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Development of a new high spatial resolution (0.25° × 0.25°) Long Period (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region

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ABSTRACT. The study discusses development of a new daily gridded rainfall data set (IMD4) at a high spatial resolution (0.25° × 0.25°, latitude × 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. 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.

Key words – Daily gridded rainfall, , Rainfall climatology, Annual cycle, High resolution, Heavy rainfall

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° × 1° 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

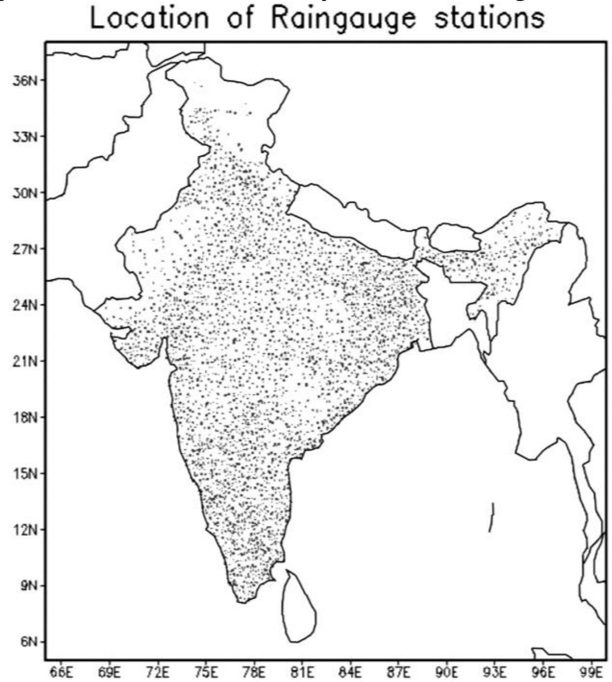

Fig. 1. Network of 6955 rain gauge stationsused for development of IMD4

Department (IMD). These are two 1° × 1° gridded daily rainfall datasets based on fixed network of rain gaugestations (Rajeevan *et al*. 2006, Rajeevan *et al.* 2008), and a 0.5° × 0.5° gridded 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° × 0.25° 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

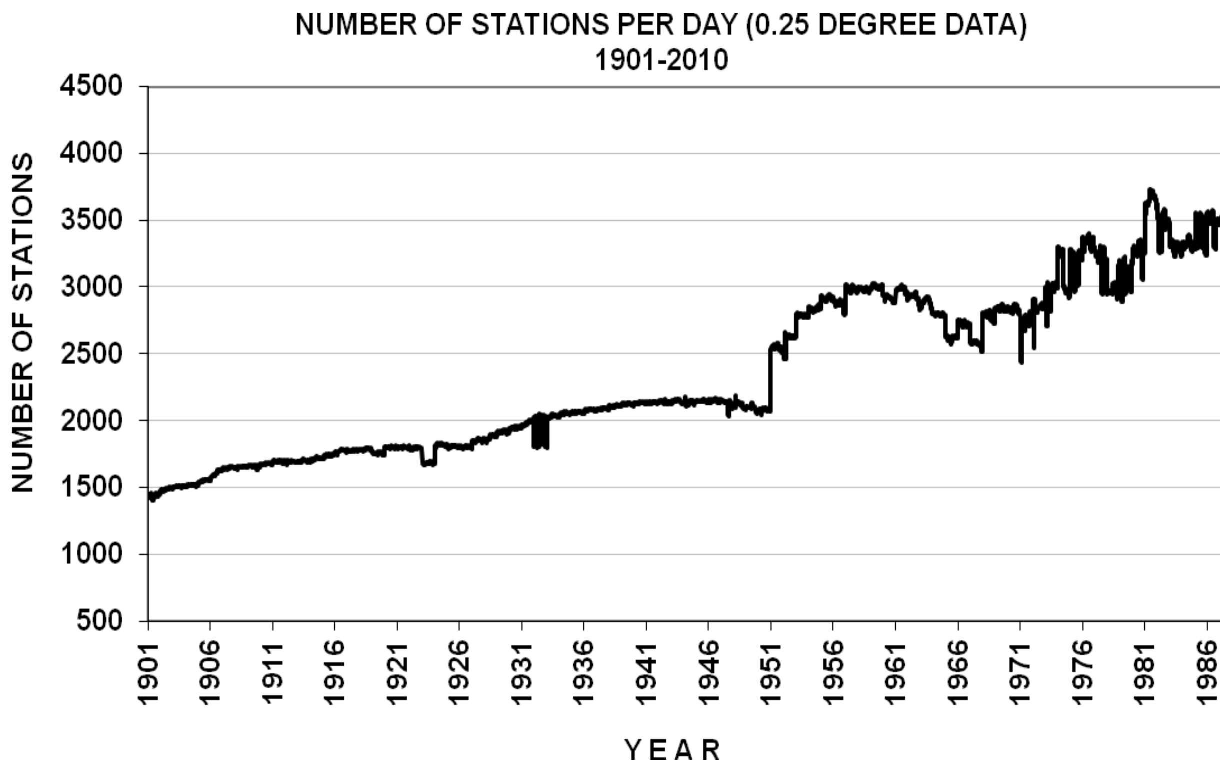

Fig. 2. Daily Variation of number of stations used for the development of IMD4

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 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.

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 section4 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° × 0.5° 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.

TABLE 1

Details of gridded daily rainfall data sets used in the study

Data set	Short name used in this study	Spatial resolution Latitude × longitude	Data period	Rain gauge Network used for preparing the gridded data	Interpolation method
IMD (Rajeevan *et al*. 2006 & 2010)	IMD1	1° × 1°	1951-2007	fixed network of 2140 rain gauge stations	Shepard (1968)
IMD (Rajeevan *et al.* 2008)	IMD2	1° × 1°	1901-1904	fixed network of 1380 rain gauge stations	Shepard (1968)
IMD (Rajeevan *et al.* 2009)	IMD3	0.5° × 0.5°	1971-2005	varying network of 6076 rain gauge stations	Shepard (1968)
APHRODITE (Yatagai *et al*. 2012)	APHRO	0.25° × 0.25°	1951-2007	varying network of rain gauge stations	Willmott *et al*. (1985)
Present Study	IMD4	0.25° × 0.25°	1901-2010	varying network of 6955 rain gauge stations	Shepard (1968)

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 (Table 1 for the brief details of the data sets). The first data set at the spatial grid of 1° × 1° 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° × 1°, 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° × 0.5° 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° × 0.25° and 0.5° × 0.5° 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° × 0.25° 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*

Before quality checking and interpolation of the station rainfall data, verification of the location information of the station and checking of coding and typographic errors in the data were carried out. After applying the standard quality control tests such as tests for typing and coding errors, missing data, duplicate station check, extreme value check etc. on the daily station point rainfall data, the data were interpolated at fixed spatial grid points of 0.25° × 0.25° 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 (Cressman 1959, Shepard 1968 & 1984), natural neighbour (Sibson 1981)], or the degree of smoothing in relation with neighboring station data points (*e.g.*, trend analysis [(Edwards 1973, Hughes 1982), multi-quadratic surface fitting (Hardy 1971, Shaw 1994)]. The geostatistical methods useboth mathematical and statistical methods that include autocorrelation (the

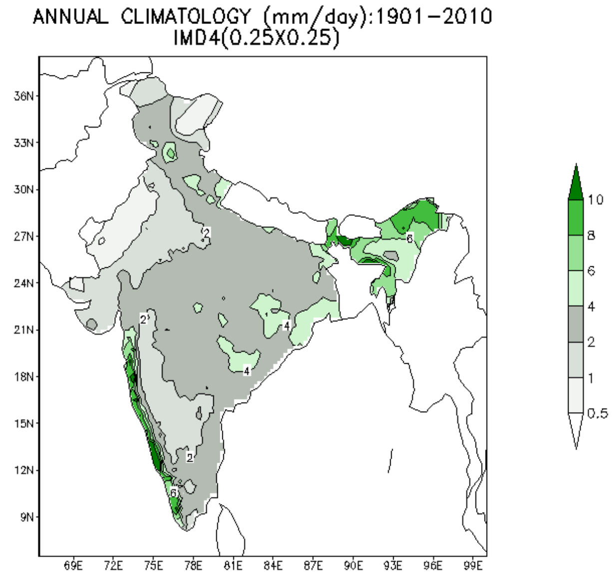

Fig. 3. Spatial distribution of the mean annual rainfall over India computed for the period 1901-2010

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).

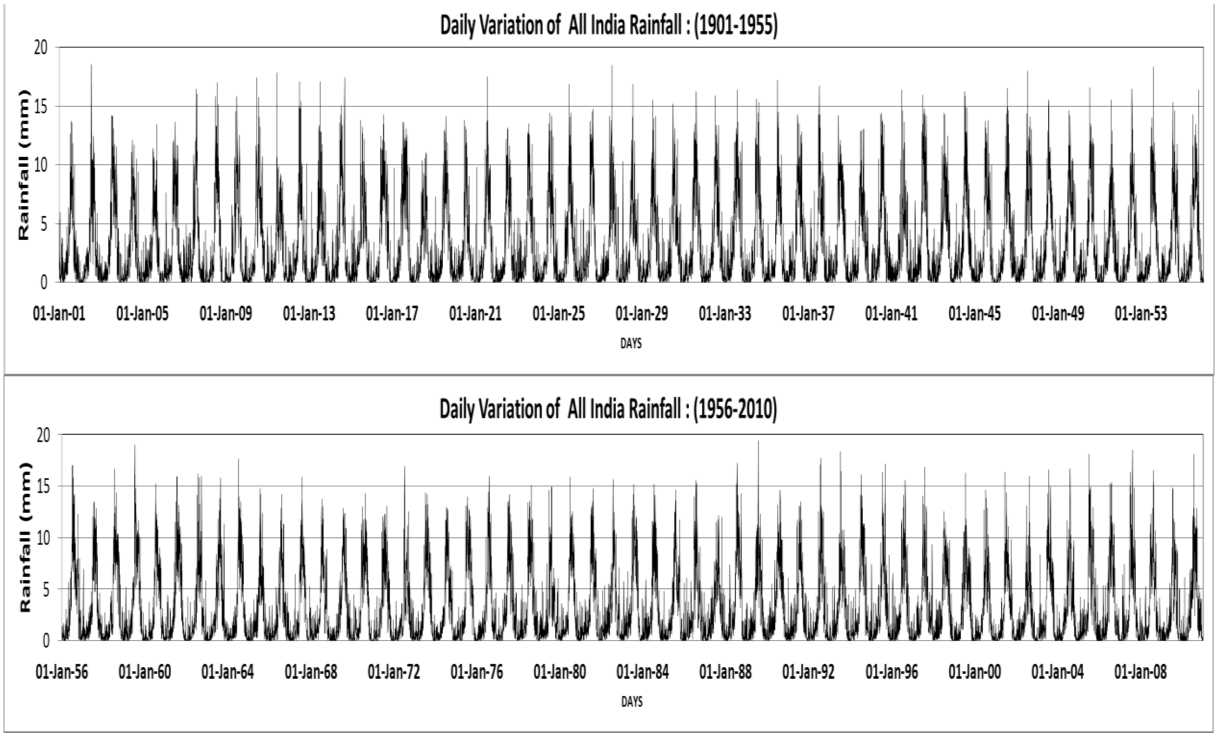

Fig. 4. Time series of all India daily rainfall for the period 1901-2010

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.

4. Results

The spatial domain of the IMD4extended 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 IMD4annual 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. As seen in the Fig. 4, both inter-annual and intra-seasonal variability are present in the daily rainfall series embedded with extreme

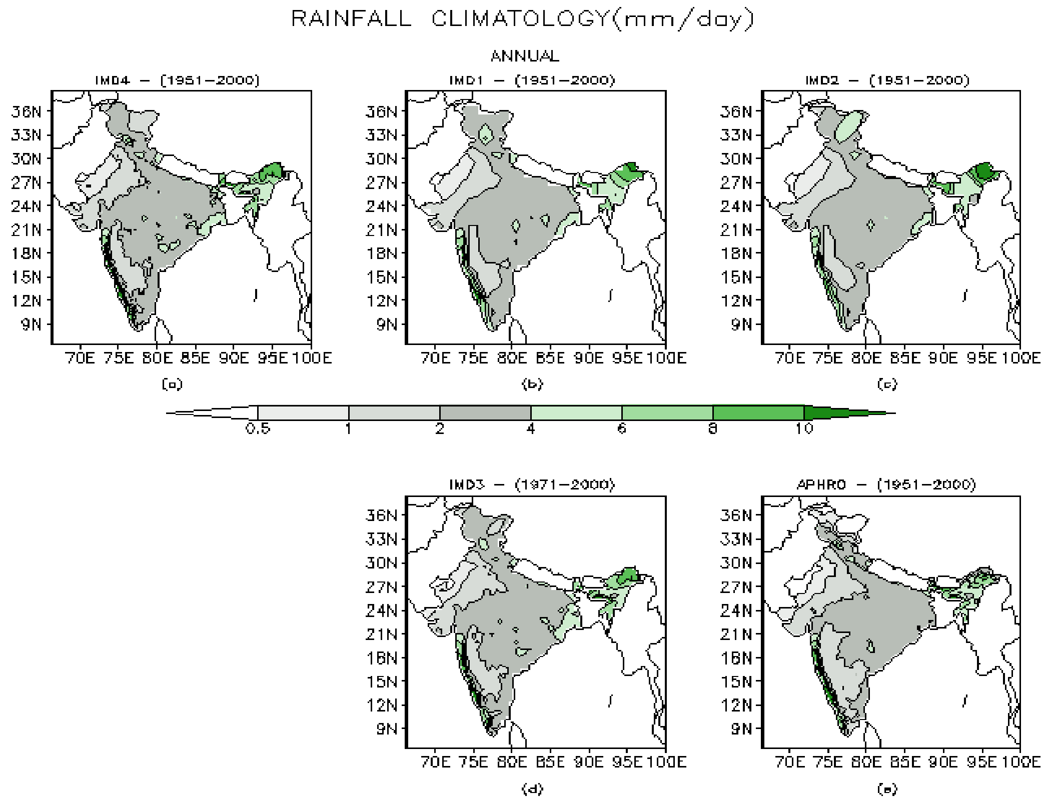

Fig. 5. Mean annual climatology of rainfall over India based on 5 gridded rainfall data sets over the region. (a) IMD4, (b) IMD1, (c) IMD2, (d) IMD3 and (e) APHRO. The climatology of IMD3 was computed using data for the period 1971-2000 & that of other data sets were computed using data for the period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

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 IMD4reflects well known large scale mean and variability features of the rainfall over India.

The monthly, seasonal and annual mean values of all India rainfall based on IMD4 data for the entire data period is given in the last column of the Table 2. As seen in this table, the all India mean annual rainfall and mean seasonal rainfall for the southwest monsoon season (June-September) for the total period (1901-2010) were 3.09 mm/day and 6.99 mm/day respectively.

4.1. *Comparison of the new gridded data set with the existing gridded rainfall data sets over India*

4.1.1. *Spatial distribution of mean annual and seasonal rainfall*

In this section, a comparison of various climatological features of rainfall over India based on IMD4 with that based on the other four rainfall datasets over India (IMD1, IMD2, IMD3 and APHRO) were examined. The climatological features examined were 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. As discussed in the Section-2, the data periods of these data

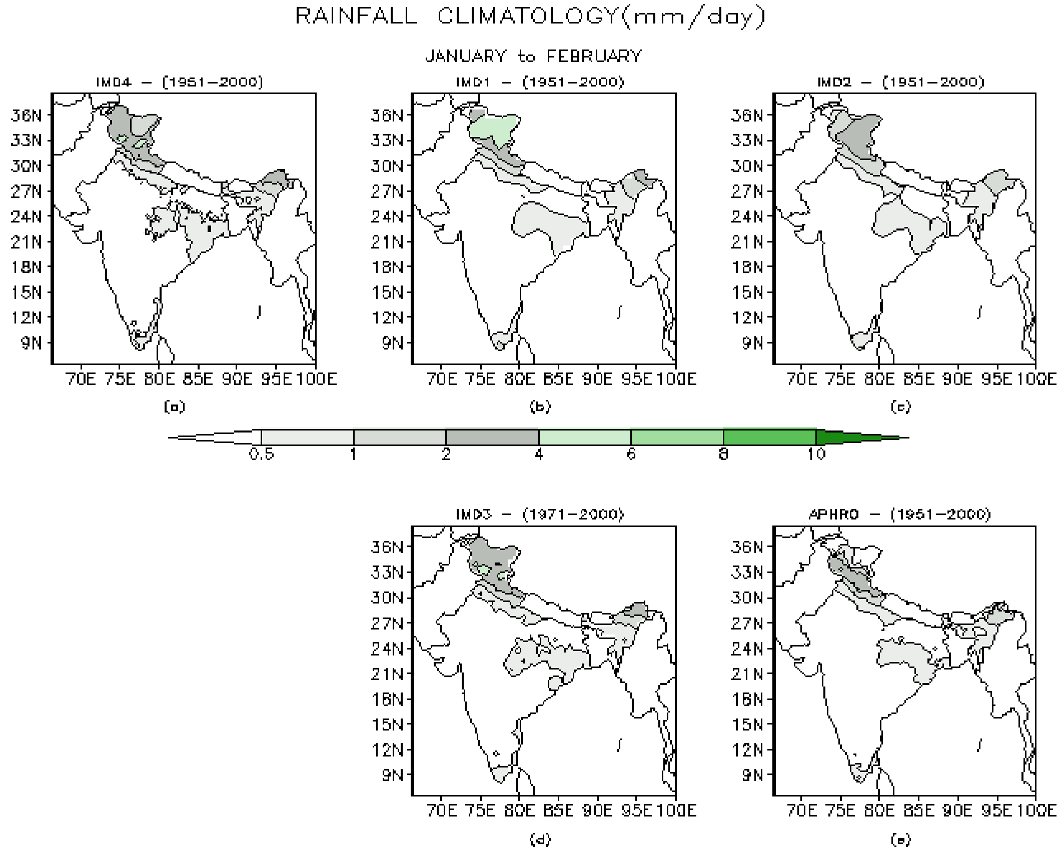

Fig. 6. Mean climatology of rainfall over India during the winter season (January-February) based on 5 gridded rainfall data sets over the region. (a) IMD4, (b) IMD1, (c) IMD2, (d) IMD3 and (e) APHRO. The climatology of IMD3 was computed using data for the period 1971-2000 & that of other data sets were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

sets were different. Therefore, climatological features of rainfall using IMD3 were prepared using data for the common period of 1971-2000 and that of other data sets were prepared using the period of 1951-2000.

Fig. 5 shows the comparison of maps showing spatial distribution of mean annual rainfall over India computed based on all the 5 rainfall data sets. All the annual rainfall climatology maps depicted 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 was that the maps [Figs. 5(b&c)] based on lower resolution (IMD1 & IMD2) data sets depict smoother patterns but with less details of spatial distribution of annual mean rainfall compared to that [Figs. 5(a, d-e)] based on higher resolution data sets (IMD4, IMD3 & APHRO). For *e.g.*, the north-south zone of rainfall areas of ≥ 4mm/day along the windward side of the Western Ghatsis narrower in Figs. 5(a, d-e) compared to Figs. 5(b&c). On the other hand, relatively more (less)areas of rainfall ≥8mm/daycan be seen along the west coast and over Assam & Meghalaya (Arunachal Pradesh) in the maps of higher resolution data sets compared to that of the lower resolution data sets. Similarly higher resolution data sets depict relatively drier climatology over northern parts of Jammu and Kashmir.

The rainfall climatology maps of higher resolution data sets show closer resemblance except along the west coast, where the zone of maximum rainfall areas is slightly narrower and the areas of rainfall ≥8mm/day are relatively more in IMD4compared to that in IMD3 & APHRO. Another difference is that 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

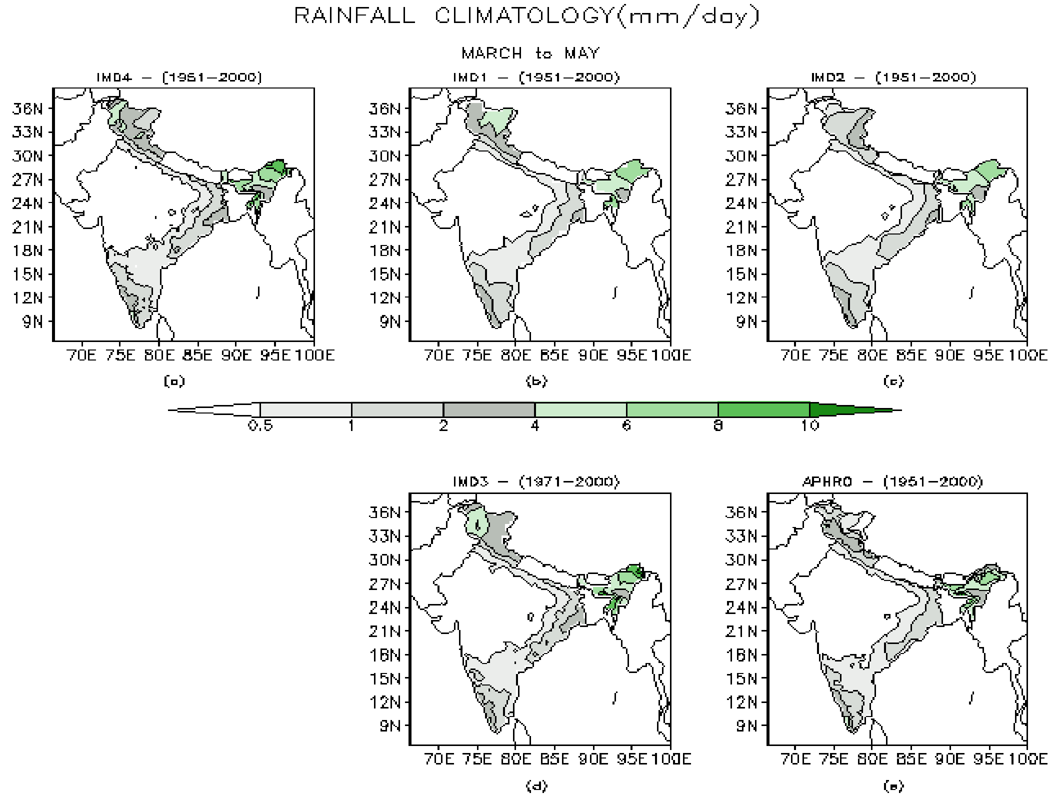

Fig. 7. Mean climatology of rainfall over India during the pre-monsoon season (March-May) based on 5 gridded rainfall data sets over the region. (a) IMD4, (b) IMD1, (c) IMD2, (d) IMD3 and (e) APHRO. The climatology of IMD3 was computed using data for the period 1971-2000 & that of other data sets were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

compared to the other two data sets. Relatively drier annual rainfall climatology is seen also over north Saurashtra and Kutch, northern part of east coast, Sikkim, and Arunachal Pradesh 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, Figs. 6 to 9 are 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, northern parts of east coast, 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. Relatively narrower zone of higher rainfall (≥15mm/day) along the west coast during southwest monsoon season is also seen in the higher resolution data sets.

4.1.2. *Mean annual cycle of all India rainfall*

In this section the mean annual cycle of the all India daily, monthly, seasonal rainfall computed using various data sets were compared. The Fig. 10 shows the mean annual cycle of the daily rainfall averaged over the Indian main land based on various data sets. The base period

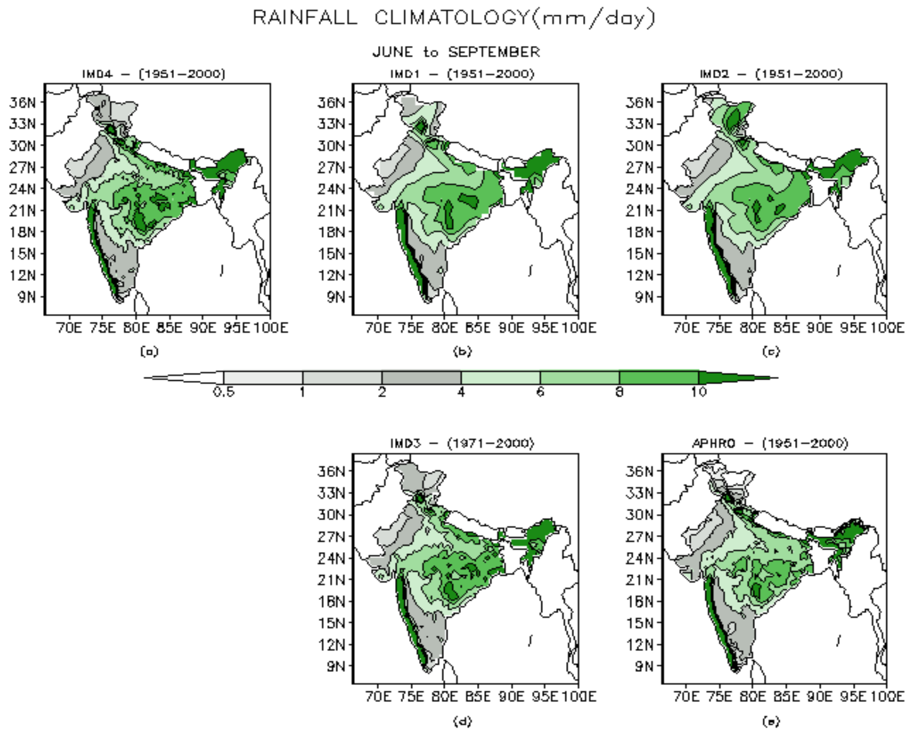

Fig. 8. Mean climatology of rainfall over India during the southwest monsoon season (June-September) based on 5 gridded rainfall data sets over the region. (a) IMD4, (b) IMD1, (c) IMD2, (d) IMD3 and (e) APHRO. The climatology of IMD3 was computed using data for the period 1971-2000 & that of other data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

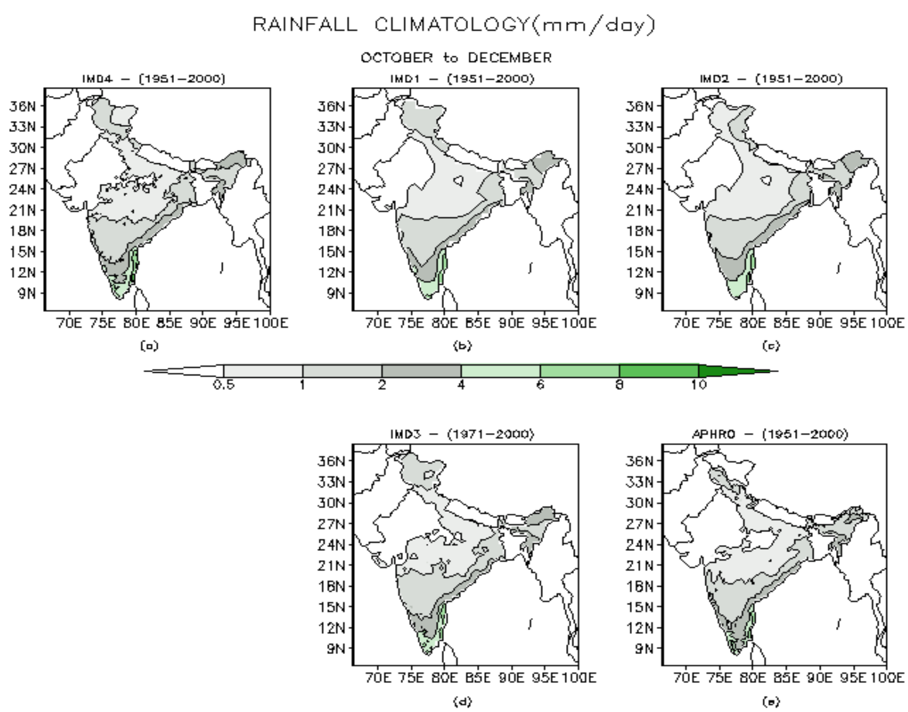

Fig. 9. Mean climatology of rainfall over India during the post monsoon season (October-December) based on 5 gridded rainfall data sets over the region. (a) IMD4, (b) IMD1, (c) IMD2, (d) IMD3 and (e) APHRO. The climatology of IMD3 was computed using data for the period 1971-2000 & that of other data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

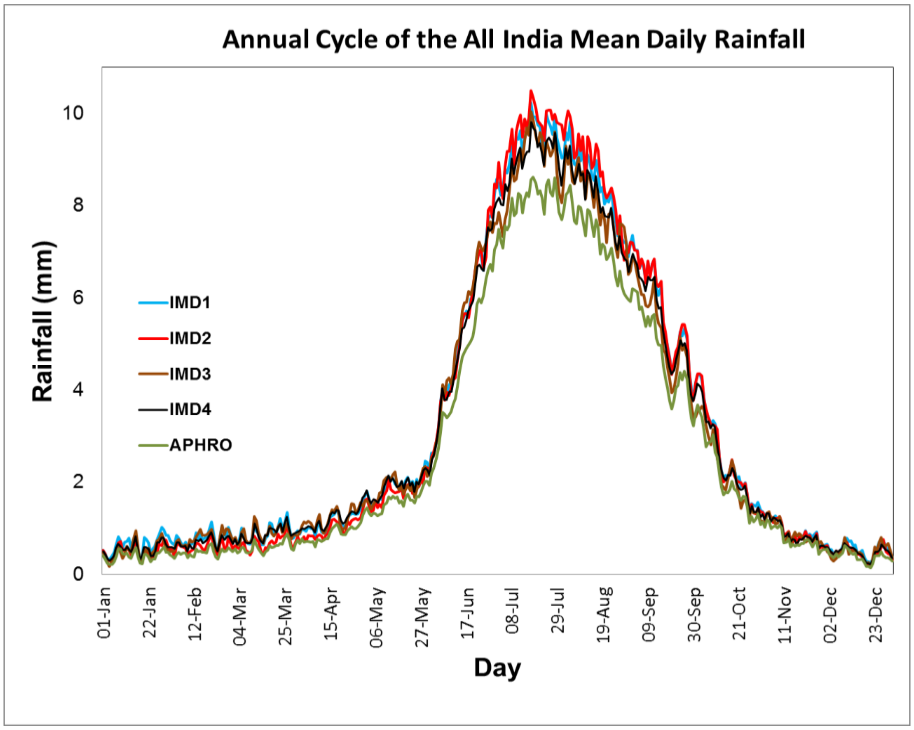

Fig. 10. Annual cycle of the all India daily mean rainfall. The climatology of IMD3 was computed using data for the period 1971-2000 & that of other data sets were computed using data for the period 1951-2000

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 orIMD4 were the highest. The difference between highest mean daily rainfall values in IMD2 and APHRO was 1.86mm/dayand that between IMD2and IMD4was 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

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 IMD4with 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 (mm/day)	CC	RMSD	BIAS (mm/day)	CC	RMSD	BIAS (mm/day)	CC	RMSD	BIAS (mm/day)	CC	RMSD	BIAS (mm/day)	CC
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

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 (0.27mm/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).

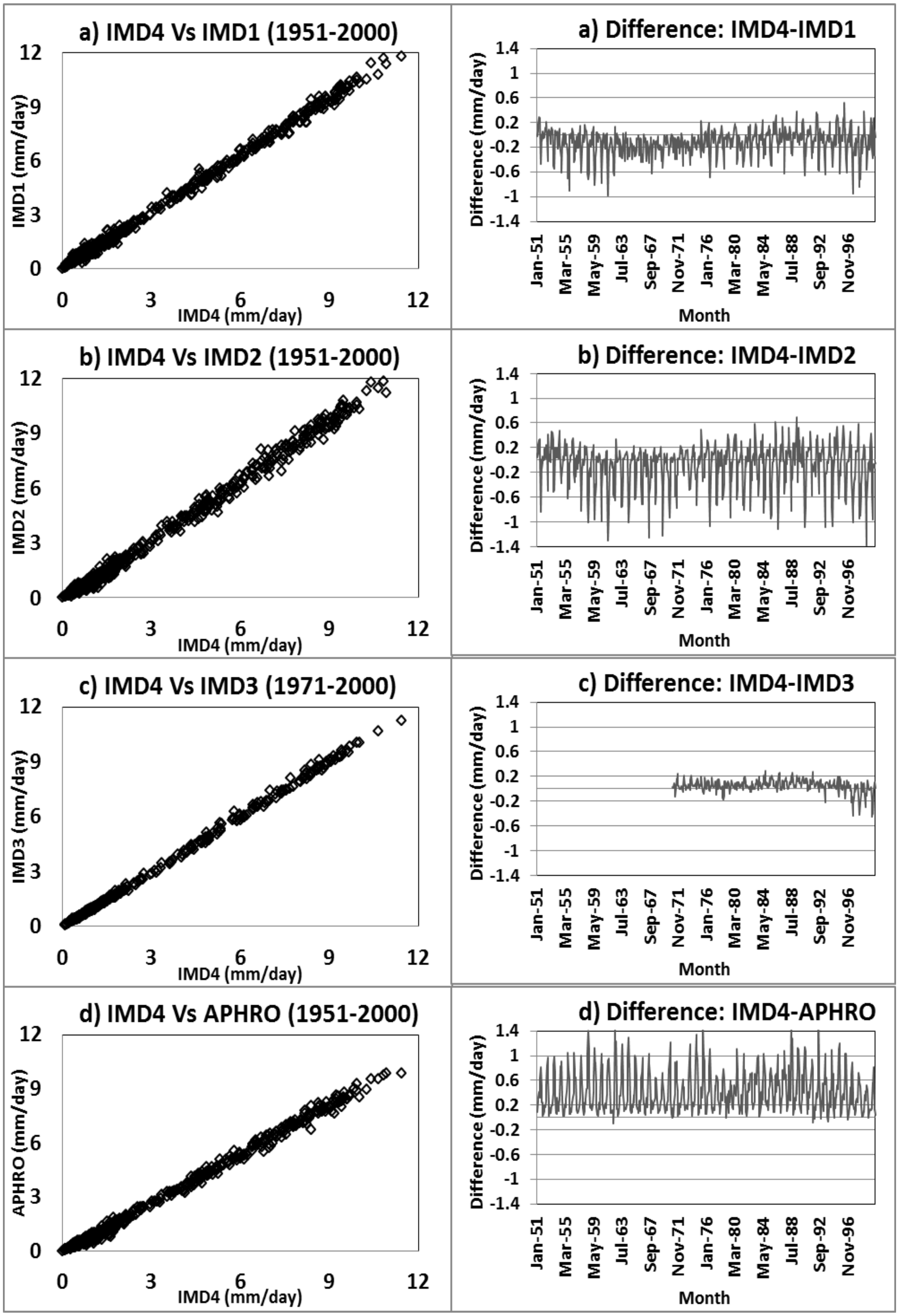

Fig. 11. Scatter plots of all India monthly rainfall computed using IMD1, IMD2, IMD3 & APHRO against that computed using the IMD4. The time series plots of their differences are also given side by side. (a) IMD1, (b) IMD2, (c) IMD3 and (d) APHRO. The plots in respect of IMD3 was prepared using data for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

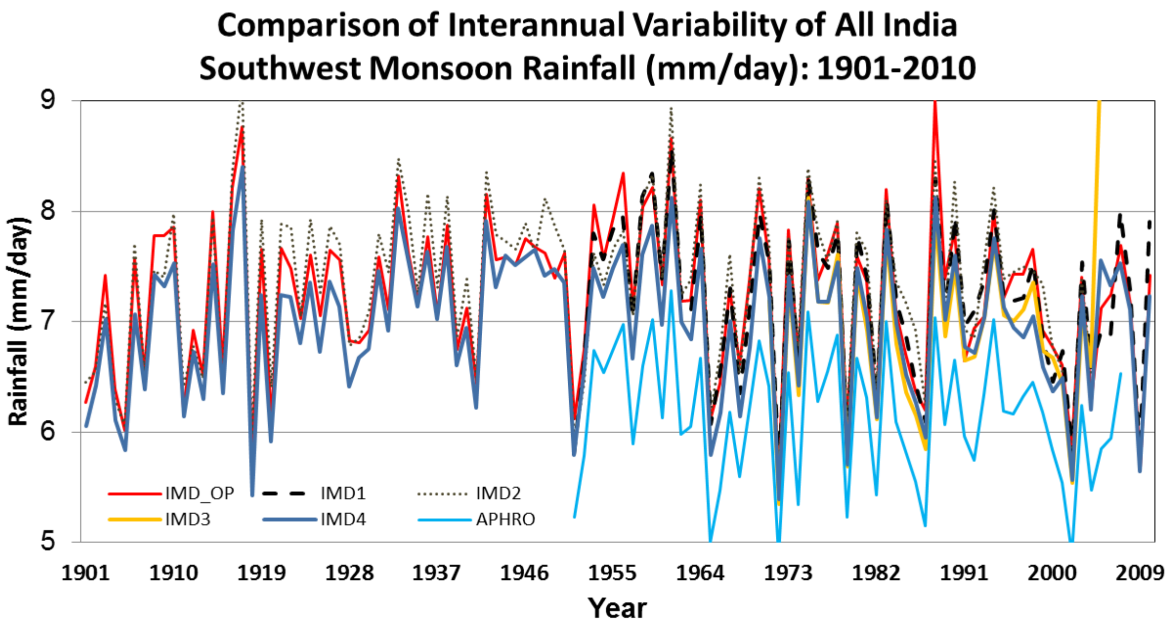

Fig. 12. Time series of all India rainfall for the southwest monsoon season computed using the 5 gridded data sets used in this study along with the IMD operational (IMD_OP) time series. Time series in respect each data sets are presented for their respective data periods; IMD1 for 1951-2007, IMD2 for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

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 with 1971-2000 mean values in (IMD1 and IMD2 (not shown here) 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 to 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.

4.1.3. *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.Care 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 internannual 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. 11(a) 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. Figs. 11(b-d) are similar to Fig. 11(a) but for IMD2, IMD3 &APHRO respectively plotted against IMD4. The 3 plots [Figs. 11(a, b&d)] were derived for the period of Jan1951 to Dec2000 and the Fig. 11(c) was derived for the period Jan1971 to 2000. It is seen from the Table 3 and the Figs. 11(a-d), when all the months of the

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
IMD4Vs IMD3 (1971-2005)	0.34	-0.04	0.90	0.11	0.03	0.94
IMD4Vs 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

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 = 0.91 mm/day and Bias = 0.84 mm/day) was observed against APHRO. The lowest RMSD (0.42 mm/day) was against IMD2 and lowest bias (-0.05mm/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 can be considered as 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.

5. Summary and conclusions

Development of a new daily gridded rainfall data set (IMD4) at a very high spatial resolution (0.25° × 0.25°, latitude × 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. Out of these existing 4 gridded daily rainfall data sets over India, two were 1° × 1° gridded daily rainfall data sets [IMD1 (Rajeevan *et al*. 2006) & IMD2 (Rajeevan *et al.* 2008)] based on fixed network of rain gauge stations, and third was 0.5° × 0.5° gridded daily rainfall data set (IMD3) based on a variable network of rain gauge stations (Rajeevan *et al*. 2009). The fourth data set (APHRO) was of spatial resolution 0.25° × 0.25°, which was developed as a part of the larger data set for the monsoon Asia region under APHRODITE 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 large climatological features of rainfall over India examined for the comparison of various gridded data sets 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 India southwest 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 data sets. For example, in all the data sets, the spatial distribution of the annual and southwest monsoon season rainfall climatology 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), APHRO showed dry bias against all the other data sets and the all India values in IMD3 & IMD4 were nearly equal with annual cycle of rainfall 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 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. 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. 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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