 km^2; annual PE: 1455.1 mm; mean annual rainfall: 1083.5 mm—winter 3.2%, summer 6.0%, monsoon 84.9% and post-monsoon 5.9%; and annual rainy days: 52.2). The Ganga originates near the Gangotri glacier (Uttar Kashi district, Uttarakhand) at an elevation of 7,010 m. The river flows through 250 km in the rugged terrain of Himalaya before descending into the plains at Rishikesh. After traversing through Uttar Pradesh and Bihar the Ganga bifurcates into Bhagirathi and Padma in West Bengal. The Bhagirathi is known as Hoogly beyond Kalna and up to '*Mouths of Ganga*' in the Bay of Bengal. The Padma enters Bangladesh and joins Brahmaputra and later Meghna in the downstream. The river further flows as Meghna. It breaks into number of estuaries that pass through Sunderban to join the Bay of Bengal. The total length of the Ganga along the Hoogly is 2,525 km—1,450 km in Uttar Pradesh, 445 km in Bihar and 520 km in West Bengal. The important tributaries from north are Yamuna, Ramganga, Gomti, Ghaghara, Gandak and Kosi and from south Chambal, Ken, Betwa, Sind, Tons and Son. The Damodar joins the river in the last reaches along the Bhagirathi and the Hoogly. The drainage area of the Ganga system of rivers accounts 26.3% of India's geographical area. The drainage area is spread over the states of Uttar Pradesh, Uttarakhand, Himachal Pradesh, Punjab, Haryana, Rajasthan, Madhya Pradesh, Chhattisgarh, Bihar, Jharkhand and West Bengal and Union Territory of Delhi. Earliest rainfall record from Kolkata is available from 1829, Bankura was added in 1831, Darjeeling in 1837 and Patna in 1842. Data for 32 stations is available from 1844 and for all 131 stations of the selected network from 1889. The longest rainfall sequence for the basin could be developed for the period 1829–2005. The major epochs in the annual rainfall fluctuation are: 1829–1853 dry, 1854–1894 wet, 1895–1913 dry, 1914–1964 wet, 1965–1992 dry and 1993–2003 wet.

The time series plots of the wet season parameters are shown in Figure 2(b).The mean ($\pm 1\ \sigma$ days) of the parameters are: starting date—10 June (±9), ending date—28 Sept. (±11) and the duration—110 days (±15). The distribution of the parameters suffers from skewness. The wet season contributes 79% to the annual total.

The Brahmaputra Major Basin (drainage area: 186,773 km^2; annual PE: 1147.4 mm; mean annual rainfall: 2478.3 mm—winter 1.8%, summer 22.1%, monsoon 68.9% and post-monsoon 7.2%; and annual rainy days: 112.4) The Brahmaputra River rises at an elevation of 5,150 m in the Kailas range of the Himalayas. After flowing 1,700 km in the Himalayas it enters India across the Sadiya frontiers. It flows 720 km in Assam to enter Bangladesh. The main tributaries are the Ngangchu, the Dibang, the Luhit, the Subansiri, the Kameng, the Manas, the Buri Dihing, the Dhansiri, the Kopilli, the Tista, the Jaldhaka, the Torsa, the Kalyani and the Raidok. Earliest rainfall record is available from 1848 for 4 stations (Nowgong, Guwahati, Dibrugarh and Sibsagar). The data for all 11 stations of the selected network is available from 1871. The longest rainfall series could be developed for the period 1848–2005. The major epochs in annual rainfall fluctuation are: 1863–1901 dry, 1902–1958 wet, 1959–1982 dry and 1983–2003 wet.

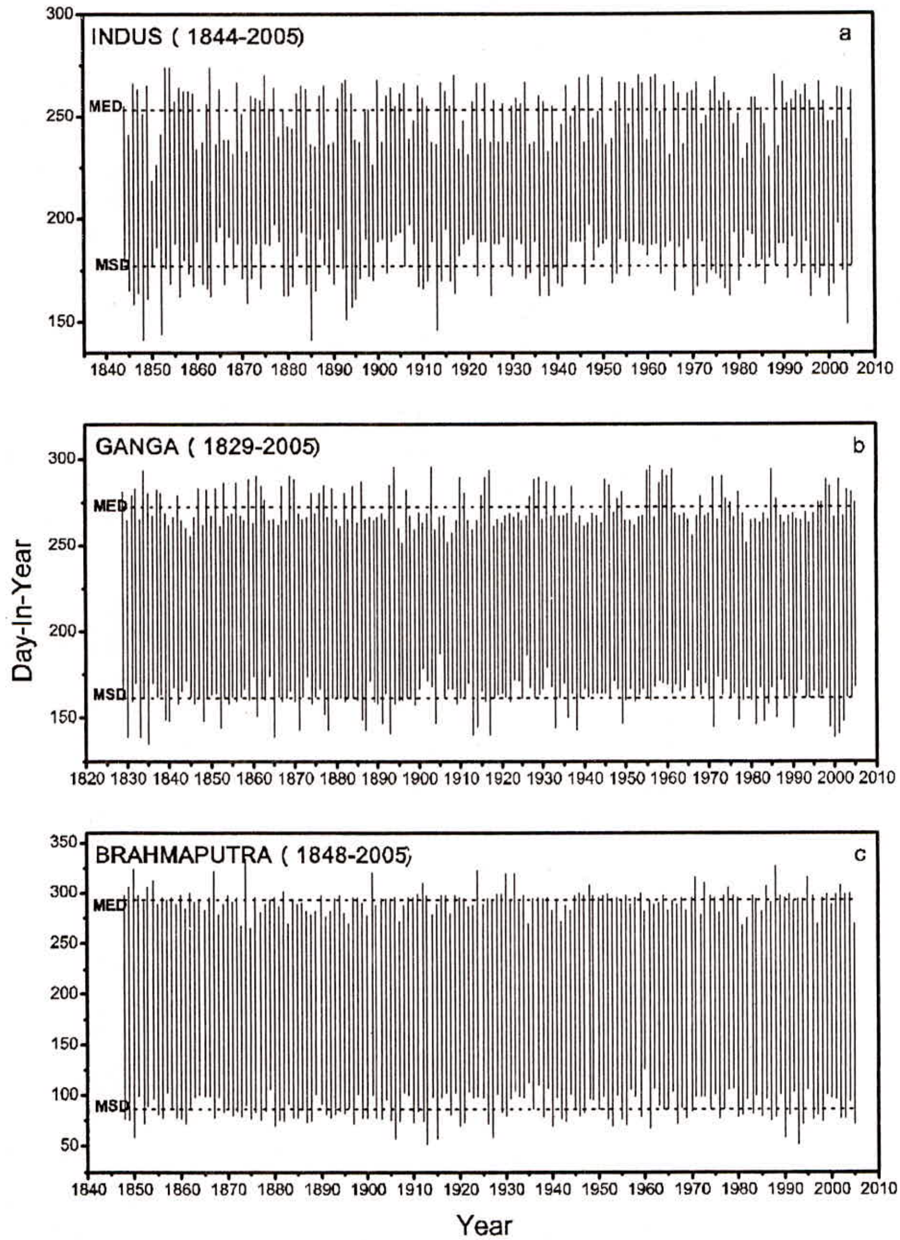

Fig. 2: Time series plots of the starting date, ending date and duration of the wet season over (a) Indus Major Basin; (b) Ganga Major Basin; and (c) Brahmaputra Major Basin

The time series plots of the wet season parameters are shown in Figure 2(c). The mean ($\pm 1\sigma$ days) of the parameters are: starting date—27 March (±15), ending date—20 October (±11) and the duration—207 days (±17). The distribution of starting date and duration is normal while ending date suffers from positive kurtosis. The wet season contributes 93% to the annual total.

The Godavari Major Basin (drainage area: 330,628 km^2; annual PE: 1609.7 mm; mean annual rainfall: 1068.3 mm—winter 2.1%, summer 4.7%, monsoon 84.4% and post-monsoon 8.8%; and annual rainy days: 57.1). The Godavari rises in the Nasik district (Maharashtra), flows for 1,465 km and falls into the Bay of Bengal. Its vast catchment area is spread over 5 states, the Maharashtra (48.6%), Madhya Pradesh (20.7%), Karnataka (1.4%), Orissa (5.5%) and Andhra Pradesh (23.8%). The important tributaries are the Wainganga, the Wardha, the Penganga, the Manjra and the Indravati. Earliest rainfall record from 1826 is available from Nagpur; Nasik and Seoni were included in 1844 and Amraoti in 1859. The data for all 22 raingauges of the selected network is available from 1871. The longest rainfall sequence for the basin could be developed for the period 1826–2005. The major

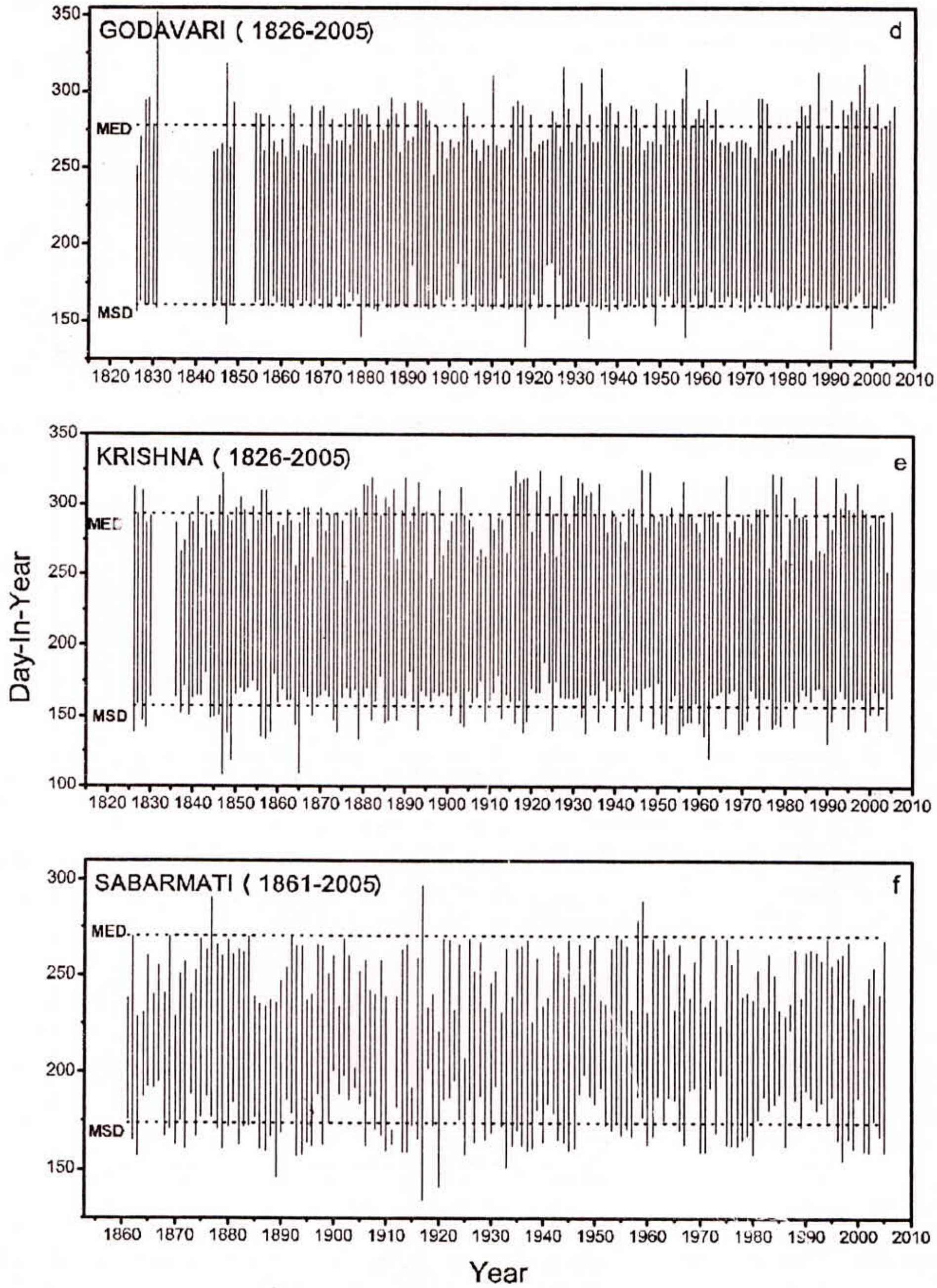

Fig. 2 contd: Time series plots of the starting date, ending date and duration of the wet season over (d) Godavari Major Basin; (e) Krishna Major Basin; and (f) Sabarmati Major Basin

epochs in annual rainfall fluctuation are: 1861–1895 wet, 1896–1930 dry, 1931–1963 wet and 1964–2003 dry.

The time series plots of the wet season parameters are shown in Figure 2(d). The mean (±1 σ days) of the parameters are: starting date—9 June (±13), ending date—4 October (±20) and the duration—117 days (±21). Distribution of starting date suffers from positive kurtosis while that of ending date and duration from positive skewness. The wet season contributes 79% to the annual total.

The Krishna Major Basin (drainage area: 295,650 km^2; annual PE: 1669.8 mm; mean annual rainfall: 825.7 mm—winter 1.2%, summer 9.5%, monsoon 70.4% and post-monsoon 18.9%; and annual rainy days: 50.9). The river rises at an elevation of 1,360 m from a water spring near Mahabalesh Warat. It flows 1,400 km to join the Bay of Bengal. The drainage area is spread over three states as Maharashtra 26.8%, Karnataka 43.8% and Andhra Pradesh 29.4%. The important tributaries are the Ghatprabha, the Bhima and the Tungabhadra. The earliest rainfall record for

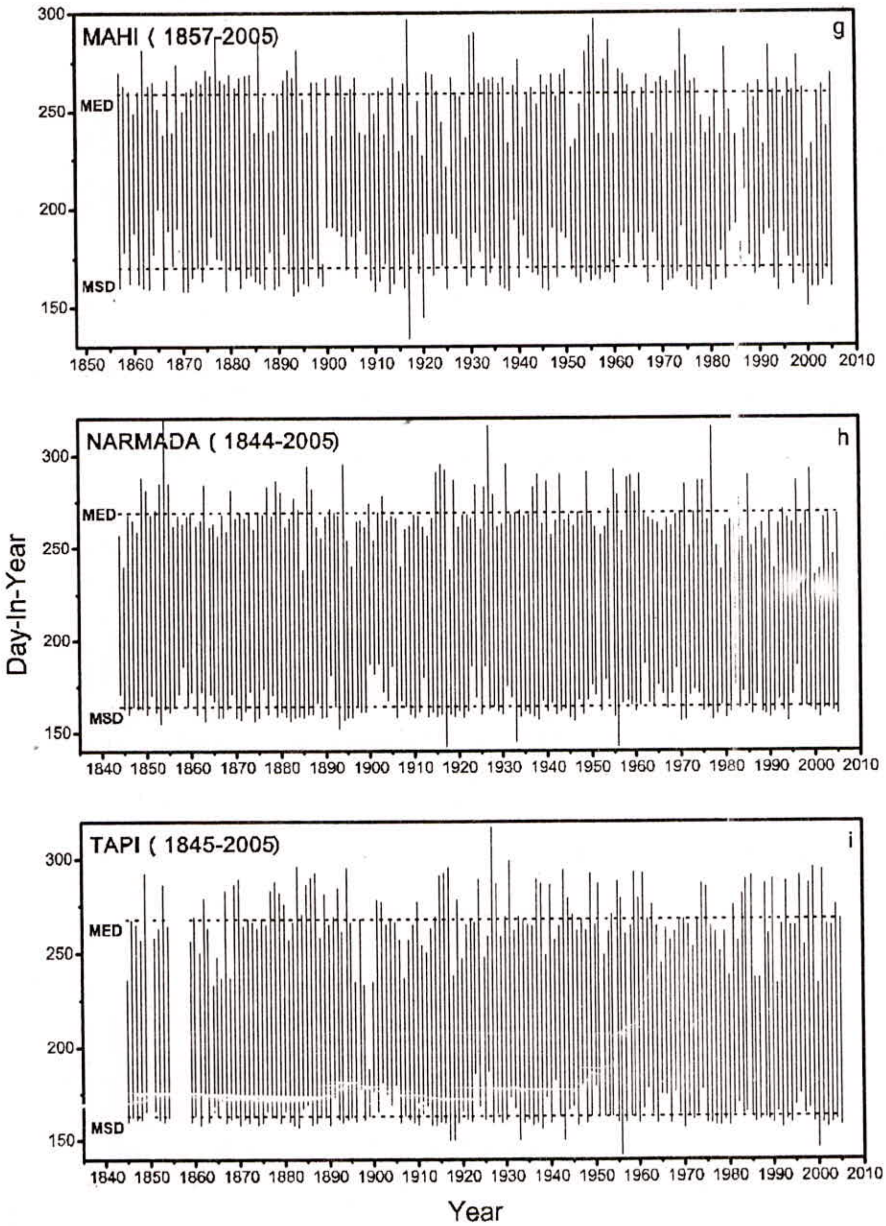

Fig. 2 contd: Time series plots of the starting date, ending date and duration of the wet season over (g) Mahi Major Basin; (h) Narmada Major Basin; and (i) Tapi Major Basin

Pune is available from 1826; Satara was added in 1836 and Shimoga in 1837. The data for 25 stations of the selected network is available from 1871. The longest rainfall sequence could be developed for the period 1836–2005. The major epochs in annual rainfall fluctuation are: 1836–1873 dry, 1874–1898 wet, 1899–1942 dry, 1943–1964 wet, 1965–1986 dry and 1987–2000 wet.

The time series plots of the wet season parameters are shown in Figure 2(e). The mean (±1 σ days) of the parameters are: starting date—5 June (±13), ending date—19 October (±17) and the duration—137 days (±23). The distribution of wet season parameters is normal. The wet season contributes 75% to the annual total.

The Sabarmati Major Basin (drainage area: 36,688 km^2; annual PE: 1676.8 mm; mean annual rainfall: 742.8 mm— winter 0.4%, summer 1.4%, monsoon 95.4% and post-monsoon 2.8%; and annual rainy days: 34.5). The river rises in the Aravalli hills and flows 300 km through the Rajasthan and the Gujarat states to join the Arabian Sea. The Sei, the Wakul, the Harnar, the Hathmati and the Watrak are the main tributaries. Earliest rainfall record for Ahmedabad is available from 1843; Kaira was included in 1861. The data for

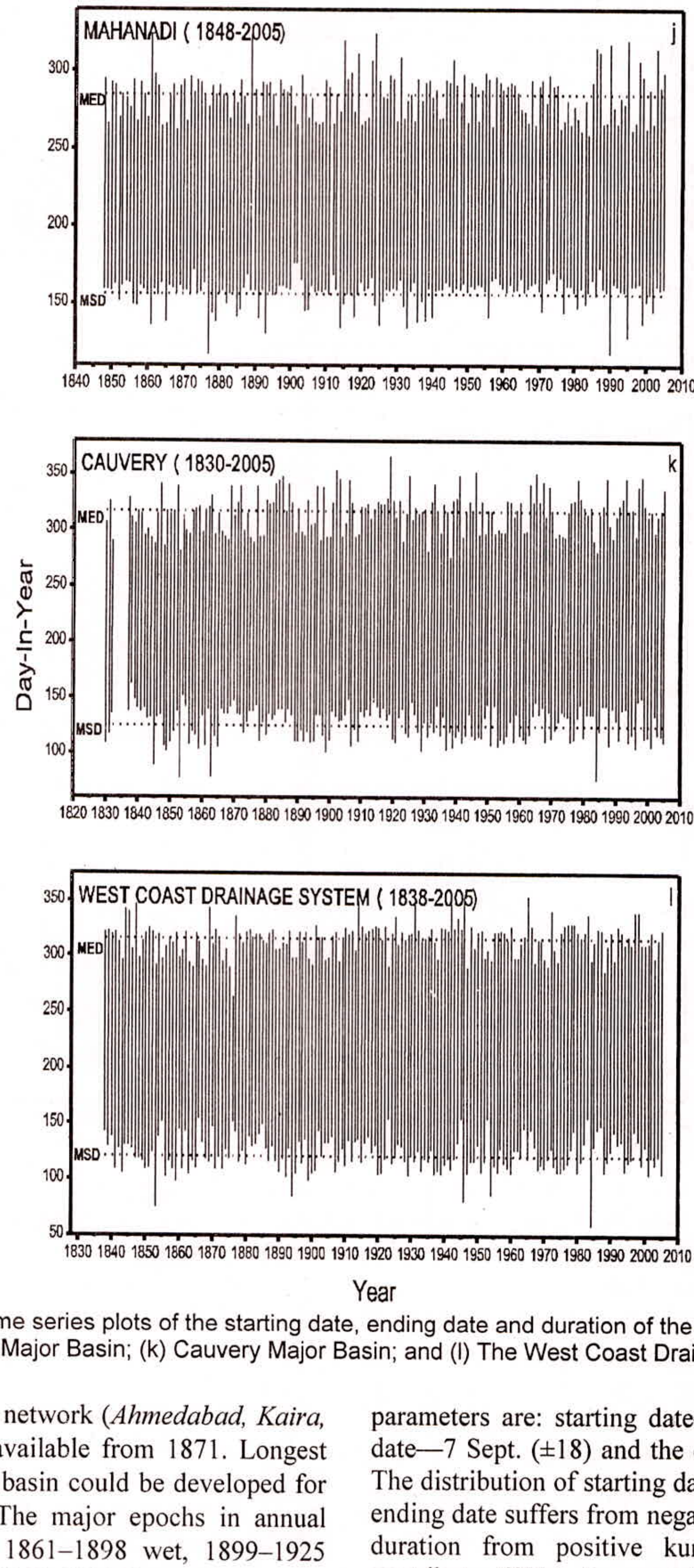

Fig. 2 contd: Time series plots of the starting date, ending date and duration of the wet season over (j) Mahanadi Major Basin; (k) Cauvery Major Basin; and (l) The West Coast Drainage System

4 stations of the selected network (*Ahmedabad, Kaira, Idar and Wadhwan*) is available from 1871. Longest rainfall sequence for the basin could be developed for the period 1861–2005. The major epochs in annual rainfall fluctuation are: 1861–1898 wet, 1899–1925 dry, 1926–1959 wet and 1960–2003 dry.

The time series plots of the wet season parameters are shown in Figure 2(f). The mean (±1 σ days) of the parameters are: starting date—22 June (±14), ending date—7 Sept. (±18) and the duration—77 days (±24). The distribution of starting date is normal while that of ending date suffers from negative skewness and that of duration from positive kurtosis. The wet season contributes 69% to the annual total.

The Mahi Major Basin (drainage area: 41,179 km^2; annual PE: 1653.4 mm; mean annual rainfall: 836.1

mm—winter 0.7%, summer 1.5%, monsoon 93.5% and post-monsoon 4.3%; and annual rainy days: 40.1). The river rises in the Vindhyas at an elevation of 500 m. It flows through the Madhya Pradesh, the Rajasthan and the Gujarat states a length of 533 km and falls eventually in the Arabian Sea. The Son, the Anas and the Panam are the main tributaries. Earliest rainfall record for Udaipur is available from 1857; Neemuch was included in 1860 and Baria in 1869. The data for all 8 raingauges of the selected network (*Udaipur, Neemuch, Baria, Pratapgarh, Dungarpur, Banswara, Jhabua and Baroda*) is available from 1871. The longest rainfall sequence for the basin could be developed for the period 1857–2005. The major epochs in annual rainfall fluctuation are: 1857–1898 wet, 1899–1940 dry, 1941–1963 wet and 1964–2003 dry.

The time series plots of the wet season parameters are shown in Figure 2(g). The mean (±1 σ days) of the parameters are: starting date—18 June (±12), ending date—14 Sept. (±17) and the duration—88 days (±21). The distribution of the different wet season parameters is normal. The wet season contributes 80% to the annual total.

The Narmada Major Basin (drainage area: 94,562 km^2; annual PE: 1466.7 mm; mean annual rainfall: 1107.3 mm—winter 2.3%, summer 2.2%, monsoon 90.1% and post-monsoon 5.4%; and annual rainy days: 54.1). The river rises at an elevation of 900 m near Amarkantak (Madhya Pradesh). It flows through the Madhya Pradesh, the Maharashtra and the Gujarat states for a length of 1,312 km before falling into the Arabian Sea. The Burhner is the major tributaries. Rainfall data from 1844 is available for 4 stations Mandla, Jabalpur, Narsinhapur and Hoshangabad. The data for all 8 raingauges of the selected network (*Mandla, Jabalpur, Narsimhapur, Hoshangabad, Broach, Khandwa, Raisen and Barwani*) is available from 1871 onwards. The longest rainfall sequence could be developed for the period 1844–2005. The major epochs in annual rainfall fluctuation are: 1844–1868 dry, 1869–1894 wet, 1895–1913 dry, 1914–1949 wet and 1950–2003 dry.

The time series plots of the wet season parameters are shown in Figure 2(h). The mean (±1 σ days) of the parameters are: starting date—12 June (±9), ending date—24 Sept (±14) and the duration—104 days (±17). The distribution of starting date is significantly different from normal however that of ending date and duration is normal. The wet season contributes 83% to the annual total.

The Tapi Major Basin (drainage area: 65,041 km^2; annual PE: 1665.3 mm; mean annual rainfall: 894.4 mm—winter 1.8%, summer 2.7%, monsoon 87.4% and post-monsoon 8.1%; and annual rainy days: 48.6). The river rises near Multai (Betul district, Madhya Pradesh) at an elevation of 730 m. It flows 724 km through the Madhya Pradesh, the Maharashtra and the Gujarat states before falling into the Arabian Sea. The Purna, the Vaghur, the Girna, the Bori, the Panjhra and the Aner are the important tributaries. Earliest rainfall record is available from 1844 for Betul; Amraoti and Buldhana were included in 1861. The data for all 7 raingauges of the selected network (*Betul, Amraoti, Buldhana, Dhulia, Akola, Surat and Jalgaon*) is available from 1871. The longest rainfall sequence for the basin could be developed for the period 1844–2005. The major epochs in annual rainfall fluctuation are: 1859–1881 dry, 1882–1894 wet, 1895–1930 dry, 1931–1964 wet and 1965–2003 dry.

The time series plots of the wet season parameters are shown in Figure 2(i). The mean (±1 σ days) of the parameters are: starting date—11 June (±8), ending date—25 Sept. (±18) and the duration—106 days (±16). The distribution of starting date is significantly different from normal however that of ending date and duration is normal. The wet season contributes 80% to the annual total.

The Mahanadi Major Basin (drainage area: 145,040 km^2; annual PE: 1519.4 mm; mean annual rainfall: 1410.4 mm—winter 2.6%, summer 5.5%, monsoon 84.0% and post-monsoon 7.9%; and annual rainy days: 70.2). The river originates from a pond near a village called 'Pharsiya' (Raipur district, Jharkhand). It flows for 587 km and beaks into two branches, the Katjuri and the Birupa, that fall into the Bay of Bengal. Its drainage area is spread over the Jharkhand, the Orissa, the Bihar and the Maharashtra states. Earliest rainfall record from 1848 is available for Puri; Sambalpur was included in 1861. The data for all 11 raingauge stations of the selected network (*Puri, Sambalpur, Bilaspur, raipur, Cuttack, Raigarh, Rajgangapur, Bolangir, Phulbani, Bhawanipatna and Durg*) is available from 1871. The longest rainfall sequence for the basin could be developed for the period 1848–2005. The major epochs in annual rainfall fluctuation are: 1848–1878 dry, 1879–1961 wet and 1962–2003 dry.

The time series plots of the wet season parameters are shown in Figure 2(j). The mean (±1 σ days) of the parameters are: starting date—4 June (±10), ending date—10 October (±16) and the duration—128 days (±20). The distribution of ending date is normal while that of starting date and duration is significantly different from normal. The wet season contributes 84% to the annual total.

The Cauvery Major Basin (drainage area: 91,691 km^2; annual PE: 1499.1 mm; mean annual rainfall:

1265.5 mm—winter 1.4%, summer 13.8%, monsoon 60.6% and post-monsoon 24.2%; and annual rainy days: 64.3). The Cauvery rises at an elevation of 1,340 sq. km in the Brahmagiri range of the Western Ghats in the Coorg District of Karnataka. It flows 800 km and joins the Bay of Bengal at Kaveripatnam. State-wise drainage area of the basin is distributed as 3.3% in Kerala, 41.2% in Karnataka and 55.5% in Tamil Nadu. The Cauvery splits into two branches, the Cauvery and the Vennar, which feed the Tanjore delta. The important tributaries are the Harangi, the Hemavati, the Shimsha, the Arkavati, the Lakshmanatirtha, the Kabini and the Suvarnavati in Karnataka and the Bhavani, the Noyli and the Amaravati in Tamil Nadu. Earliest rainfall record from 1829 is available for Ootacamund; Tumkur and Mysore were included in 1837. The data for all 13 stations of the selected network (*Ootacamund, Tumkur, Mysore, Tiruchirapalli, Salem, Coimbataore, Bangalore, Tanjavore, Chikmagalur, Hassan, Mandya, Mercara and Dharampur*) is available from 1871. Longest reliable rainfall sequence for the basin could be prepared for the period 1837–2005. The major epochs in annual rainfall fluctuation are: 1837–1928 dry and 1929–1964 wet, 1965–1990 dry and 1991–2000 wet.

The time series plots of the wet season parameters are shown in Figure 2(k). The mean (±1 σ days) of the parameters are: starting date—4 May (±13), ending date—14 November (±20) and the duration—194 days (±21). The distribution of ending date and duration is normal while that of starting date suffers from negative kurtosis. The wet season contributes 86% to the annual total.

The West Coast Drainage System (drainage area: 117,962 km^2; annual PE: 1564.3 mm; mean annual rainfall: 2528.5 mm—winter 0.7%, summer 9.0%, monsoon 77.4% and post-monsoon 12.9%; and annual rainy days: 102.2)– Twenty five small rivers originate in the Sahayadri Range and flow into the Arabian Sea. On any small size map it's difficult to delineate the catchment's area of different rivers. The combined area of all the catchments of the Sahayadri is referred to as the West Coast Drainage System (WCDS). Earliest record of Mumbai station in the drainage system is available from 1817; Tiruvanthapuram was included in 1838 and Cochin 1842. The data for all 21 raingauges of the selected network (*Mumbai, Trivandrum, Fort Cochin, Thana, Ratnagiri, Mangalore, Cannanore, Kozhokode, Goa, Karwar, Surat, Palghat, Ahwa, Bulsar, Alibag, Ponnani, Trichur, Kottayam, Haripad, Punalur and Nagarcoil*) is available from 1871. The longest monsoon rainfall series for the WCDS could be developed for the period 1838–2005. The major epochs in annual rainfall fluctuation are: 1838–1911 dry, 1912–1964 wet and 1965–2003 dry.

The time series plots of the wet season parameters are shown in Figure 2(l). The mean (±1 σ days) of the parameters are: starting date—29 April (±16), ending date—12 November (±15) and the duration—197 days (±20). The distribution of ending date is normal whereas that of starting date and duration significantly different from normal. The wet season contributes 93% to the annual total.

The Whole India (geographical area: 3,188,111 km^2; annual PE: 1519.4mm; mean annual rainfall: 1165.9 mm—winter 2.7%, summer 8.7%, monsoon 77.8% and post-monsoon 10.8%; annual rainy days: 57.4). As general information longest monthly, seasonal and annual rainfall series have also been prepared for the whole country. Details of the available rainfall data of 316 stations are given in '*Rainfall Data Used*'. The longest rainfall series for the whole country could be developed for the period 1813–2005. The major epochs in annual rainfall fluctuation are: 1813–1863 dry, 1864–1894 wet, 1895–1941 dry, 1942–1964 wet, 1965–1992 dry, 1993–1999 wet and 2000–2004 dry.

The time series plots of the wet season parameters are shown in Figure 3. The mean (±1 σ days) of the parameters are: starting date—29 May (±11), ending date—12 October (±13) and the duration—136 days (±18). The distribution of ending date and duration is normal whereas that of starting date suffers from significant negative skewness. The wet season contributes 79% to the annual total.

CORRELATION BETWEEN PAIR OF PARAMETERS OF THE WET SEASON

The product-moment Correlation Coefficient (CC) between pair of parameters of the wet season (starting date, ending date, duration and seasonal rainfall) for different basins and the whole country is given in Table 1. In general, the starting date is highly correlated with the duration with is highly correlated with ending date and the rainfall amount. But the starting date is weakly correlated with the ending date. It may be noted that results of application of this statistical relationship can be realized after trial of large number of years rather than on year to year basis. Generally, the correlation between the ending date and the duration is the highest and that between starting date and ending date lowest.

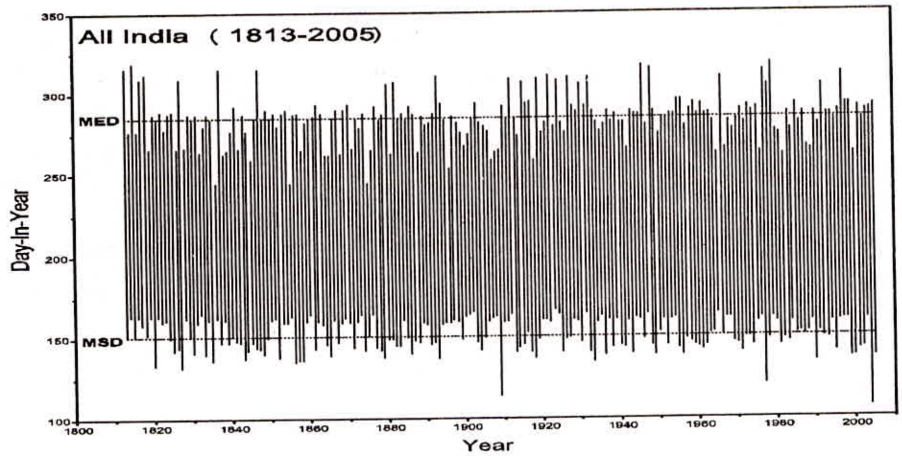

Fig. 3: Time series plots of the starting date, ending date and duration of the wet season over the whole country

Table 1: Correlation Between Pair of Parameters of the Wet Season over 11 Major Basins, The West Coast Drainage System (WCDS) and the Whole Country (Data period: 1901–2005). Bold Figures Are Significance at 1% Level and Above

Basins	*Start vs End*	*Start vs Duration*	*Start vs Rainfall*	*End vs Duration*	*End vs Rainfall*	*Durtion vs Rainfall*
Indus	0.06	**–0.65**	**–0.31**	**0.72**	**0.66**	**0.71**
Ganga	–0.09	**–0.69**	**–0.45**	**0.78**	**0.58**	**0.70**
Brahamputra	0.10	**–0.78**	**–0.35**	**0.55**	**0.32**	**0.50**
Godavari	–0.12	**–0.53**	**–0.44**	**0.90**	**0.53**	**0.64**
Krishna	–0.22	**–0.70**	**–0.31**	**0.85**	**0.44**	**0.49**
Sabarmati	–0.05	**–0.62**	**–0.28**	**0.82**	**0.50**	**0.55**
Mahi	–0.02	**–0.60**	**–0.35**	**0.81**	**0.58**	**0.67**
Narmada	–0.06	**–0.54**	**–0.34**	**0.88**	**0.59**	**0.67**
Tapi	–0.03	**–0.45**	–0.21	**0.91**	**0.56**	**0.59**
Mahanadi	–0.17	**–0.63**	**–0.43**	**0.88**	**0.43**	**0.55**
Cauvery	**0.29**	**–0.46**	–0.23	**0.72**	**0.32**	**0.47**
WCDS	0.11	**–0.71**	**–0.26**	**0.62**	0.12	**0.29**
India	–0.10	**–0.45**	–0.21	**0.91**	**0.56**	**0.59**

SUMMARY AND CONCLUSION

The present report documents the data, display and description of statistical and fluctuation characteristics of the parameters of the wet season over different basins of India. The chief features of the characteristics are:

1. Annual rainfall fluctuation over the different major basins, the west coast drainage system and the whole country is characterised by aperiodic oscillation. A documentation of the dry and wet epochs is provided in the text.
2. Excluding south peninsula, northeast and extreme northern India, over remaining parts of the country starting and ending dates of the wet season are in close agreement with onset and withdrawal dates, respectively, of the summer monsoon (IMD, 1943).
3. Average standard deviation of the wet season across the country is ±16 days that of ending date ±17 days and that of duration ±23 days.
4. For majority of river basins probability distribution of starting date, ending date and duration of the wet season is near-normal. However, it would be interesting to know the unified probability distribution function for frequency analysis of these parameters across the country which can be taken up as separate study.
5. There is no significant long term trend in the parameters of the wet season for any of the major basins. But each one of them displayed domination of inter-decadal fluctuation characterized by short term rising and declining trends.
6. The starting date is highly correlated with the duration and the rainfall amount for different basins and the whole country. Generally, the correlation between the starting date and the duration is the highest. But the starting date and the ending date is weakly correlated.
7. On an average the wet season contributes about 81% rainfall to the annual total across the major basins.

Fluctuation characteristics of the wet season and rainfall over different basins based on longest available instrumental observations documented in this report are expected to provide vital information to water resource managers including those working for '*interlinking of rivers*' program of the country. Further, research in this area could be to refine this start and cessation dates of the wet season using shorter period rainfall data such as daily, pentad or weekly. Of course, the shorter period rainfall data is available only from 1901 onwards.

ACKNOWLEDGEMENTS

The authors are extremely grateful to Prof. B.N. Goswami, Director, Indian Institute of Tropical Meteorology, Pune for necessary facilities to pursue this study. The rainfall data used in this study is provided by the India Meteorological Department, Pune which is thankfully acknowledged.

REFERENCES

Ananthakrishnan, R. and Soman, M.K. (1988). "The onset of the southwest monsoon over Kerala: 1901–1980". *J. Climatol.*, 8, 283–296.

Blanford, H.F. (1886). *Rainfall of India.* India Meteorological Memoirs, Vol. 81, Vol. III, pp. 658.

Elliot, J. (1902). *Monthly and annual rainfall of 457 stations in India to the end of 1900.* India Meteorological Department Memoirs, Vol. XIV, pp. 709.

India Meteorological Department (IMD) (1943). *Climatological Atlas for Airmen.3.* India Meteorological Department, New Delhi.

Klein, W.H., Lewis, B.M., and Enger, I. (1959). "Objective prediction of five-day mean temperatures during winter". *J. Meteor.*, 16(6), 672–682.

Lau , K.-M. and Yang, S. (1997). "Climatology and interannual variability of the southeast Asian summer monsoon". *Adv. Atmos. Sci.*, 14, 141–162.

Mooley, D.A. and Parthasarathy, B. (1984). "Fluctuations in all-India summer monsoon rainfall during 1871–1978". *Climatic Change*, 6, 287–301.

NATMO (1996). *Land Resource Atlas: Drainage*, Plate No. 3.

Rainbird, A.F. (1967). *Methods of Estimating Areal Average Precipitation.* WMO/IHD Report No. 3, WMO, Geneva, pp. 42.

Rao, C.R. (1952). *Advanced Statistical Methods in Biometric Research.* New York, John Wiley & Sons, p. 210.

Rao, K.L. (1975). *India's Water Wealth—Its Assessment, Uses and Projections.* Orient Longman Limited, New Delhi, pp. 255.

Rao, K. N., George, C.J. and Ramasastri, K. S. (1971). *Potential evapotranspiration (PE) over India.* Pre-published Sci. Rep. No. 136, Meteorological Office, Poona

Singh, N. (1984). "Fluctuations of different moisture regimes in India". *Arch. Met. Geophys. Biocl.*, B35, 239–256

Singh, N. (1986). "On the duration of the rainy season over different parts of India". *Theor. Appl. Climatol.*, 37, 51–62.

Singh, N. (1994). "Optimizing a network of stations over India to monitor summer monsoon rainfall variation". *Int. J. Climatol.*, 14, 61–70.

Singh, N. and Sontakke, N.A. (2002). "On climatic Fluctuations and environmental changes of the Indo-gangetic Plains, India". *Climatic Change*, 52, 287–313.

Singh, N., Pant, G.B. and Mulye, S.S. (1991a). "Distribution and long term features of spatial variation of the moisture regions over India". *Int. J. Climatol.*, 11, 4, 413–427.

Singh, N., Pant, G.B. and Mulye, S.S. (1991b). "A statistical package for constructing representative area-averagedrainfall series and its updating using selected stations data". *Proc. Natn. Semi. Use of Computers in Hydrology and Water Resources*, 16–18 Dec. 1991, Indian Institute of Technology Delhi, Vol. II, pp. 122–134.

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

Tanaka, M. (1992). "Intraseasonal oscillation and the onset and retreat dates of the summer monsoon over the east, southeast and western north Pacific region using GMS high cloud amount data". *J. Meteor. Soc. Japan*, 70, 613–629.

Tao, S. and Chen, L. (1987). "A review of recent research on the East Asian summer monsoon in China". *Monsoon Meteorology*, C.-P. Chang and T.N. Krishnamurti, Eds., Oxford University Press, 60–92.

Walker, G.T. (1910). "On the meteorological evidence for supposed changes of climate in India". *Indian Meteorological Memoirs*, 21, Part I, pp. 1–21.

Wang, B. (1994). "Climatic regimes of tropical convection and rainfall". *J. Climate*, 7, 7, 1109–1118.

Wang, B. and LinHo (2002). "Rainy season of the Asian-Pacific summer monsoon". *J. Climate*, 15, 2, 386–398.

Wigley, T.M.L., Briffa, K.R. and Jones, P.D. (1984). "On the average value of correlated time series, with application in dendroclimatology and hydrometeorology". *J. Climat Appl. Meteorol.*, 23:202–213.

W.M.O. (1966). *Climaric Change.* World Meteorological Organization Technical Note No. 79, WMO No. 195–TP–100, Geneva, p. 79.