High resolution daily gridded rainfall data for the Indian region: Analysis of break and active monsoon spells

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Here, we report the development of a high resolution (1° × 1° lat./long.) gridded daily rainfall dataset for the Indian region. There are only 1803 stations with minimum 90% data availability during the analysis period (1951–2003). For the analysis, we have followed the interpolation method proposed by Shepard. Standard quality-controls were performed before carrying out the interpolation analysis. Comparison with similar global gridded rainfall datasets revealed that the present rainfall analysis is better in accurate representation of spatial rainfall variation.

Using this gridded rainfall dataset, an analysis was made to identify the break and active periods during the southwest monsoon season (June–September). Break (active) periods during the monsoon season were identified as those in which the standardized daily rainfall anomaly averaged over Central India (21–27°N, 72–85°E) is less than –1.0 (more than 1.0). The break periods thus identified for the period 1951–2003 were comparable with those identified by earlier studies. Contrary to a recent study, no evidence was found for any statistically significant trends in the number of break or active days during the period 1951–2003. This gridded rainfall dataset is available for non-commercial applications.

Keywords: Daily rainfall, gridded data, intra-seasonal variability, monsoon breaks.

INFORMATION on spatial and temporal variations of rainfall is important in understanding the hydrological balance on a global/regional scale. The distribution of precipitation is also important for water management in agriculture, power generation and drought-monitoring. In India, rainfall received during the southwest monsoon season (June–September) is crucial for its economy. Real-time monitoring of rainfall distribution on a daily basis is required to evaluate the progress and status of monsoon and to initiate necessary action to control drought/flood situations.

High resolution observed rainfall data are also required to validate regional/mesoscale models, and to examine and model intra-seasonal oscillations like Madden–Julian Oscillation (MJO) over the Indian region. Gridded rainfall datasets are useful for regional studies on the hydrological cycle, climate variability and evaluation of regional models. In recent years, there has been considerable interest in developing high-resolution gridded rainfall datasets[1–10].

Here, we discuss the development of a high resolution (1° × 1° lat./long.) daily gridded rainfall dataset for the Indian region for 53 years (1951–2003). Details of data used, quality control adopted and methodologies of interpolation are discussed.

Rainfall data and quality control

After the major drought of 1877 and the accompanying famine, the India Meteorological Department (IMD) established a large network of rain gauge stations, which provided a valuable source of data to analyse the space–time structure of the monsoon rainfall and its variability. With the introduction of the telegraph system, daily rainfall and also other meteorological observations were collected and analysed on a daily basis. Over the years, IMD has maintained high standards in monitoring rainfall and other meteorological parameters over India with great care and accuracy[11].

A brief historical account and description of the rainfall data collection by IMD are given by Walker[12] and Parthasarathy and Mooley[13]. Using the IMD daily rainfall data of 1901–70, Hartman and Michelsen[14] converted them into a gridded dataset by grouping the station data into 1° lat./long. grid boxes. Using this gridded rainfall dataset, Hartman and Michelsen[14], Krishnamurthy and Shukla[15] and Krishnamurthy and Shukla[16] studied the intra-seasonal and interannual variability of rainfall over India.

For the present analysis, we have used the daily rainfall data archived at the National Data Centre, IMD, Pune. IMD operates about 537 observatories, which measure and report rainfall that has occurred in the past 24 h ending 0830 h Indian Standard Time (0300 UTC). In addition, most of the state governments also maintain rain gauges for real-time rainfall monitoring. IMD digitizes, quality-controls and archives these data also along with rainfall

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data recorded at IMD observatories. Before archiving, IMD makes multi-stage quality control of observed values.

We have considered rainfall data for the period 1951–2003 for the present analysis. Standard quality control is performed before carrying out the analysis. First, station information (especially location) was verified, wherever the details are available. The precipitation data themselves are checked for coding or typing errors. Many such errors were identified, which were corrected by referring to the original manuscripts.

For the period 1951–2003, IMD has the rainfall records of 6329 stations with varying periods. Out of these, 537 are IMD observatory stations, 522 are under the Hydrometeorology programme and 70 are Agromet stations. The remaining are rainfall-reporting stations maintained by state governments. However, only 1803 out of 6329 stations had a minimum 90% data availability during the analysis period (1951–2003). We have used only these 1803 stations for the analysis in order to minimize the risk of generating temporal inhomogeneities in the gridded data due to varying station densities. The network of stations (1803 stations) considered for this study is shown in Figure 1. The density of stations is not uniform throughout the country. Density is the highest over south peninsula and poor over northern plains of India (Uttar Pradesh, for example) and eastern parts of Central India. Figure 2 shows day-to-day variation of the number of rainfall stations which were available for analysis. On an average, 1600 station data were available for the analysis. However, after 1995, the number of stations available for analysis dropped significantly. This is due to the delay in digitizing and archiving the manuscripts which are received at IMD in a delayed mode.

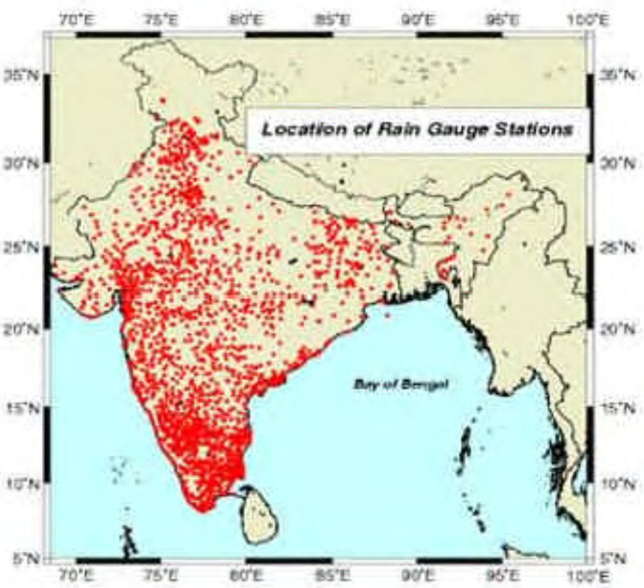


Figure 1. Location of 1803 rain gauge stations.

Interpolation method

There are different methods of numerical interpolation of irregularly distributed data to a regular *N*-dimensional array[17]. Bussieres and Hogg[18] studied the error of spatial interpolation using four different objective methods. For application to the specific project grid, the statistical optimal interpolation technique displayed the lowest root mean square errors. This technique and Shepard OA, displayed zero bias and would be useful for areal average computations. The Global Precipitation Climatology Project (GPCC) used a variant of the spherical-coordinate adaptation of Shepard's method[19] to interpolate the station data to regular grid points. These regular points are then averaged to provide area mean, monthly total precipitation on 2.5 grid cells. New *et al.*[6] used the thin plate splines proposed by Hutchinson[20]. Mitra *et al.*[8] used the successive correction method of Cressman[21].

For the present analysis, we have used the interpolation scheme proposed by Shepard[22]. In this method, interpolated values are computed from a weighted sum of the observations. Given a grid point, the search distance is defined as the distance from this point to a given station. The interpolation is restricted to the radius of influence. For search distances equal to or greater than the radius of influence, the grid point value is assigned a missing code when there is no station located within this distance. In this method, interpolation is limited to the radius of influence. A predetermined maximum value limits the number of data points used which, in the case of high data density, reduces the effective radius of influence. We have also considered the method proposed by Shepard to locally modify the scheme for including the directional effects and barriers. In this interpolation method, no initial guess is required. More details of the method are given in Shepard[22] and Rajeevan *et al.*[23].

We have interpolated station rainfall data into a rectangular grid (35 × 32) for each day for the period 1951–2003. The starting point of the grid is 6.5°N and 66.5°E.

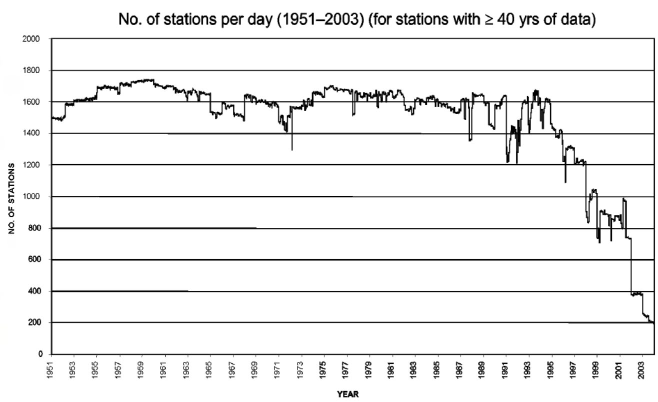


Figure 2. Number of stations per day available for analysis.

From this point, there are 35 points towards east and 32 points towards north. We have created one binary file for each year. For the leap year, we have created data for 366 days.

Comparison with global dataset

After completing the rainfall analysis for the period 1951–2003, we have compared the IMD gridded dataset with Variability Analysis of Surface Climate Observations (VASClimo) dataset, which is a global gridded rainfall dataset. Since in the IMD analysis, data density drops drastically after 1995, we have restricted our analysis with the data 1951–95 only. German Weather Service and Johann Wolfgang Goethe-University, Frankfurt jointly carried out a climate research project, named VASClimo, which was started in October 2001. The main objective of this project is the creation of new 50-yr precipitation climatology for the global land-areas gridded at three different resolutions (0.5° lat./long., 1° lat./long. and 2.5° lat./long.) on the basis of quality-controlled station data. More details of this new rainfall climatology are available in Beck *et al.*[10]. To compare the IMD analysis with the VASClimo dataset, we have considered the VASClimo data of 1951–95. Since both these global data are available on monthly time scale, we have added IMD daily gridded rainfall data into monthly total before comparing with the global datasets. The results of comparison of the southwest monsoon seasonal (June to September) rainfall only are presented here.

Figure 3 shows the spatial distribution of the seasonal (June–September) mean rainfall averaged for the period 1951–95 derived from the IMD gridded rainfall dataset. The rainfall pattern suggests a maximum along the west coast of India and NE India. Rainfall minimum is observed over NW India as well as over SE India.

Figure 4 *a* shows the difference between the present analysis (IMD) and VASClimo dataset and Figure 4 *b* shows the correlation coefficient between the IMD analysis and VASClimo dataset.

Over most parts of India, differences between the VASClimo and IMD data are of the order of 50 mm only. However, along the west coast of India, IMD rainfall values are more than the VASClimo values. However, the correlation between VASClimo and IMD rainfall data is large (exceeding even 0.8) over Central and NW parts of India.

We have further compared the inter-annual variations of rainfall among the datasets. For this, area weighted rainfall for the southwest monsoon (June–September) season was calculated with both datasets. However, we have excluded the NE parts of India for calculating the area weighted rainfall. The seasonal mean and standard deviation of rainfall for two datasets are given in Table 1.

Both the datasets show similar coefficient of variation, i.e. 11.8%. Figure 5 shows the interannual variation of the southwest monsoon seasonal (June–September) rainfall calculated from IMD analysis as well as the VASClimo dataset. There is similarity in the inter-annual rainfall variation between the datasets with all major drought and excess years being well captured by both the datasets. The correlation coefficient for the period 1951–95, between the IMD and VASClimo datasets is high (0.97).

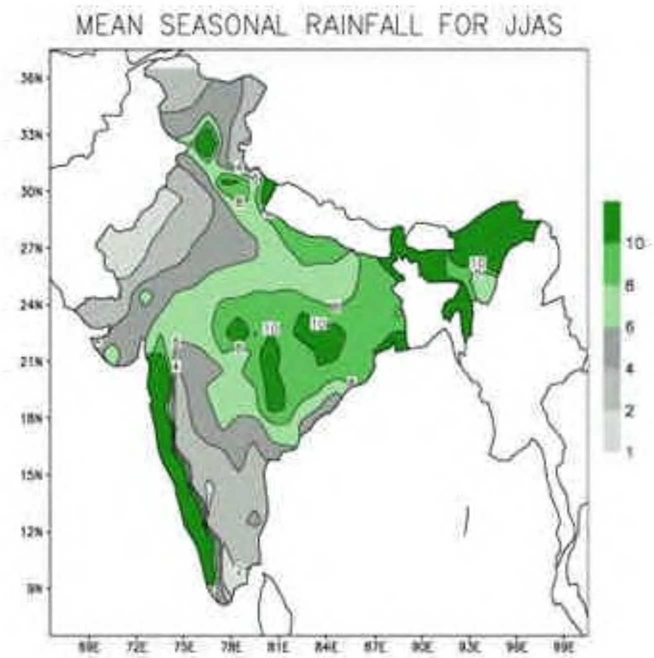


Figure 3. Spatial pattern of southwest monsoon seasonal (June to September) mean rainfall (mm/day).

Analysis of break days

The gridded daily rainfall data presented here will be useful for many applications. Some of them are validation of general circulation and numerical weather prediction models while others are on studies on intra-seasonal variability like active and break cycles. In the past, similar gridded datasets (1901–70) were used to examine the intra-seasonal variability[14–16] of the Indian summer monsoon.

The present rainfall dataset has been used to identify the active–break periods during the southwest monsoon season. Long intense breaks are often associated with poor monsoon seasons, and they have a large impact on rainfed agriculture[24]. Traditionally monsoon breaks have been identified at IMD on the basis of surface pressure and wind patterns over the Indian region. The traditional breaks as followed by IMD have been documented by Ramamurthy[25] and De

Table 1. Seasonal mean and standard deviation of rainfall for two datasets

Rainfall product	Mean rainfall (m)	Coefficient of variation (%)
IMD (1951–95)	837	11.8
VASClimo (1951–95)	842	11.8

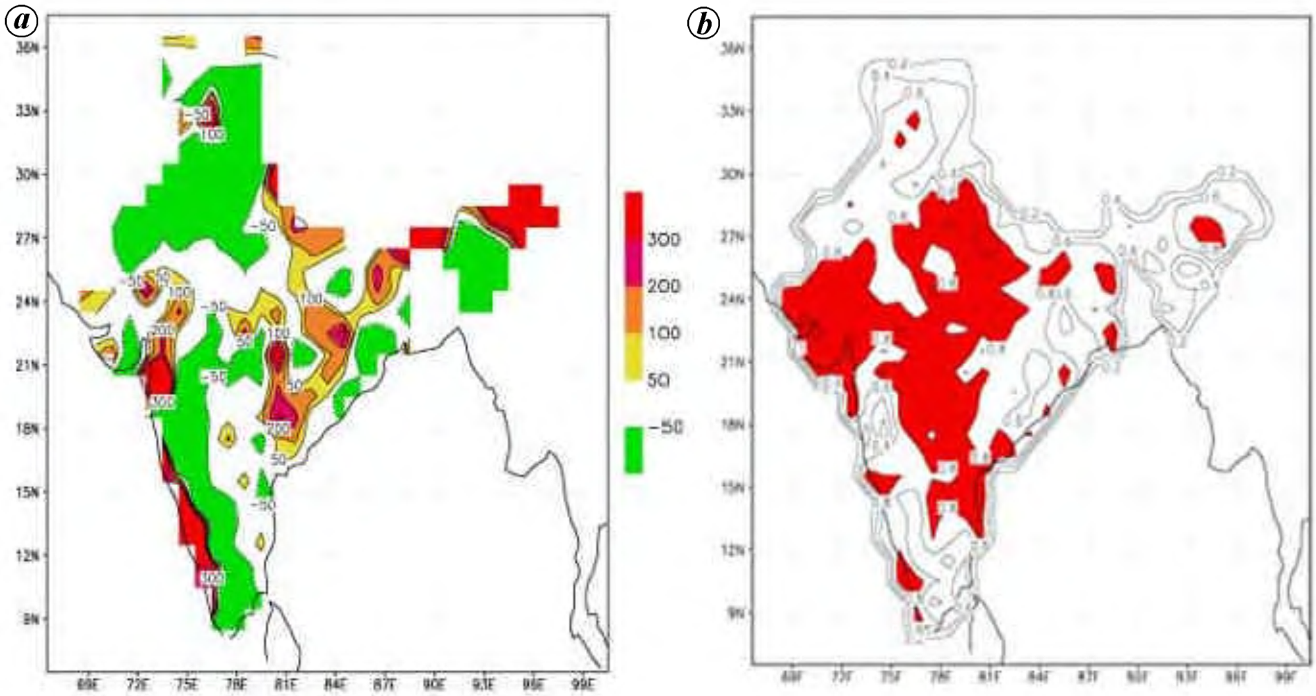


Figure 4. ***a***, The difference (in mm) between IMD gridded rainfall data and VASClimo gridded rainfall data for southwest monsoon season. Period: 1951–95. ***b***, Correlation coefficient between IMD rainfall data and VASClimo rainfall data during southwest monsoon season (June–September). Period of analysis: 1951–1995.

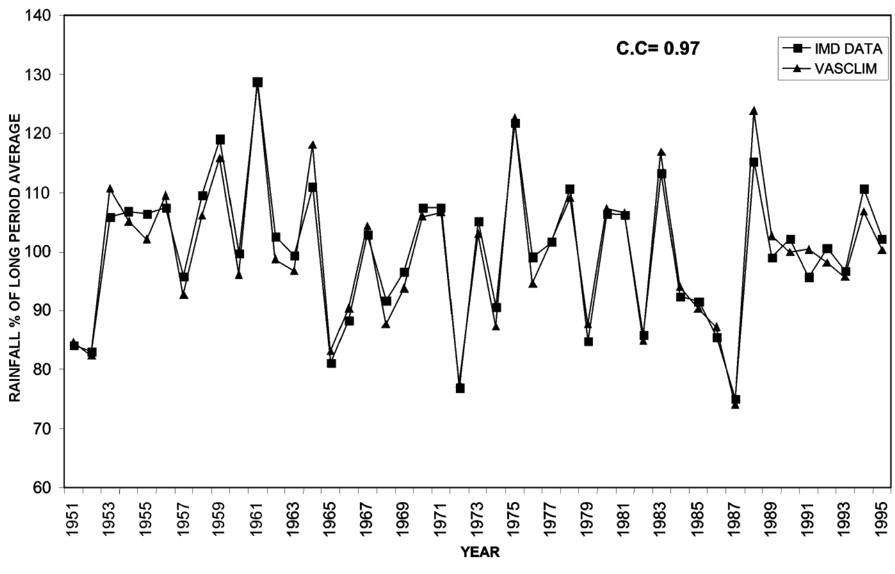


Figure 5. Interannual variation of southwest monsoon season (June–September) rainfall from IMD gridded analysis and VASClimo analysis. Period: 1951–1995.

et al.[26]. Recently, Gadgil and Joseph[24] have examined the active and break periods (1901–89) using only rainfall data over the monsoon zone area covering the central parts of India.

In the present analysis, the active and break periods during the southwest monsoon season have been identified in the following way. The area-averaged daily rainfall time series for each year from 1951 to 2003 has been prepared by simply taking the arithmetic mean of all rainfall at all grid points over the Central India (21–27°N, 72–85°E). For each calendar day, the climatological mean and standard deviation of rainfall were calculated using the data of 1951–2003. Then for each year, the area averaged daily rainfall time series has been converted to standardized rainfall anomaly time series, by subtracting the daily rainfall time series from the climatological mean and then dividing by its daily standard deviation. The break period has been identified as the period during which the standardized rainfall anomaly is less than –1.0, provided it is maintained consecutively for three days or more. Similarly, the active period has been identified as the period during which the standardized rainfall anomaly is more than 1.0, provided it is maintained consecutively for three days or more. Over Central India, on an average there were 400 stations for this analysis. During the recent years, however, it dropped to 150–200 stations. However, we feel that the rainfall data density considered in this analysis is fair enough to identify the active and break periods using this criterion. Gadgil and Jospeh[24] used about 150 stations from Central India to identify the break spells. However, they have considered a criterion using actual rainfall amounts to identify breaks, which may be sensitive to the density of the rain-gauge network considered. For example, if the density changes from year to year, the threshold to identify the breaks may also change. In the present analysis, we have considered standardized rainfall anomalies to identify the breaks, which may not be so sensitive to the density of the rain-gauge network. Moreover, as discussed below, the breaks identified in this analysis are comparable with those identified by Ramamurthy[25], and Gadgil and Joseph[24]. The standardized rainfall anomaly time series for the year 1988 (an excess monsoon year) and 2002 (a deficient monsoon year) is shown in Figure 6. For the year 2002, the break periods have been identified as 6–17 July and 23–31 July.

We have examined the active and break periods for other years also based on the above-mentioned criteria. We have listed the break days during July and August only, provided they last consecutively for three days or more. The results giving the break periods during the period 1951–2003 are shown in Tables 2 and 3. Break days as defined by Ramamurthy[25], De *et al.*[26] and Gadgil and Joseph[24] are also shown for comparison. The break periods identified in this study are comparable with others, especially Gadgil and Joseph[24].

To examine the spatial structure of rainfall during the break phases, lagged composites of daily rainfall anomalies were constructed. The lagged break composites for lags ranging from –14 to +12 days are shown in Figure 7. Lag-0 refers to the midpoint of each break period. At lag-6, positive anomalies are seen along the foothills of the Himalayas, associated with the shift in the monsoon trough over that region. At lag-10 days, negative rainfall anomalies appear over east central parts of India, which increase and slowly expand northwestwards. At lag-0 large negative anomalies cover most parts of India, except the NE and SE parts. Positive anomalies over SE parts of India first develop around lag-8 and slowly expand in area. From lag+2 days, negative anomalies over central parts of India decrease both in area and magnitude. During this period, positive anomalies slowly move northwestwards. By lag+12, large positive anomalies are observed along the west coast. With the revival of monsoon, at lag+12, positive anomalies appear over the coast of Orissa and adjoining areas.

Recently, Joseph and Simon[27] have reported that duration of break (weak) monsoon spells in a monsoon season increased by 20–30% during the period 1950–2002. Weak monsoon is defined as the one with mean zonal wind at 850 hPa in 10–20°N, 70–80°E, equal to or less than 9 or 11 m/s. The number of break or weak monsoon days has increased by about 31 and 22% for winds equal to 9 and 11 m/s respectively. These are alarming findings for a country whose food production and economy depend heavily on monsoon rainfall. Joseph and Simon have used wind data derived from the NCEP/NCAR reanalysis[27].

To confirm the findings of Joseph and Simon[27] and to further explore the issue, we have made a similar analysis with 53 years of IMD daily gridded rainfall data. Using the standardized daily rainfall anomaly averaged over Central India (21–27°N, 72–85°E), the number of break and active days during the period June–September was calcu-

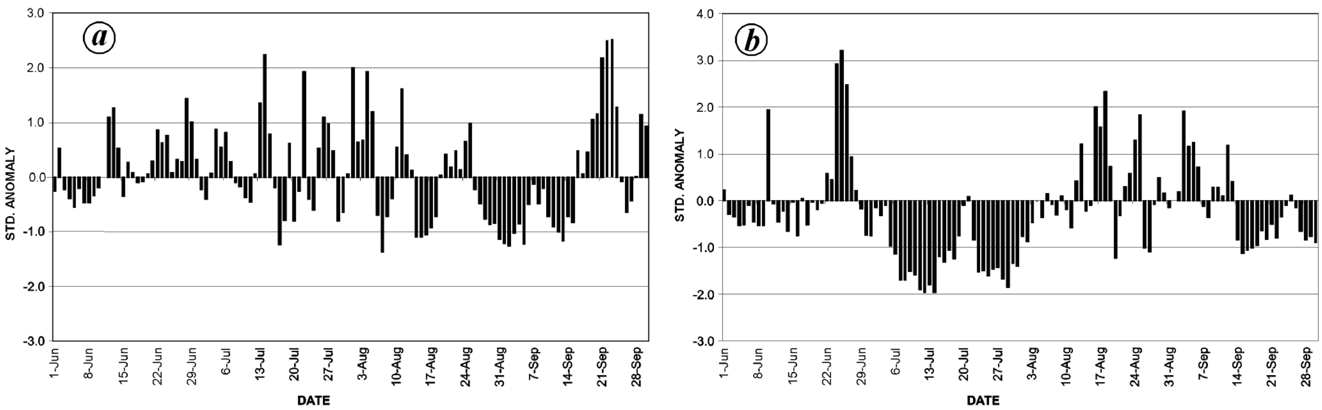


Figure 6. Standardized rainfall anomaly time series for (***a***) 1988 and (***b***) 2002 during the period 1 June to 30 September.

Table 2. Break days identified in the present analysis and previous studies (1951–89)

Year	Break days – July and August		
	Gadgil and Joseph[24]	Ramamurthy[25] up to 1967 De *et al.*[26] from 1968 to 1989	Present analysis
1951	14–15J, 24–30A	1–3 J, 11–13 J, 15–17 J, 24–29A	9–14J, 21–24J, 25–30A
1952	1–3 J, 10–13J, 27–30A	9–12J	9–15J
1953	–	24–26J	–
1954	22–29A	18–29J, 21–25A	22–29A
1955	24–25J	22–29J	–
1956	23–30A	23–26A	23–30A
1957	28–29J	27–31J, 5–7A	–
1958	–	10–14A	–
1959	–	16–18A	–
1960	20–24J, 30–31A	16–21J	20–23J
1961	–	–	–
1962	27–28J, 1–2A, 7–8A, 25–26A	18–22A	27–29A
1963	18–19J, 22–23J	10–13J, 17–21J	16–18J, 21–23J
1964	–	14–18J, 28J–3A	1–5A
1965	7–11J, 4–14A	6–8J, 4–15A	6–14J, 3–14A, 17–19A
1966	2–12J, 22–31A	2–11J, 23–27A	2–13J, 24–31A
1967	6–15J	7–10J	10–14J
1968	25–31A	25–29A	25–31A
1969	27–31A	17–20A, 25–27A	29–31A
1970	14–19J, 23–26J	12–25J	14–19J, 23–26J
1971	8–10J, 5–6A, 18–19A	17–20A	5–7A, 18–20A
1972	19J–3A	17J–3A	11–14J, 19J–3A
1973	24–26J, 30J–1A	23J–1A	24–26J
1974	24–26A, 29–31A	30–31A	29–31A
1975	–	24–28J	–
1976	3–4J, 21–22A	–	1–4 J
1977	15–19A	15–18A	14–21A
1978	–	16–21J	–
1979	2–6J, 15–31A	17–23J, 15–31A	2–7J, 12–31A
1980	17–20J, 14–15A	17–20J	–
1981	19–20A, 24–31A	26–30J, 23–27A	26–31A
1982	1–8J	–	1–9J, 16–19J
1983	8–9J, 24–26A	22–25A	7–9J, 14–16J
1984	–	20–24J	12–14A
1985	2–3J, 23–25A	22–25A	11–13 A, 24–27A
1986	1–4J, 31J–2A, 22–31A 16–17J, 23–24J, 31J–4A	23–26A, 29–31A	3–5J, 26–31A 16–18 J, 30 J–3A
1987	11–13A	28J–1A	8–10A, 14–18A
1988	14–17A	5–8J, 13–15A	14–16A
1989	30–31J	10–12J, 29–31J	18–20J, 31J–3A

lated for each year for the period 1951–2003. The criterion followed to identify the breaks was the same as that discussed above. The time series of the number of break and active days for the period 1951–2003 derived from the present analysis is shown in Figure 8 *a*, *b* respectively. The time series of break days has high negative correlation (–0.86) with southwest monsoon seasonal (June–September) rainfall. With the time series of active days, the corresponding correlation is +0.62. In the study by Joseph and Simon[27], the number of break or weak monsoon days was identified using a different criterion as mentioned above for the period 1950–2002. Their study revealed weaker correlations of –0.58 and 0.54 respectively, for number of break and active days. Thus the time series of break and active days prepared in this study is a more representative measure of monsoon activity during the season. However, Figure 8 does not show any statistically significant trend either in number of break days or number of active days, which is contrary to the results of Joseph and Simon[27].

This difference in the results on break days discussed above, may be due to different criteria used to identify the break days. In the present study, we have used the standardized rainfall anomaly averaged over Central India. The present study used observed rainfall data to examine the break days. We discussed earlier that the network of rain-gauge stations over Central India considered in this study is adequate to represent the rainfall variation over the region. To examine the sensitivity of the network, we have repeated a similar analysis with the full network of 6329 stations. There were minor differences in the break

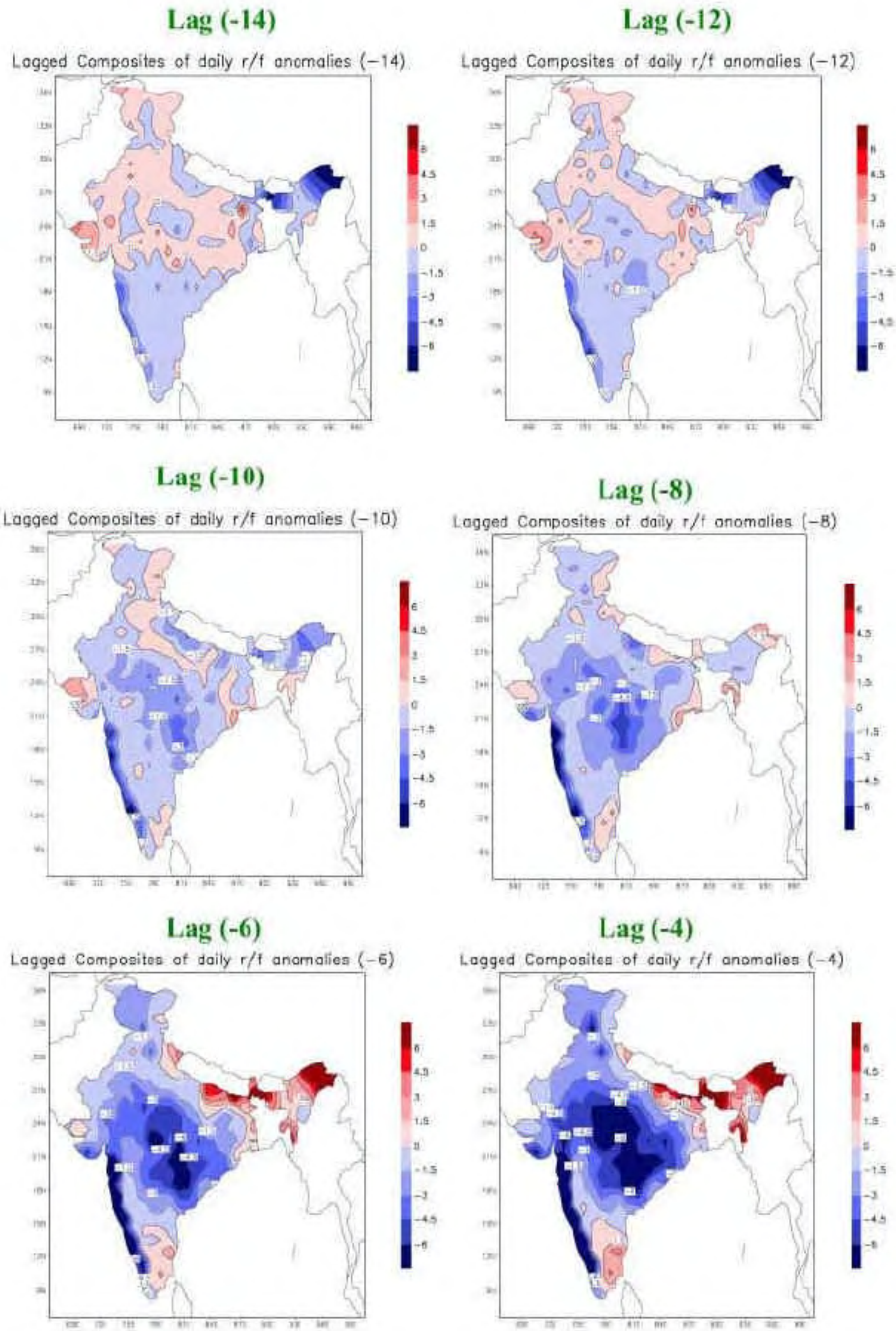
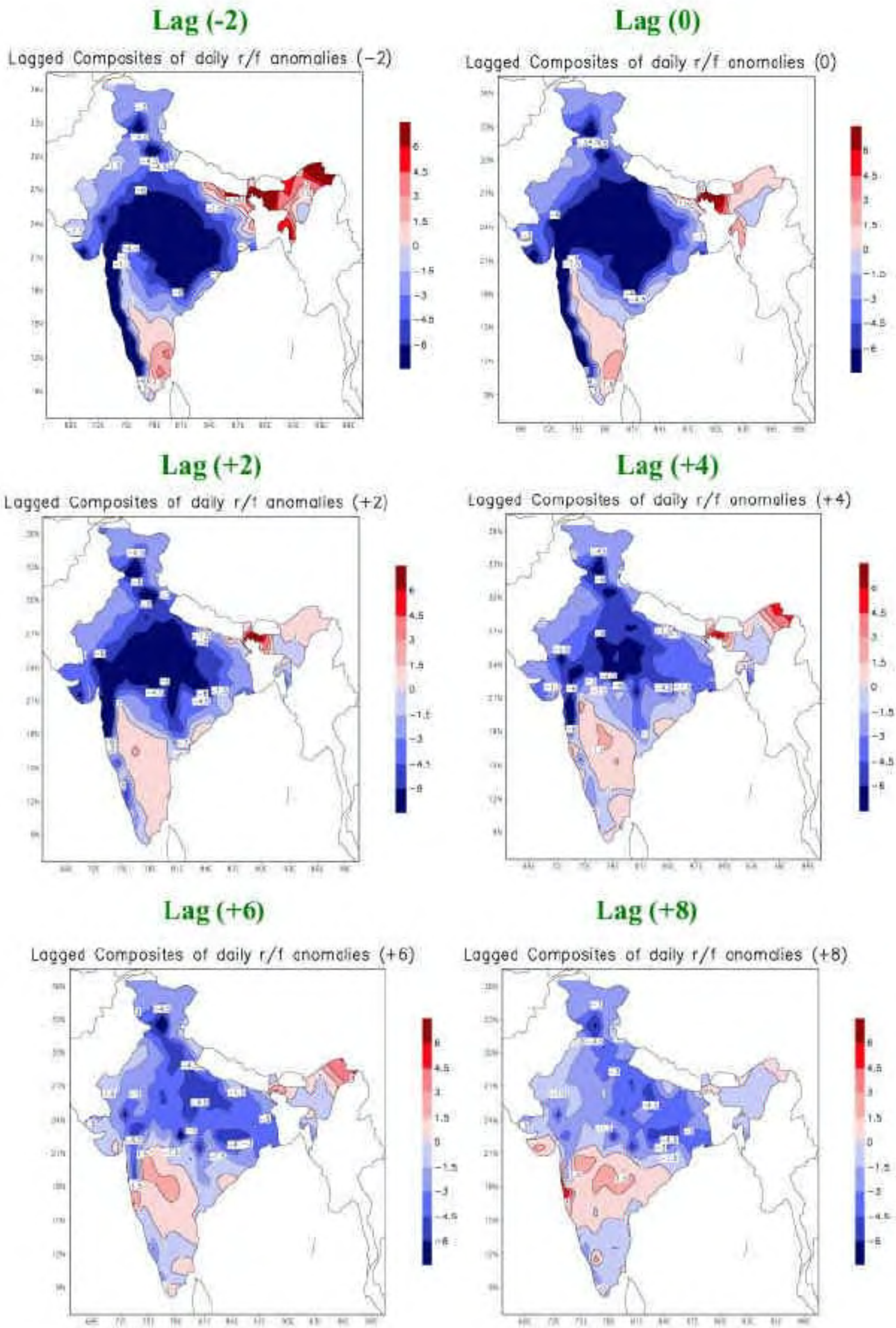


Figure 7. (*Contd...*)



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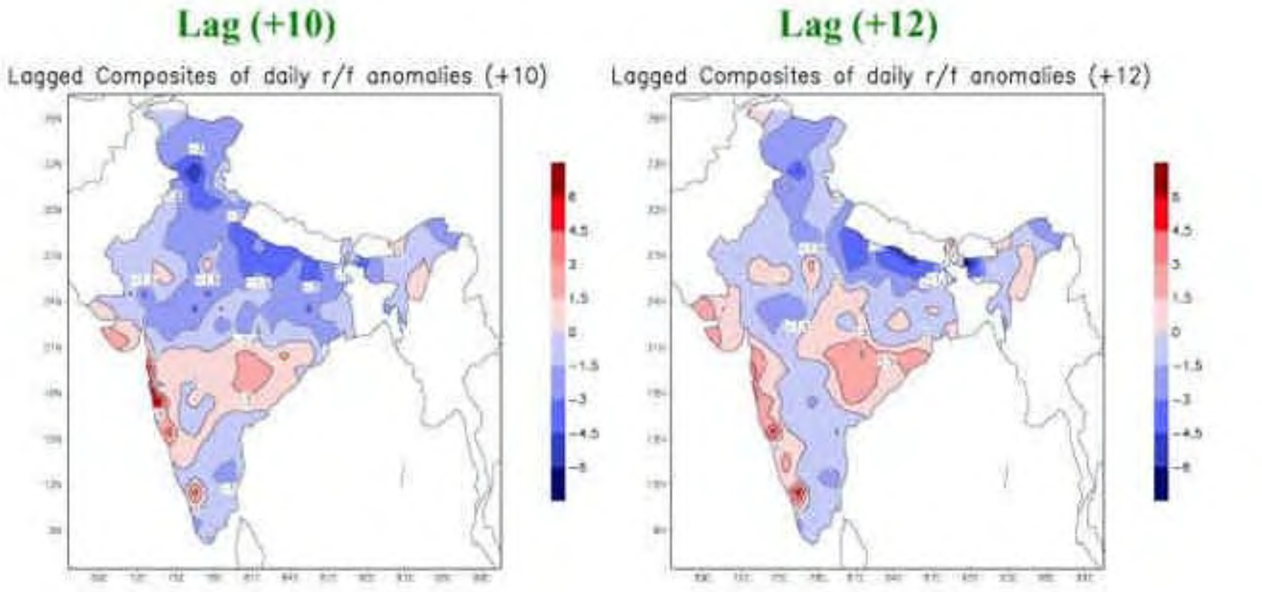

Figure 7. Lagged break phase composites of daily rainfall anomalies (mm/day) for June–September season 1951–2003. Lag–0 corresponds to midpoint of each break phase.

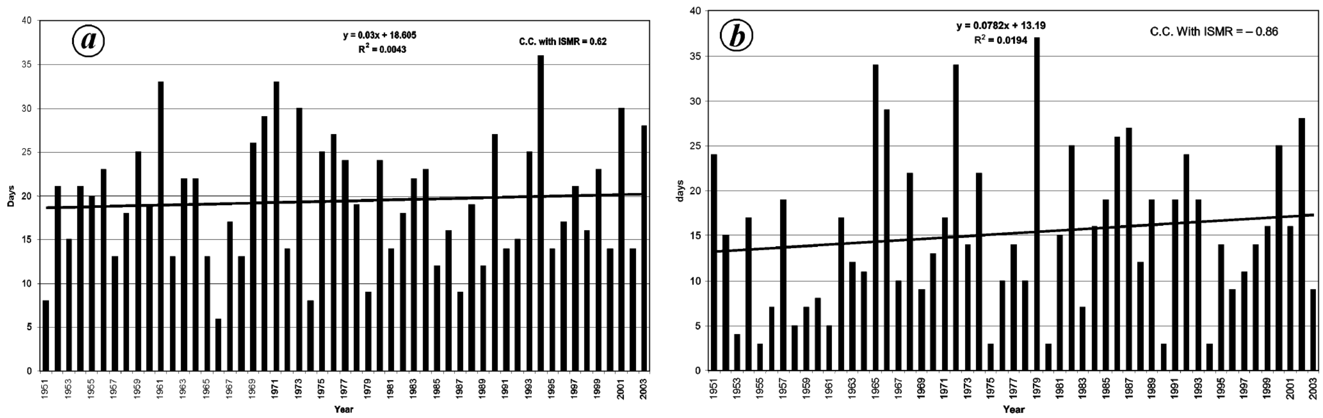

Figure 8. Time series of active days (***a***) and (***b***) break days during the monsoon season (1951–2003).

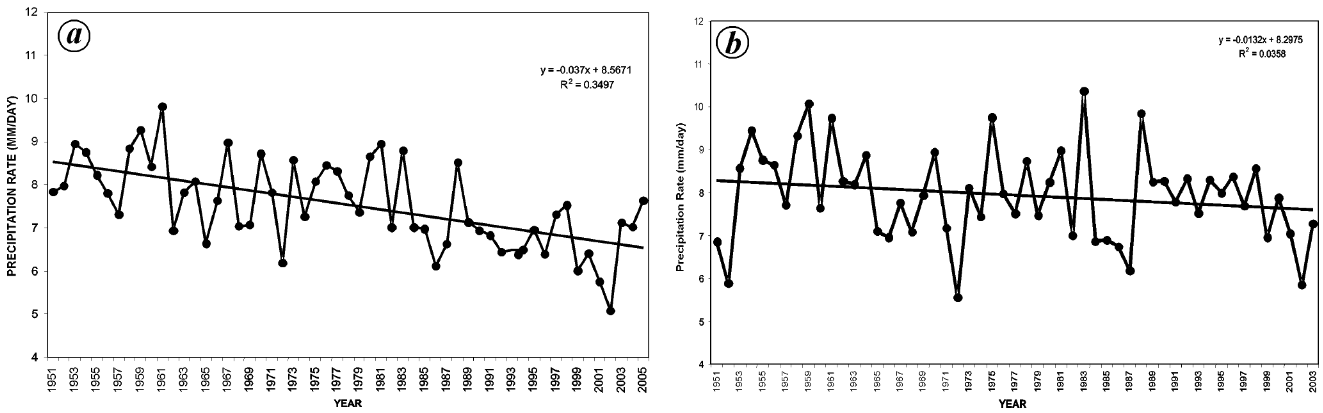

Figure 9. Time series of precipitation rate during monsoon season (June–September) over the box 10–20°N, 70–80°E in the NCEP/NCAR reanalysis (***a***) and IMD gridded rainfall analysis (***b***).

Table 3. Break days identified in the present analysis (1990–2003)

Year	Break days (present analysis)
1990	–
1991	2–8J
1992	4–10J
1993	19–23J, 8–14A
1994	–
1995	4–7 J
1996	3–5 J
1997	13–17A
1998	21–26J
1999	1–5J, 18–20A, 22–24A
2000	22–24J, 2–8A, 24–27A
2001	–
2002	6–17J, 23J–31J
2003	–

days, especially break spells of short duration. However, total number of break days in each year was found to be similar to that identified with the 1803 stations. Thus, the results obtained in the present study on break days based on standardized rainfall anomaly are robust.

Joseph and Simon[27] used the criterion based on wind speed at 850 hPa over a box over Central India. It may be mentioned that wind speed is a derived product from the NCEP/NCAR reanalysis. Any systematic bias in the analysis model (for example, rainfall over India) may impact the analysis of wind data also. We have prepared a time series of precipitation rate averaged over the area 10–20°N, 70–80°E using the NCEP/NCAR reanalysis to examine any significant trends. The results are shown in Figure 9 *a*. It suggests a statistically significant trend in the NCEP/NCAR reanalysis rainfall over the box. However, the rainfall rate over the same rectangular box, derived from the IMD gridded rainfall data (Figure 9 *b*) does not show any significant decreasing trends. Therefore, the decreasing trend of rainfall over the box in the NCEP/NCAR reanalysis is not the same as that observed. The decreasing trend in wind speed over the box observed by Joseph and Simon[27] may be due to this kind of artificial trend in the NCEP/NCAR rainfall analysis.

Further studies may be required to confirm this. It may be worthwhile to find out whether similar results will be obtained if we use another reanalysis data, for example, the ECMWF reanalysis (ERA-40)[29] and observed IMD upper air data over the Indian region. However, this is beyond the scope of the present study.

Conclusion

In this article, the results of the development of a high resolution (1° × 1° lat./long.) daily gridded rainfall data are discussed. We have considered 1803 stations which had a minimum 90% of data availability during the analysis period, 1951–2003. We have considered the Shepard[22] method with directional effects for interpolation to 1° × 1° lat./long. regular grids. Before interpolation, quality-control of the data was carried out. The gridded rainfall dataset thus developed, was compared with other similar global gridded rainfall datasets. The present IMD gridded rainfall analysis is better in accurate representation of rainfall over the Indian region, especially along the west coast and NE India. The correlation coefficients between the IMD rainfall time series and other global datasets are more than 0.80. The present rainfall dataset is used to identify the active and break periods during the southwest monsoon season using an objective criterion based on standardized daily rainfall anomaly. The active and break periods thus identified were found comparable with those identified by earlier studies. Contrary to a recent study of Joseph and Simon[27], the present study revealed no significant trend in the number of break and active days during the southwest monsoon season during the period 1951–2003.

It is believed that the present IMD gridded rainfall dataset will be extensively used for many applications like validation of climate and numerical weather prediction models and also for studies on intra-seasonal variability and monsoon predictability studies. We shall be further updating the present rainfall analysis from 1901 onwards, so that more than 100 years of gridded daily rainfall data are available to the research community. The 53 years of daily gridded rainfall dataset is available for scientific research at a nominal cost. For obtaining the dataset, contact M. Rajeevan (rajeevan@imdpune.gov.in) or the National Climate Centre, IMD, Pune (ncc@imdpune.gov.in).

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Agrobacterium-mediated transformation of mature embryos of *Triticum aestivum* and *Triticum durum*

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Plant regeneration studies in cereals have been undertaken in immature embryos, scutellum and also in immature inflorescence tissue. The wheat mature embryos can also be employed for callusing and regeneration, as they are available throughout the year and have presently been employed for transformation studies. An efficient and reproducible method for *Agrobacterium*-mediated transformation of mature embryos of hexaploid bread wheat (*Triticum aestivum*) and tetraploid pasta wheat (*Triticum durum*) is reported. Presence of acetosyringone at 200 μM concentration in the bacterial growth medium, inoculation medium and co-cultivation medium was essential for achieving a 1.5–2.0 fold increase in transient expression of the introduced *gus* gene. Successful generation of *T. aestivum* and *T. durum* transgenic plants at a transformation frequency ranging from 1.28 to 1.77% has been achieved following 2–3 days co-cultivation using mature embryos and also mature embryo-derived calluses with binary *Agrobacterium* strain LBA4404 (pBI101 :: *Act1*) and LBA4404 (p35SGUSINT) respectively. Paromomycin and phosphinothricin served as effective selection agents as they did not adversely affect plantlet regeneration. Successful integration as well as inheritance of the transgene was confirmed by Southern hybridization and PCR amplification in T_0 as well as T_1 generation. Optimization of this method facilitated the introduction of *bar* gene as a selectable marker conferring herbicide resistance as well as potato proteinase inhibitor gene (*pin2*) for insect resistance into wheat.

Keywords: *Agrobacterium*, embryos, transformation, *Triticum aestivum*, *Triticum durum*, wheat.

GENETIC transformation of crop plants by *Agrobacterium*-mediated co-cultivation is an efficient and cost-effective method for gene delivery. Monocotyledonous plants, including important cereals were earlier thought to be recalcitrant to *Agrobacterium*-mediated gene transfer[1,2], but the scenario has changed in the last few years. Consistent efforts by researchers on cereal crop plants have resulted in the development of protocols for efficient gene delivery via *Agrobacterium* into rice[3,4], maize[5], barley[6] and wheat[7]. One of the key points in these protocols has been the use of actively dividing cells/tissues such as immature embryos and immature embryo-derived calluses that were further co-cultivated with *Agrobacterium* in the presence of potent inducers of virulence genes[8]. Mooney and coworkers[9] were the first to demonstrate the wound-independent *in vitro* attachment of *Agrobacterium* to wheat embryos. Subsequently, Chen and Dale[10] reported a higher frequency of infection by incubation of exposed apical meristems of dry wheat seeds with *Agrobacterium*. Previous work from this laboratory also reported the transient expression of *gus* gene in meristematic leaf bases, calluses, mature seeds and mesocotyl punctured seedlings following co-cultivation with different strains and vectors of *Agrobacterium tumefaciens*[11]. Stable *Agrobacterium*-mediated transformation of wheat and transmission of the transgenes to subsequent generations have now been reported by many workers[7,12–15]. Nonetheless, the widescale application of this methodology in diverse genotypes is still restricted.

The present study thus focuses on the use of excised mature embryos and mature embryo-derived calluses as primary explants for *Agrobacterium*-mediated transformation of bread wheat (*Triticum aestivum*) and also the macaroni wheat (*Triticum durum*). The optimized protocol was subsequently used for the introduction of potato proteinase inhibitor (*pin2*) gene into *T. aestivum* and *T. durum*, the successful use of which had conferred insect resistance in *japonica* rice[16]. The use of proteinase inhibitors for genetic engineering of insect resistance in wheat has also been reported[17]. Here we report *Agrobacterium*-mediated transformation of *T. aestivum* and *T. durum* using mature embryos as recepient explants.

Materials and methods

Plant materials and culture conditions

Seeds of *T. aestivum* cvs HD2329, CPAN1676, PBW343 and *T. durum* cvs PDW215, PDW233 and WH896 were obtained from IARI, New Delhi as well as the Directorate of Wheat Research, Karnal, Haryana, India. Seeds were initially washed with a liquid detergent (Teepol, Reckitt & Coleman of India) for 1 min with running tap water, and

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