Climatic Changes in Basin-scale Monsoon Rainfall in Relation to 3-D Global Atmospheric Thermal Changes

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Abstract:

Changes in rainfall fields across India in association with monsoon circulation are mostly governed by the tropospheric temperature changes across the globe. The climatological and fluctuation features of the annual and seasonal rainfall of 11 major basins, 9 independent minor basins, west coast drainage system (WCDS) and for the whole country are studied using longest instrumental area-averaged basin-scale monthly rainfall series reconstructed back up to 1813. Distinct epochs can be identified in categorized (very dry, moderately dry, normal, moderately wet and very wet) monsoon rainfall series of all basins as well All India. Significant Short-term tendencies (15-year), medium-term fluctuations (31-year), long-term trend (51-year), and secular trend (101-year) in rainfall time series of each river basins are also studied using Cramer's t_k statistics. Inter-annual variations and recent year changes in the 3-D global thermal field during 1949-2015 monsoon over 11 climatic zones of the globe are studied using Climate Forecast System reanalysis (CFSR) dataset.

Results show that normal (1901-2000) monsoon rainfall of the river basins across the country varies from 255.3mm (Vaigai) to 1957mm (WCDS). A significant increasing trend is noticed in recent 101 years (1915-2015) in monsoon rainfall over Krishna major (2.7%), Tapi (3.6%), WCDS (2.3%) and the whole country (1.4%) compare to preceding instrumental period. Brahmaputra major, Mahi, Mahanadi, Brahmani, Pallar, and Ponnaiyar showed a non-significant decreasing trend. In recent 15 years (2001-2015), monsoon rainfall over Ganga major is decreased significantly by -7.4%, Brahmaputra major -10.5% and Cauvery -19.8% relative to entire available instrumental records. Compare to 20th century (1901-2000) monsoon rainfall over basins in northeast India, central northeast India, northwest India, and south peninsular India has been lesser while that over central northwest India, north peninsular India and north India is higher in recent 15 years (2001-2015). For the whole country, the period 1998-2015 was drier by 5.4% compared to the preceding wet period of 1988-1998.

Consistent global warming trend is noticed in the column-area mean monthly temperature of the troposphere (1000-250hPa) of the globe, northern hemisphere, southern hemisphere and nine climatic zones across the globe during 1979-2018. The trend is statistically significant on global, hemispheric and zonal scale except south pole and south midlatitude. In general, rate of rising trend increases from south polar towards north polar. Since 1979, tropospheric temperature has been increased by 0.29°C/decade over the globe. NH is warming at a faster rate (0.30°C/decade) than SH (0.20°C/decade). The highest rate of increase is noticed over the NP (0.37° C/decade) while lowest is observed over the SP (0.05°C/decade). In recent 10 years, the TT of the globe has been increased by 0.50°C, NH (0.57°C) and SH (0.43°C). Across the nine climatic zones, the increase in TT varies from 0.83°C for the NP to 0.11°C for the SP. Rise in the global tropospheric temperature over the northern hemisphere, escalate the asymmetry in the inter-hemispheric temperature contrasts over most of the climatic zones. It may lead to westward shift in the monsoon circulation and enhanced monsoon activities over northern and northwestern India and subdued over rest parts of the county.

Keywords: *Global temperature change, Basin rainfall trend, Climatic zones, Tropospheric temperature change*

I. INTRODUCTION

Over the last few decades, heterogeneity in global temperatures throughout the atmosphere have been observed to make spatiotemporal changes in global rainfall characteristics. Potential climate change and its impacts on rainfall distribution pose a threat to water resources throughout the world. Recent understanding through global climate models predicts that, the hydrological cycle will accelerate as climate warms, and leads to changes in patterns of extreme floods and droughts. After general acceptance of global warming a reality, numerous studies have been undertaken to generate information useful for the assessment of hydro-meteorological disasters in order to comprehend the impact of climate change on water resources in different parts of the world as well as to respond to important issues raised by world scientific community. The Intergovernmental Panel on Climate Change (IPCC, 2007) reported that 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 of the globe. As per IPCC report, by the middle of the twenty-first century, annual average river runoff and water availability would 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. There could be increase in heavy precipitation events in terms of frequency and intensity in some parts of the world, while the drought affected areas also likely to be increased in other parts. According to special report of IPCC (2018) titled '*Global warming of 1.5°C'*, human activities are responsible for the 1°C of global warming. The report also concluded that, the additional 0.5°C warming could be avoided by drastically reducing greenhouse gas emissions in next 10 years.

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. Earlier we have studied climatological and fluctuation features of parameters of the hydrological wet season in 11 major and 36 minor river basins in India. We did not find any significant long-term trends in wet season parameters for any basin, but noticed a declining tendency in wet season rainfall in some major basins of the Central India (Ranade et.al. 2008). Extreme monsoon rains cause severe flooding and disasters across India every year in some parts or other, surprisingly even during large-scale drought years also. there is a wide spread belief that, in recent global warming period, due to intensification of hydrological cycle, extreme rain events are increasing (Senior et al. 2002; IPCC 2007, Goswami et al. 2006; Rajeevan et al. 2008; Guhathakurta 2011; Ranade and Singh 2014). Our earlier studies show that, small-scale, short duration extremes are embedded in the large-scale, long period heavy rain spells (Singh and Ranade 2010). We have studied variations in spatio-temporal extreme rainfall fields over the Indian region. It is shown that small-scale, short-duration EREs are embedded in large-scale, long-period intense wet spells, and rainwater generated during the main monsoon wet period is highly correlated with the Asia-Pacific monsoon intensity (Ranade and Singh 2014).

Changes in rainfall fields across the globe in association with global/monsoonal/regional circulation are observed to be governed by the global tropospheric temperature changes. Locations of warming and cooling across the globe are the determinant of the plausible locations for the origin of various type of weather systems. Few case studies of extreme rain events carried out by us revels that, abrupt warming and cooling in the atmosphere drastically modulates the monsoon circulation and intensify the associated weather systems causing heavier rains over a region. Persistence in temperature and circulation anomalies across the globe are strongly linked to the occurrences of severe rain events over a wide-ranging scale from small-scale short-period heavy rain events to large-scale long-period extreme wet spells. Types of weather systems and general and monsoonal circulation associated with the occurrence of extreme rain events in different parts of the country could be different. There is pressing need to understand the climatic changes in 3-D structure of global temperature. Jones et.al. (1982) studied the surface air temperature variations over monthly, seasonal and annual scale and concluded the beginning of warming from late 1970s over northern hemisphere. Kelly et.al. (1982) did the same work for Arctic region. Keeping in mind recent changes in global atmospheric parameters, monsoon circulation pattern, occurrence of EREs and their linkages with the global thermal structure, we have studied the rainfall variability in annual and seasonal rainfall of 11 major basins and 9 independent minor basins with following objectives.

1. Study of short-term tendencies, medium-term fluctuations and long-term trends in annual, seasonal and monthly rainfall of 11 major and 9 independent minor river basins.
2. To investigate 3D changes in global tropospheric thermal structure on global, hemispheric, zonal scales;

II. DATASET AND STUDY AREA

The longest instrumental area-averaged monthly rainfall series for 11 major river basins and 9 independent minor river basins earliest available from 1813 to 2000 (Sontakke and Singh, 1996) are used in this study. Classification of the country's river systems into major and minor basins by K. L. Rao (1975) has adopted for the above. The 11 major basins with the no. of available rain gauges since 1901 are- the Indus (19), the Ganga (131), the Brahmaputra (11), the Godavari (22), the Krishna (25), the Sabarmati (4), the Mahi (8), the Narmada (8), the Tapi (7), the Mahanadi (11), the Cauvery (13), the WCDS (21). The other nine minor basins are Luni, Surma, Kasai, Damodar, Suvarnarekha, Brahmani, Penner, Palar & Ponnaiyar and Vaigai.

The global 6-hourly reanalysis product of the atmospheric temperature at 12 standard vertical isobaric levels (1000-100hPa) available at 2.5º grid resolution from 1979 to 2018 from 'The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR & CFSv2) (Saha et al. 2010, 2014) are used for global temperature changes studies. The Mean of four 6-hourly observations in a day is calculated to obtain calendar date values for each year. Tropospheric mean temperature (TT) are calculated by considering troposphere level at 250hPa. Observations show that temperature up to this height is always lower than that of the equator throughout the year.

III. RESULTS AND DISCUSSION

Longest instrumental area averaged basin-scale monthly rainfall dataset of 11 major basins, 9 minor basins, west coast drainage system and for the whole country available from 1813 to 2000 has been updated from 2001 to 2015 using one degree gridded rainfall data. The starting year of the dataset varies from one basin to another. For the major basins the starting years are: *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; The West coast drainage system 1817; and All India 1813*. For independent minor basins the start is: *Luni* 1856; *Surma* 1848; *Kasai* 1831; *Damodar* 1829; *Subarnarekha* 1848; *Brahmani* 1871; *Penner* 1813; *Palar* & *Ponnaiyar* 1853; *Vagai* 1846 and The *West Coast Drainage System (WCDS)* 1817. Longest possible monthly rainfall series earliest from 1813 to 2015 were developed in three different phases. In the first phase, for the period 1901 to 2000, simple arithmetic mean of all available gauges in the basin from fixed well spread instrumental network of 316 rain gauge stations were used. In second phase the dataset was extended backward from 1900 to 1813 by applying theoretically vindicated numerical method on limited available observations (Sontakke and Singh, 1996). In the third phase, the dataset was updated by using 1-deg gridded daily rainfall with the ratio method suggested by Rainbird (1967) and approved by WMO. In the first two phases, station datasets were used for the construction, while in third phase, each station value has been extracted from the corresponding value of the grid from the gridded rainfall dataset.

1. Chief statistical features of seasonal rainfall

Area-averaged monthly, seasonal (Jan-Feb, March-April-May, June-July-Aug-Sept and Oct-Nov-Dec) and annual rainfall series for all basins, WCDS and All India have been developed and analyzed. Normally the mean annual rainfall of all major river basins varies from 742.8mm over Sabarmati to 2478.3mm over Brahmaputra. The WCDS gets 2528.5 mm annual rainfall in normal year. The coefficient of variation of the annual rainfall varies from 9.6% (Brahmaputra) to 36.2% (Sabarmati). The year-wise highest rainfall normally varied between 1116.4 mm (Krishna) and 3161.6mm (Brahmaputra), while that of lowest from 248.9mm (Sabarmati) to 1979.2mm (Brahmaputra). For the country as whole, All India gets 1165.9mm rainfall annually with the highest rainfall as high as 1435.3mm and as low as 895.7mm. For independent minor basins, the mean annual rainfall varies form 487.7mm over luni to 2519.5mm over Surma. The coefficient of variation varies from 12.1%(Surma) to 37.4% (Luni). The year-wise highest annual rainfall was for Surma (3352.5mm) and the lowest for Luni 9167.5mm).

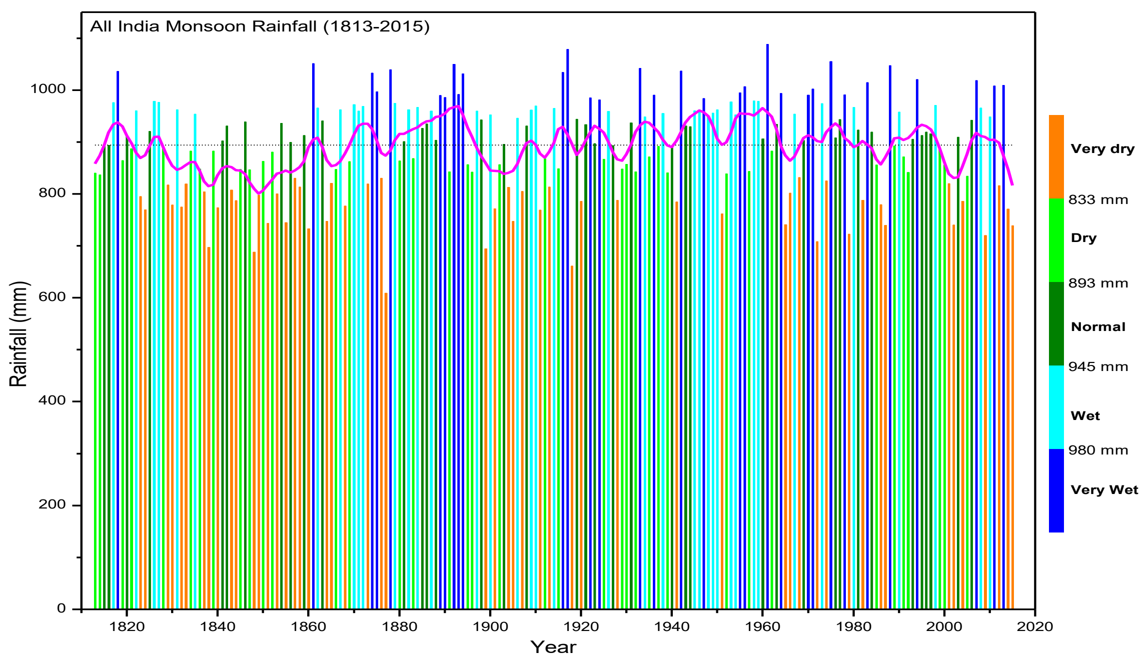

Fig.1 Interannual variations in categorized rainfall distribution from 1813-2015

Inter-annual variations in annual, seasonal and monthly rainfall are filtered with 9-point filtering technique in order to suppress the high frequency components and understand the variability in low frequency mode. The smoothed series display many aperiodic fluctuations. Epochs with persistently large-or smaller period under wet or dry condition (with respect to climatological normal) can be seen in the graphs. Seasonal and annual rainfall condition of a particular year are categorized as *very dry, moderately dry, normal, moderately wet and very wet* by using quintiles as a threshold calculated from the dataset of 1901-2000. Categorized rainfall time series for all major and minor basins have been prepared and analyzed. The inter-annual variation in the categorized monsoonal rainfall during 1813 to 2015 for the country as a whole is shown in fig.1. For All India monsoon rainfall series rainfall less that 833mm is considered as very dry, 834-894mm dry, 895-945mm normal, 945-980mm wet and more than 980mm very wet. Distinct epochs can be identified in the rainfall fluctuations of all India monsoon rainfall. From the visual examination, major epochs noticeable in the monsoon rainfall fluctuations are: 1821-1861 dry, 1862-1897 wet, 1898-1931 dry, 1932-1964 wet, 1965-1988 dry, 1989-1999 wet, 2000-2015 dry.

2. Short-term and Long-term rainfall fluctuations

The Cramer's t_k statistics (WMO 1966) has been applied to moving averages of each of the time series to determine the broad nature of (+ve and –ve) short-term tendencies (15-year), medium-term fluctuations (31-year), long-term trend (51-year), and secular trend (101-year). The t_k value is calculated and significance is tested for times series of all major and independent minor river basins. The test compares the means of the sub-periods to the mean of the entire record. Visual examination revels that the monthly, seasonal and annual rainfall is found to exhibit wide range of fluctuation characteristics across the country. The major epochal patterns and significant highest and lowest values in running means for monsoonal rainfall of All India and major basins are listed below.

2.1 All India: Fig.2 represent the Cramer's t_k statistics for All India annual and monsoon rainfall during 1813-2015. The 15-year running mean of monsoonal rainfall first decreased and attain a low value (significant at 1%) centered around 1844 during 15-year period. The means then increases continuously and becomes significantly larger than the overall mean (at 5% level) during the 15-year period centered around 1888. Afterwards it fluctuates within normal limit first decrease and then increase significantly (5% level) up to year centered around 1949. After that, it shows continuous decrease within the normal limit up to 2015. On broader scale five period can be identified in 15-year running means: 1825-1867 dry, 1868-1898 wet, 1999-1815 dry, 1916-1972 wet, 1972-1996 stationary and 1997-2008 dry. 31-year running mean shows five epochal patterns: 1828-1871 dry, 1872-1905 wet, 1906-1919 dry, 1920-1987 wet, 1988-2000 stationary. The lowest significant (1% level) decrease in 31 year running mean is centered on 1845, however the highest significant (1% level) increase is centered on 1948. In 51-year two epochal patterns can be seen. 1838-1973 is dry, 1974-1989 is wet. The significant lowest (1% level) is centered on 1844 and significant (1% level) highest on 1939. In 101 year cycle only two epochs are identified. 1862-1896 dry, 1897-1964 wet, significant at 1% level up to 1936 and then it is significant at 5%.

2.2 Indus major basin: In 15-year window, the running mean attain lowest values (significant 5% level) centered around 1906, 1908 and 1986 while the highest values are centered on 1960 and 1964 (5% level). In recent period, the means are fluctuating. Three broad epochs can be identified. 1859-1946 dry, 1947-1975 wet and 1976-1990 dry. The lowest significant (5% level) decrease in 31 year running mean is centered on 1926, however the highest significant (1% level) increase is centered on 1962. Two epochal patters (1862-1845 dry and 1846-1978 wet) can be identified. In 51-year two epochal patterns can be seen. 1873-1938 is dry, 1939-2000 is wet. The significant lowest (1% level) is centered on 1921 and highest on 1955. In 101 year cycle, epochs are not identified. The running mean series shows continuous increase but still below normal up to 1957, afterwards it shows increase above normal.

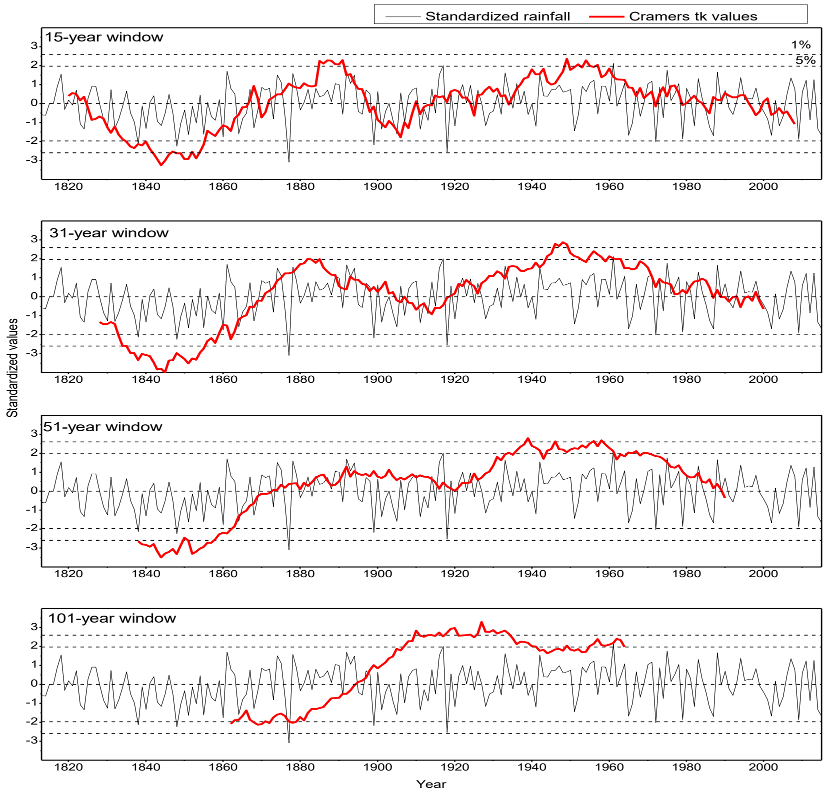

Fig.2. Cramers t_k statistics for 15-, 31-, 51- and 101-year moving averages of All India summer rainfall

***2.3 Ganga Major Basin**:* During the entire period, the 15-year running mean of monsoon rainfall attain the lowest significant decrease centered around 1843 (5% level) and highest around 1891 (5% level). In recent period, sharp decline is noticeable. During entire record two dry epochs (1836-1856 and 1898-1915) and two wet epochs (1857-1898 and 1916-1997) are observed. In 31-year window, lowest values are not significant while the highest significant increase is centered around 1885 (5% level). Broadly two wet epochs are noticeable (1863-1905 and 1921-1987). 51-year running window shows only one wet epoch from 1864-1980. The significant highest increase is observed around 1939 (5% level). The 101 year means also show only one wet epoch starting from 1880.

2.4 Brahmaputra Major: The highest significant increase (1%) in 15-year running mean is centered around 1865 and lowest significant decrease (1 %) around 2000. Two major epochs can be noticed. The 1855 to 1947 is wet and 1948 to 2008 is dry. In 31-year running mean also two major epochs are seen: 1863-1944 wet, 1845-2000 dry. The highest increase is centered around 1872 (1% level) and lowest decrease around 2000(5% level). In 51-year cycle, the highest significant increase is noticed around 1882 (1% level) and lowest around 1990 (1% level.) In 101 year running mean the highest significant increase is centered on 1907 and lowest decrease around 1965. In both 51-y and 101-y running means, no epochal pattern is seen. There is continuous decrease is observed throughout the entire record.

2.5 Godavari Major: The 15-year running means shows two major wet epochs (1876-1898 and 1929-1966) and two dry epochs (1899-1928 and 1967-2007). The highest increase is centered around 1888 (1% level) and lowest decrease is around 1925 (5% level). In 31-year running means, four periods can be identified (1874-1907 wet, 1908-1920 dry, 1921-1974 wet and 1975-2000 dry. The highest significant increase is centered around 1946 (1% level) while lowest decrease is not significant. In 51-year window, only one epoch is observed. Staring from 1859 to 1978 the period was wet and afterwards decrease can be seen. The highest increase is noticed around 1956 (significant at 5% level) while lowest is not significant. In 101 year window, the values entire statistics is above normal. The highest increase is centered around 1920 (at 1% level).

2.6 Krishna Major: In 15-year window, the running mean attain lowest values (significant 1% level) centered around 1852 and 1961 while the highest increase centered on 1960 (1% level). Four broad epochs can be identified. 1843-1876 dry, 1877-1915 wet and 1916-1946 dry and 1947-2008 wet. The lowest significant (1% level) decrease in 31 year running mean is centered on 1851, however the highest significant (1% level) increase is centered on 1968. Four epochal patters (1851-1878 dry, 1879-1907 wet, 1908-1939 dry and 1940-2000 wet) can be identified. In 51-year two epochal patterns can be seen. 1861-1931 is dry, 1932-1990 is wet. The significant lowest (1% level) is centered on 1861 and highest on 1975. In 101-year cycle, epochs are not identified. The running mean series shows continuous increase from lowest centered around 1886 (significant at 1%) to highest increase around 1964 (significant at 1%).

2.7 Sabarmati Major: During the entire period of 15-year running mean the lowest significant decrease is not found significant however the highest significant increase is centered around 1949 (at 5 % level) . On broader scale four major epochs can be identified: 1873-1893 wet, 1894-1925-dry, 1926- 1962 wet, 1963- 2000 dry. In 31-year window, lowest values are not significant while the highest significant increase is centered around 1941 (5% level). Two dry epochs (1898-1927 and 1971-2000) and one wet epoch (1828-1970) are noticeable. 51-year running window shows only two epochs: from 1886-1926 dry and 1927-1967 wet. After 1968 continuous decrease can be seen. The highest increase and lowest decrease are not significant. The 101 year means also show two epochs: 1911-1936 wet and 1937-1965 dry.

2.8 Mahi Major: 15-year running means shows two major wet epochs (1864-1893 and 1930-1978) and two dry epochs (1894-1929 and 1979-2007). The highest increase is centered around 1948 and 1952 (5% level) and lowest decrease is around 1904 (5% level). In 31-year running means, four periods can be identified (1872-1892 wet, 1893-1929 dry, 1930-1970 wet and 1971-2000 dry. The highest significant increase is centered around 1948 (5% level) while lowest decrease around 1910 (5% level). In 51-year window, only two epoch are observed: 1890-1929 dry and 1930-1971 wet. After 1972 continuous decrease is seen. The highest increase or lowest decrease is not significant. In 101 year window, continuous decrease is noticed which is not significant.

2.9 Narmada Major: The highest significant increase (1%) in 15-year running mean is centered around 1887 and 1941 and lowest significant decrease (1%) around 1906. Four major epochs can be noticed: 1886-1897 wet, 1898-1926 dry, 1927-1956 wet and 1957-2008 dry. In 31-year running mean also four major epochs are seen: 1865-1898 wet, 1899-1922 dry, 1923-1963 wet and 1964-2000 dry. The highest increase is centered around 1888 and 1946 (1% level) and lowest decrease around 1914 (5% level). In 51-year cycle, the highest significant increase is noticed around 1939 and 1953 (5% level) and lowest not significant. Only one prominent wet epoch from 1921-1970 is noticed. In 101 year running mean the highest significant increase is centered from

1911-1915 and lowest decrease is insignificant. In 101-y running means, also one wet epoch can be noticed from 1894-1944.

2.10 Tapi Major: During the entire period, the 15-year running mean of monsoon rainfall attain the lowest significant decrease centered around 1905 (5% level) and highest around 1938 (5% level). During entire record two wet epochs (1876-1894 and 1927-2008) and one dry epochs (1895-1926) are observed. In 31-year window, lowest decrease is centered around 1914 (1% level) while the highest significant increase is centered around 1946 (1% level). Broadly two epochs are noticeable (1894-1927 dry and 1928-2000 wet). 51-year running window shows increasing tendency from 1885 to 1954 and decrease thereafter. The significant highest increase is observed around 1954 (1% level). The 101 year means also show continuous increase starting from 1911 and significant around 1964 (1% level).

2.11 Mahanadi Major: During the entire period of 15-year running mean the lowest significant decrease is found around 1971 and 1972 (1% significant) and the highest significant increase is centered around 1940 (at 1% level) . On broader scale three major epochs can be identified: 1863-1877 dry, 1878-1961wet, and 1962- 2008 dry. In 31-year window, significant lowest value is centered around 1977 (1% level) while the highest significant increase is centered around 1932 (1% level). Two epochs (1880-1958 wet and 1959-2000 dry) are noticeable. 51-year running window shows only one wet epoch from 1893-1962 and sharp decline afterwards. The highest increase are found from 1932 to 1942 (1 % significance) and lowest decrease around 1990 (1% level). The 101 year means also show smooth decline centered from 1965.

2.12 Cauvery Major: In 15-year window, the running mean attain lowest value (significant 1% level) centered around 2008 while the highest values centered on 1902 (5% level). In recent period, sharp decline is seen. Two broad epochs can be identified. 1837-1876 dry, 1988-1996 wet. The lowest significant (5% level) decrease in 31 year running mean is centered on 2000, however the highest significant (5% level) increase is centered on 1985. Two epochal patters (1845-1881 dry and 1882-1995 wet) can be identified. In 51-year only one wet epochal pattern is identified from 1882-1987. The significant lowest (5% level) is centered on 1855 and highest on 1971 (1% level). In 101 year epochal pattern is not identified. The running mean series shows continuous increase from start up to highest centered around 1946 (1% level) and then decrease thereafter.

2.13 West Coast Drainage System: The 15-year running mean of monsoon rainfall attain the lowest significant decrease centered around 1851 (5% level) and highest increase not significant. During entire record two epochs (1835-1919 dry and 1920-2008 wet) are observed. In 31-year window, lowest significant decrease is noticed form 1845 to 1855 (5% level) while the highest significant increase is centered around 1968 (5% level). Broadly two epochs are noticeable (1832-1931 dry and 1932-2000 wet). 51-year running window shows only two wet epoch from 1842-1931 dry and wet thereafter. The significant highest increase is observed around 1968 (5% level) and significant lower decrease afro 1857 to 1881 (5% level). The 101 year means does not show epochal pattern. There is continuous increase from lowest observed around 1895 (5% level) to 1964 highest significant increase centered around 1964 (1% level).

3. Recent changes in seasonal rainfall

3.1 Recent 15-, 31-, 51-, 101-year change relative to entire record:

Recent 15-, 31-, 51- and 101-year percent changes in summer monsoon rainfall of 11 major basins, 9 independent minor basins, west coast drainage system and All India relative to entire rainfall records are documented in table 1. Significance has been tested using Cramers t_k test. For most of the basins the changes are not significant. But few of them shows consistent significant changes from 15-year to 101-year window. E.g. In Brahmaputra major basin, recent 15 year monsoon rainfall change by -10.5% (significant at 1% level); for 31-year -4.4% (5% level) and for 51-year -4% (1% level). Krishna, Tapi and WCDS major basins in recent 101 years shows significant increase in Rainfall by +2.5% (significant at 5% level), +3.6% (1% level) and +2.3% (5% level) respectively. Mahanadi major basin shows significant decrease in rainfall of -6% (1% level) in recent 51-years. While Cauvery shows significant decrease of 19.8% (at 1% level) and -5.9% (at 5% level) in recent 15-year and 31-years respectively. For independent minor basins, Brahmani shows significant decrease of -12.5%, -7.3% and -7.5% (significant all at 1% level) in recent 15-years, 31-years and 51-years. Pallar and Ponniyar also shows significant decrease in monsoon rainfall of -31.5% and -12.6% (both significant at 1%) during recent 15-year and 31-years respectively. Overall for the country as a whole, there is decrease in monsoon rainfall in recent 15-, 31- and 51-years but not statistically significant. However in recent 101 years surprisingly All India monsoon rainfall is showing increasing tendency (+1.4% significant at 5%).

3.2 Recent 15-year change compare to last century (1901-2000)

Changes in annual and monsoon rainfall of basins during 2001-2015 have been tested in relation to more reliable instrumental monthly rainfall records of last 100 years (1901-2000). The significance of the changes have been tested by using students' t test for the difference between the two sub-period means. It has been seen that, in recent years most of the basins shows negative percentage change compare to last century. Most significant change in annual and monsoon rainfall recorded for Ganga, Brahmaputra, Cauvery, Surma, Brahmani and Pallar & Ponniyar river basins. The annual and monsoonal rainfall of Ganga basin has been decreased significantly by -6.7% and -8.0% (5% level of significant); Brahmaputra basin -11.1% and -11.0% (1% level) and Cauvery basin: -15.4% and -22.9% (1% level) respectively in recent years. For independent minor basins also significant decrease in annual as well monsoonal rainfall has been noticed. For Surma basin, the decrease is -10.7% and -9.1% (1% level); Brahmani basin: -15.1% and -13.6% (15 level); Pallar & Ponniyar basin: -25.2% and -34.7% (1% level) respectively. For the country as whole the ALL India annual rainfall has been decreased by -3.0% and monsoonal rainfall by -4.2%, but statistically significant. The spatial distribution of recent 15 changes in monsoon rainfall compare to 20th century (1901-2000) are given in figure 3.

4. Trends in tropospheric temperature across the globe

We have analyzed the asymmetry in the 3-D thermal structure in recent years at global, hemispheric and zonal scale. Based upon geographical, astronomical and meteorological characteristics and climatic conditions (temperature, wind pattern, precipitation etc.), the whole globe is divided into nine climatic zones: north polar (70°-90°N), north mid-latitudes (45°-70°N), north subtropic (25°-45°N), north tropic (2.5°-45°N), equator (2.5°S-2.5°N), south tropic (2.5°-25°S), south subtropic (25°-45°S), south mid-latitudes (45°-70°S), south polar (70°-90°S). Thermal condition of each latitudinal belt is determinant of apparent movement of the sun from the Tropic of Cancer in northern hemisphere (NH) to the Tropic of Capricorn in southern hemisphere (SH). As we go away from the equator, seasonality started developing. Equator is least seasonal while pole is of highest seasonal variations in temperature across the globe. Equator is the region where, temperature variation is least while precipitation is abundant throughout the year. North-South tropics are the one where temperature variation is seasonal (summer and winter) but major seasonal precipitation occurs during summer season. In subtropical belts, in spite of seasonal temperature variation, precipitation is sparse throughout the year. The mid-latitude areas in both hemispheres are having winter wet and summer dry. Subpolar regions are having ample precipitation in all seasons. The polar zones come under the sparse precipitation throughout the year.

Table 1. Recent 15-, 31-, 51- and 101-year changes in summer monsoon rainfall of river basins and All India relative to entire records (superscript indicates level of significance)

Sr. No.	**Basin Name**	**Recent 15-year change (%age)**	**Recent 31-year change (%age)**	**Recent 51-year change (%age)**	**Recent 101-year change (%age)**
1.	Indus major	1.4	1.3	1.0	0.5
2.	Ganga major	-7.4^{5}	-3.3	-2.0	0.5
3.	Brahmaputra major	-10.5^{1}	-4.4^{5}	-4.0^{1}	-1.4
4.	Godavari Major	-0.7	-2.0	-2.3	0.3
5.	Krishna major	3.4	3.6	3.1	2.7^{5}
6.	Sabarmati	9.7	-4.0	-3.1	0.1
7.	Mahi	-1.1	-8.3	-5.5	-1.0
8.	Narmada	-3.7	-3.3	-3.2	0.6
9	Tapi	8.6	4.3	3.8	3.6^{5}
10.	Mahanadi	-2.8	-4.2	-6.0^{1}	-0.1
11.	Cauvery	-19.8^{1}	-5.9^{5}	-2.1	0.5
12.	WCDS	2.2	2.2	2.3	2.3^{5}
13.	All India	-2.8	-1.1	-0.5	1.4^{5}
Independent minor basins					
14.	Luni	-0.6	-2.6	-0.7	1.1
15.	Surma	-6.9	-3.8	-0.8	1.2
16.	Kasai	-2.2	4.1	2.2	1.0
17.	Damodar	-1.7	3.5	1.0	1.0
18.	Suvarnarekha	3.6	2.3	1.5	1.5
19.	Brahmani	-12.5^{1}	-7.3^{1}	-7.5^{1}	-1.5
20.	Pennar	4.5	8.9^{5}	6.4^{5}	2.8
21.	Pallar & Ponniyar	-31.5^{1}	-12.6^{1}	-4.6	-1.3
22.	Vaigai	2.8	-0.8	-0.8	-0.8

The column-area mean monthly temperature of the troposphere (1000-250hPa) has been area averaged for the globe, NH, SH and 9 climatic zones. The calendar month-year temperature data of the period 1979-2018 has been deseasonalized and homogenized (mean removed and standard deviation equated) before plotting. Deseasonalization has been done in order to remove average seasonal cycle from temperature records and data homogenization has been done in order to make the monthly temperature variations comparable. The adjusted data revel that the tropospheric temperature over the globe has been increased at the rate of 0.25° per decade. Northern hemisphere is warming at faster rate (0.30°/decade than southern hemisphere (0.20°/decade). All climatic zones across the globe show consistent global warming trend that is significant for all zones except South Pole and South Mid-latitude. The highest rate of increase is seen over North Pole (0.37°/decade) while lowest over South Pole (0.05°/decade). In general, rate of rising trend increases from south polar towards north polar, which could be the cause of many usual weather events across the globe (fig.4). In recent 10 years (2009-2018) compare to earlier 30 years (1979-2008), the TT of the globe has been increased by 0.50°C, NH (0.57°C) and SH (0.43°C). Across the 9 climatic zones, the increase in TT varies from 0.83°C for the NP to 0.11°C for the SP. The increase in TT across the globe is significant at 0.1% level of significance except SP.

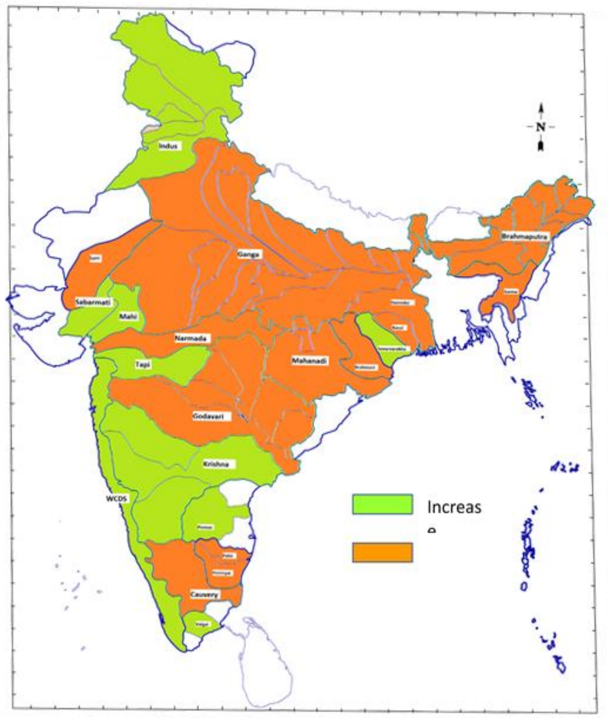

Fig. 3. Recent 15 year changes in seasonal (JJAS) rainfall compare to last century (1901-2000)

The global spatial pattern of changes in TT across the globe revels some important facts. Though surface air temperature of the northern hemisphere is rising but performance of summer monsoon rainfall is weaker over most parts of the country. Due to rising trend in global tropospheric temperature, monsoon rainfall and spatio-temporal extreme rainfall show westward shift. Northern and northwestern India are likely to experience excessive monsoon rains.

IV. CONCLUSIONS

1. Normal (1901-2000) annual rainfall of the river basins across the country varies from 487.7mm (Luni) to 2519.5mm (Surma). Normal annual rainfall of the country is 1165.9mm, highest rainfall of 1435.3mm occurred during year 1917 and 895.7mm during year 1918.
2. Significant increasing trend is noticed in recent 101 years (1915-2015) in monsoon rainfall over Krishna major (2.7%), Tapi (3.6%), WCDS (2.3%) and the whole country (1.4%) compare to preceding instrumental period. Brahmaputra major, Mahi, Mahanadi, Brahmani, Pallar and Ponnaiyar showed non-significant decreasing trend.
3. In recent 15 years (2001-2015), monsoon rainfall over Ganga major is decreased significantly by 7.4%, Brahmaputra major 10.5% and Cauvery 19.8% relative to entire available instrumental records.

4. Significant increasing trend is noticed in tropospheric temperature of globe, two hemispheres and 9 climatic zones other than South Pole and South Midlatitude. The regression coefficient varies from 0.67 to 0.23.
5. Since 1979, tropospheric temperature has been increased by 0.29°C/decade over the globe. NH is warming at a faster rate (0.30°C/decade) than SH (0.20°C/decade). The highest rate of increase is noticed over the NP (0.37° C/decade) while lowest is observed over the SP (0.05°C/decade).

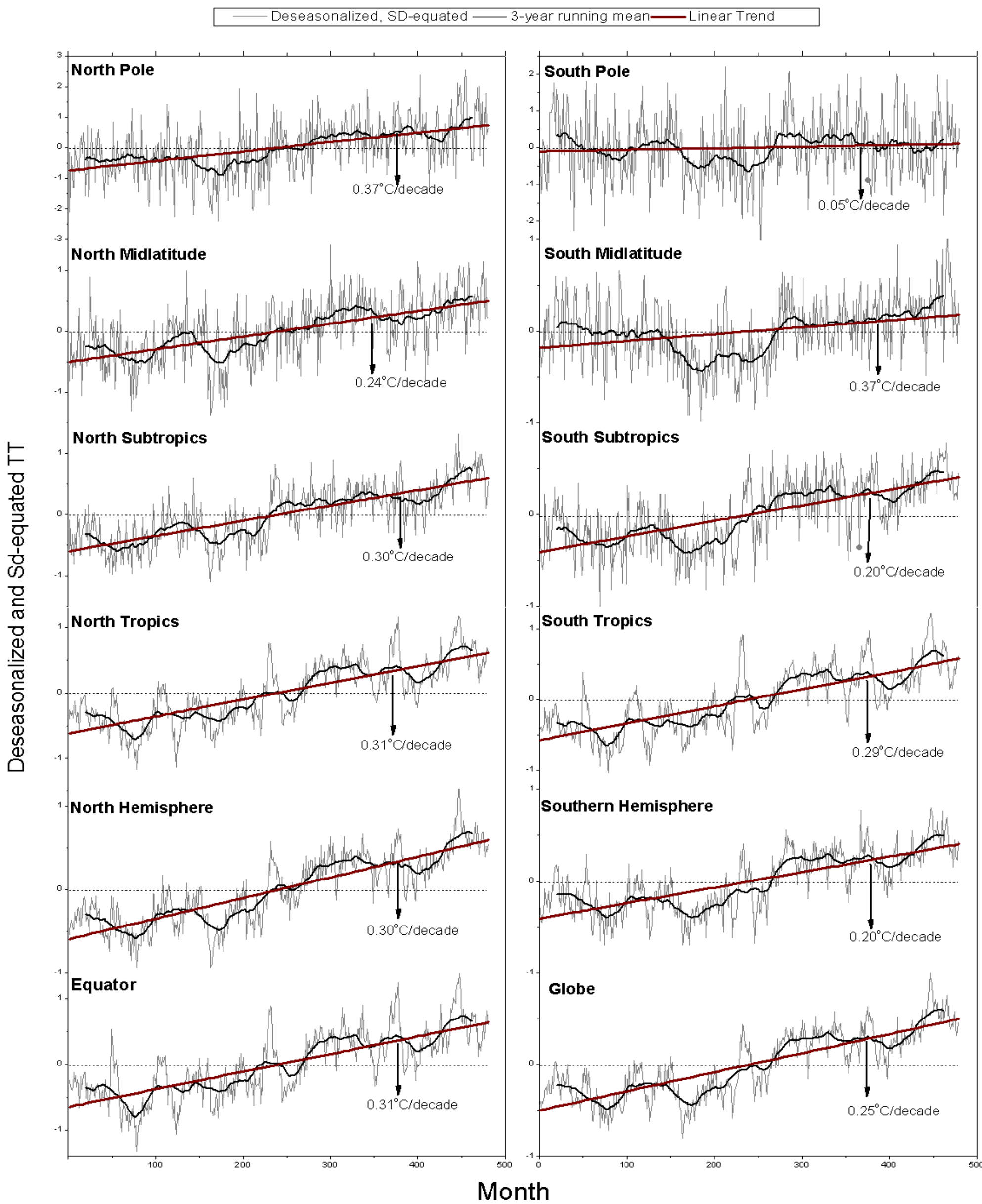

Fig 4. Homogenized (seasonalized and annual standard deviation equated) month-year troposphere (1000−250-hPa) temperature variation during January 1979-2018 over nine climatic zones, the two hemispheres and the globe. Thick curve is 3-year (or 36-month) running mean and straight-line linear trend

References:

Guhathakurta P, Sreejith OP and Menon PA (2011) Impact of climate change on extreme rainfall events and flood risk in India. *J Earth Syst Sci* 120(3): 359–373Goswami et al. 2006;

IPCC (2007) Climate change 2007. The physical science basis. The contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 504–511

IPCC (2018) Global warming of 1.5ºC, An IPCC Special Report (SR -15).

Jones P.D., Wigley, T.M.L. and Kelly, P.M. (1982) "Variations in surface air temperatures: part 1. northern hemispher, 1881-1980", *Mon. Weath. Rev.,* 110, 2, 59-70.

Kelly P.M. , Jones, P.D., Sear, C.B., Cherry, B.S.G. and Tavakol, R.K. (1982) "Variations in surface air temperatures: part 2. arctic regions, 1881-1980", *Mon. Weath. Rev.,* 110, 71-83.

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

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

Rajeevan M Bhate J (2008) A high resolution daily gridded rainfall Data Set (1971-2005) for Mesoscale Meteorological Studies. National Climate Center, India meteorological Department, research report no.9.

Ranade A and Singh N (2014) large-scale and spatio-temporal extreme rain events over India: a hydrometeorological study. *Theor Appl Climatol* 115: 375-390

Ranade, Ashwini, N. Singh, H.N. Singh, and N.A. Sontakke, 2008: On variability of hydrological wet season, seasonal rainfall and rainwater potential of the river basins of India (1813-2006). *J. Hydrol. Res. Devpt*., **23**, 79-108.

Saha S et al. (2010) The NCEP Climate Forecast System Reanalysis. *Bull Amer Meteo* Soc 91(8): 1015-1057. doi: 10.1175/2010BAMS3001.1

Saha S et al. (2014) The NCEP Climate Forecast System Version 2. *J Climate* 27: 2185-2208. doi: 10.1175/JCLI-D-12-00823.1

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.

Senior CA, Jones RG, Lowe JA, Durman CF, Hudson D (2002) Predictions of extreme precipitation and sea-level rise under climate change. *Phil Trans R Soc Lond* A 360:1301–1311

Singh N and Ranade A (2010) The wet and dry spells across India during 1951-2007. *J Hydrometeorol* 11: 26-45

WMO (1966) Climatic Change. World Meteorological Organization, Technical Note No. 79, WMO No 195-TP-100; Geneva, 79.
