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Development and Analysis of a New High Spatial Resolution (0.25° x 0.25°) Long Period (1901-2010) Daily Gridded Rainfall Data Set over India

D. S. Pai
Latha Sridhar
M. Rajeevan
O.P. Sreejith
N.S. Satbhai
B. Mukhopadhyay

NATIONAL CLIMATE CENTRE
OFFICE OF THE
ADDITIONAL DIRECTOR GENERAL OF METEOROLOGY (RESEARCH)
INDIA METEOROLOGICAL DEPARTMENT
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**D. S. Pai, Latha Sridhar, M. Rajeevan,
O. P. Sreejith, N.S. Satbhai and B. Mukhopadhyay**

Sivapai@hotmail.com

**National Climate Centre
India Meteorological Department
Pune – 411005
India**

ncc@imdpune.gov.in

Executive Summary

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Development and Analysis of A New High Spatial Resolution (0.25° x 0.25°) Long Period (1901-2010) Daily Gridded Rainfall Data Set Over India

D. S. Pai[1], Latha Sridhar[1], M. Rajeevan[2],
O. P. Sreejith[1], N.S. Satbhai[1] and B. Mukhopadyay[1]
India Meteorological Department, Pune[1]
Earth System Science Organization, Ministry of Earth Sciences, New Delhi[2]

Abstract

The study discusses development of a new daily gridded rainfall data set (IMD4) at a high spatial resolution (0.25° X 0.25°, latitude X longitude) covering a longer period of 110 years (1901-2010) over the Indian main land. A comparison of IMD4 with 4 other existing daily gridded rainfall data sets of different spatial resolutions and time periods has also been discussed. Based on the IMD4 data set, the present study also presents an analysis of (1) break and active monsoon spells and (2) extreme daily rainfall (ER) events over three regions over the country; central India (CI), northeast India (NEI) and west coast (WC).

For preparing the new gridded data, daily rainfall records from 6995 rain gauge stations in India were used, highest number of stations used by any studies so far for such a purpose. The gridded data set was developed after making quality control of basic rain-gauge stations. The comparison of IMD4 with other data sets suggested that the climatological and variability features of rainfall over India derived from IMD4 were comparable with the existing gridded daily rainfall data sets. In addition, the spatial rainfall distribution like heavy rainfall areas in the orographic regions of the west coast and over northeast, low rainfall in the lee ward side of the Western Ghats etc. were more realistic and better presented in IMD4 due to its higher spatial resolution and to the higher density of rainfall stations used for its development.

IMD4 was used to identify the break and active spells for the entire data period (1901-2010) using a rainfall criteria. The break and active spells identified in this study were mostly comparable with that identified in the earlier studies based on similar rainfall criteria during the common data period (1951-2007). However, some noticeable differences were observed in the rainfall anomaly pattern associated with the break monsoon spells identified in this study and that identified based on the synoptic criteria in the earlier studies. The stringent rainfall criteria used in this study seems to be better

criteria for identifying the breaks. During the study period (1901-2010), both the active and break spells of short durations were more frequent than the longer durations with about 63.6% of the break spells and 93.5% of the active spells falling in the range of 3-6 days. There were no active spells of duration ≥ 13days. Whereas, about 7% of the break spells were of duration ≥ 13days. During the both the halves of the data period (1901-55 & 1956-2010), there was no change in the distribution of the break events. However, the number of active spells showed an increase of about 18% in the in the second half, which was mainly in the lower duration (3-6 days) spells. During the data period, decadal variations of break days showed an out phase of relationship with the number of monsoon depressions. Relatively stronger in phase relationship was observed between the decadal variation of monsoon depressions and that of the active days till around early 1980s which failed later due to sudden decrease in the number of monsoon depressions. During the same period, both the active & break days were in the increasing phase. This was also coincided with the sudden and significant increase in the number of monsoon lows, which seems to have compensated the decrease in the monsoon depressions and helped in the occurrence of the active spells of lower durations.

The analysis of extreme rainfall or ER events (≥ 5mm) over CI, NEI & WC using IMD4 showed some interesting results. There is increased disaster potential over CI due to significant increasing trends in the heavy rainfall or HR (≥100mm to 150mm) events and very heavy rainfall or VHR (≥150mm) events during the recent period (1956-2010). On the other hand, during the same period, the disaster potential over NEI has reduced as HR events show significant decreasing trend and no trend is observed in the VHR events. There is not much change in the disaster potential over west coast as no significant trends were observed in the HR and VHR events over the region.

The significant increasing trends in the HR & VHR events over CI during recent period seems to be primarily due to the increasing trend in the monsoon lows during recent decades which is also cause for increased active monsoon events as discussed earlier. The increased instability in the atmosphere due to increased moisture content associated with the global warming trend might have also helped. On the other hand, the increasing trend in the monsoon lows has opposite impact on the heavy rainfall events over NEI as the strong convergence in the low pressure systems over central India blocks the moisture supply over NEI which inhibits deep convective activity and reduces heavy rainfall events over NEI.

1. Introduction

Rainfall and surface air temperature are the two key elements of climate that are commonly used as indicators of global climate change due to the availability of long time series of these elements from most parts of the world. Rainfall, a component of terrestrial hydrological cycle determines the availability of water and the level of the soil moisture. The information regarding climatology, long term trends, variability, extreme events etc. of the rainfall over a region are very valuable for scientists, engineers, planners, and managers working in water-related sectors like agriculture, ecology, hydrology, hydro-electric power generation, and water resources. The accurate prediction of rainfall variability at various time and spatial scales are also very valuable for these water-related sectors. The variation in the timing, distribution and amount of rainfall, even if in a small scale, can subsequently be a cause of significant societal consequences. Therefore, understanding the rainfall variability at various scales, identifying the mechanisms behind it and its prediction has always been one of the priorities of climate research globally. Its importance has further increased due to the projected changes in the rainfall patterns and frequency of extreme rainfall events over various parts of the globe in associated with the global warming (IPCC, 2007) and its possible impacts on vulnerable sections of our society. Although, the station (sample point) data are the primary source for the diagnostic studies of climate change and variability studies, these observations are often biased and distributed in homogeneously in space and time. There can be missing data, unknown errors attributed to certain observation methodologies and more importantly a change of methodology can lead to a time-varying bias. It is therefore necessary to convert the station data to a regular space-time grid and to correct or remove the erroneous values before such observations can be used for diagnostic studies. Gridded data are also preferred for the model validations, as the model outputs are generated at fixed spatial grid points. However, depending on the application, requirement of spatial and temporal resolution of the gridded data can be different. For example, the spatial and temporal resolutions of the data required for examining intra-seasonal variation and validation of mesoscale models are relatively higher than that required for examining climate change and variability and validation of climate models. However, as mentioned earlier, for climate change studies requirement of length of data is very much higher than that for mesoscale studies. There are several global, continental and regional gridded rainfall data sets available for use. These data sets are however differ in terms of spatial resolution, temporal resolution, spatial and temporal coverage, types of basic data used (like raingauge, satellite based precipitation) and methods used for interpolation of data from the sample points (rainfall gauges) to the grid points.

Over India, daily rainfall data observations from most parts of the country are available for a very long time period (more than 125 years). A brief history of the rainfall data collection and archival in India can be obtained from Walker (1910) and Parthasarathy and Mooley (1978). Currently, these historical rainfall data are archived at the National Data Center (NDC), India Meteorological Department (IMD), Pune. The first gridded daily rainfall for Indian region was prepared by Hartman and Michelsen (1989). They prepared the grid point data at the 1^0X 1^0 by grouping the station data into grid boxes using the IMD daily rainfall data of 1901-1970. Using this gridded rainfall data set, Hartman and Michelsen (1989), Krishnamurthy and Shukla (2000) and Krishnamurthy and Shukla (2007 & 2008) studied the intra-seasonal and interannual variability of rainfall over India. Recently, three daily gridded rainfall data sets over Indian main land at different spatial grids and temporal periods were made available by India Meteorological Department (IMD). These are two 1^oX1^ogridded daily rainfall datasets based on fixed network of rain gauge stations (Rajeevan et al. 2006, Rajeevan et al. 2008), and a 0.5^oX0.5^ogridded daily rainfall dataset based on a variable network of raingauge stations (Rajeevan et al. 2009). In addition, another daily gridded rainfall data set over Indian region was made available as a part of the larger data set developed for the monsoon Asia region under Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation of the Water Resources (APHRODITE) project (Yatagai et al. 2012).

In this study, as a part of IMD's efforts to make use of all the available quality rain gauge data over the country to prepare a high resolution daily rainfall data set for various applications such as climate variability & climate change studies, validation of model rainfall at various scales, hydrological modelling, drought monitoring etc., development of a new daily gridded rainfall data set over India at a spatial resolution 0.25^oX0.25^o for 110 years (1901-2010) have been discussed. The data set was prepared using the daily rainfall data from all the rain gauge stations over the country available in the IMD archive. Another objective of this study was to compare the newly developed daily rainfall data set with the existing 4 daily rainfall datasets over India (3 IMD data sets and the APHRODITE data set mentioned in the earlier paragraph) to evaluate the capability of the new data set in representing the rainfall climatology and variability over the country at various special and temporal scales. This was achieved by (i) comparing the various climatological and variability features of rainfall over India prepared using the above 5 gridded daily rainfall datasets over the region for some common data period, and (ii) re-examining results of some of the recent research studies on variability and long term trends of monsoon rainfall over India conducted using already available gridded daily rainfall data sets over the region.

The section 2 provides details of the basic rain gauge data used for the preparation of IMD4 and other data sets used in this study. The section-3 discusses the methodology used for the preparation of the new data set and computation of area averaged rainfall over various regions from different gridded rainfall data sets. The section 4 describes various results of the study and the section 5 presents summary and conclusions.

2. Data Used

2.1. Rainfall Station Data for the Preparation of New Gridded Data Set

For the preparation of the new gridded daily rainfall data set (referred hereafter as IMD4), daily rainfall data from the archive of National Data Centre, IMD, Pune for the period 1901-2010 were used. The daily rainfall records from 6955 rain gauge stations with varying availability periods were used for the study. The number of stations used for the preparation of the new grid point data (IMD4) is nearly 900 more than that used by Rajeevan et al. (2009) for the preparation of $0.5^o X 0.5^o$ gridded daily rainfall data. Out of these 6955 stations, 547 are IMD observatory stations, 494 are hydro-meteorology observatories and 74 are Agromet observatories. The remaining are rainfall reporting stations maintained by the State Governments. The locations of all the 6955 rain gauge stations considered for preparing the new gridded rainfall data are shown in Fig 1. As seen in the Fig.1, the spatial density of the station points is not uniform throughout the country. The density of the stations is relatively high in the south Peninsula and relatively low over northern most areas of the country, northwest India, northeast India, and eastern parts of central India. The daily variation of number of stations used for the analysis is shown in Fig.2. On an average, data from about 2600 stations per year were available for the preparation of daily grid point data. However, the data density varied from year to year from about 1450 in the first year (1901) to about 3950 during the period 1991-94. The data density was relatively higher (≥3100 stations per day) from 1951 onwards except in the last 2-3 years when the density reduced to about 1900 stations per day.

2.2. The daily gridded rainfall data sets over India

Four daily rainfall data sets over the region were used in this study to compare with the newly developed rainfall data set (see Table-1 for the brief details of the data sets). The first data set at the spatial grid of $1^oX1^o$for the period 1951-2003 was initially developed by Rajeevan et al. (2006) using a fixed network of 1803 rain gauge stations that having minimum 90% data availability during the analysis period and was used to analyse the break and active events in the south monsoon rainfall over India. Goswami et al. (2006) used this data set to examine the frequency and the magnitude of extreme rain events over central India during the monsoon season for the period 1951-2000. Krishnamurthy and Ajayamohan (2010) extended the data set for the period 1901-1950 by following exactly the same procedure of Rajeevan et al. (2006) and the resultant data set for the period 1901-2003 was used to examine the daily rainfall variability associated with the formation of low pressure systems in the Indian monsoon region during the period and its impact on the seasonal mean rainfall. To improve the data quality over northern part of India, Rajeevan et al. (2010)reconstructed the data set of Rajeevan et al. (2006) using a fixed network of 2140 that having minimum 90% data availability and the data period was extended up to 2007. For the IMD operational purposes, this data set was extended up to 2010 using the same network of 2140 rain gauge stations, which is a subset of the 6955 stations data used in this study. As the number of presently available stations within the fixed network during each day of the period (2004-2007) was more than that used by Rajeevan et al. (2010) by about 400 to 600, the gridded data for the period 2004 to 2007 was recalculated with increased number of stations from the fixed network. For the period 2004-2010, around 1050 stations per day from the fixed network were available. In this study, hereafter this updated data set has been referred as IMD1.

Another daily 1^oX1^o, gridded rainfall data set (hereafter referred as IMD2) extending for a period of 1901-2004 was developed by Rajeevan et al. (2008) for examining variability and long-term trends of extreme rainfall events over central India. IMD2 was prepared based on a fixed network of only 1380 rain gauge stations that having at least 70% data availability during the analysis period. For mesoscale studies and model validation, Rajeevan et al. (2009) developed a daily $0.5^{o}X0.5^{o}$, gridded rainfall data set (hereafter referred as IMD3) for the period of 1971-2004. IMD3was prepared based on a varying network of 6076 rain gauge stations. All the above 3 IMD daily rainfall data sets over India used Shepard (1968) interpolation method for interpolating daily rainfall from rain gauge (sample) points to grid points. The directional effects and barriers were also included.

The fourth daily rainfall data set used to compare the newly developed rainfall data in this study is the APHRODITE daily rainfall data set (APHRO_V1101) which is available at the spatial resolutions of $0.25^{o}X\ 0.25^{o}$ and $0.5^{o}\ X\ 0.5^{o}$ for the period 1951-2007. The dataset, used rain gauge observation data from thousands of Asian stations in addition to those reporting to the WMO Global Telecommunications System. This data set was prepared using the basic algorithm of Xie et al. (2007). Details of the project and the data set are discussed in Yatagai et al. (2012). The daily APHRODITE data set is available at http://www.chikyu.ac.jp/precip/. In this study the APHRODITE data set with spatial resolution at $0.25^{o}X\ 0.25^{o}$ has been used (hereafter referred as APHRO).

2.3. Other Data Sets Used

One of the additional data set used for this study was the time series of area weighted rainfall over the Indian land region during the southwest monsoon rainfall and that during the full year (annual) for the period 1901-2010 which is being currently used by IMD for operational purpose. The data set was obtained from National Data Center, IMD, Pune. This data set was computed as the area weighted average of the district rainfall data which are computed from rainfall data of variable subset of about 3500 stations. In this study, the IMD operational time series of all India rainfall is referred as IMD_OP.

Another data set used in this study is the number of monsoon low pressure areas (monsoon lows) and monsoon depressions formed over Indian region for the period 1901-2010. The data were obtained from the daily weather reports published by the IMD.

3. Methodology

3.1. Development of the new Gridded Daily Rainfall Data over India

Standard quality checks like geographic location checks, checks for coding and typographic errors, duplicate station check, extreme value check etc. were applied on the basic rainfall data before the data were interpolated to fixed spatial grid points of 0.25^{o}X 0.25^{o} resolution. A common approach used for converting station rainfall data into grid point data is the spatial interpolation, which assumes that spatially distributed station rainfall values are spatially correlated or that the stations, which are close together tend to have similar rainfall characteristics. There are a variety of interpolation methods, which can be broadly divided into deterministic and geostatistical methods. The deterministic interpolation methods assign values to grid points based on the measured rainfall from surrounding stations (at sample points) and on specified mathematical formulas that calculate the rainfall values at grid points based either on the degree of similarity (e.g.inverse distance weighting (Cressman1959, Shepard 1968 &1984), natural neighbour (Sibson 1981)), or the degree of smoothing in relation with neighboring station data points (eg. trend analysis (Edwards 1973, Hughes 1982), multi-quadratic surface fitting (Hardy 1971, Shaw 1994)).The geostatistical methods use both mathematical and statistical methods that include autocorrelation (the statistical relationship among the station rainfall data). Because of this, geostatistical techniques not only have the capability of producing an estimation surface of the variable but also provide some measure of the certainty or accuracy of the estimations. Kriging is an advanced geo-statistical procedure (Zhang and Wang 2010) that generates an estimated surface from a scattered set of points.

For the development of the new data set, as in Rajeevan et al. (2006, 2008, 2009 & 2010),we have used the simplest form of inverse distance weighted interpolation(IDW) scheme proposed by Shepard (1968). In this method, interpolated values were computed from a weighted sum of the observations. Inverse distance weighted methods are based on the assumption that the interpolating surface should be influenced most by the nearby points and less by the more distant points. The interpolating surface is a weighted average of the station rainfall around the interpolation grid point and the weight assigned to each station data diminishes as the distance from the interpolation point to the station point increases. To speed up the computation, we used only rainfall data from few nearest neighbour stations (minimum of 1 point and maximum of 4 points) within a radial distance of 1.5 degree around the grid point to calculate weighted average. The scheme was locally modified by including the directional effects and barriers as proposed by Shepard (1968). More details about the interpolation method used in the study are given in Rajeevan et al. (2006).

3.2. Computation of Area Weighted Rainfall

In this study, the grid point rainfall data at different resolutions have been used for preparing the daily rainfall over various spatial regions. The daily rainfall over a given region was computed as the area weighted rainfall over all the grid boxes over the region. The area weight assigned to each grid box was taken as the fractional grid box area enclosed by the outer boundaries of the reference region multiplied by a cosine factor (the cosine of the latitude of the centre point of the grid box). The cosine factor is required to account for the convergence of the meridians which lessens the impact of high-latitude grid points that represent a small area of the globe. The annexure – I shows the monthly, seasonal and annual area weighted rainfall over the country as a whole (all India) computed using IMD4 for the period 1901-2010.

4. Results

The spatial domain of the IMD4 extended from 6.5°N to 38.5°N in latitude (129 points), and from 66.5°E to 100°E in longitude (135 points) covering the main land region of India (excluding the island parts). The temporal domain of the data set extends from 1stJanuary, 1901 to 31st December, 2010. Fig.3 depicts the spatial distribution of mean annual rainfall over India computed using IMD4 data for the entire period of 1901-2010. As seen in the Fig.3, the spatial distribution of rainfall immediately brings out its strong dependence on the orography. The Western Ghats of the peninsula and the great Himalayan arc extending from Kashmir to Assam in the north and hills of Burma and Khasi and Jaintia Hills of Meghalaya have profound effect on the rainfall of India. The heavy orographic rainfall on the windward side of hill ranges of Western Ghats, and the rapid decrease of rainfall on the leeward side of the hills. The mean annual rainfall along the west coast was ≥4 mm/day with many areas in the Konkan and coastal region exceeding 8 mm/day. East of the western

Ghats, there is a large north-south oriented area, which receives mean annual rainfall ≤2mm/day. Across the sub Himalayan regions of west Bengal, Sikkim, Assam and Meghalaya, Arunachal Pradesh etc., the mean annual rainfall exceeded 4 mm/day with some areas receiving ≥8mm/day. Annual rainfall of ≥4 mm/day was also observed over some isolated areas of Himachal Pradesh, Uttarakhand and hills of West Uttar Pradesh. However, western Rajasthan and Northern parts of Saurashtra and Kutch receives annual rainfall of <1mm/day.

Fig.4 is a time series of IMD4 annual cycle of daily rainfall over the Indian main land. The daily rainfall over the main land was computed as the area weighted rainfall over all the grid points over the main land. The all India mean annual rainfall and mean seasonal rainfall for the southwest monsoon season (June-September) for the total period (1901-2010) were 3.09mm/day and 6.99mm/day respectively (Table-2). As seen in the Fig.4, both inter-annual and intra-seasonal variability are present in the daily rainfall series embedded with extreme rainfall events over the 110-year record. The annual cycle of the rainfall over the country is linked to the movement of Inter-tropical Convergence Zone (ITCZ) across the tropical Indian Ocean and land regions. During the monsoon season, the ITCZ shifts northwards from the equatorial Indian Ocean region to the Indian main land associated with the progress of the southwest monsoon. Climatologically, the annual rainfall maximum over India typically develops during the middle of the monsoon season (JJAS), when the (ITCZ) merges with the monsoon trough. The north-south meandering of the monsoon trough within the season causes the intraseasonal variation of the rainfall across the region. The maximum in the annual rainfall is followed by the annual minimum during the months of December through May when the ITCZ shifts back to the oceanic region south of the country. From the above discussion, it is clear that the IMD4 reflects well known large scale mean and variability features of the rainfall over India.

4.1. Comparison of the New Gridded Data Set with the Existing Gridded Rainfall Data Sets over India

4.1.1. Rainfall Climatology over India: Spatial Distribution and Annual Cycle

In this section, a comparison of various climatologies based on IMD4data set with that based on the other four rainfall datasets over India (IMD1, IMD2, IMD3 and APHRO) has been presented. This is done by comparing various climatological features of rainfall over India such as spatial distribution of mean annual and seasonal rainfall over the country, annual cycle of mean monthly and daily rainfall averaged over the country as a whole etc. The data periods of these data sets are different; the data periods of IMD1, IMD2, IMD3 and APHRO are 1951-2010, 1901-2004, 1971-2005 & 1951-2007 respectively. Therefore, for the comparison, climatological features of rainfall using IMD1, IMD2, APHRO and IMD4 were prepared using data for the common period of 1951-2000. However, climatological rainfall features of IMD3 were prepared using the period of 1971-2000.

Fig.5 shows the comparison of spatial distribution of mean annual rainfall over India computed based on all the 5 rainfall data sets. It is seen that annual rainfall climatology over India based on all the 5 data sets, depicts nearly similar large scale features such as maximum rainfall areas along the west coast and over northeast India, rapid decrease of rainfall in the leeward side of the Western Ghats, and minimum rainfall over northwest India. As expected the major difference in the climatology prepared using various data sets is that the climatology based on lower resolution (1^ox1^o) data sets (Figures 5b & 5c) depicts smoother patterns compared to that based on higher resolution (0.25^ox0.25^o and 0.5^ox0.5^o) data sets (Figures 5a, 5dto5e). More details of spatial distribution of mean annual rainfall are visible in the climatology based on higher resolution data sets. For example, the zone of higher rainfall areas (≥ 4mm/day) along the windward side of the Western Ghats is narrower in Figures 5a, 5d to 5e compared to Figures 5b & 5c. On the other hand, relatively more (less) areas of rainfall ≥8mm/day can be seen along the west coast, and over Assam &Meghalaya (Arunachal Pradesh) in higher resolution data sets compared to lower resolution data sets. Similarly higher resolution data sets depict relatively drier climatology over northern parts of Jammu and Kashmir.

The mean annual rainfall climatology patterns based on higher resolution data sets (IMD4, IMD3 & APHRO) show closer resemblance except along the west coast, the zone of maximum rainfall areas is slightly narrower and the areas of rainfall ≥8mm/day are relatively more in IMD4 compared to other two data sets. Another difference is the areas of ≤ 2mm/day in the leeward side of the Western Ghats, North Jammu & Kashmir and a thin belt along northern parts of Uttarakhand are relatively more in APHRO compared to the other two data sets. Over north Saurashtra and Kutch, Sikkim and Arunachal Pradesh also relatively drier annual rainfall climatology is seen in APHRO compared to other two data sets. Overall, the annual climatology patterns in IMD4 & IMD3 showed highest resemblance mainly due to the near same basic station rainfall data and commonality in the method of interpolation used for the preparation of these two data sets.

For the visualisation of comparison of seasonal rainfall climatology based on the same five data sets, Figures 6 to 9are presented here. These figures depict the seasonal rainfall climatology over Indian main land computed for the four seasons (winter (January- February), pre-monsoon (March-May), southwest monsoon (June – September) & northeast monsoon season (October-December)) of India. It is seen from the Figures 6 to 9 that during all the seasons, the large scale climatology features were nearly same in all the data sets except for higher spatial details seen in the higher resolution data sets. However, like in the case of annual climatology (Fig.5), the most noticeable point was the relatively drier climatology over North Jammu & Kashmir and a thin belt along northern parts of Uttarakhand, Sikkim and Arunachal Pradesh in APHRO compared to the 4 IMD data sets during all the four seasons. Similarly, relatively drier rainfall climatology during the southwest monsoon season is seen over many areas in the leeward side of the Western Ghats in APHRO compared to other data sets. Another noticeable point was the relatively narrower zone of higher rainfall (≥15mm/day) along the west coast during southwest monsoon season observed in IMD4.

The Fig.10shows the mean annual cycle of the daily rainfall averaged over the Indian main land based on IMD1, IMD2,IMD3,IMD4 and APHRO.The base period used for computing mean annual cycle of IMD3 was 1971-2000 and that for other 4 data sets was 1951-2000. The mean annual cycle with peak during the middle of the monsoon season and minimum during the winter season is seen in all the data sets. However, it is seen that throughout the annual cycle, the daily mean values in APHRO is the lowest. The daily average rainfall in IMD2 was the highest in peak segment of the annual cycle (from around end of June to around end of September). Average daily values of IMD1were the highest during most days of the first 3 months and many days in the last segment of the annual cycle. Over other parts of the annual cycle, daily values of either IMD3 or IMD4 were the highest. The difference between the highest mean daily rainfall values in IMD2 (on 17th July) and APHRO (on 18th July) was 1.86mm/day and that between IMD2and IMD4 (17th July) was 0.68mm/day. Another striking feature was the near coincidence of the mean annual cycles in IMD3 & IMD4 irrespective of the difference in the base periods used for computing the averages.

The first 4 columns of the Table-2 show the mean monthly, seasonal and annual area weighted rainfall over the Indian main land derived from IMD1, IMD2, IMD4 and APHRO for the base period of 1951-2000. The same information derived from IMD4 and IMD3 but for the base period of 1971-2000 is given in the next two columns. All the values are expressed in terms of mm/day. The monthly mean values of all the data sets showed very similar annual cycles with peak in July and minimum during December- January period. However, the most noticeable point is that the lowest mean values in all the categories (monthly, seasonal and annual) were observed in APHRO.

For the 1951-2000 climatology, the highest mean monthly values are observed in IMD1 for the first 3 months of the year (January to March), June and the last 3 months of the year (October to December), in IMD2 for the last 3 months (July to September) of the southwest monsoon season, and in IMD4 for the 2 pre monsoon months (April – May). Accordingly, the highest mean seasonal values are observed in IMD1 for the winter and post monsoon seasons, in IMD2 for the southwest monsoon season, and in IMD4 for the pre-monsoon season. The mean annual rainfall is also the highest in IMD1. The difference between highest and lowest mean annual rainfall is 0.53 mm/day. The difference of the all India mean annual rainfall in IMD4 with the highest mean annual rainfall and is about 0.12 mm/day and that with the lowest mean annual rainfall is 0.41 mm/day. i.e. The all India annual mean rainfall in IMD4 is drier than that in IMD1 by about 4% and wetter than that in APHRO by about 13%. Among the seasons, the difference between highest and lowest mean season rainfall in the data sets is highest (1.17mm/day) for southwest monsoon season and minimum (0.27 mm/day) for winter season. The difference between the highest mean season rainfall in all data sets and the mean season rainfall value in IMD4 is about 0.39 mm/day for southwest monsoon season. Among the months, the maximum difference between highest and lowest mean month rainfall in the data sets is maximum (1.56 mm/day) for July and minimum (0.15 mm/day) for December. The difference between the highest mean monthly rainfall in all data sets and the mean monthly rainfall in IMD4 was highest in July (0.61 mm/day) and lowest in March (0.28 mm/day).

It is seen in the last two columns of Table-2 that the 1971-2000 based mean monthly, season and annual rainfall over the Indian main land in both the higher resolution versions of the IMD data sets (IMD4 and IMD3) are very close to each other. However, in most of these cases (except for June & July), the mean values in IMD4 are slightly higher than that in IMD3. The monthly values are higher by (0.01-0.12 mm/day), seasonal values are higher by (0.02-0.08mm/day) and annual rainfall is higher by 0.05 mm/day. The all India annual rainfall in IMD4 is wetter than that in IMD3 by about 1.5%. On comparing the 1971-2000 mean values (not shown here), it was found that the mean southwest monsoon season and annual rainfall averaged over the Indian main land in the higher resolution versions of the IMD data sets (IMD4 and IMD3) show dry bias of the order of about 0.11 -0.13 mm/day compared to that in the lower resolution versions (IMD1 and IMD2). The main reason for the same is the relatively narrower zone of higher rainfall along the west coast during south west monsoon season in the higher resolution data sets.

4.1.2. Temporal Variation of All India Rainfall

In this section, monthly area weighted all India (averaged over the country as a whole) rainfall derived from IMD4 was compared with that derived from IMD1, IMD2, APHRO & IMD3. For this, various statistical quantities such as correlation coefficient (C.C), average difference (Bias) and root mean square difference (RMSD) of the all India monthly rainfall derived from IMD4 with that derived from IMD1, IMD2, APHRO & IMD3 were computed for each of the four seasons during the period considered and for the total period (Annual) and is given in the Table-3. All quantities except the C.C are expressed in mm/day. About 76% of the annual rainfall over the country as a whole is obtained during the southwest monsoon season (June to September) and its year to year variation has profound impact on the sectors like agriculture, Hydro-electric power generation. So it is important to examine how the interannual variability of all India southwest monsoon rainfall is represented in IMD4 data set. Therefore, the all India southwest monsoon season rainfall derived from IMD4 was compared with that derived from various gridded rainfall data sets. A comparison was also carried out with the IMD_OP all India southwest monsoon season rainfall time series.

The Fig. 11a shows the scatter plot of the all India monthly rainfall derived from IMD1 against that derived from IMD4 and time series plot of the difference between these two series. Figures 11b to 11d are similar to Fig.11a but for IMD2, IMD3 & APHRO respectively plotted against IMD4. The 3 plots (Figures 11a, 11b &11d) were derived for the period of Jan1951 to Dec 2000 and the Fig.11c was derived for the period Jan 1971 to 2000. It is seen from the Table-3 and the Figures

11a to 11d, when all the months of the period are considered (annual),all the four data sets are highly consistent with that of IMD4 as all the C.Cs are nearly 1. The differences were the least with IMD3 (Bias=0.05mm/day RMSD=0.11mm/day) and highest with APHRO (Bias=0.41mm/day RMSD=0.52 mm/day). However, IMD4 show dry bias with IMD1 and IMD2 and wet bias against APHRO& IMD3. In fact, IMD4 shows wet bias with IMD3 & APHRO during all the seasons of the year. IMD4 shows dry bias with IMD1 during all the seasons except MAM, and show dry bias with IMD2 during JJAS & OND and wet bias during the other two seasons. Among various seasons, in all the data sets, highest consistency and the differences with IMD4 were observed during the monsoon season. On the other hand, the consistency and differences of IMD4 with other data sets were least during the winter season. Among all the data sets, IMD3 showed highest consistency and least difference with IMD4.

Fig.12 show the year to year variation of the all India southwest monsoon season (June to September) derived from each of the 5 gridded rainfall data sets used in this study along with IMD_OP time series. As discussed in the section 2, each of the data sets are of different periods and for preparing Fig.12 all the available data were used. Thus the time series derived from IMD3 is available for the period 1971-2005. Whereas the all India time series derived from the IMD4 and IMD_OP are available for the period 1901-2010. All the values are expressed in mm/day.Table-4 shows various statistical measures (C.C, Bias and RMSD) relating interannual variability of all India summer monsoon rainfall derived from IMD4 with that that derived from IMD1, IMD2, APHRO, IMD3 & IMD-OP. These statistical measures were computed using all the available data and are expressed in mm/day. Table-4 also shows similar measures for the interannual variation of the all India annual rainfall.

A first look in the Fig.12 reveals that the year to year variation in the all India southwest monsoon season time series in respect of IMD4 is in phase with the time series derived from other gridded rainfall data sets during most part of the respective common data periods. This is also reflected in the significant C.C. values (0.90 to 0.97) shown in the Table-4. In the Fig.12, it can also see that the all India southwest monsoon season rainfall derived from APHRO have the lowest values among all the time series during all the years of its data period (1951-2007). On the other hand, the IMD2 time series have relatively higher values among all the time series during most of the years of its data period (1901-2004). The time series of IMD1 shows slightly higher values compared to that of IMD4 during most of the years of 1951-2010. On the hand, IMD3 & IMD4 time series nearly match each other during most of the period (1971-2005) except in 2005 when the IMD3 value was more than IMD4 value by about 2mm/day. Only because of the large difference of values in 2005, the C.C. between the all India time series of IMD3 & IMD4 was reduced (0.90 for southwest monsoon season). On removing the year 2005 the C.C between IMD3 & IMD4 series was 0.98.

As seen in the Table-4, in respect of all India southwest monsoon season rainfall, IMD4 showed dry bias against IMD1, IMD2 & IMD3 and wet bias against APHRO. The highest difference (RMSD = 0.84 mm/day and Bias= 0.81mm/day) was observed against APHRO. The lowest RMSD (0.42mm/day) was against IMD2 and lowest bias (-0.04mm/day) was against IMD3. The interannual variation of IMD4 series was also highly consistent with that of IMD_OP series with a C.C of 0.97 for the period 1901-2010. The difference (RMSD of 0.32 mm/day, Bias = -0.26mm/day) of IMD4 seasonal times series against the IMD_OP series was also lower than that with the seasonal time series derived from the gridded rainfall data sets. The results of statistical measures in respect of all India annual rainfall presented in the Table-4 was more or less consistent with that in respect of all India seasonal rainfall.

Thus, it can be summarised that though there is some bias among the various time series, there is strong consistency in all these time series in respect of their year to year variation. Further the southwest monsoon rainfall time series derived from the IMD4 closely matched with the IMD_OP series throughout the total data period (1901-2010). It was also observed that the highest 10 rainfall years and lowest 10 rainfall years in the time series of both the IMD4 & IMD_OP were nearly same except for the difference in the order of rank.

4.2. Analysis of Break and Active Monsoon Events over India Using the New Gridded Rainfall Data Set (IMD4)

Over India, the large scale rainfall during the SW monsoon season is received in spells with intermediate dry spells. As discussed in the section 3, after SW monsoon gets established over Central India, the ITCZ merges with the monsoon trough and causes copious rainfall over large areas of the country with maximum along the west coast and over central India. During the peak monsoon rainfall months (July and August) of the season, the monsoon trough shifts north and south about its normal position causing large scale intraseasonal rainfall variation over the country. The intervals of dry monsoon conditions during which the large-scale rainfall over the monsoon trough zone (the zone between which the monsoon trough fluctuates north and south wards) is interrupted for several days in July and August are known as the breaks (Ramamurthy 1969, Raghavan 1973, Krishnamurti and Bhalme 1976, Alexander et al. 1978). On the other hand, the intervals between spells of dry monsoon conditions when the rainfall is higher than normal are known as active spells. Ramamurthy (1969) was the first to propose criterion for identifying breaks and identify break spells for the period 1988-1967. Ramamurty (1968) used synoptic criteria to define break as the situations when the trough of low pressure was not seen on the surface chart (the shifting of monsoon trough to the foot hills of Himalayas) and the easterlies were practically absent in the lower tropospheric levels up to about 1.5 km above sea level for more than 2 days. However, Ramamurthy (1969) did not propose any criteria for identifying active spells. De et al. (1998) using the criteria of Ramamurthy (1969) identified breaks for the period 1968-1996. Later simplified definition of the monsoon break and active spells based on rainfall over India was used by several studies (Rodwell 1997, Annamalai & Slingo 2001, Gadgil& Joseph 2003, Ramesh Kumar and Prabhu Desai 2004, Mandke et al. 2007, Krishnamurthy and Shukla 2000, 2007 & 2008, Rajeevan et al. 2010). Rajeevan et al. (2010) based on IMD1 data set, suggested criteria for identification of active and break events of the Indian summer monsoon on the basis of average rainfall over a critical area over central India, called the core monsoon zone. Accordingly the active and break events were defined as periods in which the normalized anomaly of the rainfall over the core monsoon zone exceeds 1 or is less than -1.0 respectively, provided the criterion is satisfied for at least three consecutive days. Rajeevan et al. (2010) identified the active and break spells for the period 1951-2007 using these criteria and found to be mostly comparable with those identified by Ramamurthy (1969) and De et al. (1998).

In this study, we have used the criteria suggested by Rajeevan et al. (2010) but using IMD4 to identify the break and active spells for the entire data period of 1901-2010. For this purpose, the normalised daily anomaly index of the rainfall over the region whose domain is shown in the Fig.13 was used with 1951-2000 as the base period. This region is nearly same as the core monsoon zone proposed by Rajeevan et al. (2010).

The Tables 5 & 6 lists the break and active spells identified in this study for the period of 110 years (1901-2010). During the study period of 1901-2010, there were 140 break spells of 869 days and 201 active spells of 809 days. To examine the spatial distribution of rainfall anomaly over India associated with the break and active events, composite daily rainfall maps of these 869 break days and 890 active days were examined (Figures 14a & 14b). As seen in Figures 14a & 14b, the broad composite daily rainfall anomaly patterns in respect of active & spells were found to be exactly opposite to each other. During the active (break) days, the rainfall along the west coast and over most areas of monsoon trough zone were above (below) normal by ≥6mm, that along the Himalayas were below (above) normal by ≥3mm and that over southeastern Peninsula were below (above) normal by 0-3mm.

It was observed that the break and active spells identified in this study are comparable and nearly consistent with that identified by Rajeevan et al. (2010) for the common period of 1951-2007. This was expected as both the present study and Rajeevan et al. (2010) used similar criteria and similar rainfall based index (though derived from two data sets with different grid resolution) to identify the break events. Therefore, a comparison of break and active spells identified by these two studies has not been shown here. However, a comparison analysis of break spells identified by this study based on the rainfall criteria and those by Ramamurthy 1969& De et al. 1998 based on the synoptic conditions for the period 1901-1996 has been discussed (see the next section). The study also discusses various climatological and variability features of the break and active spells identified in this study for the entire data period of 1901-2010.

4.2.1. Comparison of Breaks Events – Synoptic Vs Rainfall Criteria

Tables-5shows the days of break spells identified based on synoptic criteria for the period 1901-1996 in addition to that identified based on rainfall criteria in this study. As seen in the Table-5, during the common period of 1901-1996, there were 116 break spells consisting of 721 days based on the rainfall criteria and equal number of break spells consisting of 719 days based on synoptic criteria. About 68% of the break spells (78 spells) identified by each of these two criteria were comparable, as there was overlapping between these break spells based on both the criteria. These overlapping break spells from both the cases can considered as the break spells that satisfied both the rainfall and synoptic criteria. However, 38 break spells (about 32%) consisting of 162 days based on rainfall criteria did not overlap with that based on synoptic criteria. Similarly, 38 break spells (about 32%) consisting of 161 days based on synoptic criteria did not overlap with that based on rainfall criteria. The break spells that did not have overlapping between the two criteria are marked in the Table-5 using bold letters, most of which were found to be of shorter durations.

In order to distinguish between the break spells identified by rainfall and synoptic criteria, composite daily rainfall anomaly patterns associated with these events were examined. The Figures 15a & 15b show the composite daily rainfall anomaly maps of 78 break spells each identified by the rainfall and synoptic criteria respectively which are overlapping to each other. Figures 15c & 15d are similar to Figures 15a & 15b respectively but for the non-overlapping break spells.

All the figures (15a to 15d)exhibit typical broad break monsoon rainfall anomaly distribution (similar to14a)with negative rainfall anomalies over the monsoon trough zone and along west coast and positive rainfall anomalies along the Himalayan foothills and southeast Peninsula. The composite rainfall anomaly patterns of overlapping break spells in respect of both the criteria (Figures 15a & 15b) were nearly same except for slightly stronger negative anomalies over some central areas of monsoon trough zone in Fig.15a compared to Fig.15b. On the other hand, there were noticeable differences in the composite rainfall anomaly maps of non- overlapping break spells (Figures 15c & 15d). The negative anomalies over many areas of the monsoon trough zone in the composite map of break days identified based on rainfall criteria (Fig.15c) are stronger by about 3-6mm/day than that based on synoptic criteria (Fig.15d). In addition, whereas the Fig.15c resembled close to Figures 15a & 15b, the Fig.15d showed extension of positive rainfall anomalies along the Himalayas southward into the monsoon trough zone resulting in the reduced spatial extent of the negative anomalies over the region. This indicates that the 38 non-overlapping break spells identified by synoptic criteria may actually be weak monsoon rainfall spells as the breaks basically means the interruption/ significant decrease in the rainfall over the monsoon zone region.

4.2.2. Climatological and Variability Features of Breaks and Active Events

In this section, statistical properties of break and active events identified in the present study for the period of 1901-2010 were computed and examined. The statistical features were also computed for the two equal halves (1901-55 & 1956-2010) of the data period to examine climate shift if any in the break and active events.

During the study period of 1901-2010, there were 140 break spells of durations varying from 3 to 18 days (57 in July, 72 in August and 11 in July to August (starting in July and ending in August)). Similarly there were 201 active spells of durations varying from 3 to 12 days (95 in July, 93 in August and 13 in July to August). The average duration of the break spells was 6.2 days (5.9 days in July, 6.2 days in August and 8.4 days in July to August) and that of the active spells was 4.3 days (4.1 days in July, 3.9 days in August and 4.4 days in July to August). During the total data period (1901-2010), the longest break spell of 18days duration was occurred in 1928 (30th July to 16th August) followed by 3 break spells of 17days duration each occurred in 1902(1-17th August), 1918 (10-26th July) and 1972 (18th July- 3rd August). During the same period the longest active spell of 12 days duration was occurred in 2006 (27th July to 7th August) followed by an active spell of 11 days duration occurred in 1907 (11-21st August).

During 1901-55, there were 70 break spells of durations varying from 3 to 18 days (26 in July, 40 in August and 4 in July-August overlapping period) and 92 active spells of durations varying from 3 to 11 days (44 in July, 43 in August and 5 in July-August). The average duration of the break spells was 6.3 days (6.2 days in July, 6.4 days in August and 8.8 days in July to August overlapping period) and that of the active spells was 4.0 days (4.2 days in July, 3.8 days in August and 4.4 days in July to August overlapping period).

During 1956-2010, there were 70 break spells of durations varying from 3 to 17 days (31 in July, 32 in August and 7 in July-August) and 109 active spells of durations varying from 3 to 12 days (51 in July, 50 in August and 8 in July to August overlapping period). The average duration of the break spells was 6.3 days (5.6 days in July, 5.8 days in August and 8.1 days in July to August overlapping period) and that of the active spells was 3.9 days (4.0 days in July, 3.7 days in August and 4.8 days in July to August overlapping period).

Fig.16a shows the histogram of duration of break and active spells for the total period of 1901-2010. It is seen in this figure that in general, both active and break spells of short durations were more frequent than the longer durations with about 63.6% of the break spells and 93.5% of the active spells falling in the range of 3-6 days. There were no active spells of duration ≥ 13days. However,, about 7% of the break spells were of duration ≥ 13days.

The Figures 16b & 16c show the histogram of the duration of break and active spells for 1901-55 & 1956-2010. During the period 1901-55, the number of break (active) spells was 70 (92) and that during the period 1956-2010 it was 70 (109) indicating nearly equal number of break spells during the two halves of the period and an increase of about 18% in the number of active spells in the second half. It is further seen that the rise in the active spells during the second half is mainly in the lower duration (3-6 days) spells. In the intermediate and longer duration (≥ 7 days) side, the number of active spells shows slight decrease. On the other hand, in case of breaks, the distribution of spells of various durations is more or less same during both the halves of the data period.

Below we discuss the various statistical features of break and active spells in terms of days of the event rather than in terms of spells.

The year to year variation of the number of break and active days for the period 1901–2010with trend lines fitted for the total and two halves of the data period is shown in Figures 17a & 17b respectively. The Table-7 shows some statistical features of the interannual variability of breaks and active days for July, August and July+August computed for 3 different periods (1901-2010, 1901-55 & 1856-2010). During the total period, there were 869 break days with an average of 7.9 days and standard deviation (SD) of 6.5 days per season. In the same period, there were 809 active days with an average of 7.4 days and SD of 4.8 days per season. Similarly the average & SD of break days in August (4.6 days & 4.8 days) were more than that in July (3.3 days & 4.4 days). On the other hand the average of active days in July (3.8 days) was more than that in August (3.6 days). But S.D of active days in August (3.68 days) was slightly more than that in July (3.4 days). July is more favoured for active days (52% of the total active days) than break days (42% of the break days). On the other hand, August is more favoured for breaks days (58% of the break days) than active days (48% of total active days). During the period 1901–2010, the maximum number of break days occurred in 1941 (28days with 16 days in July and

12 days in August) followed by 2002 (23 days in July). The maximum number of active days occurred in 1994 (24 days= 13 days in July and 11 days in August) followed by 2006 (23 days = 9 days in July and 14 days in August).

On comparing the statistics during the two halves of the data period, it can be seen that there occurrence of average break days in August was more during the first half by about 1 day per season comparing to that in the second half. In July, the case was opposite but with a difference of about half a day per season. As a result the occurrence of average break days in the July+ August period was slightly more during the first half compared to that in the second half. However, in case of active days the occurrence of active days during the second half was relatively more than first half in all the cases. As seen in the Fig.17a, a decreasing trend was observed in the break days during the first half and increasing trend during the second half. As a result no trend was observed for the entire period. In case of active days (Fig.17b), during all the data periods, slight increasing trends were observed. However in all the cases of breaks and active days, the observed trends were not statistically significant.

Table-8a & 8b show the decadal distribution of the number of break & active days respectively during the period 1901-2010. The distribution of the events within the two months period (July-August) is shown by dividing July and August months into 3 near equal periods of 10 days each (last period is of 11days). In the Table-8a, the decadal distribution of break days shows that during each of the months, middle 10 days is most prone for breaks. However, when both the months taken together, the middle 10 days followed by first 10 days both of August recorded highest number of break days (25% & 17% respectively of the season). The decadal variation shows that the highest number of break days during the first 4 decades (1901-10,1911-20,1921-30 & 1931-40) was recorded during the middle decade of August, that during the next 2 decades (1941-50&1951-60) was recorded during the last 10 days of the August. Again the highest number of break days during the decades 1971-80 &1991-2000 was during the middle 10 days of the August and that during 1981-1990 & 2001-2010, it was last 10 days of the August. Thus it can be seen that during 10 of the 11 decades, the highest number of breaks were recorded in August during either middle or last 10 days s. It was only in the decade 1961-1970 that the 10 days wise highest number of breaks was observed in July (middle 10 days). However, it is also interesting to note that during the decade (1951-60), there was not a single break day during the first two 10 days of August. On examining decadal variation of month wise break days, it is observed that there were only 3 decades (1951-60& 1961-70) when the break days were more during July compared to August. In the recent decade (2001-2010) the number of break days during July and August was nearly equal (47 & 49 days each). In case of decadal variation of season wise break days, maximum number of break days (108 days) was observed during 1911-20 & minimum number of break days (43 days) was observed during 1951-1960.

In case of active events (Table-8b), 52% of the total 809 active days was in July with an average of 3.8 days per season and 48% was in August with an average of 3.6 days per season. It is also seen that, during the two months period, the last 10 days (in fact 11days) of both the months are most and equally favourable for active events (21% of the total active days each) with an average of 1.5 days per season. The decadal variation shows that during 4 (1921-30, 1941-50, 1961-70 &1991-2000) of the 11 decades, highest number of active days was observed in the last 10 days of July and during another 4 decades (1911-20,1931-40,1971-80,1981-1990), that was in the last 10 days of August. In the remaining 3 decades, the highest number of active days was experienced in the first 10 days of July during 1 decade (1951-60), in the second 10 days of August during 1 decade (1901-10) and in the first and last 10 days of August during 1 decade (2001-2010). The decadal variation of month wise activedays shows that during 6 of the 11 decades including the last two decades, the number of active days in July was higher compared to August. The decadal variation of season wise active days shows that the maximum number of active days (90 days) was observed during 1941-50 & minimum number of active days (53 days) was observed during 1951-1960.

Ramamurthy (1969) on examining the decadal variation of the breaks for the 80 years period (1888 -1967), observed a mutually exclusive relationship with decadal variation of number of monsoon low pressure systems (lows and depressions) formed over the Indian region during July and August. To re-examine the above relationship with the new break/active monsoon information obtained in the present study, 11 years moving average of break days has been plotted along with the 11 years moving average of number of lows as well as that of number of monsoon depressions formed in the Indian region during July and August (Fig.18). For this purpose, data for the entire period of 1901-2010 was used. The Fig.18 also depicts decadal variation of active days. As seen in the Fig.18, the break days shows multi-decadal variation with maxima around late 1900s, late 1930s, late 1960s and late 1990s and minima during the 1920s, late 1950s and early 1980s. In addition, a general decreasing trendis seen from the beginning of the data period to around the middle of the data period (late 1950's) and then an increasing trend till the end of the data period. On the other hand, the active days show decadal variation with maxima around early 1940s, early 1970s & early 2000s and minimum around early 1900s, early 1960s, & early 1980s. However, no secular trends are seen in the decadal variation of active days. On comparing with the decadal variation of monsoon depressions, it can be seen that there is a general out of phase relationship between the number of monsoon depressions and break days as suggested by Ramamurthy (1969). But the more interesting aspect in the Fig.18 is the relatively stronger in phase relationship between the decadal variation of monsoon depressions and that of the active days till around early 1980s which failed later due to sudden decrease in the number of monsoon depressions. Several earlier studies have reported decreasing trend in the number of the monsoon depressions since 1976 (Stowasser et al.2009, RajendraKumar and Dash 2001, Sikka 2006, Ajayamohan et al. 2010, Rao et al. 2008, Rao et al.2004, Mani et al. 2009, Jadhav and Munot 2009).As seen in the Fig.18, during the decreasing phase of monsoon depressions, both break and active days showed general increase; but the increase in the break days being relatively more with the break days per season increasing from around 3 days to 5 days. On the hand, the active days per season increased from around 3 days to 4 days. The observed failure of the in phase relationship between the active days and number of monsoon depressions after early 1980s can be explained by the sudden increase in the number of monsoon lows over Indian region during the same period. As seen in the Fig.18, from the beginning of the data period to till late 1970s, the decadal average of the number of monsoon lows during July and August was between 2 to 3which doubled in the later period. Decadal analysis of monsoon lows and monsoon depressions by Jadhav and Munot (2009) has also revealed significant increase(decrease) in the frequency and duration of monsoon lows (monsoon depressions) during recent decades. Based on daily rainfall analysis for the period 1901-2003, Krishnamurthy and Ajayamohan (2008) have shown that the daily rainfall pattern when any of the monsoon low pressure systems such as lows, depressions, cyclonic storms etc. are present in the

Indian monsoon region represents the active monsoon phase and that when the low pressure systems are absent represents the break monsoon phase. Thus the decrease in the monsoon depressions was compensated by the increase in the monsoon lows which kept the active days to its normal or above normal limit during the recent decades.

4.3. Extreme Rainfall Events during the Southwest Monsoon Season

According to a recent IPCC report (IPCC, 2007), during the last few decades, the world's surface temperatures have increased at an unprecedented rate due to global warming. This has impacted the hydrological cycle and precipitation patterns over the globe. Changes have been observed in the amount, intensity, frequency and type of precipitation and these changes generally exhibit large natural variability. Pronounced long-term trends have been observed in the precipitation amounts in some places. Increases in the evaporation from the warming oceans and water holding capacity of the atmosphere under warming climate have caused increase in the water vapour content in the atmosphere especially at lower latitudes. As a result, widespread increases in heavy precipitation events have been observed, even in places where total precipitation amounts have not changed or decreased. Increases have also been observed in the seasonal droughts and floods events in some regions and in the global area affected by drought since the 1970s.

Recently there have been also several studies on daily extreme rainfall events over India based on station and grid point rainfall data (Sen Roy and Balling 2004, Joshi and Rajeevan 2006, Goswami et al. 2006, Rajeevan et al. 2008, Ghosh et al. 2009, Krishnamurty et al. 2009, Guhathakurta et al. 2011). Joshi and Rajeevan (2006) using station data of about100Indian stations for the period 1901 to 2000, carried out linear and parametric trend analysis on various measures ofextremes and found increasing trends over west coast and northwestern India. Guhathakura et al. (2011) based on the daily rainfall data of about 2599 stations having at least 30 years of data during the period 1901-2005observed that the frequency of heavy rainfall days (days with rainfall ≥64.5mm) over major parts of central and north India is decreasing and that over peninsular, east and north east India is increasing. Goswami et al. (2006) using the IMD1 examined the trends in the extreme rainfall (ER) events over central India during the southwest monsoon season (June-September) for the period 1951-2000 by classifying the ER events into three categories; moderate rainfall (≥5mm to 100mm) or MR events, heavy rainfall (≥100mm) or HR events and very heavy rainfall (≥150mm) or VHR events. Goswami et al. (2006) observed significant rising trends in the frequency and the magnitude of HR and VHR events and significant decreasing trend in the frequency of MR events resulting in to insignificant trend in the mean rainfall over central India during the period. Rajeevan et al. (2008), following the definition of extreme rainfall events by Goswami et al. (2006) and using IMD2 for the period 1901-2004 examined the variability and long-term trends of ER events over central India. Rajeevan et al. (2008) found a statistically significant long term trend of 6% per decade and significant inter-annual & inter-decadal variations in the number of VHR events over central India and found an association with the SST anomalies over the equatorial Indian Ocean. Rajeevan et al. (2008) also found significant decreasing trend in the number of MR events.

In this section, the objective is to re-examine the variability and long term trends in the extreme rainfall over central India (CI) during the southwest monsoon season (June-September) using the IMD4, which is of higher spatial resolution and longer period compared to previously used data sets for the same purpose (IMD1 and IMD2). In addition, variability and trend analyses have been carried out over other two regions that experience ER events on several occasions during the southwest monsoon season; northeast India (NEI) where the topography plays important role in deciding the rainfall pattern over the region &west coast (WC), which is on the windward side of the mountain range of Western Ghats.

The spatial domains of CI, NEI and WC enclosing 2152, 398, & 234 grids respectively are given in the Fig.19 which depicts grid point frequency of ER events. As seen in the Fig.19, the grid points within CI receive about 30-60 days per season of ER events and the most of the grid points within the other two regions (WC & NEI) receive ≥ 60 days per season of ER events. It has been observed that ER events occur during 34%, 54% & 51 % of the total possible grid point days (number grid points X number of days (122)) per season respectively over CI, NEI & WC. The highest grid point rainfalls recorded over CI, NEI & WC during the entire data period were 763.38mm, 939.45mm &820.86mm respectively.

Various statistical properties including trends of area weighted rainfall and grid point ER events over CI, NEI & WC during the southwest monsoon season are given in the Tables 9, 10 & 11 respectively. In order to check whether there is any climate shift in the rainfall characteristics during the data period, statistics were also prepared for each of the two halves (1901-1955 & 1956-2010) of the data period and the same are also presented in these tables. In the Tables 9, 10 & 11, means in the two halves that are significantly different at 95% (99%) and the trends that are significant at 95% (99%) are shown with asterisk or * (double asterisk or **). It was observed that the area weighted rainfall and ER events of all the three regions are highly correlated. The C.C. between the area weighted rainfall and number of ER event during the data period 1901-2010 for CI, NEI & WC were 0.95, 0.84 & 0.82 respectively.At the same time 98.8% of the ER events in CI, 98.3% of ER events in NEI and 96.5% of the ER events in WC were in the MR category. Also the ER events contributed 92.9% (MR = 85.7% & HR & VHR = 7.2%) of the total rainfall over CI. These figures for NEI and WC were 95.8% (MR = 86.1% & HR & VHR = 9.7%) and 95.2% (MR = 80.1% & HR & VHR = 16.0%) respectively. This indicates that major portion of the season rainfall received over all these regions during the southwest monsoon season is in the form of MR events. However, over the west coast, about 16% of the total rainfall is received in the form of HR & VHR events.

As seen in the Table-9, CI receives area weighted mean rainfall (averaged over 1901-2010) of 7.85mm/day during the monsoon season with a standard deviation of 0.84mm/day (coefficient variation (CV) of 10.7%). However, no significant difference was observed between the rainfall means during the two halves of the data period. No significant linear trend was also observed in the season rainfall over CI during the data period. However, a positive linear trend of 0.15mm/day per decade significant at 95% level was observed during the first half (1901-1955).

In respect of ER events, a significant (at 95% level) decrease in the mean number of ER events with increased variability was observed over CI during the second half compared to the first half. This was mainly caused by the significant decrease in the mean number of the MR events (from 90426 events/season during the first half to 86520 events/season during the second half). On the other hand, the mean number of HR and VHR events showed increase in the second half compared to the first half with the difference in the means of VHR events being significant at 99% (from 229 events/season during 1901-1955 to 290 events per season during 1956-2010).

The long term linear trend in the number of ER events per monsoon season during the total period showed decrease of 538.7 events per decade which is not statistically significant. However, increasing trend of 1748.2 events per decade during the first half and decreasing trend of 1902.7 events per decade during the second half of the data period both significant at 95% level were observed. Fig. 20 shows the interannual variation of category wise number of ER (MR, HR & VHR) events over CI respectively for the period 1901-2010 with trend lines fitted for the total and two halves of the data period. Among the various categories of ER events over CI, during the entire data period, MR events showed decreasing trend (564.2 events per decade),HR events showed increasing trend (12.3 events per decade) and VHR events showed increasing trend (13.3 events per decade) all at 95% significant level. During first half, significant increasing trend (1731.6 events per decade at 95% significant level) was observed only in the MR events. On the other hand, during the second half, significant decreasing trend (1984.3 events per decade at 95% level) was observed in the MR events, while increasing trends were observed in the HR (42.9 events per decade at 95% level) and VHR events (38.6 events per decade at 1% level).

Over NEI, the mean and standard deviation of the area weighted rainfall for the monsoon season for the period of 1901-2010 were 13.73 mm/day and 1.85mm/day respectively (Table-10),i.e., C.V of 13.5%. Significant climate shift in the season rainfall over NEI was observed during the period with the mean rainfall being significantly (at 95% level) less and the variability being higher during the second half of the period compared to these measures during the first half. Decreasing trends were observed in the mean monsoon season rainfall over NEI during the total period and during the second half of the season. But these trends were not significant. However, an increasing trend of 0.34 mm/day per decade significant at 99% level was observed during the first half.

The mean number of ER events during the second half was found to be significantly (at 99% level) less than that during the first half. The variability of the number of ER events was higher in the second half. The difference in the mean ER events between the two halves was mainly caused by the significant (at 99% level) decrease in the mean number of the MR events in the second half compared to the first half. However, the mean number of HR and VHR events showed increase in the second half compared to the first half with the difference in the means of NHR events being significant at 99% (from 88 events/season nearly doubled to 164events per season).

The long term linear trend in the number of ER events during the total period showed decrease of 179.9 events per decade significant at 99% level. Interestingly, positive trends of 395.3 events per decade (significant at 99% level) and 6.2 events per decade were observed during the first and second halves of the period. The interannual variation of category wise number of extreme rainfall events over NEI for the entire data period with trend lines fitted for various data periods are shown in the Fig.21. As seen in the Fig.21& Table-10, during the total data period, there is decreasing trend in the MR events (196.3events per decade at 1% significant level), and increasing trends in HR events (4.1 events per decade) and VHR events (12.3 events per decade at 95% significant level). During the first half, significant increasing trends were observed in all the 3 categories of ER events. On the other hand, during the second half (1956-2010) significant trend (decreasing) was observed only in the HR events (35.7 events per decade at 99% level).

Over the WC, the mean and standard deviation of the area weighted rainfall for the monsoon season during the entire data period of 1901-2010 were 15.04mm/day and 2.12mm/day respectively (Table-11), i.e., C.V of 14.1%. No significant difference was observed in the mean rainfalls over WC between two halves of the data period. No significant long term linear trends were also observed in the season rainfall over WC during the entire data period as well as during the two halves of the data period.

There was slight insignificant decrease in the mean number of ER events over WC with slight increase in the variability from first to second half of the period. This was result of significant (at 95% level) decrease in the mean number of MR events (14165events per season to 13665events per season) from first to the second half being partly compensated by the increase in the mean number of HR events (355 events per season to 393 events per season) and VHR events (116 events per season to 143events per season at 95% level). Fig.22 shows the interannual variation of category wise number of ER events over WC for the entire data period with trend lines fitted for various data periods. As seen in the Table-11 & Fig.22, no significant long term linear trends were observed in the number of ER & MR events during the total period as well as two halves of the data period. However, significant increasing trends were observed in the HR events (6.8 events per decade at 95%

level) and VHR events (5.0 events per decade at 99% level) during the total period. A significant increasing trend in the HR events (19.2 events per decade at 95% level) during the first half was also observed.

5. Summary and conclusions

Development of a new daily gridded rainfall data set (IMD4) at a very high spatial resolution (0.25^o X 0.25^o, latitude X longitude) covering a long period of 110 years (1901-2010) over Indian main land and its comparison with 4 existing daily gridded rainfall data sets over the region have been discussed. Use of IMD4 to examine climatology, variability and long term trends of two different types of rainfall events over India, namely (1) break and active monsoon spells and (2) extreme daily rainfall events over India have also been discussed. Out of the 4 gridded daily rainfall data sets over India used for comparison with IMD4, 3data sets were developed by India Meteorological Department (IMD); two 1^oX1^ogridded daily rainfall data sets (IMD1 (Rajeevan et al. 2006 & 2010) & IMD2 (Rajeevan et al. 2008)) based on fixed network of rain gauge stations, and a $0.5^oX0.5^o$gridded daily rainfall data set (IMD3) based on a variable network of rain gauge stations (Rajeevan et al. 2009). The fourth daily rainfall data set (APHRO) of spatial resolution $0.25^oX0.25^o$used for comparison with IMD4 was developed as a part of the larger data set for the monsoon Asia region under Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation of the Water Resources project (Yatagai et al. 2012).

For the development of IMD4, daily rainfall records from 6995 rain gauge stations from the country for the period 1901-2010 sourced from the archive of IMD were used, which is the highest ever number of stations over Indian mainland used by any studies so far to prepare gridded rainfall over the region. For the preparation of the gridded data for each day of the data period, on an average, about 3500 stations that varied between 1450 & 3900 were used. Various standard quality checking tests were applied on the data before the interpolation of the station rainfall data on to fixed spatial grid points. For the interpolation, the study used the well tested inverse distance weighted interpolation (IDW) scheme of Shepard (1968), which was also used for the preparation of IMD1, IMD2 & IMD3. For the period 1901-2010, the all India annual and southwest monsoon season mean rainfalls computed using IMD4 were 3.09mm/day and 6.99mm/day respectively with standard deviations of 0.27mm/day & 0.66mm/day respectively.

The climatological features of rainfall over India in the various gridded daily rainfall data sets examined for the comparison were (a) large scale spatial patterns of mean annual rainfall and mean rainfall during all the four seasons (winter (January-February), pre-monsoon (March-May), southwest monsoon (June-September) & post monsoon (October-December)), (b) annual mean cycle of all India daily, monthly and seasonal rainfall. Each of these data sets was of different spatial resolutions and data periods. Therefore, comparison of climatology features in IMD4 with IMD3 was done for the common period of 1971-2000 & that with other 3 data sets was done for the common period of 1951-2000. The variability features of rainfall in the various gridded rainfall data sets examined for comparison were the temporal variation of monthly all India rainfall for the year and that for the four seasons. The interannual variation of all Indiasouthwest monsoon season rainfall derived from the various gridded data sets was also compared.

It was observed that the large scale climatological features in the mean annual rainfall and the seasonal mean rainfall patterns during each of the four seasons were nearly similar in all the various gridded rainfall data sets. For example, the spatial distribution of the annual and southwest monsoon season rainfall climatology derived from all the data sets depicted the large scale features such as maximum rainfall areas along the west coast and over northeast India, rapid decrease of rainfall in the leeward side of the Western Ghats, and minimum rainfall over northwest India. However, the zone of higher rainfall areas along the west coast was narrower in the higher resolution data sets (IMD3, IMD4 & APHRO (narrowest in IMD4)) compared to that in IMD1 & IMD2. The mean annual cycle of all India rainfall in all the data sets was also identical with peak during the middle of the monsoon season and minimum during the winter season. Throughout the annual cycle (whether in daily, monthly or seasonal scale) the all India mean rainfall values in APHRO were lowest and that in IMD3 & IMD4 were nearly equal with climatological values in IMD4 being slightly wetter than that in IMD3 in all time scales (daily, monthly, seasonal & annual). However, the highest values during the peak segment (July- September)of the annual cycle were observed in IMD2 and that during most of the other segments were observed in IMD1. The all India mean annual rainfall was highest in IMD1 (3.21mm/day) and lowest in AHRO (2.68mm/day) with that in IMD4 being drier than the former value by about 4% and wetter than later value by about 13%. The wetter all India annual and southwest monsoon season climatologies in IMD1 & IMD2 compared to that in IMD3 & IMD4 were due to relatively narrower zone of higher rainfall along the west coast in the higher resolution data sets.

The comparative study of the interannual variation of the all India southwest monsoon season rainfall derived from various rainfall gridded data sets along with IMD operational all India rainfall time series (IMD_OP) showed that though there is some bias among the various time series, there is strong consistency in the variation in all the time series. Further the southwest monsoon rainfall time series derived from the IMD4 closely matched with the IMD_OP series throughout the total data period (1901-2010). It was also observed that the highest 10 rainfall years and lowest 10 rainfall years in the time series of both the IMD4 & IMD_OP were nearly same except for the difference in the rank.

Thus the comparison of IMD4 with other data sets suggested that the climatological and variability features of rainfall over India derived from IMD4 based on the daily varying network or rain gauges were comparable with the existing gridded daily rainfall data sets (IMD1 & IMD2) based on the fixed network of rain gauges as well as those (IMD3 & APHRO) that based on the varying network of rain gauges.

IMD4 was used to identify the break and active spells for the entire data period (1901-2010) using the rainfall criteria of Rajeevan et al. (2010). The composite daily rainfall anomaly patterns in respect of break and active spells were found to be nearly opposite to each other. During break (active) spells, the rainfall anomalies were significantly negative (positive) over monsoon trough zone & along the west coast and that along the foothills of Himalayas &over southeast Peninsula were positive (negative). As expected the break and active spells identified in this study using IMD4 and Rajeevan et al. (2010) using IMD1 during the common data period (1951-2007) were mostly comparable as both the studies used same rainfall criteria though using gridded rainfall data of different spatial resolutions. However, the break monsoon spells identified in this study showed some differences with that identified by Ramamurthy (1969) & De et al. (1998) for the period 1901-1996 using the synoptic criteria of Ramamurthy (1969) and hence a comparison of break spells based on these two criteria has been discussed. This study has also discussed various climatological and variability features of the break and active spells identified in this study for the entire data period of 1901-2010.

During the period 1901-1996, there were 118 break spells each based on rainfall and synoptic criteria. However, about 68% of the break spells based on each criteria were comparable with that based on other as these break spells were having overlapping dates. However, the remaining (32%) of the break spells based on both the criteria were not overlapping with each other. The composite rainfall anomaly patterns of overlapping break spells in respect of both the criteria were nearly similar both in terms of distribution and strength of the anomalies. However, there were differences in the composite rainfall anomaly maps of non- over-lapping break spells based on the two criteria. Whereas the composite rainfall anomaly pattern in respect of rainfall criteria resembled closer to that of overlapping breaks spells, the pattern in respect of synoptic criteria showed significantly weaker negative anomalies over many areas of the monsoon trough zone. In the latter case, southward extension of the positive rainfall anomalies along the Himalayas into the monsoon zone also resulted in the reduced spatial extent of the negative anomalies over the region. This indicates that the non-overlapping break spells identified by synoptic criteria may actually be weak monsoon rainfall spells as the breaks basically means the interruption/ significant decrease in the rainfall over the monsoon zone region. Thus the stringent rainfall criteria used in this study and Rajeevan et al. (2010) seems to be better criteria for identifying the breaks. The rainfall criteria also helped in identifying the active spells whereas there are no known criteria based on synoptic conditions to identify the active spells.

During the study period (1901-2010), there were 140 break spells of average duration 6.2 days with durations varying from 3 to 18 days and 201 active spells of average duration 4.3 days with durations varying from 3 to 12 days. Both the active and break spells of short durations were more frequent than the longer durations with about 63.6% of the break spells and 93.5% of the active spells falling in the range of 3-6 days. There were no active spells of duration ≥ 13days. Whereas, about 7% of the break spells were of duration ≥ 13days. This indicates that the transition from active to break/ normal monsoon conditions is much faster than that from break to active/ normal monsoon conditions. This is because the active monsoon conditions are generally associated with the passage of synoptic scale systems such as monsoon lows and depressions along the monsoon trough zone.

The life period of these synoptic scale systems are also of 3-6 days. Whereas, the break conditions are caused by the shifting of monsoon trough from the central India to the foot hills of Himalayas or the large scale subsidence over the monsoon zone region resulted from strong rising motion over convective areas around the region. During the both the halves of the data period (1901-55 & 1956-2010), equal number of break events (70 each) occurred with more or less similar distribution into various durations. On the hand, there was an increase of about 18% (92 to 109%) in the number of active spells in the second half and this increase was mainly in the lower duration (3-6 days) spells.

During 1901-2010, In terms of days, there were 869 break days with an average of 7.9 days and standard deviation (SD) of 6.5 days per season. In the same period, there were 809 active days with an average of 7.4 days and SD of 4.8 days per season. July favoured active days (52% of the total active days) than break days (42% of the break days) and August favoured breaks days (58% of the break days) than active days (48% of total active days). The dekadal (10 days) climatological distribution of break days showed that the middle 10 days followed by first 10 days both of August are most favoured for break days (25% & 17% respectively of the season) and the last 10 days (in fact 11days) of both the July and August were most and equally favourable for active events (21% of the total active days each). As in the case of the number of spells, the occurrence of number of break days during the two halves of the data period was nearly equal. But the occurrence of number of active days was significantly more in the second half of the data period than the first half. A decreasing trend was observed in the break days during the first half and increasing trend during the second half. As a result no trend was observed for the entire period. On the other hand, during data period and its two halves, slight increasing trends were observed in the active days. But all these long term trends were not statistically significant. Earlier studies (Ramesh Kumar et al. 2009, Joseph and Simon 2005)have also reported increasing trend in the break events during recent half of the data period.

During the data period, an out phase of relationship was seen between decadal variations of the number of break days and number of monsoon depressions formed during July and August months. Relatively stronger in phase relationship was observed between the decadal variation of monsoon depressions and that of the active days till around early 1980s which failed later due to sudden decrease in the number of monsoon depressions. During the same period, both the active & break days were in the increasing phase. This increase in the active days as noticed earlier was mainly due to the increase in lower duration active spells (3-6 days). The out of phase relationship between active days and monsoon depressions after early 1980s was coincided with the sudden and significant increase in the number of monsoon lows, which nearly doubled during the period. Thus the increase in the monsoon lows seems to have compensated the decrease in the monsoon depressions and helped in the occurrence of the active spells of lower durations.

IMD4 was also used to examine climatological features and the long term trends in the extreme rainfall (grid point rainfall of ≥ 5mm) or ER events during the southwest monsoon season over three regions over the country which were most favourable for the ER events; central India (CI), northeast India (NEI) and west coast (WC). In this study, the ER events were classified as per Goswami et al. (2006) as moderate rainfall (≥5mm to 100mm) or MR events, heavy rainfall (≥100mm) or HR events and very heavy rainfall (≥150mm) or VHR events. It was also observed that the season rainfall and the number of ER events over these regions were significantly correlated and that the major portion of the area weighted season rainfall over these 3 regions (86% for CI & NEI and 80% for WC) was received in the form of MR events.

Over CI, the ER & MR events showed significant increasing trends in the first half and significant decreasing trend in the second half of the data period (1901-2010). However, the decreasing trends were observed in the ER and MR events during the total period with trend in the MR events being statistically significant. On the other hand, the HR and VHR events showed increasing trends during both the halves as well as during the total period, with trends during the second half & total period being significant. Thus the signs of the trends in the ER events over CI during the total period as well during the two halves of the period were same as that of MR. However, significant trends in MR events but of opposite signs during the two halves of the period resulted relatively weaker decreasing trend in MR events during the total period. This along with significant increasing trends in the HR & VHR events caused insignificant decreasing trend in ER events during the total period. The signs of the trends in the area weighted rainfall over CI during total data period and the two halves of the data period were same as that of the number of ER events.

Thus the results on long term trends in the ER events reported here are consistent with the results of Goswami et al. (2006) & Rajeevan et al. (2008). However, the significant increasing trend of 13.3 events per decade in the VHR events over CI during 1901-2010 was equal to about 5.1% (of mean value of 259 events) per decade which was less than the 6% per decade increasing trend reported by Rajeevan et al. (2008) for the period 1901-2004 using IMD2 data. On the other hand, the increasing trend of 13.3% (of mean value of about 290 events) per decade in the VHR events for the period 1956-2010 observed in this study was significant at 99% level and relatively higher than the increasing trend of about 10% per decade as reported by Goswami et al. (2006) for the period 1951-2000 using the IMD1 data.

Over NEI during first half (1901-55), significant increasing trends were observed in all categories of ER events. As a result highly significant increasing trends were observed in the number of ER events as well as in the area weighted season rainfall. On the other hand, during the second half, only significant (decreasing) trend was observed in the HR events. Insignificant increasing trends were observed in the number of ER & MR events and no trend was observed in the VHR events. Goswami et al. (2010) using daily rainfall data from 15 stations for the period 1975–2006 has also observed significant decreasing trend in the VHR events over NEI. In this study, the magnitude of increasing trend in MR over NEI was close to that of decreasing trend in the HR events which resulted in insignificant decreasing trend in the area weighted season rainfall over the region. During the total period (1901-2010), significant decreasing trends were observed in the MR& ER events. As a result, area weighted season rainfall also showed insignificant decreasing trend in spite of significant increasing trend in the VHR events.

Over WC, the increasing trends in all categories of ER events during the first half with significant trend only In HR events resulted insignificant increasing trend in the ER events but significant increasing trend in the area weighted season rainfall over the region. In the second half, slight increasing trend was observed in VHR events and insignificant decreasing trends in all the other categories of ER events. During the entire data period (1901-2010) insignificant decreasing trend was observed in the MR events. However, like in the case of CI, significant increasing trends were observed in the HR and VHR events. But insignificant decreasing trend in ER events and no trend in the area weighted season rainfall over the region was observed.

As seen from the analysis of extreme rainfall over CI, NEI & WC, the sign of the trends in the number of ER events and the area weighted season rainfall over these regions as 80 to 85% of the ER events occurs in the form of MR events and the area weighted season rainfall over these regions is highly correlated with the number of ER events. There is increased disaster potential over CI due to significant increasing trends in the HR and VHR events over the region during the recent period (1956-2010). On the other hand, during the same period, the disaster potential over NEI has reduced as HR events show significant decreasing trend and no trend is observed in the VHR events. There is not much change in the disaster potential over west coast as no significant trends were observed in the HR and VHR events over the region.

During monsoon season, in an average about 13 low pressure systems (lows, depressions, cyclonic storms etc.) form over the India monsoon region and majority of them from over the head Bay of Bengal or central India (Krishnamurthy and Ajayamohan 2008). These systems generally follow a northwest ward track along the quasi-stationary monsoon trough across central India causing active monsoon conditions over the region. The strong moisture convergence associated with these systems results heavy rainfall over the region during its life span of about 3-6 days. At the same time strengthening of low level winds associated with the presence of these systems along the monsoon trough also results active monsoon conditions and increased rainfall activity along the west coast. On the other hand, presence of these systems over central India reduces the moisture supply to NEI by way of diverting monsoon flow towards the systems resulting in conditions less conducive for deep convective activity and reduced heavy rainfall events over NEI. Thus the significant increasing trends in the HR & VHR events over CI and decreasing trend in HR events over NEI during the recent period (1956-2010) seems to be primarily due to the increasing trend in the monsoon lows during recent decades. The increased instability in the atmosphere due to increased moisture content associated with the global warming trend might have also helped.

The study has shown that the new very high resolution data set developed in this study (IMD4) is comparable with the earlier gridded daily rainfall data sets over the Indian region. In addition, the rainfall distribution features like known heavy rainfall areas in the orographic regions of the west coast and over northeast, decreased rainfall in the lee ward side of the Western Ghats etc. were more realistic and better presented in IMD4 due to its higher spatial resolution and to the higher density of rainfall stations used for its development. This study also showed utility of the IMD4 in examining long term variability and trends in the rainfall over the country. The study has provided the longest ever climatological and variability information about the break and active monsoon events based on a single criteria (rainfall). This study through the use of IMD4 examining the long term trends in the extreme rainfall events has also showed that due to its long period (1901-2010) and high spatial resolution, IMD4 data is also suitable for climate change studies over the region. The use of daily varying network of sufficient number of rain gauges from all parts of the country for gridding has given an opportunity to make use of observations from huge number of rain gauges throughout the county for the preparation of IMD4. However, it may be mentioned that the data availability from these rain gauges showed large variation. This method has also provided opportunity to make use observations from new rain gauges likely to get established in the country. At the same time the closure of any of the existing rain gauges in future will not have any effect on the real time preparation of the data. As IMD will be updating this data set in real time, the data can also be used for important operational services such as real time drought monitoring at various spatial and temporal scales, flood forecasting, stream flow forecasting etc.

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Table-1. Details of gridded daily rainfall data sets used in the study

Data Set	Short Name used in this study	Spatial Resolution Latitude X longitude	Data Period	Rain gauge Network Used for preparing the gridded data	Interpolation method
IMD (Rajeevan et al. 2006 & 2010)	IMD1	1^o x1^o	1951-2007	fixed network of 2140 rain gauge stations	Shepard (1968)
IMD (Rajeevan et al. 2008)	IMD2	1^o X1^o	1901-1904	fixed network of 1380 rain gauge stations	Shepard (1968)
IMD (Rajeevan et al. 2009)	IMD3	0.5^o X0.5^o	1971-2005	varying network of 6076 rain gauge stations	Shepard (1968)
APHRODITE (Yatagai et al. 2012)	APHRO	0.25^o X0.25^o	1951-2007	varying network of rain gauge stations	Willmott et al. (1985)
Present Study	IMD4	0.25^o X0.25^o	1901-2010	varying network of 6955 rain gauge stations	Shepard (1968)

Table-2. Climatology of area weighted rainfall over the country as a whole (all India) for the all the 12 months, 4 season and annual computed using various gridded daily rainfall data sets used in this study. All figures are expressed in mm/day.

MONTH / SEASON	IMD1	IMD2	APHRO	IMD4	IMD4	IMD3	IMD4
	(1951-2000)				(1971-2000)		(1901-2010)
JANUARY	0.65	0.50	0.40	0.55	0.54	0.52	0.56
FEBRUARY	0.78	0.60	0.47	0.69	0.79	0.76	0.73
MARCH	0.89	0.67	0.59	0.87	0.93	0.88	0.83
APRIL	1.14	0.98	0.87	1.19	1.28	1.20	1.21
MAY	1.92	1.80	1.59	1.93	1.96	1.89	1.89
JUNE	5.37	5.34	4.61	5.22	5.39	5.42	5.28
JULY	9.33	9.58	8.02	8.97	8.84	8.85	9.01
AUGUST	8.45	8.67	7.28	8.10	8.08	8.07	8.01
SEPTEMBER	5.74	5.77	4.80	5.52	5.36	5.26	5.55
OCTOBER	2.56	2.54	2.13	2.45	2.39	2.27	2.35
NOVEMBER	0.94	0.92	0.79	0.90	1.00	0.91	0.95
DECEMBER	0.54	0.47	0.39	0.49	0.52	0.48	0.45
JF	0.71	0.55	0.44	0.61	0.66	0.64	0.64
MAM	1.32	1.15	1.02	1.33	1.39	1.33	1.31
JJAS	7.25	7.37	6.20	6.98	6.94	6.92	6.99
OND	1.35	1.31	1.11	1.29	1.30	1.22	1.25
ANNUAL	3.21	3.17	2.68	3.09	3.11	3.06	3.09

Table-3: The statistical measures of difference of the all India monthly rainfall time series computed using IMD4 with that computed using IMD1, IMD2, IMD3 & APHRO for the annual and various seasons. The statistical measures for the IMD1, IMD2 & APHRO were computed for the period 1951-2000 & and that for IMD3 were computed for the period 1971-2000

DATA	JF			MAM			JJAS			OND			ANNUAL		
	RMSD	BIAS	CC	RMSD	BIAS	CC	RMSD	BIAS	CC	RMSD	BIAS	CC	RMSD	BIAS	CC
	(mm/day)			(mm/day)			(mm/day)			(mm/day)			(mm/day)		
IMD4 Vs IMD1 (1951-2000)	0.16	-0.10	0.92	0.17	0.01	0.96	0.36	-0.27	0.99	0.14	-0.07	0.99	0.24	-0.12	0.99
IMD4 Vs IMD2 (1951-2000)	0.13	0.07	0.92	0.25	0.18	0.95	0.54	-0.39	0.99	0.14	-0.03	0.99	0.35	-0.08	0.99
IMD4 Vs IMD3 (1971-2000)	0.04	0.02	0.99	0.09	0.07	0.99	0.15	0.02	0.99	0.11	0.08	0.99	0.11	0.05	0.99
IMD4 Vs APHRO (1951-2000)	0.21	0.18	0.93	0.35	0.31	0.96	0.82	0.77	0.99	0.23	0.18	0.99	0.52	0.41	0.99

Table-4: The statistical measures of difference of the all India seasonal and annual rainfall time series computed using IMD4 with that computed using IMD1, IMD2, IMD3 & APHRO. The statistical measures for each of the data sets were computed using all the available data. The statistical measures of all India rainfall series computed using IMD4 with the IMD operational time series computed for the period 1901-2010 have also been presented.

DATA	JJAS			ANNUAL		
	RMSD	BIAS	C.C.	RMSD	BIAS	C.C.
	(mm/day)			(mm/day)		
IMD4 Vs IMD1 (1951-2010)	0.32	-0.25	0.96	0.14	-0.11	0.96
IMD4Vs IMD2 (1901-2004)	0.42	-0.37	0.96	0.12	-0.08	0.96
IMD4 Vs IMD3 (1971-2005)	0.34	-0.04	0.90	0.11	0.03	0.94
IMD4 Vs APHRO (1951-2007)	0.84	0.81	0.95	0.43	0.42	0.95
IMD4 Vs IMD_OP (1901-2010)	0.32	-0.26	0.97	0.18	-0.16	0.95

Table-5: Break spells identified based on rainfall criteria in the present study for the period 1901-2010 along with that identified based on synoptic criteria by Ramamurthy (1969) & De et al. (1998) for the period 1901-1996.

BREAK SPELLS DURING JULY-AUGUST (1901-1950)		
YEAR	**RAINFALL CRITERIA**	**SYNOPTIC CRITERIA**
1901	13-16J	12-15J
1902	1-17A	9-15A
1903	**6-8J**, 10-13A	12-15A
1904	**16-19A**	**12-14J**,**25-29J**
1905	15-18J, **29-31J**, 6-13A	15-18J,6-14A
1906	1-6A, 12-17A	**9-15J**, 29J-19A
1907	4-12J, 17-19J	-
1908	-	**14-18J**
1909	4-18A	**19-22J**, 4-19A
1910	11-21J, 15-20A	8-20J, 24-27J, 15-17A
1911	15-27J, **11-13A**	15-25J
1912	16-23A	13-23A
1913	1-4J, 10-21A	1-4J, **10-12J**, 12-20A
1914	11-13A, 28-31A	**1-4A**, 10-13A, 26-31A
1915	5-13J, **17-19J**, 10-18A	6-12J, 9-17A
1916	-	**9-11A**
1917	7-9J	5-11J, **25-27J**
1918	10-26J, 8-14A	7-23J, 7-12A
1919	-	**15-18J**
1920	9-18A, 20-22A	**18-20J**, 9-14A, 18-20A
1921	1-4J, **20-22A**, 26-28A	1-4J, **15-17A**, 27-30A
1922	6-17A	7-13A
1923	-	-
1924	13-21A	12-19A
1925	-	**22-24J**, **9-12A**
1926	19-21J	16-21J
1927	2-6A	1-5A
1928	30J-16A	3-14A
1929	**5-8A**, **10-12A**	-
1930	16-25A	22-28A
1931	-	-
1932	11-14A	9-28A
1933	**3-7J**, 13-19A	13-20A
1934	13-19J	11-18J
1935	8-11A, 19-21A	8-10A, 19-23A
1936	**11-16J**	-
1937	9-20A	8-15A
1938	**29J-3A**	-
1939	25-29J, **1-3A**	25-28J
1940	-	-
1941	14-29J, **5-7A**, **22-30A**	16-24J
1942	6-8A	7-10A
1943	**11-15A**	-
1944	-	-
1945	**31J-7A**	-
1946	9-12J	9-11J, **29-31A**
1947	6-8J, 6-8A	6-9J, 3-10A
1948	31J-2A	1-3A
1949	19-23A	**19-23J**, 21-25A
1950	15-26A	15-24A

BREAK SPELLS DURING JULY-AUGUST (1951-2010)		
YEAR	**RAINFALL CRITERIA**	**SYNOPTIC CRITERIA**
1951	13-15J, 24-30A	**1-3J**, 11-13J, 15-17J, 24-29A
1952	8-15J, **28-30A**	9-12J
1953	-	**24-26J**
1954	22-28J	18-29J, **21-25A**
1955	24-26J	22-29J
1956	25-29A	23-26A
1957	-	**27-31J**, **5-7A**
1958	-	**10-14A**
1959	-	**16-18A**
1960	18-24J	16-21J
1961	**11-13A**	-
1962	**27-29J**	**18-22A**
1963	13-23J	10-13J, 17-21J
1964	**28-30J**,**1-4A**	**14-18J**
1965	6-12J, 1-14A	6-8J, 4-15A
1966	2-12J, 21-30A	2-11J, 23-27A
1967	7-14J	7-10J
1968	25-31A	25-29A
1969	-	**17-20A**, **25-27A**
1970	13-19J	12-25J
1971	**8-10J**, **5-7A**, 17-19A	17-20A
1972	18J-3A	17J-3A
1973	24-26J, 30J-1A	23J-1A
1974	**28-31A**	-
1975	-	**24-28J**
1976	-	-
1977	15-20A	15-18A
1978	-	**16-21J**
1979	**2-7J**, 14-29A	**17-23J**, 15-31A
1980	17-20J, **13-15A**	17-20J
1981	24-27A	**26-30J**, 23-27A
1982	**1-8J**	-
1983	**14-16J**	**22-25A**
1984	**28-30J**	**20-24J**
1985	23-25A	22-25A
1986	23-31A	23-26A, 29-31A
1987	**23-25J**, 30J-4A, **9-13A**	28J-1A
1988	14-17A	**5-8J**, 13-15A
1989	**18-20J**, 30J-3A	**10-12J**, 29-31J
1990		**8-10J**, **27-31J**
1991	**1-3J**	-
1992	**4-10J**	-
1993	20-23J, **8-13A**, **22-28A**	19-21J
1994	-	-
1995	**3-7J**, 11-17A	12-15A
1996	**11-13A**	**1-5J**
1997	11-15J, 9-17A	
1998	21-26J, 16-21A	
1999	1-5J, 12-18A, 22-24A	
2000	29J-8A	
2001	31J-2A, 27-29A	
2002	4-16J, 22-31J	
2003	-	
2004	10-13J, 19-22J, 26-31A	
2005	7-14A, 24-31A	
2006	-	
2007	18-23J, 15-17A	
2008	16-21J, 21-24A, 28-30A	
2009	29J-9A, 17-19A	
2010	-	

Table-6: Active spells identified based on rainfall criteria in the present study for the period 1901-2010.

ACTIVE SPELLS DURING JULY-AUGUST (1901-2010)			
YEAR	**RAINFALL CRITERIA**	**YEAR**	**RAINFALL CRITERIA**
1901	-	1956	2-8J, 11-14J, 1-5A
1902	15-17J, 25-27A	1957	20-24A
1903	19-24J	1958	8-11J
1904	-	1959	26-29J
1905	-	1960	1-4J
1906	20-23J, 26-30A	1961	6-10J, 16-18J
1907	11-21A	1962	16-20J, 12-14A
1908	7-9J, 14-16A	1963	9-11A
1909	16-18J, 31J-2A	1964	5-7J, 15-17A, 23-25A
1910	1-6J, 2-4A	1965	27-29J, 24-26A
1911	-	1966	29-31J
1912	25-30J, 2-4A, 27-29A	1967	1-3J, 24-29J, 31J-3A
1913	25-27J, 31J-2A, 23-25A	1968	7-10J, 29-31J, 4-6A
1914	11-13J	1969	29J-1A
1915	-	1970	1-3J, 17-19A, 25-29A
1916	14-17A, 20-22A, 24-27A	1971	19-21J, 26-31A
1917	2-5J, 9-13A, 23-26A	1972	4-7J
1918	-	1973	7-9J, 13-15J, 12-14A, 26-31A
1919	1-3A, 21-24A, 27-29A	1974	16-20A
1920	6-9J, 23-25J	1975	13-15J, 17-19J, 12-15A, 18-20A
1921	27-31J	1976	16-21J, 30J-2A, 28-31A
1922	19-21A	1977	5-7J, 6-8A
1923	27-30J	1978	15-17A, 24-26A, 28-30A
1924	27-29J, 26-31A	1979	3-5A, 7-12A
1925	10-13J	1980	1-3J
1926	11-18A	1981	7-10J
1927	22-30J	1982	21-23A, 12-14 A
1928	26-31A	1983	18-20A
1929	24-26J, 23-25A	1984	1-3A, 9-11A, 16-19A
1930	1-4J	1985	15-17J, 30J-2A, 6-8A
1931	10-12A, 15-17A, 21-23A, 26-28A	1986	21-24J, 13-15A
1932	12-15J, 21-23J	1987	24-29A
1933	14-19J, 31J-6A, 8-11A, 24-26A	1988	26-28J
1934	1-4J, 17-19A, 22-24A	1989	-
1935	8-11J	1990	2-4J, 21-24A, 29-31A
1936	-	1991	21-24J, 29-31J, 22-24A
1937	11-13J, 21-26J	1992	27-29J, 16-21A
1938	-	1993	7-11J, 15-17J
1939	13-16J, 17-20A, 24-26A	1994	2-4J, 9-16J, 30J-2A, 18-20A, 25-27A, 29-31A
1940	1-3J, 31J-2A, 22-25A	1995	18-20J, 22-25J
1941	1-7J, 9-11A	1996	24-28J, 19-21A
1942	3-7J, 10-12J, 24-27J, 2-5A	1997	30J-1A, 21-25A
1943	10-13J, 26-29J	1998	3-5J
1944	10-16J, 24-26J, 31J-2A, 20-22A	1999	7-9A
1945	2-4J	2000	12-14J, 17-20J
1946	24-28J, 1-3A, 19-24A	2001	9-12J
1947	25-31A	2002	23-25A
1948	19-21J	2003	23-28J, 27-29A
1949	1-3A	2004	8-13A, 21-23A
1950	10-14J, 25-29J	2005	1-5J, 25-29J, 31J-2A
1951	25-27J	2006	3-6J, 27J-7A, 13-15A, 17-20A
1952	23-30J	2007	1-9J, 6-9A
1953	3-7J, 3-5A, 12-19A	2008	10-12A
1954	9-12A	2009	13-16J, 20-23J
1955	29-31A	2010	-

Table-7: Various Statistical Properties of Break and Active Monsoon Days over India.

Statistical Property	Period	Break Days			Active Days		
		1901 to 2010	1901 to 1955	1956 to 2010	1901 to 2010	1901 to 1955	1956 to 2010
Frequency (Total Days)	July + August	869	452	417	809	383	426
	July	365	167	198	418	196	222
	Aug	504	285	219	391	187	204
Average (days/season)	July + August	7.9	8.2	7.6	7.4	7.0	7.7
	July	3.3	3.0	3.6	3.8	3.6	4.0
	Aug	4.6	5.2	4.0	3.6	3.4	3.7
standard deviation (S.D) (days/season)	July + August	6.5	6.5	6.5	4.8	4.8	4.8
	July	4.4	4.4	4.4	3.4	3.3	3.4
	Aug	4.8	4.9	4.6	3.7	3.9	3.5
Median (days/season)	July + August	7.0	7.0	7.0	7.0	7.0	8.0
	July	2.5	0.0	3.0	3.5	4.0	3.0
	Aug	3.0	4.0	3.0	3.0	3.0	3.0
Trend (days/decade)	July + August	-0.11	-0.98	0.82	0.21	0.63	0.18
	July	0.06	-0.27	0.15	0.14	0.52	0.08
	Aug	-0.17	-0.72	0.67	0.07	0.12	0.10
Maximum days & (Year)	July + August	28 (1941)	28 (1941)	23 (2002)	24 (1994)	20 (1933)	24 (1994)
	July	23 (2002)	17 (1918)	23 (2002)	13 (1994)	12 (1942)	13 (1994)
	Aug	17 (1902)	17 (1902)	16 (1979)	14 (2006)	13 (1933)	14 (2006)

Table -8a: Temporal Distribution of Number of Break Days During the period 1901-2010. Distribution is presented in decade wise and for 10 days period within the Season.

Decade	Number of Break Days/season								
	1-10 Jul	11-20 Jul	21-31 Jul	1-10 Aug	11-20 Aug	21-31 Aug	Total Jul	Total Aug	Total Jul+ Aug
1901-1910	10	23	4	29	37	0	37	66	103
1911-1920	14	22	13	7	42	10	49	59	108
1921-1930	4	2	3	25	29	11	9	65	74
1931-1940	5	13	8	11	24	1	26	36	62
1941-1950	5	9	11	18	13	18	25	49	74
1951-1960	3	11	14	0	0	15	28	15	43
1961-1970	18	23	9	14	7	17	50	38	88
1971-1980	9	7	16	7	19	13	32	39	71
1981-1990	8	6	10	9	7	16	24	32	56
1991-2000	20	6	12	13	32	11	38	56	94
2001-2010	8	19	20	16	10	23	47	49	96
Sum	104	141	120	149	220	135	365	504	869
Average/season	0.9	1.3	1.1	1.4	2.0	1.2	3.3	4.6	7.9

Table -8b: Temporal Distribution of Number of Active Days During the period 1901-2010. Distribution is presented in decade wise and for 10 days period within the Season.

Decade	Number of Active Days/season								
	1-10 Jul	11-20 Jul	21-31 Jul	1-10 Aug	11-20 Aug	21-31 Aug	Total Jul	Total Aug	Total Jul+ Aug
1901-1910	9	9	8	5	13	9	26	27	53
1911-1920	8	3	13	10	8	23	24	41	65
1921-1930	5	3	24	0	10	16	32	26	58
1931-1940	10	18	11	12	13	19	39	44	83
1941-1950	19	17	23	14	4	13	59	31	90
1951-1960	19	5	15	10	11	7	39	28	67
1961-1970	18	8	19	9	10	11	45	30	75
1971-1980	13	16	4	12	17	25	33	54	87
1981-1990	7	3	9	10	14	16	19	40	59
1991-2000	12	20	23	6	10	16	55	32	87
2001-2010	20	7	20	17	8	13	47	38	85
Sum	140	109	169	105	118	168	418	391	809
Average/season	1.3	1.0	1.5	1.0	1.1	1.5	3.8	3.6	7.4

Table-9: Statistical properties of rainfall averaged over Central India (CI) and extreme daily rainfall events (of various categories) over CI during the southwest monsoon season (June to September) computed for the total data period (1901-2010) and its two halves (1901-1955 & 1956-2010). Means in the two halves that are significantly different at 95% (99%) and the trends that are significant at 95% (99%) are shown with * (**).

Statistical Properties of Rainfall Averaged over the region				
Statistical Property	**Categories of Extreme Rainfall**	**Period**		
		1901-2010	**1901-1955**	**1956-2010**
Mean (mm/day)		7.85	7.99	7.72
Standard Deviation (SD) (mm/day)		0.84	0.76	0.89
Median (mm/day)		7.91	8.01	7.83
trend/decade (mm/day/decade)		-0.03	0.15*	-0.09
Statistical Properties of grid point extreme daily rainfall events				
Rainfall maximum at any grid (mm)		763.38	515.79	763.38
Mean (grid point events per season)	≥5mm	89565	91470*	87661*
	5mm-100mm	88473	90426*	86520*
	100-150mm	834	815	852
	≥150mm	259	229**	290**
Standard deviation (grid point events per season)	≥5mm	9791	9190	10083
	5mm-100mm	9771	9168	10045
	100-150mm	198	177	216
	≥150mm	118	75	143
Median (grid point events per season)	≥5mm	90464	93285	88425
	5mm-100mm	89398	92152	87311
	100-150mm	816	813	817
	≥150mm	252	227	261
Trend (grid point events per decade)	≥5mm	-538.7	1748.2*	-1902.7*
	5mm-100mm	-564.2	1731.6*	-1984.3*
	100-150mm	12.3*	15.5	42.9*
	≥150mm	13.3**	1.1	38.6**

Table-10: Statistical properties of rainfall averaged over Northeast India (NEI) and extreme daily rainfall events (of various categories) over NEI during the southwest monsoon season (June to September) computed for the total data period (1901-2010) and its two halves (1901-1955 & 1956-2010). Means in the two halves that are significantly different at 95% (99%) and the trends that are significant at 95% (99%) are shown with * (**).

Statistical Properties of Rainfall Averaged over the region				
Statistical Property	**Categories of Extreme Rainfall**	**Period**		
		1901-2010	**1901-1955**	**1956-2010**
Mean (mm/day)		13.73	14.06*	13.40*
Standard Deviation (SD) (mm/day)		1.85	1.56	2.07
Median (mm/day)		13.84	13.76	13.97
trend/decade (mm/day/decade)		-0.07	0.34**	-0.22
Statistical Properties of grid point extreme daily rainfall events				
Rainfall maximum at any grid (mm)		939.45	525.83	939.45
Mean (grid point events per season)	≥5mm	26424	27267**	25580**
	5mm-100mm	25968	26870**	25066**
	100-150mm	330	309	350
	≥150mm	126	88**	164**
Standard deviation (grid point events per season)	≥5mm	2225	1648	2415
	5mm-100mm	2144	1548	2286
	100-150mm	148	133	160
	≥150mm	109	77	124
Median (grid point events per season)	≥5mm	26797	27343	25457
	5mm-100mm	26258	26791	25066
	100-150mm	321	275	326
	≥150mm	93	64	149
Trend (grid point events per decade)	≥5mm	-179.9**	395.3**	6.2
	5mm-100mm	-196.3**	356.3**	41.7
	100-150mm	4.1	23.5*	-35.7**
	≥150mm	12.3*	15.5*	0.2

Table-11: Statistical properties of rainfall averaged over West Coast (WC) and extreme daily rainfall events (of various categories) over WC during the southwest monsoon season (June to September) computed for the total data period (1901-2010) and its two halves (1901-1955 & 1956-2010). Means in the two halves that are significantly different at 95% (99%) and the trends that are significant at 95% (99%) are shown with * (**).

Statistical Properties of Rainfall Averaged over the region				
Statistical Property	**Categories of Extreme Rainfall**	**Period**		
		1901-2010	**1901-1955**	**1956-2010**
Mean (mm/day)		15.04	14.94	15.14
Standard Deviation (SD) (mm/day)		2.12	2.06	2.19
Median (mm/day)		14.84	14.73	14.92
trend/decade (mm/day/decade)		0.05	0.38*	-0.22
Statistical Properties of grid point extreme daily rainfall events				
Rainfall maximum at any grid (mm)		802.86	802.86	550.44
Mean (grid point events per season)	≥5mm	14419	14636	14201
	5mm-100mm	13915	14165*	13665*
	100-150mm	374	355	393
	≥150mm	130	116*	143*
Standard deviation (grid point events per season)	≥5mm	1319	1299	1315
	5mm-100mm	1256	1251	1222
	100-150mm	111	109	109
	≥150mm	63	62	61
Median (grid point events per season)	≥5mm	14553	14837	14269
	5mm-100mm	14091	14272	13783
	100-150mm	355	332	374
	≥150mm	119	95	130
Trend (grid point events per decade)	≥5mm	-53.4	207.9	-160.7
	5mm-100mm	-65.3	180.8	-157.5
	100-150mm	6.8*	19.2*	-6.3
	≥150mm	5.0**	7.8	3.0

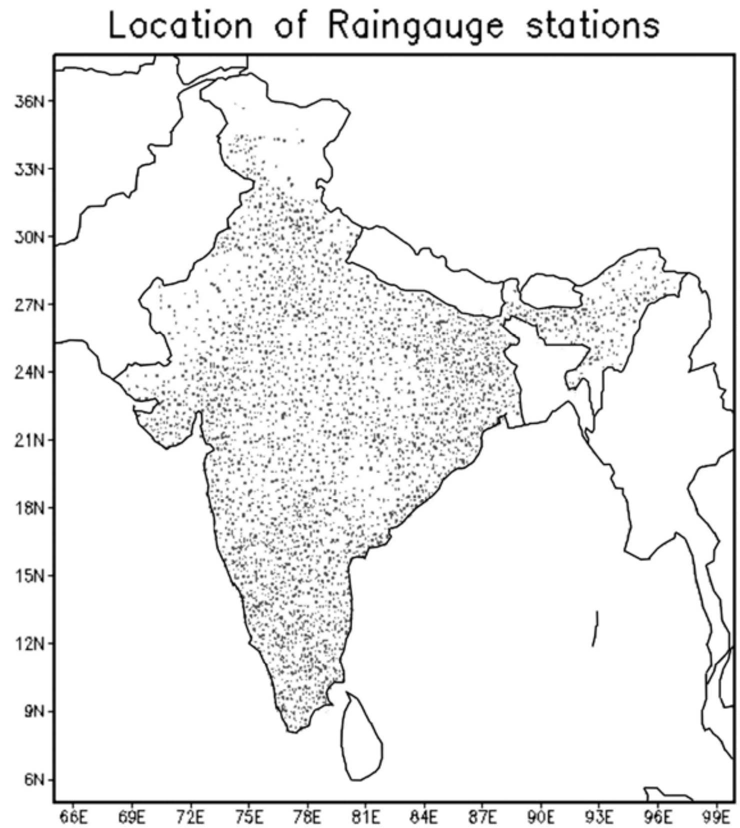

Fig.1. Network of 6955 rain gauge stations used for development of IMD4.

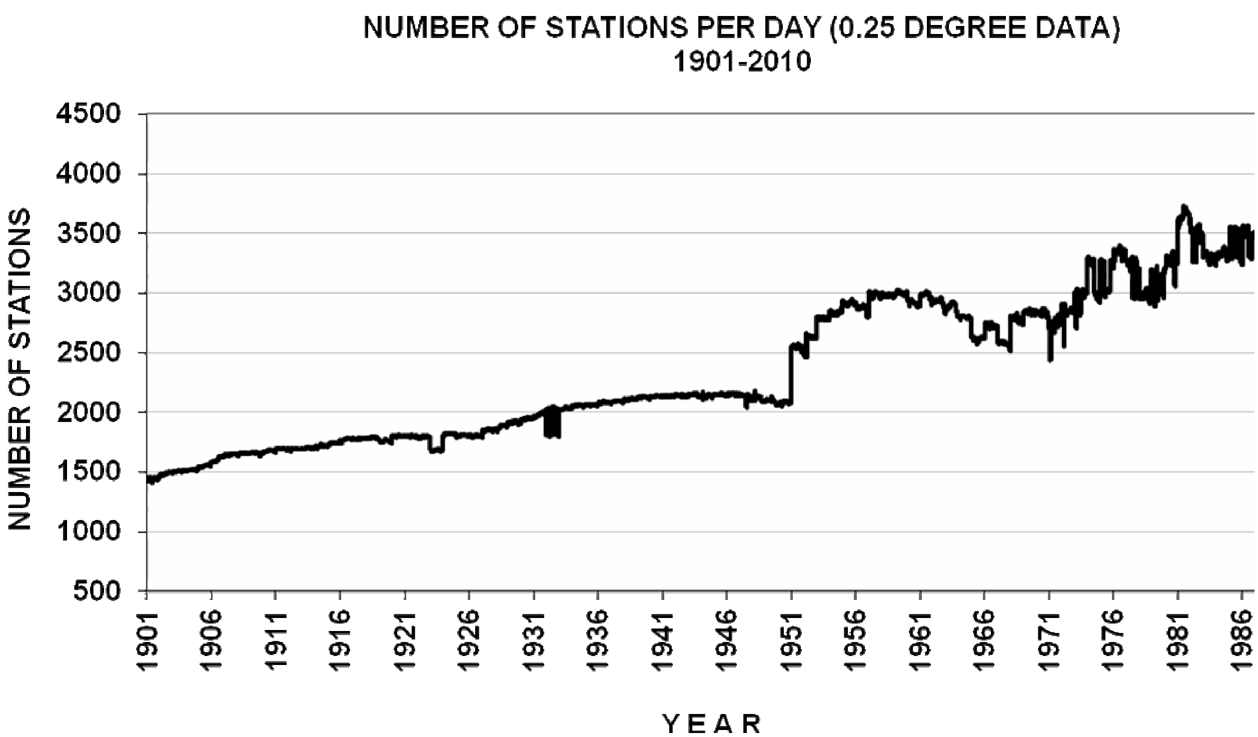

Fig.2. Daily Variation of number of stations used for the development of IMD4.

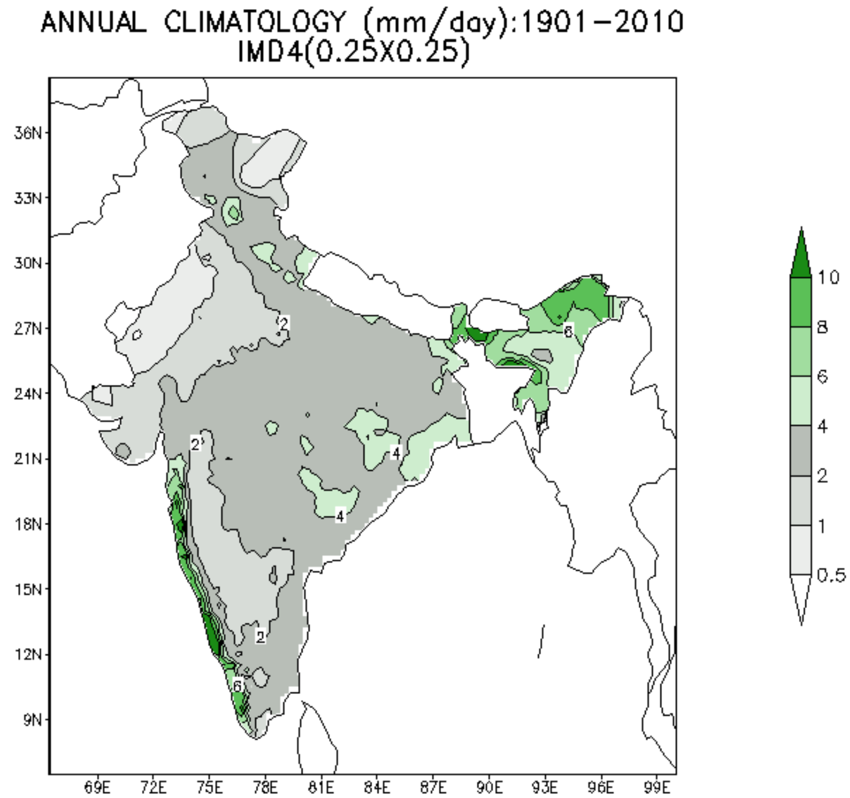

Fig.3. Spatial distribution of the mean annual rainfall over India computed for the period 1901-2010.

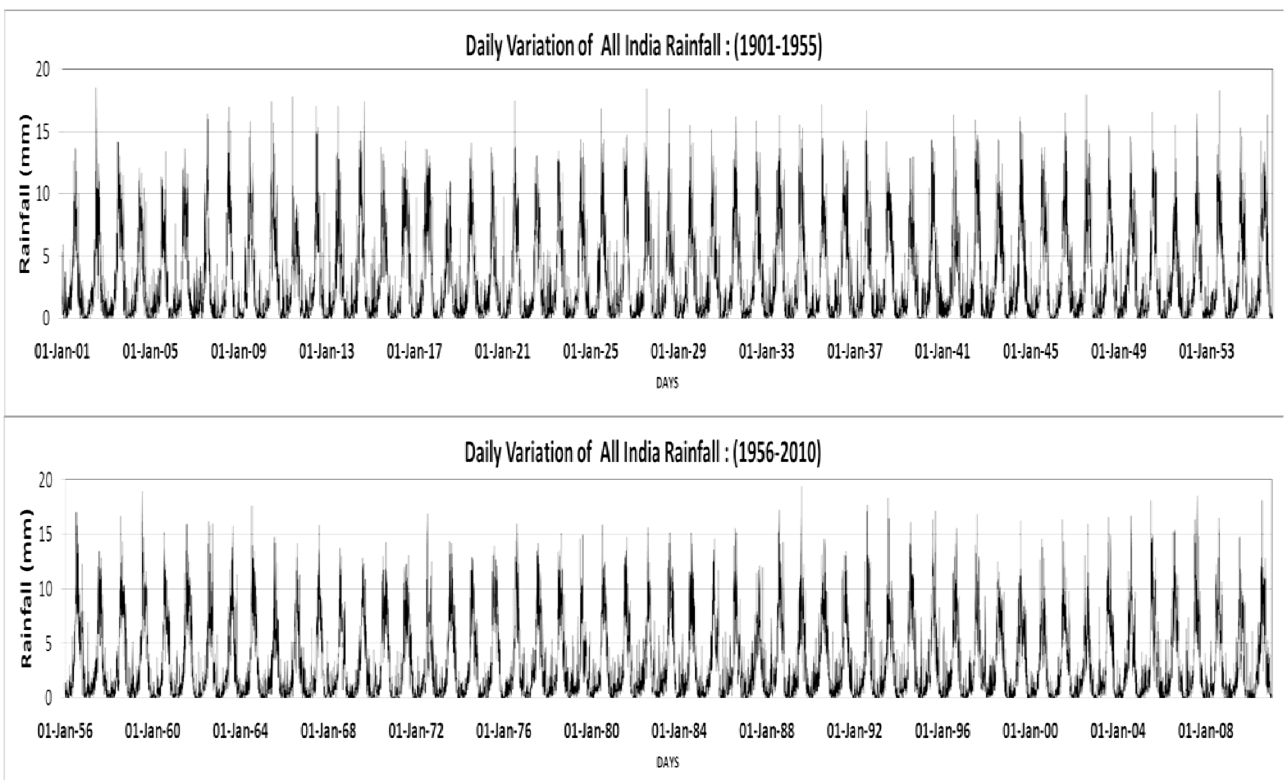

Fig.4. Time series of all India daily rainfall for the period 1901-2010.

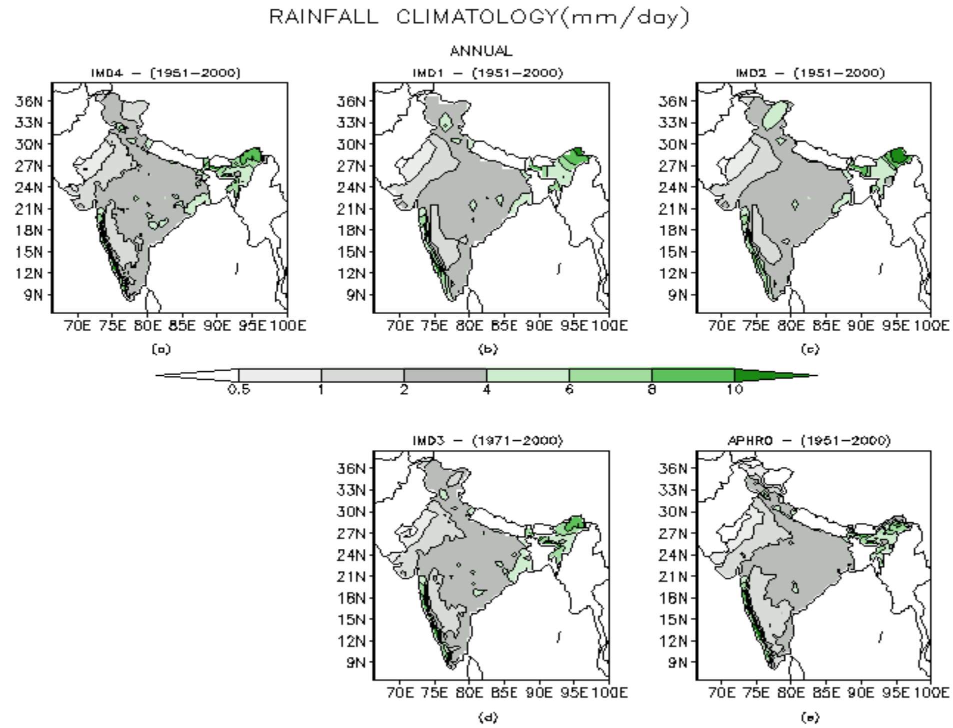

Fig.5. Mean annual climatology of rainfall over India based on 5 gridded rainfall data sets over the region. **a)** IMD4, b) IMD1, c) IMD2, d) IMD3 and e) APHRO. The climatology of IMD3 was computed using data for the period 1971-2000 & that of other data sets were computed using data for the period 1951-2000.

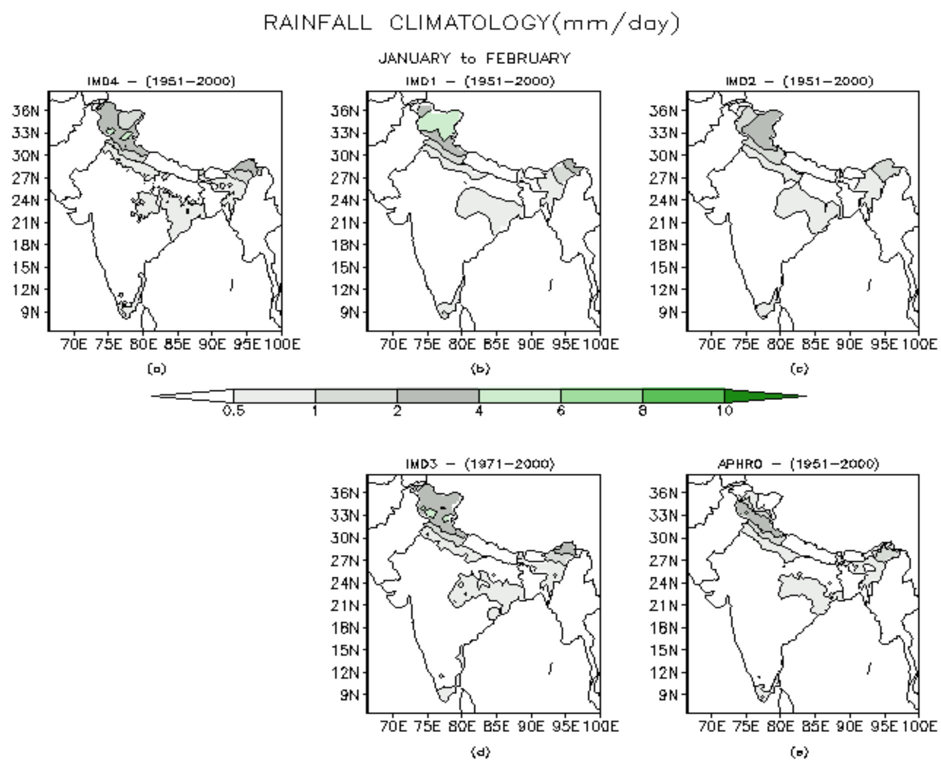

Fig.6. Mean climatology of rainfall over India during the winter season (January-February) based on 5 gridded rainfall data sets over the region. **a)** IMD4, b) IMD1, c) IMD2, d) IMD3 and e) APHRO. The climatology of IMD3 was computed using data for the period 1971-2000 & that of other data sets were computed using data for the period 1951-2000.

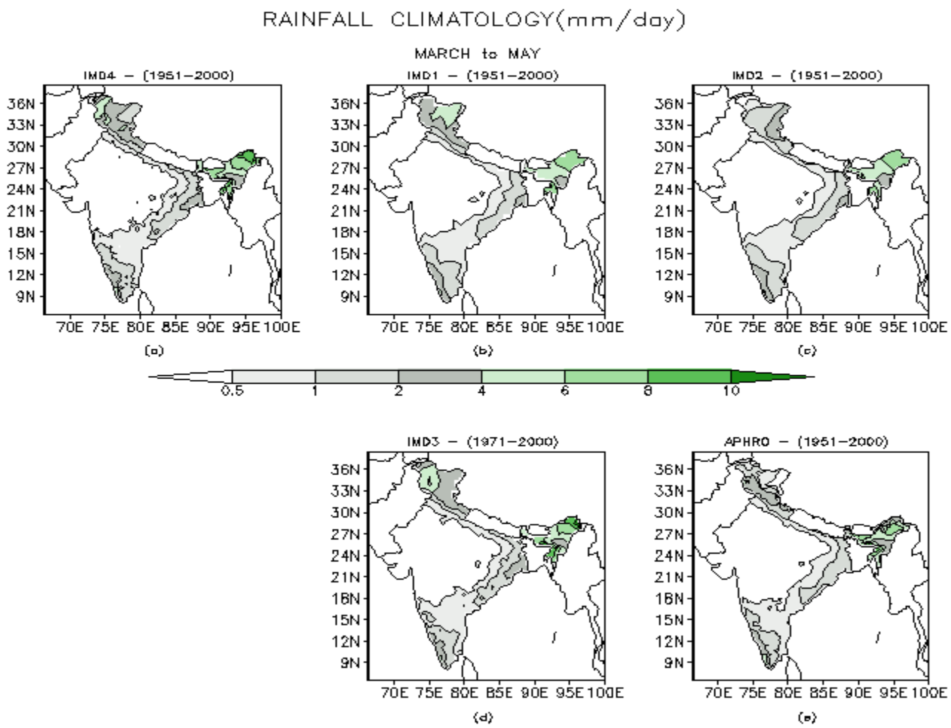

Fig.7. Mean climatology of rainfall over India during the pre-monsoon season (March-May) based on 5 gridded rainfall data sets over the region. **a)** IMD4, b) IMD1, c) IMD2, d) IMD3 and e) APHRO. The climatology of IMD3 was computed using data for the period 1971-2000 & that of other data sets were computed using data for the period 1951-2000.

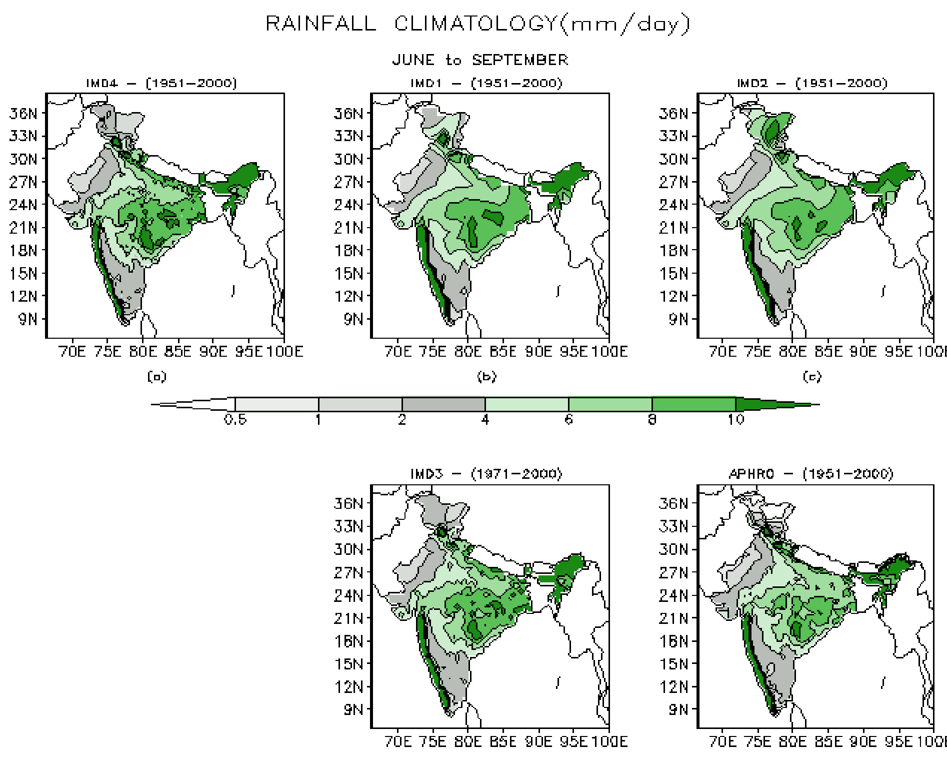

Fig.8. Mean climatology of rainfall over India during the southwest monsoon season (June-September) based on 5 gridded rainfall data sets over the region. **a)** IMD4, b) IMD1, c) IMD2, d) IMD3 and e) APHRO. The climatology of IMD3 was computed using data for the period 1971-2000 & that of other data sets were computed using data for the period 1951-2000.

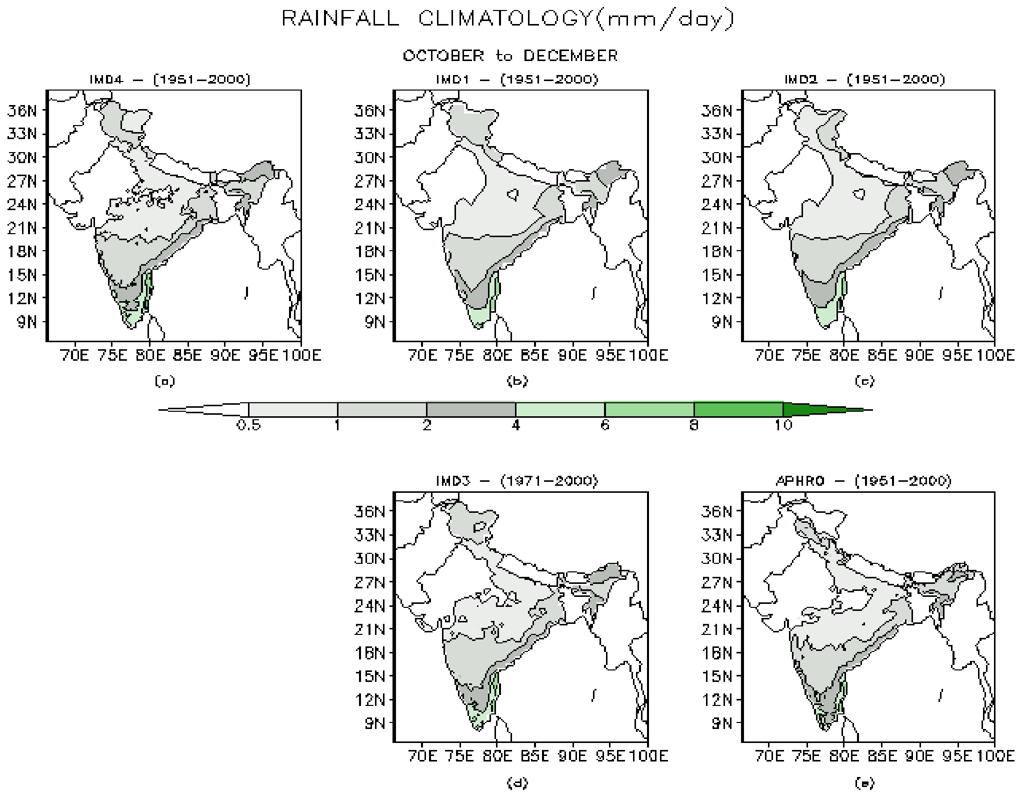

Fig.9. Mean climatology of rainfall over India during the post monsoon season (October-December) based on 5 gridded rainfall data sets over the region. **a)** IMD4, b) IMD1, c) IMD2, d) IMD3 and e) APHRO. The climatology of IMD3 was computed using data for the period 1971-2000 & that of other data sets were computed using data for the period 1951-2000.

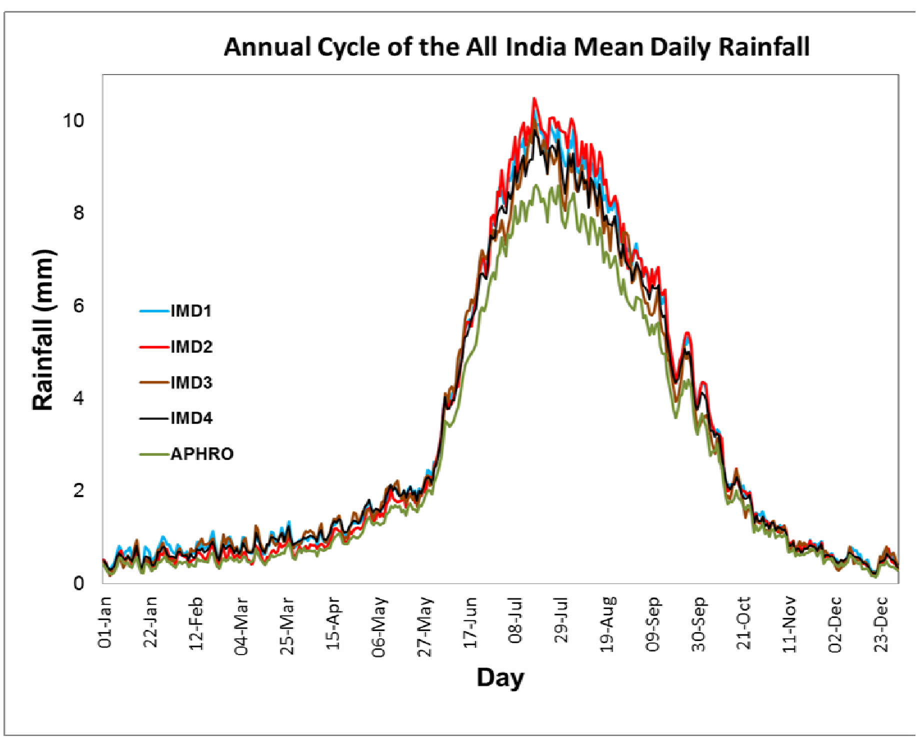

Fig.10. Annual cycle of the all India daily mean rainfall. The climatology of IMD3 was computed using data for the period 1971-2000 & that of other data sets were computed using data for the period 1951-2000.

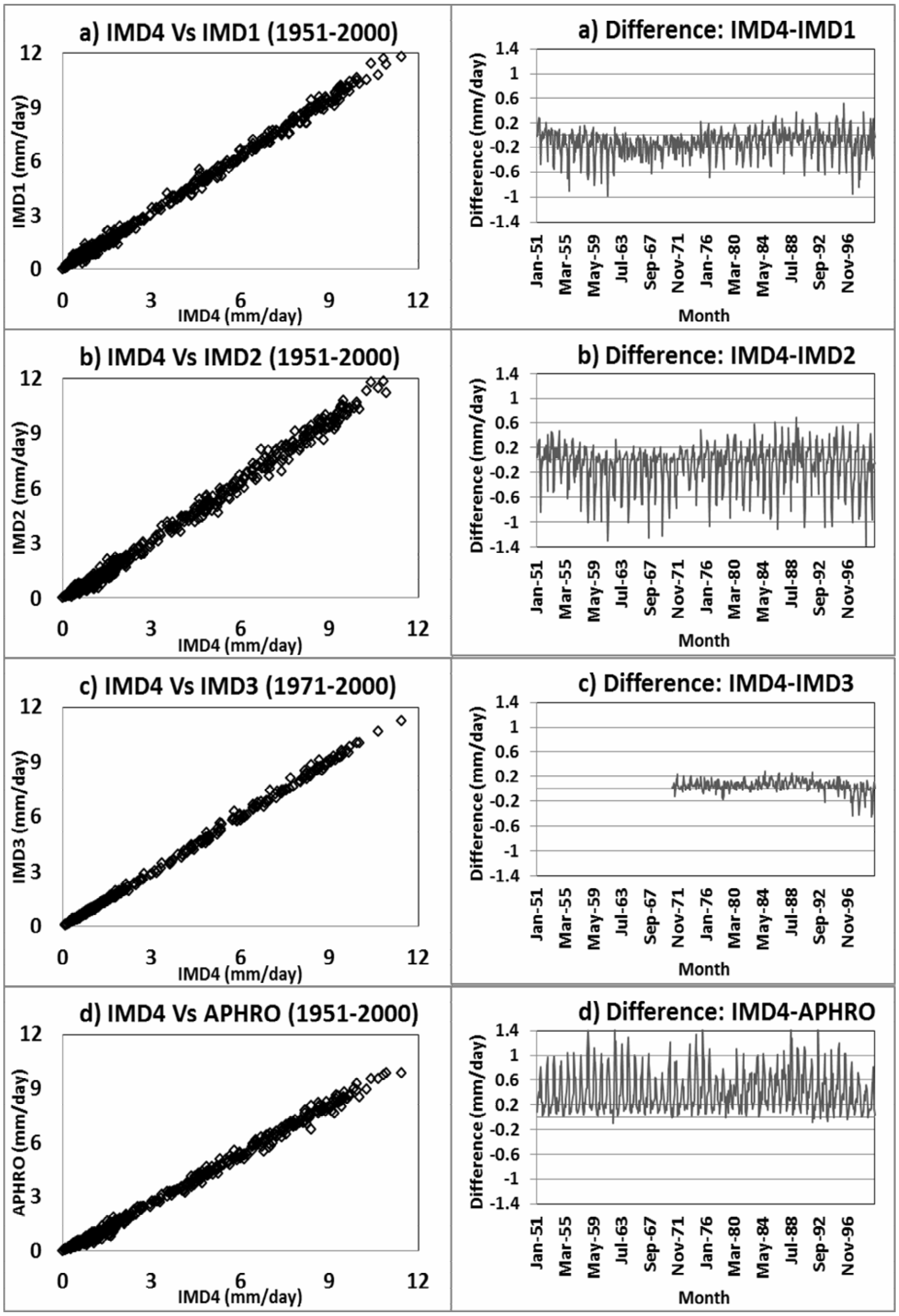

Fig.11. Scatter plots of all India monthly rainfall computed using IMD1, IMD2, IMD3 & APHRO against that computed using the IMD4. The time series plots of their differences are also given side by side. **a)** IMD1, b) IMD2, c) IMD3 and d) APHRO. The plots in respect of IMD3 was prepared using data for the period 1971-2000 & that with respect to other data sets were prepared using data for the period 1951-2000.

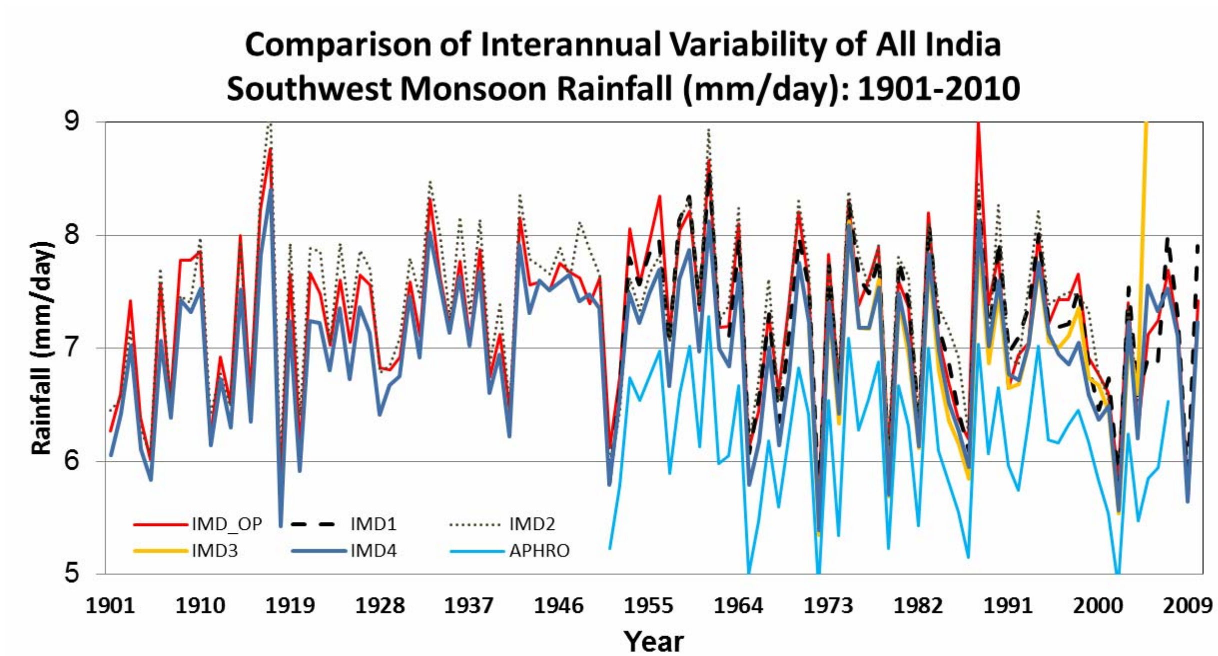

Fig.12. Time series of all India rainfall for the southwest monsoon season computed using the 5 gridded data sets used in this study along with the IMD operational (IMD_OP) time series. Time series in respect each data sets are presented for their respective data periods; IMD1 for 1951-2007, IMD2 for 1901-2004, IMD3 for 1971-2005, IMD4 for 1901-2010, APHRO for 1951-2007 & IMD_OP for 1901-2010.

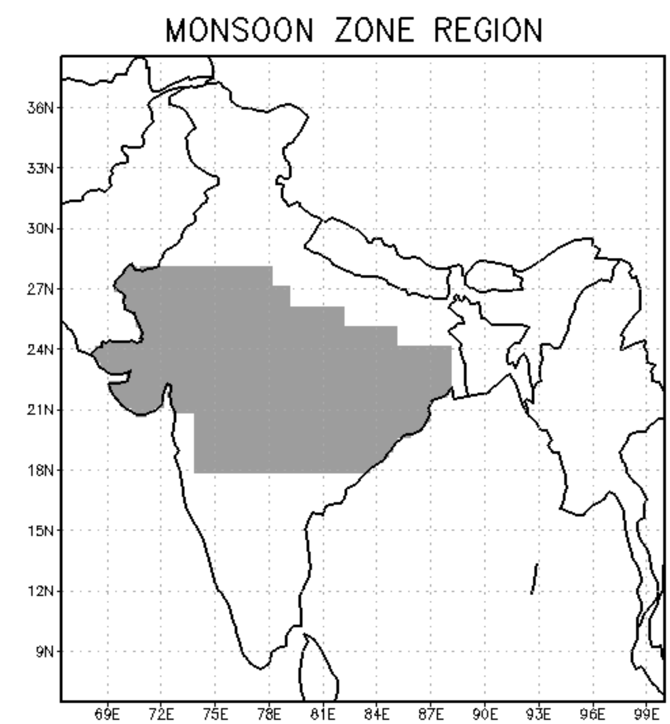

Fig.13. Spatial domain of the monsoon core zone (MCZ) used for defining the breaks and active monsoon events in this study.

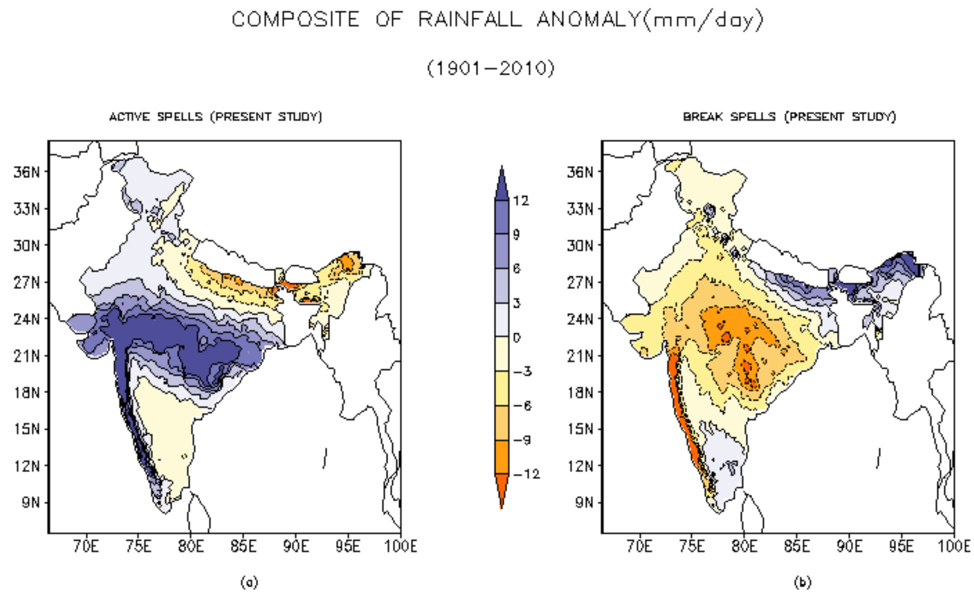

Fig.14. Composite daily rainfall anomaly map of **a)** active spells and **b)** break spells identified in the present study for the period 1901-2010.

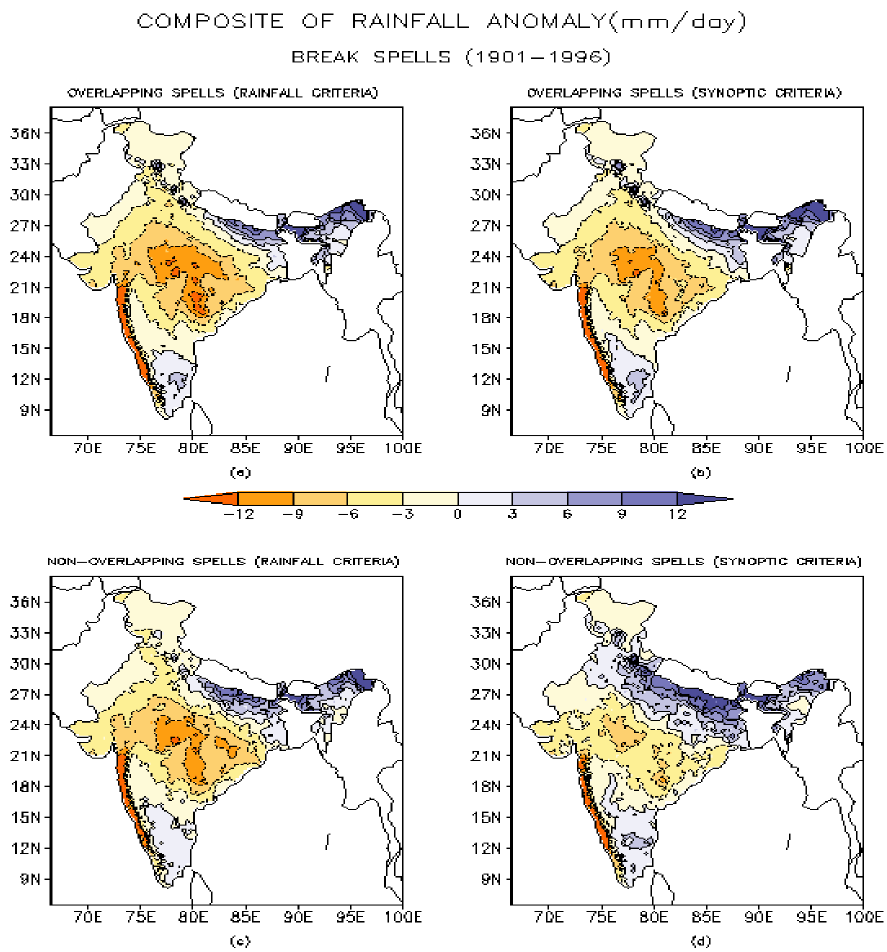

Fig.15. Composite daily rainfall anomaly map of **a)** 78 overlapping break spells based on rainfall criteria, **b)** 78 overlapping break spells based on synoptic criteria, **c)** 38 non overlapping break spells based on rainfall criteria, and **d)** 38 overlapping break spells based on synoptic criteria. The composite maps were prepared for break monsoon spells for the period 1901-1996.

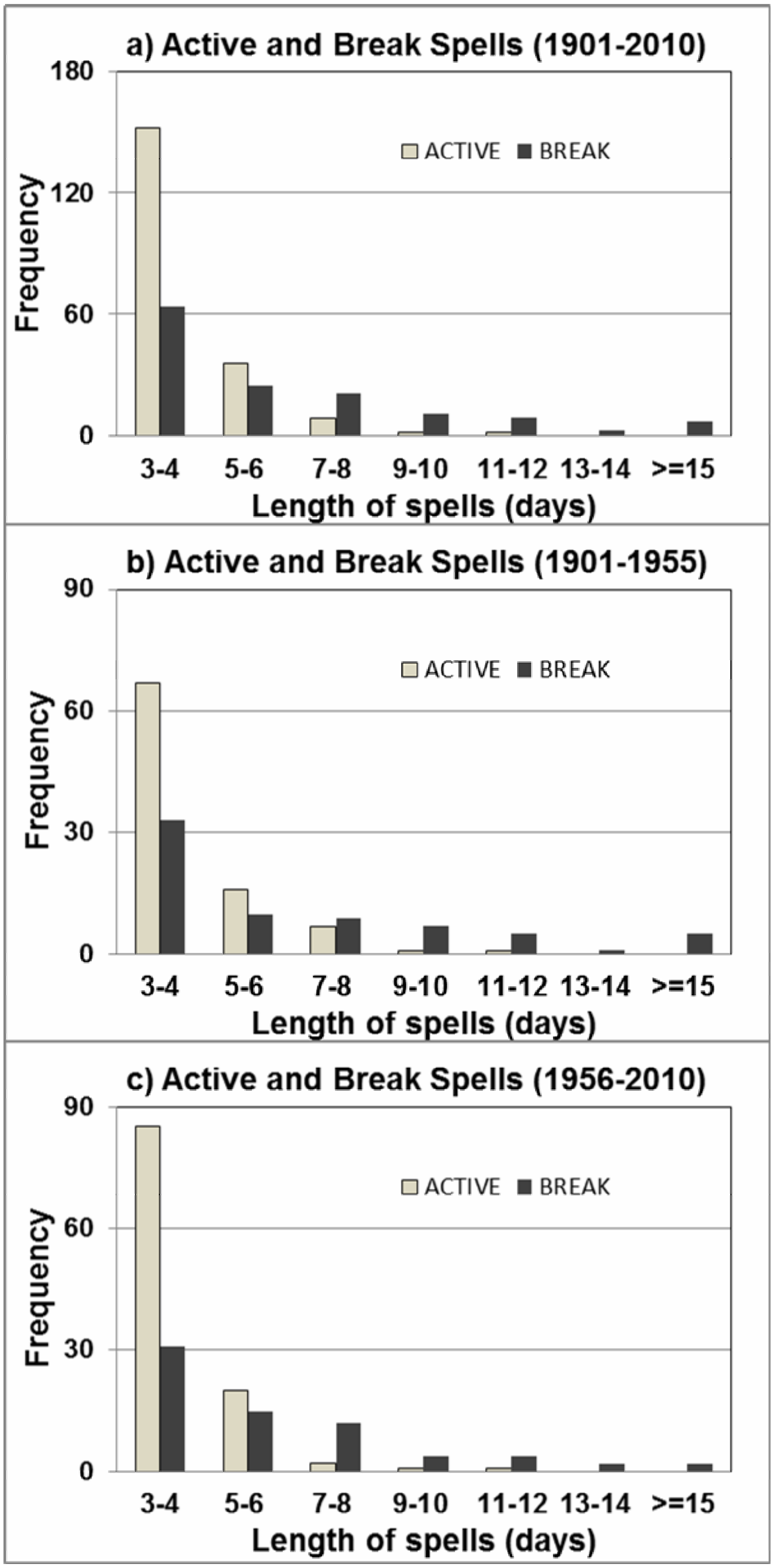

Fig.16. Histogram of duration of break and active spells for the periods **a)** 1901-2010, **b)** 1901-1955 & **c)** 1956-2010.

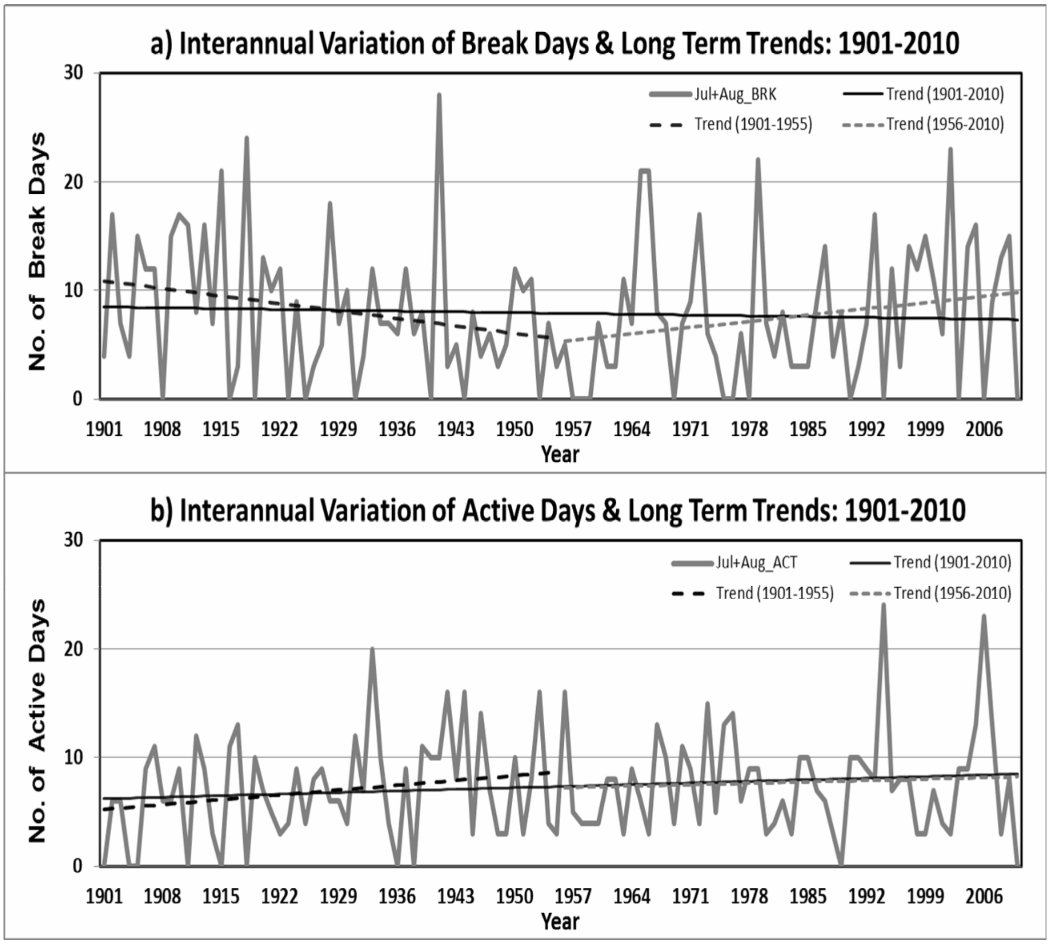

Fig.17. Year to year variation of the number of **a)** break and **b)** active days for the period 1901–2010 with trend lines fitted for the total and two halves of the data period.

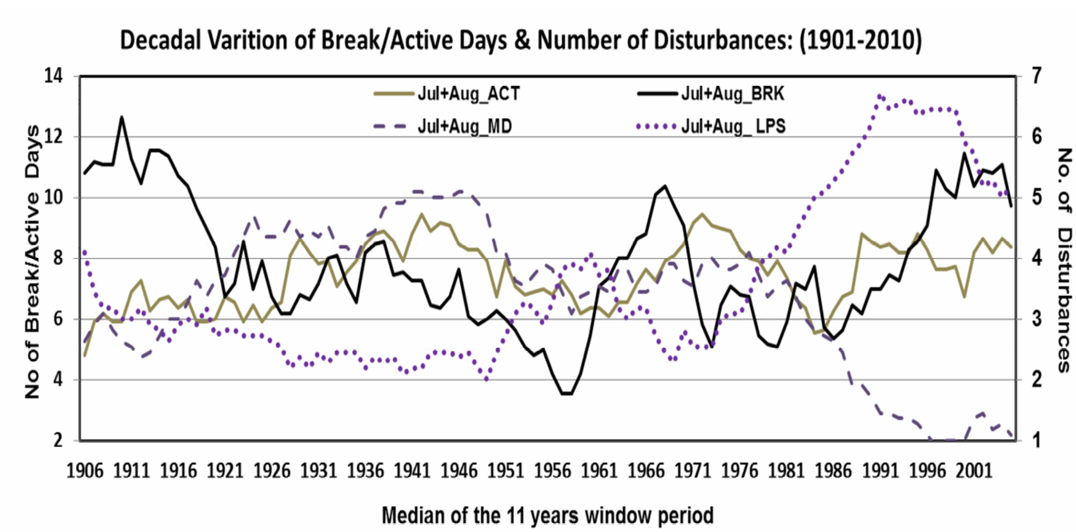

Fig.18. Moving averages of the active and break days for the period 1901-2010 computed based on 11- years window period. The moving averages of the number of monsoon low pressures and that of monsoon depressions are also given.

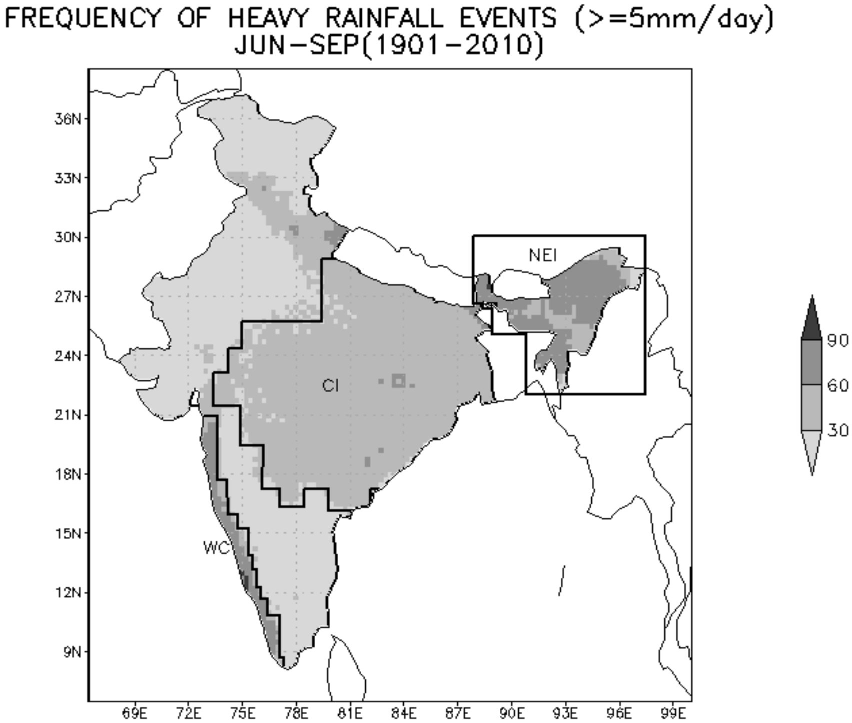

Fig.19. Map showing the grid point frequency of extreme rainfall (≥5mm) events. The spatial domains of 3 regions used for ER analysis are also shown in the map.

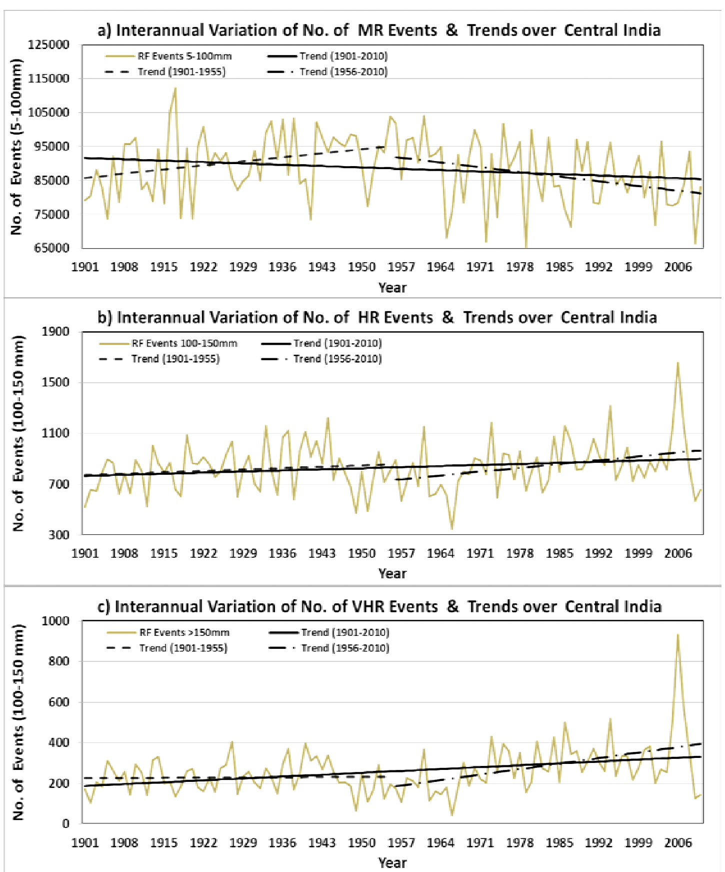

Fig.20. Interannual variation of category wise number of extreme rainfall events (**a)** MR, **b)** HR & **c)** VHR events) over Central India (CI) for the period 1901-2010 with trend lines fitted for the total and two halves of the data period.

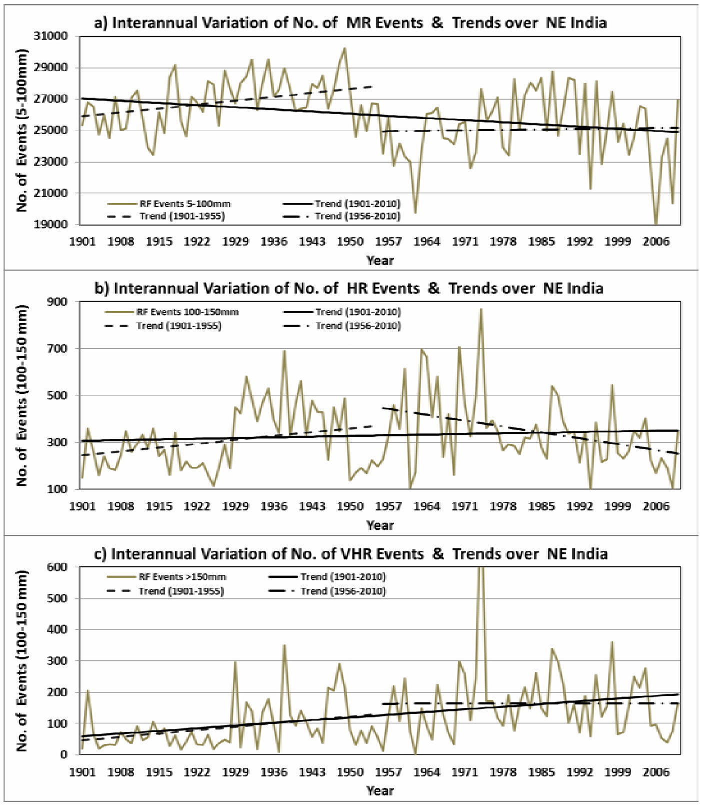

Fig.21. Interannual variation of category wise number of extreme rainfall events (**a)** MR, **b)** HR & **c)** VHR events) over Northeast India (NEI) for the period 1901-2010 with trend lines fitted for the total and two halves of the data period.

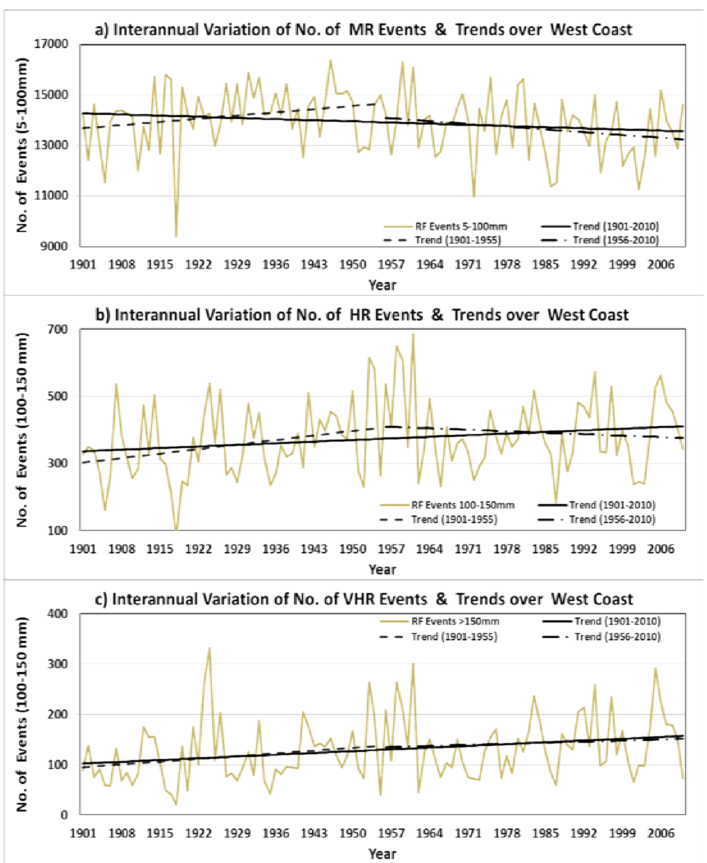

Fig.22. Interannual variation of category wise number of extreme rainfall events (**a)** MR, **b)** HR & **c)** VHR events) over West Coast (WC) for the period 1901-2010 with trend lines fitted for the total and two halves of the data period.

ANNEXURE-I

All India Monthly, Seasonal and Annual Rainfall (in mm) for the period 1901-2010 derived from the new IMD daily gridded (0.25 x 0.25) rainfall data set.

ALL INDIA MONTHLY, SEASONAL AND ANNUAL RAINFALL (in mm) (JANUARY TO DECEMBER) (1901-1930)																	
YEAR	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**JF**	**MAM**	**JJAS**	**OND**	**ANN**
1901	34.8	37.0	15.3	36.6	48.9	109.7	240.9	269.7	118.7	48.1	37.0	8.3	71.8	100.9	739.0	93.3	1005.0
1902	8.2	4.7	20.0	46.8	49.3	103.4	276.7	203.9	199.3	61.9	25.3	24.5	12.8	116.2	783.2	111.7	1023.9
1903	15.7	8.0	24.9	20.3	59.0	119.0	279.0	269.2	189.6	118.1	38.0	16.1	23.7	104.1	856.9	172.2	1156.9
1904	12.4	10.0	28.3	39.6	74.0	160.7	255.0	206.8	122.2	65.9	9.6	13.0	22.4	142.0	744.8	88.6	997.7
1905	20.6	19.2	39.0	34.9	55.3	91.0	250.3	205.4	164.8	50.4	10.7	7.8	39.8	129.2	711.5	68.8	949.3
1906	18.6	45.6	29.2	28.4	37.1	171.6	276.8	247.8	166.1	47.6	16.7	24.6	64.2	94.7	862.3	88.9	1110.1
1907	15.4	39.7	34.9	62.0	30.9	149.8	227.0	301.2	100.6	20.4	20.8	11.6	55.1	127.9	778.6	52.8	1014.4
1908	18.1	16.0	9.1	31.9	46.7	127.7	327.2	301.3	150.2	39.0	4.4	5.4	34.1	87.6	906.4	48.7	1076.9
1909	23.6	12.7	6.1	65.8	54.1	207.7	300.4	229.5	155.5	34.2	8.9	24.6	36.3	126.0	893.1	67.7	1123.0
1910	11.5	10.7	17.8	31.5	41.2	207.7	247.6	278.0	185.2	114.0	32.3	5.1	22.2	90.5	918.6	151.4	1182.6
1911	33.6	5.2	40.3	28.2	52.9	194.1	166.4	211.2	177.4	69.0	40.1	11.2	38.8	121.4	749.1	120.4	1029.6
1912	15.7	23.4	18.9	37.4	43.3	107.8	329.9	261.4	121.0	56.1	50.5	4.8	39.1	99.6	820.2	111.4	1070.3
1913	5.3	37.6	25.4	38.4	77.1	207.7	260.0	186.8	114.0	66.6	14.4	22.5	42.9	140.9	768.4	103.6	1055.8
1914	4.1	23.4	24.0	40.8	65.9	152.0	334.2	241.4	189.8	42.0	20.0	16.3	27.5	130.7	917.4	78.3	1153.9
1915	18.8	34.3	42.3	33.1	64.8	149.7	228.5	224.0	172.2	84.8	42.0	7.5	53.1	140.3	774.4	134.3	1102.1
1916	4.4	16.5	12.0	29.9	53.1	206.2	260.4	296.0	192.0	130.4	43.7	3.9	20.8	94.9	954.6	178.1	1248.4
1917	9.3	37.0	20.1	35.4	73.4	214.1	268.7	275.0	267.7	151.7	26.0	7.7	46.3	128.9	1025.5	185.4	1386.2
1918	12.4	4.7	31.3	30.5	82.4	175.8	152.9	229.2	104.2	17.5	43.2	12.3	17.1	144.1	662.2	73.1	896.5
1919	44.0	17.2	18.6	28.1	52.8	173.6	282.2	271.7	155.7	72.2	50.0	15.1	61.2	99.5	883.3	137.3	1181.2
1920	22.6	14.9	40.6	31.7	52.5	151.3	288.9	166.3	115.0	42.0	24.6	1.9	37.5	124.9	721.5	68.5	952.4
1921	39.6	8.0	19.1	47.0	41.6	169.2	262.3	257.8	193.8	63.1	15.5	13.2	47.6	107.6	883.1	91.8	1130.1
1922	26.2	8.3	13.7	26.4	43.7	177.4	296.0	213.6	194.3	48.0	52.3	11.6	34.5	83.9	881.3	112.0	1111.6
1923	23.6	39.0	24.4	30.7	50.0	91.8	314.7	254.5	169.3	57.8	16.3	16.7	62.6	105.1	830.4	90.7	1088.8
1924	18.7	16.0	11.5	27.8	51.1	107.5	313.1	239.6	237.0	60.6	53.9	13.1	34.7	90.5	897.2	127.6	1149.9
1925	9.4	8.6	13.3	42.0	91.0	187.2	291.4	223.8	117.9	64.2	38.9	15.7	18.0	146.3	820.2	118.7	1103.3
1926	26.8	11.0	52.2	33.3	56.8	83.4	300.8	317.6	197.0	52.3	10.6	6.8	37.9	142.3	898.8	69.7	1148.7
1927	11.3	29.7	22.2	33.6	45.3	154.3	324.8	236.5	154.8	57.1	56.1	10.1	40.9	101.1	870.4	123.3	1135.7
1928	18.3	36.3	19.7	31.8	48.2	154.7	284.8	208.9	133.5	115.0	18.7	20.3	54.7	99.6	781.9	153.9	1090.1
1929	25.8	17.4	13.5	50.7	61.5	176.9	285.7	229.2	122.3	89.4	19.2	34.1	43.1	125.7	814.0	142.7	1125.6
1930	17.9	18.9	23.4	43.6	52.1	172.9	280.7	201.7	168.5	92.4	51.4	9.7	36.8	119.1	823.7	153.5	1133.3

ALL INDIA MONTHLY, SEASONAL AND ANNUAL RAINFALL (in mm)

(JANUARY TO DECEMBER) (1931-1960)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JF	MAM	JJAS	OND	ANN
1931	9.4	27.4	15.9	36.0	55.9	120.1	301.6	301.6	186.5	117.7	40.4	20.3	36.8	107.9	909.9	178.3	1232.8
1932	8.4	15.6	17.3	26.1	74.8	122.4	308.3	229.4	184.2	69.3	50.8	16.7	24.0	118.1	844.3	136.8	1123.3
1933	14.5	26.1	19.3	45.6	95.9	204.4	269.7	303.5	202.5	91.0	18.9	16.3	40.6	160.7	980.0	126.3	1307.6
1934	21.6	11.0	14.3	41.4	48.0	199.6	273.0	288.1	164.2	62.8	30.8	9.5	32.6	103.7	924.9	103.1	1164.3
1935	24.0	19.1	16.6	35.8	32.2	147.7	306.6	232.7	183.9	46.9	15.2	10.9	43.1	84.6	871.0	73.0	1071.7
1936	10.4	37.4	32.1	29.8	75.0	233.8	280.8	230.7	186.6	60.9	57.4	20.1	47.8	136.9	931.9	138.4	1254.9
1937	6.6	48.2	17.6	54.5	50.2	150.8	331.4	202.4	172.7	88.6	19.7	14.0	54.8	122.3	857.3	122.3	1156.7
1938	26.2	25.4	28.7	31.4	63.2	253.1	283.6	241.6	158.5	72.9	14.2	5.2	51.6	123.3	936.8	92.2	1203.9
1939	12.7	27.9	27.3	38.5	35.9	160.7	264.0	229.3	151.3	87.1	28.3	1.3	40.7	101.8	805.3	116.7	1064.4
1940	11.3	23.5	41.5	27.0	77.5	168.1	297.3	270.6	111.7	60.0	40.1	16.0	34.8	145.9	847.6	116.2	1144.6
1941	21.4	14.7	17.1	30.2	71.4	159.8	228.5	223.3	147.2	58.4	25.0	16.7	36.0	118.7	758.7	100.1	1013.5
1942	18.6	39.4	17.8	42.2	58.3	175.0	335.3	278.7	176.8	32.9	16.6	21.7	58.0	118.3	965.8	71.2	1213.4
1943	50.0	9.2	26.2	44.9	87.6	157.7	302.6	229.5	202.5	88.8	17.0	4.9	59.2	158.7	892.2	110.7	1220.8
1944	24.7	33.3	52.1	30.6	55.9	145.9	344.6	286.8	150.0	86.5	28.7	13.8	58.0	138.5	927.3	128.9	1252.8
1945	29.6	8.2	18.8	41.1	51.6	150.4	322.6	235.4	207.6	80.7	17.4	3.3	37.8	111.4	916.1	101.3	1166.7
1946	4.0	16.9	20.4	44.0	63.9	204.9	297.5	284.9	138.2	79.3	72.5	32.9	20.9	128.2	925.5	184.7	1259.4
1947	20.5	15.8	25.4	37.0	46.1	120.2	301.4	277.0	235.4	67.9	6.5	19.3	36.4	108.6	934.0	93.7	1172.6
1948	24.8	25.4	30.7	41.5	76.5	149.4	303.8	276.3	174.9	61.8	69.0	9.3	50.1	148.7	904.4	140.1	1243.3
1949	12.1	30.6	22.6	48.3	83.9	150.4	304.0	238.4	219.5	95.0	10.6	9.8	42.8	154.9	912.3	115.4	1225.5
1950	35.7	28.9	29.7	21.6	48.6	144.5	328.3	237.6	186.8	49.9	25.1	7.8	64.5	99.8	897.1	82.7	1144.2
1951	13.5	9.6	39.7	46.9	55.7	141.5	237.1	212.0	116.3	67.4	32.2	3.4	23.1	142.2	707.0	103.1	975.4
1952	7.8	16.4	30.5	30.5	64.8	157.5	273.4	245.1	120.6	75.0	6.7	19.8	24.3	125.7	796.6	101.5	1048.1
1953	25.2	9.0	25.9	33.6	45.5	152.1	305.3	286.3	169.3	83.3	10.7	6.2	34.2	105.0	913.0	100.2	1152.4
1954	29.0	29.5	16.4	27.6	54.9	138.6	286.8	221.3	234.6	72.7	3.7	14.8	58.5	98.9	881.2	91.3	1129.8
1955	21.2	4.5	26.9	30.3	69.2	170.1	231.5	300.9	210.7	143.7	22.2	9.4	25.7	126.4	913.1	175.2	1240.4
1956	16.4	8.8	29.9	32.6	85.8	196.2	338.8	243.4	160.7	148.3	42.8	13.1	25.2	148.3	939.2	204.2	1316.9
1957	34.1	12.3	25.1	32.1	67.4	143.7	285.8	258.5	125.5	59.0	26.5	12.5	46.4	124.6	813.5	98.0	1082.4
1958	12.1	17.4	16.4	35.5	70.9	114.3	308.8	292.5	213.1	102.9	28.9	13.6	29.5	122.8	928.7	145.4	1226.4
1959	27.6	22.2	17.6	26.2	72.2	155.8	336.6	249.9	217.9	110.4	22.9	5.1	49.8	116.1	960.1	138.5	1264.4
1960	11.9	2.3	30.8	18.1	53.5	147.2	291.6	242.1	169.6	65.9	32.6	7.1	14.3	102.5	850.5	105.5	1072.8

ALL INDIA MONTHLY, SEASONAL AND ANNUAL RAINFALL (in mm)
(JANUARY TO DECEMBER) (1961-1990)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JF	MAM	JJAS	OND	ANN
1961	22.7	30.5	20.8	25.2	71.7	172.3	323.8	270.6	225.1	118.1	18.4	9.8	53.1	117.7	991.7	146.3	1308.8
1962	11.7	15.9	14.3	30.7	47.8	106.2	284.7	253.5	209.4	74.9	17.4	26.5	27.6	92.8	853.8	118.8	1093.1
1963	6.7	7.9	29.0	40.4	52.1	144.5	241.4	298.4	150.7	92.4	24.6	13.0	14.5	121.4	835.0	130.1	1101.1
1964	12.5	13.3	16.0	32.6	46.1	158.6	318.8	264.9	192.7	61.9	20.7	9.7	25.7	94.8	935.0	92.3	1147.8
1965	8.9	20.7	22.1	37.3	42.4	114.2	268.5	194.0	130.1	31.9	16.6	20.5	29.6	101.7	706.7	69.1	907.2
1966	12.9	20.4	14.9	27.0	53.9	167.6	241.7	209.3	134.7	53.0	49.3	15.2	33.2	95.8	753.4	117.6	1000.0
1967	9.2	11.1	54.8	25.0	39.8	140.1	294.6	256.6	163.2	38.1	11.5	48.4	20.3	119.6	854.5	98.1	1092.5
1968	24.0	17.4	25.6	32.7	44.6	134.4	287.2	199.2	128.2	65.5	19.1	10.2	41.3	102.9	749.1	94.7	988.1
1969	11.3	9.7	16.1	38.0	60.8	121.0	295.0	243.8	166.3	51.7	35.3	12.7	21.0	114.9	826.1	99.7	1061.6
1970	21.9	20.6	21.2	28.1	58.5	202.5	237.1	294.4	212.0	67.7	12.9	0.9	42.6	107.8	946.0	81.5	1177.9
1971	16.2	17.1	9.3	45.7	68.0	217.8	260.8	259.6	143.4	99.2	13.2	11.3	33.3	123.0	881.6	123.8	1161.7
1972	8.4	22.4	16.6	34.8	54.4	117.5	199.6	213.8	126.9	61.2	27.9	21.0	30.9	105.8	657.8	110.1	904.6
1973	15.3	17.0	15.6	24.8	54.7	150.2	271.0	298.4	184.0	112.7	16.2	14.5	32.3	95.1	903.5	143.5	1174.4
1974	13.9	11.4	17.3	29.7	61.2	124.8	282.3	234.3	142.0	97.1	9.8	8.5	25.3	108.1	783.4	115.4	1032.3
1975	15.7	19.8	24.2	33.6	48.9	172.6	311.0	279.8	224.1	114.9	21.2	4.1	35.6	106.7	987.4	140.2	1269.9
1976	9.3	20.6	24.5	38.0	45.5	152.7	293.6	288.7	141.3	33.1	53.0	7.2	29.9	108.0	876.4	93.2	1107.4
1977	18.5	9.9	14.2	64.2	83.4	179.9	308.4	242.0	145.4	84.0	63.1	15.5	28.3	161.8	875.8	162.7	1228.6
1978	11.0	26.3	40.9	32.6	55.5	198.1	283.8	276.3	161.2	49.5	50.4	18.6	37.3	128.9	919.5	118.6	1204.3
1979	22.8	34.2	29.2	22.7	54.3	130.9	230.1	203.0	131.8	53.9	73.2	15.3	57.0	106.2	695.8	142.4	1001.4
1980	13.6	23.2	30.9	35.4	51.8	222.9	292.0	258.1	140.9	47.2	21.6	16.7	36.8	118.1	913.9	85.5	1154.3
1981	24.0	17.9	42.4	32.6	60.9	139.3	300.2	234.5	184.2	44.4	25.9	13.8	42.0	136.0	858.2	84.1	1120.2
1982	26.9	25.8	43.7	51.5	60.0	135.1	223.0	268.0	122.0	48.7	44.1	13.3	52.8	155.1	748.2	106.1	1062.1
1983	18.6	20.8	42.0	54.5	65.7	146.5	275.9	288.8	245.1	85.3	10.1	23.3	39.4	162.1	956.3	118.8	1276.7
1984	19.2	36.4	21.1	47.4	53.7	184.3	271.6	249.5	145.7	57.6	15.3	14.9	55.6	122.2	851.1	87.9	1116.7
1985	25.5	9.3	22.9	39.5	56.7	148.7	273.4	223.9	148.8	112.9	17.8	25.6	34.8	119.1	794.7	156.3	1104.9
1986	14.5	37.3	33.8	52.5	48.8	174.3	252.5	215.8	121.1	69.7	42.6	26.9	51.8	135.1	763.8	139.1	1089.7
1987	13.2	20.0	29.0	48.0	64.9	124.2	216.9	237.8	146.9	92.0	41.5	20.9	33.2	141.9	725.8	154.3	1055.3
1988	9.2	26.0	51.4	40.8	62.7	146.2	355.0	285.8	204.0	47.1	14.1	17.4	35.2	154.9	991.0	78.7	1259.9
1989	14.8	15.9	26.6	37.1	56.1	176.8	290.8	230.3	157.5	45.2	19.7	15.1	30.7	119.8	855.3	80.0	1085.8
1990	14.3	39.7	50.3	43.6	103.2	182.4	275.9	281.7	187.3	100.6	27.7	25.5	54.0	197.2	927.3	153.8	1332.3

ALL INDIA MONTHLY, SEASONAL AND ANNUAL RAINFALL (in mm)

(JANUARY TO DECEMBER) (1991-2010)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JF	MAM	JJAS	OND	ANN
1991	13.5	24.1	27.4	45.9	67.2	177.1	266.1	248.9	133.9	54.4	30.2	14.2	37.6	140.5	826.0	98.9	1103.0
1992	19.1	15.5	25.2	24.8	56.2	130.9	260.3	269.8	158.3	60.8	40.8	5.0	34.6	106.2	819.3	106.6	1066.6
1993	17.5	25.9	41.0	24.9	65.0	160.6	292.6	200.2	205.4	81.7	27.8	16.3	43.4	130.9	858.8	125.7	1158.8
1994	22.8	25.9	26.0	46.6	48.0	197.9	330.5	267.9	150.2	79.4	24.3	18.4	48.6	120.7	946.5	122.0	1237.8
1995	29.5	26.7	29.2	33.8	77.0	131.9	301.3	255.6	180.6	75.2	31.1	8.0	56.2	140.0	869.4	114.3	1179.9
1996	26.0	24.9	33.8	34.6	58.5	173.8	255.2	277.9	140.4	94.5	11.5	17.7	50.9	126.9	847.4	123.7	1148.8
1997	12.3	10.8	32.1	42.7	44.7	162.1	267.1	260.9	146.4	56.2	55.6	50.6	23.1	119.5	836.4	162.4	1141.5
1998	15.3	24.6	37.1	34.5	46.3	158.1	269.5	239.2	193.7	105.0	38.5	10.3	39.9	117.9	860.5	153.9	1172.3
1999	11.2	10.3	9.8	20.9	86.1	160.4	254.6	208.7	180.2	116.0	17.4	3.2	21.5	116.8	804.0	136.6	1078.8
2000	12.1	24.1	13.8	31.8	67.3	174.6	254.2	217.2	131.3	39.7	14.8	8.1	36.2	112.9	777.4	62.6	989.1
2001	5.7	8.8	18.4	41.1	56.6	211.5	268.8	203.0	108.5	99.1	18.0	6.2	14.5	116.0	791.8	123.3	1045.6
2002	16.2	19.4	24.5	38.2	52.8	162.5	141.2	238.1	137.5	53.7	13.5	4.4	35.6	115.5	679.2	71.6	901.9
2003	6.5	33.5	30.8	34.8	36.5	161.5	306.1	235.1	179.5	90.6	8.4	15.3	40.0	102.1	882.2	114.3	1138.6
2004	19.3	7.1	9.4	54.1	74.0	157.4	223.3	253.5	122.7	91.4	14.8	4.5	26.4	137.4	757.0	110.6	1031.5
2005	22.3	24.4	38.6	39.7	48.4	159.9	329.7	213.5	218.6	97.7	32.5	14.7	46.8	126.7	921.7	144.9	1240.0
2006	12.7	10.5	33.5	31.7	70.9	145.7	285.7	288.6	173.9	50.5	37.3	12.4	23.1	136.1	893.9	100.2	1153.4
2007	1.9	37.0	33.5	31.3	47.8	186.9	276.4	255.9	200.1	56.2	12.7	16.7	38.9	112.5	919.2	85.7	1156.3
2008	19.1	15.1	37.3	27.0	43.7	208.0	236.9	259.7	163.6	49.8	25.0	9.8	34.2	108.1	868.1	84.6	1095.0
2009	14.1	11.1	13.7	25.2	54.3	82.1	280.6	186.3	139.8	73.3	54.9	11.1	25.2	93.2	688.8	139.3	946.5
2010	8.7	15.1	18.7	49.0	76.3	134.4	288.1	262.5	197.8	67.0	60.5	21.5	23.8	144.0	882.8	149.1	1199.7

JF – January to February **MAM** – March to May **JJAS** – June to September **OND** – October to December **ANN** – Annual

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