The Wet and Dry Spells across India during 1951–2007

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ABSTRACT

Characteristics of wet spells (WSs) and intervening dry spells (DSs) are extremely useful for water-related sectors. The information takes on greater significance in the wake of global climate change and climate-change scenario projections. The features of 40 parameters of the rainfall time distribution as well as their extremes have been studied for two wet and dry spells for 19 subregions across India using gridded daily rainfall available on 1° latitude × 1° longitude spatial resolution for the period 1951–2007. In a low-frequency-mode, intra-annual rainfall variation, WS (DS) is identified as a ''continuous period with daily rainfall equal to or greater than (less than) daily mean rainfall (DMR) of climatological monsoon period over the area of interest.'' The DMR shows significant spatial variation from 2.6 mm day^{-1} over the extreme southeast peninsula (ESEP) to 20.2 mm day^{-1} over the southern-central west coast (SCWC). Climatologically, the number of WSs (DSs) decreases from 11 (10) over the extreme south peninsula to 4 (3) over northwestern India as a result of a decrease in tropical and oceanic influences. The total duration of WSs (DSs) decreases from 101 (173) to 45 (29) days, and the duration of individual WS (DS) from 12 (18) to 7 (11) days following similar spatial patterns. Broadly, the total rainfall of wet and dry spells, and rainfall amount and rainfall intensity of actual and extreme wet and dry spells, are high over orographic regions and low over the peninsula, Indo-Gangetic plains, and northwest dry province. The rainfall due to WSs (DSs) contributes ~68% (~17%) to the respective annual total. The start of the first wet spell is earlier (19 March) over ESEP and later (22 June) over northwestern India, and the end of the last wet spell occurs in reverse, that is, earlier (12 September) from northwestern India and later (16 December) from ESEP. In recent years/decades, actual and extreme WSs are slightly shorter and their rainfall intensity higher over a majority of the subregions, whereas actual and extreme DSs are slightly (not significantly) longer and their rainfall intensity weaker. There is a tendency for the first WS to start approximately six days earlier across the country and the last WS to end approximately two days earlier, giving rise to longer duration of rainfall activities by approximately four days. However, a spatially coherent, robust, long-term trend (1951–2007) is not seen in any of the 40 WS/DS parameters examined in the present study.

1. Introduction

Rainfall is a seasonal phenomenon in tropical monsoonal climates and occurs in spells. The start and end of the rainy season; frequency, rainfall amount, rainfall intensity, and duration of wet spells (WSs); and duration and severity of intervening (between two rain spells) dry spells (DSs) are characterized by large spatial and temporal variations. The climatology and variability of the parameters of the rainy season and the wet and dry spells are valuable information for scientists, engineers, planners, and managers working in water-related sectors (agriculture, ecology, hydrology, and water resources). Determination of yearly starting and ending dates of the rainy season and identification of wet and dry spells in the rainfall time distribution is the crucial issue of the problem. In this study, we attempt to demonstrate that demarcation of the start and end of the rainy season and identification of wet–dry spells is essentially one problem such that a single objective criterion can be used for both purposes.

In India, the terms *monsoon* and *wet season* are used synonymously. During World War II, normal onset and withdrawal dates at 180 stations over the Indian subcontinent (present day India, Pakistan, Bangladesh, Myanmar, and Sri Lanka) were determined by the India Meteorological Department (IMD) by applying a subjective approach ''characteristic monsoon rise–fall in 5-day period (known as pentad).'' For a particular station, the first

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normal pentad rainfall for a full calendar year (73 pentads) was obtained. The middle date of the pentad that showed characteristic monsoon rise (fall) in rainfall from the previous pentad was taken as the normal onset (withdrawal) date. Similarly, the dates were obtained for other stations. The dates were charted and isolines of normal onset (withdrawal) dates drawn (IMD 1943). In this historically important program, the meaning of the "characteristic monsoon rise–fall in pentad rainfall" and description of the "other factors were also considered where the premonsoon thunderstorm rains merged with monsoon rain; however information for when the transition was gradual" is not available in the literature. Nevertheless, this is the most often referred work for the IMD (IMD 1943).

Raman (1974) used daily rainfall and determined on a yearly basis (1901–70) the commencement of sowing rains at 231 locations across Maharashtra State (northwest peninsula) by applying an objective criterion: "A spell of at least 25 mm of rain in a period of 7 days with 1 mm or more on any five of these seven days." Normally, the first wet spell along the west coast (WC; Konkan area) starts between 2 and 14 June, on the leeside of the west coast (the Madhya Maharashtra and Marathwada areas in the central peninsula) between 18 June and 1 July, and over eastern Maharashtra (the Vidarbha area in central India) between 18 and 26 June. The standard deviation (SD) of the start of the first wet spell was 8 along the west coast, 8–16 over the Vidarbha area, and 10–30 days over the leeside area. He further identified secondary wet spells by applying the same objective criterion and calculated the duration of the dry spell between the two wet spells. The second wet spell occurred 8–10 days after the first wet spell over Konkan, 10–16 days after the first wet spell over Vidarbha, and 12–32 days after the first wet spell over Madhya Maharashtra and Marathwada. Ananthakrishnan and Soman (1988) suggested an objective criterion to determine the onset date of the summer monsoon over Kerala State [extreme southwest (SW) peninsula], the gateway for monsoons for India: "when rainfall on the day and mean rainfall in the following 5 day period exceeded 10 mm." Earlier Ananthakrishnan et al. (1967) suggested a criterion for declaring onset over Kerala: "beginning from 10 May if at least five out of the seven stations report 24-hourly rainfall 1 mm or more for two consecutive days the forecaster should declare on the second day that the monsoon has advanced over Kerala."

Parts of India experience a rainy season of a considerably longer duration than the summer monsoon period, because they also receive considerable rainfall from other systems in the pre- and postmonsoon periods: the western Himalaya region (Uttarakhand, Himachal Pradesh, and Jammu and Kashmir States) receives rainfall from western disturbances both in the pre- and postmonsoon periods, northeastern India from thunderstorms both in the pre- and postmonsoon periods, and the southern peninsula (south of 18°N) from thunderstorms in the premonsoon period and from northeast monsoons in the postmonsoon period. Singh (1986) has identified a climatological period of reliable rainfall (rainy season), irrespective of the system(s) that produced the rainfalls, at 466 stations across the country by applying a unified criterion: "a continuous period with each of the monthly rainfall greater than 50mm." Recently, Ranade et al. (2008) applied this criterion to yearly determine the start and end of the hydrological wet season (HWS) over 11 major and 36 minor river basins as well as the West Coast Drainage System (WCDS) and studied the variability of the HWS parameters (starting and ending dates and duration, seasonal rainfall–rainwater, and surplus rainfall–rainwater potential) over the period of longest available instrumental records (1813–2006).

In some other countries, researchers have tried different criteria to study rainy seasons and wet–dry spells. To identify wet spells across China, Bai et al. (2007) used the following criteria: (i) in a wet spell, the number of rainy days (rainfall $\geq$0.10 mm day^{-1}) should not be less than four days, and the first three days should not include a dry day; and (ii) a wet spell is over whenever there are two consecutive dry days. The duration of a wet spell is defined as the number of days between the two consecutive dry days. They have also documented different definitions attempted earlier in different geographical locations of China. A sophisticated hydrological scheme—the available water resources index (AWRI)—has been developed by Byun and Wilhite (1999) for detecting the onset, end, and accumulated stress of drought. In the AWRI, the accumulated precipitation, the duration of accumulation, and the daily reduction of water by runoff, evapotranspiration, infiltration, among others, are taken into account quantitatively. Using this scheme, the onset and ending dates, and intensities of the three rainy seasons in Korea were determined for each year and each station, and also climatologically (Byun and Lee 2002). For Peninsular Malaysia, Deni et al. (2008) defined a wet day with rainfall of at least 0.1 mm. A wet (dry) spell is defined as a period of consecutive days of exactly, say x, wet (dry) days immediately preceded and followed by a dry (wet) day. Aviad et al. (2004) studied the variation in the beginning, end, and length of the rainy season along a Mediterranean–arid climate transect with variations in rainfall thresholds. They changed the thresholds from 0.1 to 80 with intervals of 2.5 and from 80 to 200 with intervals of 5 mm, and they found that as the threshold increased, the rainy season began later, ended earlier, and consequently its length was shortened. Cook and Heerdegen (2001) defined rainy season as that period when the probability of 10-day dry spells was less than 0.5, and the wet season (monsoonal influence) as that period within the rainy season when the probability of dry spells was less than 0.1. A dry day was defined as having a rainfall of less than 5 mm. This definition was essentially meant for ecological purposes. Stern et al. (1981) defined the start of the rainy season as the first occurrence of 20 mm of rain within two successive days.

In recent years–decades, a decrease in annual rainfall is seen over 68% area of India (Sontakke et al. 2008a). Recently, the "seasons" with decreasing rainfall are winter, 47%; summer, 17%; summer monsoon, 75%; and postmonsoon, 38%. Whereas monsoon monthly rainfall in summer is June, 41%; July, 85%; August, 58%; and September, 69% (Sontakke et al. 2008a). Dai et al. (1998) have found increases in other parts of the world affected by either drought and/or excessive wetness, and the results are consistent with those expected from increased greenhouse gases in the atmosphere.

Understanding the climatic and hydroclimatic features of wet and dry spells is essential for effective agricultural and hydrological operations. In the face of global climate change background and scenario projections, the problem assumed greater importance. Therefore, in recent decades, attempts have been made worldwide to understand the problem on regional–local scales.

This comprehensive study of the wet and dry spells (including their extremes) across India is undertaken with the following main objectives:

1) to develop dynamic objective criteria for the identification of yearwise wet and dry spells in different rainfall regimes of India;
2) to study detailed climatological and fluctuation features of the wet and dry spells across the country;
3) to examine important features of extremes of wet and dry spells.

The start of the first wet spell is expected to provide a reliable estimate of the starting date of seasonal (hydrological) rainfall and the ending date of the last wet spell of the season. The second objective is to provide important input to the decision-making support system in water-related sectors, such as agriculture, hydrology, water resources, and terrestrial and freshwater aquatic ecosystems, as well as diagnostics and prediction of rainfall. And, the third objective is to understand the impact of global climate change on extreme rain events across the country.

2. Data used and division of the country for the present study

Daily rainfall data of the country on 1° latitude–longitude spatial resolution for the period 1951–2007 developed by IMD (Rajeevan et al. 2006) is utilized in the present study. In the past, because of the large geographical area (~3.3 million km^2), the country was divided into certain zones–subdivisions for different purposes: agriculture, hydrology, ecology, daily weather forecast, long-range rainfall prediction, monitoring annual–seasonal rainfall variations, among others (Sontakke and Singh 1996 and references therein). The division created for a particular purpose was not found suitable for another. We propose a new division of the country for better understanding of its climatology and variability of wet and dry spells. The following are the physical-climatological factors that are qualitatively considered to divide the country into an optimum number of subregions (SRs):

1) topographic features;
2) spatial pattern of the mean annual and southwest monsoon rainfall;
3) physiographic characteristics, such as the coast, plateau, plains, valley, desert, among others (NATMO 1986);
4) drainage pattern (NATMO 1996);
5) normal onset and withdrawal dates of the southwest monsoon across the country (IMD 1943); and
6) daily rainfall data available as 1° raster.

On the basis of the topographic considerations, the country is divided into seven regions: west coast, central highlands, eastern Himalaya–northeastern range (NEI), western Himalaya–Punjab Plains (ENI), peninsula (excluding west coast), Indo-Gangetic plains (IGPs), and northwest dry province. Considering the mean annual–monsoon rainfall, the peninsula is subdivided into the central peninsula and east coast; and the west coast is subdivided into ESWP (refer to Table 1 for expansion of names and numbers of subregions), SCWC, NCWC, and NWC. By incorporating the physiographic features, the IGPs are further divided into three subregions: EIGP, CIGP, and WIGP; central highlands into WCI and ECI; and northwestern India into two subregions, NNWI and SNWI. Including the drainage pattern as a factor in the classification, the central peninsula and east coast are divided into six subregions: ESEP, CSEP, SCP, CEC, NCP, and NEC. Daily rainfall data are available as 1° raster; therefore, rectangular boxes are drawn to arrive at the final classification of the 19 subregions. While drawing boundaries it is noted that, the monsoon advanced

TABLE 1. The geographical area, mean annual rainfall, mean onset and withdrawal dates of the summer monsoon, total monsoonal rainfall, and daily mean rainfall as well as daily mean PE of the monsoon period for the 19 SRs.

Subregion	Name of subregion	Approximate area (km^2)	Normal annual rainfall (mm)	Onset of SW monsoon (SD in days)	Withdrawal of SW monsoon (SD in days)	Rainfall of monsoon period (mm)	Daily mean rainfall of monsoon period (mm day^{-1})	Daily mean PE of monsoon period (mm day^{-1})
SR 1	Extreme southwest peninsula (ESWP)	60 000	2700.8	1 Jun (7)	19 Oct (6)	2061.2	14.6	3.8
SR 2	Extreme southeast peninsula (ESEP)	110 000	962.0	2 Jun (7)	19 Oct (6)	365.6	2.6	5.4
SR 3	Southern central west coast (SCWC)	60 000	3131.9	5 Jun (7)	17 Oct (6)	2724.4	20.2	3.0
SR 4	Central southeast peninsula (CSEP)	150 000	859.4	6 Jun (7)	17 Oct (6)	464.4	3.5	4.5
SR 5	Northern central west coast (NCWC)	60 000	2220.1	9 Jun (7)	13 Oct (5)	1990.3	15.7	3.6
SR 6	Southern central peninsula (SCP)	120 000	710.5	11 Jun (6)	14 Oct (6)	538.1	4.3	4.6
SR 7	Central east coast (CEC)	110 000	1025.8	12 Jun (6)	15 Oct (7)	715.5	5.7	4.4
SR 8	Northern west coast (NWC)	90 000	1794.5	13 Jun (6)	7 Oct (8)	1648.0	14.1	4.1
SR 9	Northern central peninsula (NCP)	180 000	1012.7	15 Jun (6)	8 Oct (7)	855.7	7.4	4.3
SR 10	Northern east coast (NEC)	210 000	1423.9	16 Jun (6)	12 Oct (6)	1080.5	9.1	3.8
SR 11	Southern northwest India (SNWI)	190 000	616.9	23 Jun (9)	28 Sep (6)	534.7	5.5	4.6
SR 12	Western central India (WCI)	240 000	1077.2	21 Jun (8)	3 Oct (6)	928.3	8.8	3.9
SR 13	Eastern central India (ECI)	150 000	1240.7	20 Jun (7)	7 Oct (6)	1036.2	9.4	3.8
SR 14	Eastern Indo-Gangetic plain (EIGP)	120 000	1422.9	13 Jun (6)	10 Oct (6)	1145.5	9.5	3.6
SR 15	Northern northwest India (NNWI)	280 000	323.9	8 Jul (8)	19 Sep (8)	230.4	3.1	5.4
SR 16	Western Indo-Gangetic plain (WIGP)	240 000	755.4	30 Jun (8)	27 Sep (8)	598.2	6.6	4.4
SR17	Central Indo-Gangetic plain (CIGP)	150 000	1140.2	21 Jun (7)	3 Oct (6)	918.8	8.8	4.2
SR 18	Northeast India (NEI)	60 000	2089.2	6 Jun (6)	15 Oct (5)	1461.6	11.1	3.1
SR 19	Extreme northern India (ENI)	290 000	873.3	1 Jul (8)	23 Sep (9)	544.6	6.4	4.1

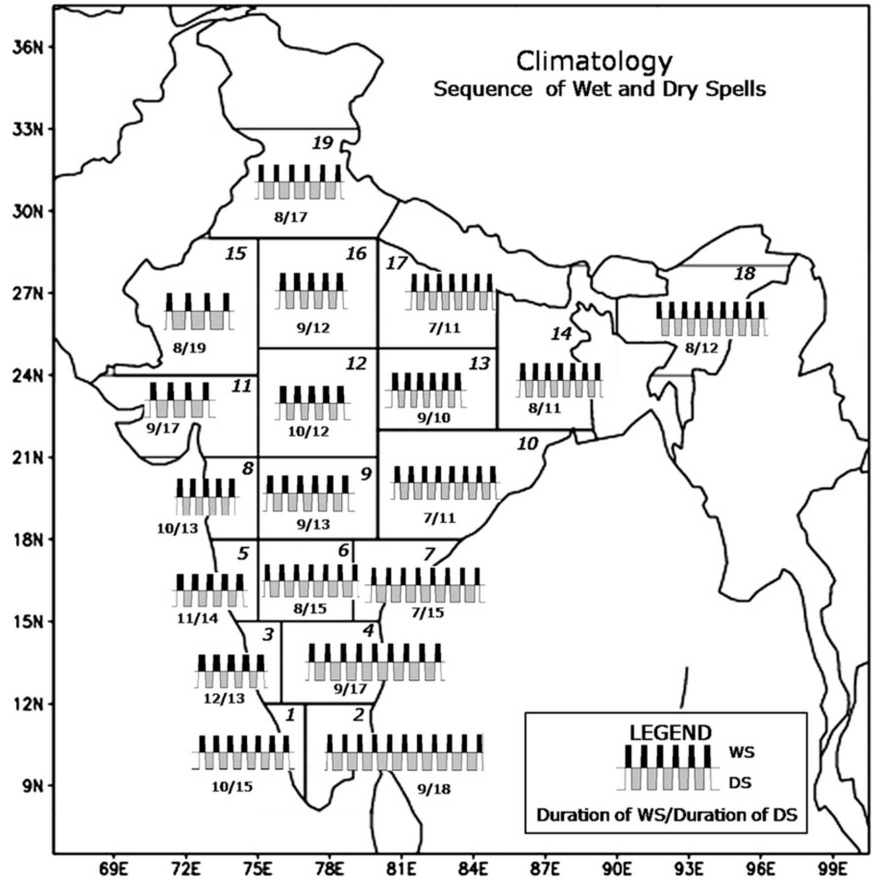

FIG. 1. The 19 subregions of India of the present study and the sequence of climatological wet and dry spells over the individual subregions.

northward with a distinct onset date from one subregion to another and that it also withdrew southward distinctly. The subregions are shown in Fig. 1, and the geographical area (in km^2) and some important climatological information about the subregions is given in Table 1.

The geographical area of the subregions ESWP, SCWC, NCWC, NWC and NEI (SRs 1, 3, 5, 8, and 18) varies from 60 000 to 100 000 km^2, that of NEC, WCI, NNWI, WIGP and ENI (SRs 10, 12, 15, 16, and 19) is 200 000–300 000 km^2 and that of other the nine subregions is 100 000–200 000 km^2. It is expected that characteristics of wet and dry spells on subregional scales would provide useful information for science (to understand the physics and dynamics of rain-producing weather systems), services (operational weather forecasting), and society (agriculture, ecology, hydrology, and water resources). Yearly area-averaged daily rainfall data for the individual subregions have been prepared from the simple arithmetic mean of the 1° latitude–longitude grids in the particular subregion.

3. Objective criterion for identification of wet and dry spells

A dynamic criterion has been developed and applied to identify yearly wet and dry spells over the 19 subregions. The rainfall threshold used in the criterion is derived from local rainfall climatology that is ''daily mean rainfall (DMR) of the climatological (long term mean or normal) summer monsoon period over the area of interest.'' Computational steps of the schemes are as follows:

(1) computation of daily rainfall climatology of the full calendar year;
(2) calculation of DMR of the normal summer monsoon period (mm day^{-1});
(3) normalization of yearwise daily rainfall amounts by dividing by the respective DMR;
(4) application of the 9-point Gaussian low-pass filter with weights 0.244, ±0.201, ±0.117, ±0.047, and ±0.013 on the normalized daily rainfall values; and

(5) identification of a continuous period with normalized, smoothed daily rainfall values equal to or greater than 1.0 as WS and less than 1.0 as DS.

Thus, in a low-frequency-mode intra-annual rainfall variation, the WS (DS) is identified as "a continuous period with daily rainfall equal to or greater than (less than) daily mean rainfall (DMR) of climatological monsoon period over the area of interest." Climatological onset and withdrawal dates of the southwest monsoon period over the subregions have been calculated (step 2) from the yearly value of the respective parameters obtained manually from the charts showing the yearly "advance of southwest monsoon" and "withdrawal of southwest monsoon" routinely prepared by the operational wing (Weather Central) of the India Meteorological Department (IMD), Pune. Yearly charts of the advance of southwest monsoon are available for the period 1960–2007 and those of the withdrawal of southwest monsoon for the period 1975–2007. Climatological onset, as well as withdrawal dates, was found to be close to the normal onset and withdrawal dates shown on the earlier published charts of the IMD (IMD 1943). For the 19 subregions, climatological onset and withdrawal dates and total monsoonal rainfall and daily mean rainfall of the monsoon period are given in Table 1. The lengths of the window width for low-pass filtering (step 5) are decided after a few trials, such as 3-, 5-, 7-, 9-, and 11-term running means, and low-pass binomial and Gaussian filters with the different window widths. The filter with longer window width (nine points) is chosen to suppress an isolated rain spell of 1- or 2-day(s) duration. To apply a unified filter, the Gaussian low-pass filter was chosen, giving satisfactory results for the 19 subregions. However, even after this careful choice, a rain spell of one or two day(s) for a few years for every subregion could not be suppressed, and they were retained as a wet spell for detailed analyses. The criterion is dynamic in the sense that the rainfall threshold used is changing from subregion to subregion. Further, the rainfall threshold is derived from the monsoon rainfall climatology of the particular subregion, which provides an objective basis for the criteria. The monsoon season is the most reliable period of rainfall activities in India; therefore, the rainfall threshold can be regarded as robust. Identification of wet and dry spells is done with respect to local rainfall climatology; therefore, it is relative rather than absolute. For different subregions the DMR exceeds the rate of potential evapotranspiration (PE; Rao et al. 1971), except in ESEP, CSEP and NNWI, where PE exceeds DMR. Climatological and fluctuation features of the following parameters of actual wet and dry spells have been studied:

(i) number of wet–dry spells
(ii) total rainfall of the wet–dry spells
(iii) total duration of the wet–dry spells
(iv) starting date of the first wet–dry spell
(v) ending date of the last wet–dry spell
(vi) rainfall amount of individual wet–dry spells
(vii) rainfall intensity of individual wet–dry spells
(viii) duration of individual wet–dry spells

Besides these parameters, characteristics of four other parameters—duration, rainfall amount, rainfall intensity and starting date—of the extremes of wet and dry spells concerning rainfall amount (mm), rainfall intensity (mm day^{-1}), and duration (days) have been studied to understand if there is any change taking place in the hydrological cycle of the area. In total, 40 parameters of the two attributes of the rainfall time distribution of wet and dry spells have been examined in this study. A description of the spatial variation of total rainfall due to wet–dry spells, and rainfall amount and rainfall intensity of an individual wet–dry spell is given in comparison with the annual rainfall distribution across the country. Spatially averaged subregional normal annual rainfall along the west coast varies from 1795 to 3132 mm, with central India ranging from 1077 to 1241 mm; the northeast at about 2089 mm; the extreme north at about 873 mm; the peninsula (excluding west coast) from 711 to 1424 mm; the Indo-Gangetic Plains from 755 to 1423 mm; and the northwest dry province from 324 to 617 mm.

4. Results and discussion

a. *Climatological features of the wet spells*

Normally, the ESEP experiences the largest number (11) of WSs. The number decreases along the east coast to seven over EIGP, then decreases to four over northwestern India (SRs 11 and 15). The SD of interannual variation of the number of WSs on a subregional scale across India (hereafter SD_{AI}) is about two (Table 2). Total duration of the WSs follows the similar pattern and decreases from 101 (ESEP) to 29 days (NNWI) (SD_{AI} = 14.3 day). Total rainfall as a result of WSs is, however, highest along the west coast at 1290–2130 mm, followed by NEI at 1262 mm, and lowest over northwestern India at 284 mm. Over the remaining areas, the total rainfall varies from 495 to 900 mm, following the annual rainfall pattern with low values over the central peninsula (NCP and SCP) and high values elsewhere. Features of individual WSs are different along the west coast. Duration varies from 10 to 12 days, rainfall amount from 263 to 327 mm, and rainfall intensity from 29 to 37 mm day^{-1}; over other areas the duration varies

TABLE 2. Mean and SD of nine parameters of the wet spells for the 19 subregions: $\overline{WS}$ indicates mean number, $WS_{\overline{TRAIN}}$ mean total rainfall and $WS_{\overline{TDUR}}$ mean total duration of the WSs; $WS_{\overline{RI}}$ mean rainfall intensity, $WS_{\overline{RAIN}}$ mean rainfall amount, and $WS_{\overline{DUR}}$ mean duration of the individual WS; $WS_{\overline{START}}$ mean starting date of the first WS; $WS_{\overline{END}}$ mean ending date of the last WS; and $WS_{\overline{\%age}}$ mean percentage contribution of the WSs rainfall to the annual total.

Subregions	$\overline{WS}$ (SD)	$WS_{\overline{TRAIN}}$ (SD) (mm)	$WS_{\overline{TDUR}}$ (SD) (day)	$WS_{\overline{RI}}$ (SD) (mm)	$WS_{\overline{RAIN}}$ (SD) (mm)	$WS_{\overline{DUR}}$ (SD) (day)	$WS_{\overline{START}}$ (SD (day)	$WS_{\overline{END}}$ (SD (day)	$WS_{\overline{\%age}}$ (SD) (%)
ESWP	6.9 (2.0)	1817.7 (538.1)	65.5 (17.3)	27.6 (2.5)	263.4 (139.1)	9.5 (4.3)	21 May (17.5)	22 Oct (25.8)	66.1 (8.6)
ESEP	10.7 (2.1)	778.8 (275.5)	100.4 (20.0)	7.6 (1.5)	72.8 (35.8)	9.4 (2.5)	19 Mar (32.6)	16 Dec (11.6)	79.3 (8.4)
SCWC	5.0 (1.4)	2130.4 (503.1)	57.7 (12.7)	36.9 (3.5)	426.1 (201.6)	11.5 (5.1)	2 Jun (11.1)	17 Sep (27.7)	67.3 (7.9)
CSEP	9.0 (2.2)	663.0 (216.9)	80.5 (17.6)	8.2 (1.5)	73.7 (37.0)	8.9 (2.6)	3 May (31.0)	4 Dec (15.1)	75.9 (7.1)
NCWC	4.8 (1.2)	1567.3 (438.9)	51.8 (12.2)	30.1 (3.3)	326.5 (134.6)	10.9 (3.7)	7 Jun (8.7)	19 Sep (27.9)	69.6 (7.8)
SCP	7.3 (1.9)	508. 9 (168.2)	57.6 (17.7)	8.9 (1.0)	69.7 (31.1)	7.9 (2.9)	30 May (26.1)	25 Oct (20.5)	70.1 (9.2)
CEC	8.3 (1.9)	711.2 (202.0)	61.2 (15.5)	11.6 (1.6)	85.7 (25.3)	7.4 (2.0)	23 May (34.6)	7 Nov (19.1)	68.3 (8.4)
NWC	4.7 (1.3)	1289.9 (386.3)	45.1 (11.8)	28.7 (3.6)	280.4 (98.9)	9.7 (3.0)	15 Jun (8.1)	15 Sep (18.7)	70.7 (8.4)
NCP	6.1 (1.7)	707.8 (216.8)	52.2 (14.6)	13.5 (1.5)	116.0 (59.2)	8.6 (3.9)	9 Jun (27.4)	6 Oct (24.4)	68.5 (11.0)
NEC	8.1 (1.7)	900.2 (235.9)	55.5 (13.8)	16.2 (1.3)	111.1 (31.2)	6.9 (1.8)	8 Jun (24.4)	19 Oct (21.4)	62.3 (9.1)
SNWI	4.1 (1.5)	494.6 (225.3)	35.9 (14.0)	13.5 (2.5)	120.6 (56.5)	8.8 (3.5)	21 Jun (15.8)	16 Sep (30.6)	77.2 (12.7)
WCI	4.8 (1.3)	761.0 (194.3)	48.4 (12.4)	15.8 (1.6)	158.5 (69.0)	10.1 (4.3)	21 Jun (18.1)	21 Sep (28.2)	69.8 (8.1)
ECI	5.6 (1.6)	820.0 (203.8)	51.4 (11.9)	15.9 (1.1)	146.4 (63.8)	9.2 (3.8)	18 Jun (27.2)	24 Sep (18.6)	65.4 (7.8)
EIGP	6.8 (1.6)	879.9 (272.0)	52.1 (14.1)	16.8 (1.5)	129.4 (38.0)	7.7 (2.0)	7 Jun (20.5)	1 Oct (14.4)	60.6 (10.3)
NNWI	3.8 (1.5)	283.7 (173.7)	29.2 (12.8)	9.2 (3.1)	78.8 (53.2)	7.7 (4.2)	22 Jun (30.4)	12 Sep (34.9)	77.4 (14.8)
WIGP	4.7 (1.5)	531.2 (160.1)	44.5 (12.9)	11.9 (1.0)	113.0 (46.2)	9.4 (3.7)	23 Jun (30.5)	19 Sep (19.9)	68.9 (10.9)
CIGP	6.5 (1.5)	776.6 (219.1)	45.8 (10.7)	16.8 (1.9)	119.5 (35.7)	7.1 (1.9)	14 Jun (28.8)	25 Sep (14.4)	66.9 (8.7)
NEI	9.2 (2.2)	1261.6 (319.2)	69.2 (15.8)	18.2 (1.5)	137.1 (36.4)	7.5 (1.8)	23 Apr (25.0)	9 Oct (22.6)	59.5 (8.7)
ENI	5.7 (1.6)	486.3 (166.7)	46.9 (14.5)	10.3 (0.9)	74.9 (28.9)	8.2 (2.4)	16 May (52.9)	20 Sep (23.1)	47.3 (11.5)
INDIA	6.4 (1.7)	914.2 (269.3)	55.0 (14.3)	16.7 (1.9)	152.8 (64.3)	8.8 (3.1)	31 May (24.8)	8 Oct (22.0)	68.0 (9.4)

from 7 to 10 days, rainfall amount from 70 to 159 mm, and rainfall intensity from 8 to 18 mm day^{-1}. The SD_{AI} of duration of individual WSs is 3.1 days, rainfall amount is 67.7 mm, and rainfall intensity is 2.0 mm day^{-1}.

Interannual variation in rainfall intensity is a weak determinant of interannual variation of the WS rainfall amount (correlation coefficient CC = ~0.45) and the respective annual rainfall (CC = ~0.36). Total duration of all the WSs is, however, strongly correlated with total rainfall. The CC of the total duration with total rainfall of the WSs is 0.72–0.98 across the 19 subregions and with the respective annual rainfall of 0.70–0.93. The CC between total rainfall as a result of WSs and respective annual rainfall is 0.72–0.95.

Normally, the first WS starts on 19 March over the ESEP, followed by 23 April over NEI, 3 May over CSEP, 16 May over ENI, 21 May over ESWP, 23 May over CEC, and 30 May over SCP. Over the peninsula, northeast India, and extreme northern India, thunderstorms associated with the first WS start 11–55 days earlier than the onset of the monsoon. Most parts of the country experience the first WS between 2 June and 23 June, that is, about five days earlier than the onset of the monsoon. Over the NNWI, the first WS starts on 22 June, 16 days earlier (8 July) than the monsoon onset. The SD of the start of the first WS is 8–11 days (smallest) over the central and northern west coast and 31–35 days over the southeast peninsula and 30–53 days over the extreme north–northwest. Hence, the time-invariant orographic effect reduces the interannual variability of the start of rains on the windward side of large-scale moist air flows from the surrounding oceans–seas. We believe that intense convection from the elevated landmass and ample moisture supplied by the perennial moist airstream inland from neighboring seas from the beginning of the summer contribute to reducing the interannual variation of the start of the first WS season.

The cessation process for the last WS starts in NNWI on 12 September; the date progressively shifts toward the east, southeast, and south and ends on 16 December in ESEP. In general, over most regions, the last WS ends approximately nine days earlier than the withdrawal of the monsoon. However, from the northeast, east coast, and southeast peninsula, the last WS ends after the withdrawal of the monsoon: 4 days later from NEI, 7 days from NEC, 11 days from SCP, 22 days from SEC, 48 days from CSEP, and 58 days from ESEP. This is because the withdrawal of the southwest monsoon is followed by the onset of the northeast monsoon over these subregions. The SD of the ending date is 12–15 days (lowest) over the southeast peninsula, 28 days along the central WC and 31–35 days over the northwest. Hence, the time-invariant orographic effect reduces variability of the ending date of the rains on the windward side. The contribution of rainfall as a result of the WSs to the respective annual total varies from 60% to 79% over different regions except over the extreme north, where it is only ~47% (Table 2). The last row of the table shows the arithmetic mean of the subregions, providing an approximate value of the parameter for the whole country.

The ESEP experiences three WSs before the onset of the summer monsoon and three WSs after the withdrawal: over CSEP, one WS before and two WSs after; over ESWP, SCP, and CEC, one WS before and one WS after; over NNWI, one WS before and no WS after; and over the northeast (SR 18) and extreme north (SR 19), two WSs before and no WS after. Over the remaining areas (SRs 3, 5, 8–14, 16 and 17), the first WS occurs with the onset of the summer monsoon and the last WS ends with the withdrawal. Sometimes this large portion of the country is referred to as the core monsoon rainfall regime (CMRR; Ranade et al. 2008).

b. Climatological features of the extremes of wet spells

Extreme wet spells are identified based on three conditions: extremely high rainfall amount, extremely high rainfall intensity, and extremely long duration. For the particular subregion, the sequence of extreme WS (1951–2007) concerning (i) rainfall amount has been obtained by yearly picking the WS with the highest rainfall amount (mm), (ii) rainfall intensity by yearly picking the WS with the highest rainfall intensity (mm day^{-1}), and (iii) duration by yearly picking the WS with the longest duration (days). Spatial features of duration, rainfall amount, rainfall intensity, and starting date of the different extreme WSs are described here in comparison with the actual WS; climatology is given in Table 3.

1) EXTREME WET SPELL CONCERNING RAINFALL AMOUNT

The duration of extreme WSs in this category is longer (22–30 days) over the south peninsula and west coast and shorter (13–21 days) elsewhere. The rainfall amount is higher (590–1051 mm) along the west coast, followed by 361–367 mm over the WCI, ECI, and NEI and lower (154–338 mm) elsewhere. The rainfall intensity is greater (32–40 mm day^{-1}) along the west coast, followed by 17–20 mm day^{-1} over east/northeast India and weaker (11–16 mm day^{-1}) elsewhere. In general, the duration of extreme WSs is 2.16 times longer than that of the actual WS (SD_{AI} = 8.7 days), the rainfall amount is 2.34 times (SD_{AI} = 173.2 mm) and the rainfall intensity is 1.12 times (SD_{AI} = 4 mm day^{-1}). The spell occurs over parts of the WC, northeast, and extreme north during the month of June, over most parts during July, and over the southeastern peninsula, moving from north

TABLE 3. Climatology (mean) of rainfall amount (mm), rainfall intensity (mm day^{-1}), duration (days), and starting date of the extreme WSs concerning rainfall amount, rainfall intensity, and duration. Column heads $\widetilde{WS}^{RAIN}$, $\widetilde{WS}^{RI}$ and $\widetilde{WS}^{DUR}$ indicate extreme WS concerning highest rainfall amount, highest rainfall intensity, and longest duration respectively. In the first group, parameters $\widetilde{WS}^{RAIN}_{RAIN}$, $\widetilde{WS}^{RAIN}_{RI}$, $\widetilde{WS}^{RAIN}_{DUR}$, and $\widetilde{WS}^{RAIN}_{START}$ indicate mean rainfall amount, mean rainfall intensity, mean duration, and mean starting date of the extreme WS concerning rainfall amount, respectively. In the second group, parameters $\widetilde{WS}^{RI}_{RAIN}$, $\widetilde{WS}^{RI}_{RI}$, $\widetilde{WS}^{RI}_{DUR}$, and $\widetilde{WS}^{RI}_{START}$ indicate mean rainfall amount, mean rainfall intensity, mean duration, and mean starting date of the extreme WS concerning rainfall intensity, respectively. In the third group, parameters $\widetilde{WS}^{DUR}_{RAIN}$, $\widetilde{WS}^{DUR}_{RI}$, $\widetilde{WS}^{DUR}_{DUR}$, and $\widetilde{WS}^{DUR}_{START}$ indicate mean rainfall amount, mean rainfall intensity, mean duration, and mean starting date of the extreme WS concerning duration, respectively.

	$\widetilde{WS}^{RAIN}$				$\widetilde{WS}^{RI}$				$\widetilde{WS}^{DUR}$			
Subregion	$\widetilde{WS}^{RAIN}_{RAIN}$	$\widetilde{WS}^{RAIN}_{RI}$	$\widetilde{WS}^{RAIN}_{DUR}$	$\widetilde{WS}^{RAIN}_{START}$	$\widetilde{WS}^{RI}_{RAIN}$	$\widetilde{WS}^{RI}_{RI}$	$\widetilde{WS}^{RI}_{DUR}$	$\widetilde{WS}^{RI}_{START}$	$\widetilde{WS}^{DUR}_{RAIN}$	$\widetilde{WS}^{DUR}_{RI}$	$\widetilde{WS}^{DUR}_{DUR}$	$\widetilde{WS}^{DUR}_{START}$
ESWP	716.7	31.7	22.5	27 Jun	504.1	35.9	14.4	10 Jul	699.8	29.6	23.1	25 Jun
ESEP	337.7	11.1	30.2	6 Oct	291.6	12.3	23.3	16 Oct	313.9	9.4	31.2	25 Sep
SCWC	1051.5	39.8	26.4	26 Jun	770.2	43.3	17.7	9 Jul	1045.9	39.1	26.5	25 Jun
CSEP	238.8	10.9	22.4	24 Sep	188.4	12.5	15.0	2 Oct	219.3	8.6	23.8	10 Sep
NCWC	767.6	33.0	23.3	2 Jul	577.8	35.3	16.5	9 Jul	758.9	32.0	23.4	30 Jun
SCP	187.7	10.5	18.3	22 Aug	142.5	12.2	12.1	27 Aug	180.9	9.4	18.8	14 Aug
CEC	220.5	15.8	15.2	30 Aug	174.8	18.1	9.8	27 Aug	186.0	11.3	16.4	13 Aug
NWC	589.7	32.6	18.3	11 Jul	520.3	34.7	15.2	12 Jul	576.0	30.9	18.6	11 Jul
NCP	284.8	14.6	19.6	22 Jul	205.0	16.7	12.3	28 Jul	281.1	14.1	19.7	22 Jul
NEC	270.0	17.6	15.8	30 Jul	158.1	22.5	7.3	28 Aug	263.5	16.4	16.2	28 Jul
SNWI	268.6	15.7	16.9	16 Jul	247.5	16.6	14.4	27 Jul	263.7	14.8	17.1	15 Jul
WCI	367.2	17.3	21.5	23 Jul	258.7	18.7	13.9	2 Aug	365.5	17.1	21.6	21 Jul
ECI	344.7	17.0	20.5	17 Jul	176.0	19.6	9.3	10 Aug	341.2	16.4	20.8	17 Jul
EIGP	295.3	18.4	16.4	18 Jul	184.1	22.2	8.3	17 Aug	290.5	17.4	16.7	13 Jul
NNWI	154.4	11.4	12.7	27 Jul	143.1	12.2	10.9	28 Jul	144.6	10.2	13.0	19 Jul
WIGP	253.7	12.4	20.7	25 Jul	136.1	14.3	9.6	13 Aug	252.4	12.2	20.7	23 Jul
CIGP	284.8	19.5	15.0	29 Jul	191.3	21.9	8.9	3 Aug	277.2	17.5	15.6	24 Jul
NEI	360.7	19.9	18.5	25 Jun	142.9	24.5	6.0	1 Aug	352.1	18.6	18.9	25 Jun
ENI	221.6	10.9	20.7	21 Jul	87.3	14.2	6.3	25 Jul	218.4	10.5	20.9	21 Jul
INDIA	379.8	19.0	19.7	28 Jul	268.4	21.5	12.2	9 Aug	356.4	17.7	20.2	23 Jul

to south, during August through October. The SD_{AI} is about 27.3 days, which suggests that extreme WS can occur anywhere during the period of rainfall activities. The most extreme wet spell during 1951–2007 over the different subregions is given in Table 4. The heaviest among the subregional extremes occurred over the SCWC, which started on 24 June 1961, continued for 42 days, and produced rainfall of 2080.2 mm at the rate of 49.5 mm day^{-1}. The year 1961 was the wettest recorded since 1813.

2) EXTREME WET SPELL CONCERNING RAINFALL INTENSITY

The duration of such extreme WS is longer (15–23 days) over the south peninsula and west coast and shorter (6–12 days) elsewhere. The rainfall amount is higher (504–520 mm) along the west coast and 259–292 mm over the ESEP and WCI and lower (87–205 mm) elsewhere. The rainfall intensity is greater (35–43 mm day^{-1}) over the west coast, followed by 20–25 mm day^{-1} over east–northeast India and weaker (12–19 mm day^{-1}) elsewhere. Broadly, the duration of the extreme WS is 1.33 times (SD_{AI} = 8.5 day), rainfall amount is 1.65 times (SD_{AI} = 185.6 mm) and rainfall intensity is 1.27 times (SD_{AI} = 4.1 mm day^{-1}) than that of the actual WS. Rainfall amount and rainfall intensity are higher over high- (annual) rainfall areas and lower over low-rainfall areas. Duration, however, shows a typical spatial pattern—it increases from north–northeast to south–southeast. The extreme WS can start around 10 July along the WC, 30 July over the northwest, 10 August over the east–northeast, and 30 September–15 October over the southeast peninsula. The SD_{AI} is about 48.3 days, which suggests the occurrence of extreme WS anywhere between the first and last WSs, inclusive. The most intense extreme wet spell occurred over the NWC, starting on 20 June 2005 with a rainfall amount of 1042.2 mm, rainfall intensity of 61.3 mm day^{-1}, and duration of 17 days (Table 4).

3) EXTREME WET SPELL CONCERNING DURATION

The duration is longer (23–31 days) along the west coast and over the central peninsula and shorter (14–22 days) elsewhere. The rainfall amount is higher (576–1046 mm) along the west coast, followed by 341–366 mm over central and northeast India and lower (145–314 mm) elsewhere. The rainfall intensity is 30–39 mm day^{-1} over the west coast and 9–19 mm day^{-1} over other places. The average duration for the whole country is 2.23 times (SD_{AI} = 8.4 day), the rainfall amount 2.28 times

TABLE 4. The most extreme wet spell over the 19 subregions during 1951–2007 concerning rainfall amount (mm), rainfall intensity (mm day^{-1}), and duration (days); RI refers to rain intensity and Dur to duration.

	Rainfall amount				Rainfall intensity				Duration			
Subregion	Rainfall	RI	Dur	Period	Rainfall	RI	Dur	Period	Rainfall	RI	Dur	Period
ESWP	1889.4	30.0	63	25 Jun 61	59.9	59.9	1	19 May 06	1889.4	30.0	63	25 Jun 61
ESEP	1645.2	18.1	91	28 Jun 05	160.4	26.7	6	22 Dec 78	1645.2	18.1	91	28 Jun 05
SCWC	2080.2	49.5	42	24 Jun 61	2037.0	55.1	37	22 Jun 59	1845.9	35.5	52	21 Jun 54
CSEP	1517.9	17.5	90	29 Jun 05	226.7	22.7	10	11 Nov 91	1517.9	17.5	90	29 Jun 05
NCWC	1627.2	37.8	43	29 Jun 54	465.4	46.5	10	16 Jun 53	1313.9	29.9	44	17 Jul 55
SCP	543.3	12.4	44	29 Jun 05	20.6	20.6	1	11 Mar 89	502.2	10.7	47	16 Sep 75
CEC	415.3	20.8	20	5 Oct 58	384.5	38.5	10	6 May 90	296.7	9.3	32	11 Aug 96
NWC	1230.0	31.5	39	11 Jul 83	1042.2	61.3	17	20 Jun 05	993.5	22.1	45	25 Jul 55
NCP	572.3	15.1	38	23 Jul 63	411.8	24.2	17	31 Aug 06	572.3	15.1	38	23 Jul 63
NEC	552.5	15.8	35	17 Jul 92	37.0	37.0	1	12 Nov 02	552.5	15.8	35	17 Jul 92
SNWI	682.5	20.1	34	20 Aug 06	596.5	33.1	18	30 Jul 79	497.2	11.8	42	11 Jul 83
WCI	694.6	16.5	42	2 Jul 56	288.0	24.0	12	21 Aug 87	660.5	14.4	46	29 Jun 59
ECI	1206.7	17.8	68	13 Jun 94	33.7	33.7	1	10 Nov 95	1206.7	17.8	68	13 Jun 94
EIGP	652.5	18.6	35	1 Jul 87	302.9	37.9	8	21 Sep 99	652.5	18.6	35	1 Jul 87
NNWI	490.7	14.0	35	20 Aug 06	264.4	29.4	9	17 May 99	490.7	14.0	35	20 Aug 06
WIGP	563.9	15.2	37	2 Aug 67	147.7	21.1	7	3 Oct 60	547.9	11.9	46	25 Jun 77
CIGP	727.4	19.7	37	1 Jul 55	247.5	35.4	7	9 Aug 87	727.4	19.7	37	1 Jul 55
NEI	904.4	20.1	45	22 May 54	37.8	37.8	1	20 Oct 87	904.4	20.1	45	22 May 54
ENI	640.0	11.0	58	18 Jun 78	22.3	22.3	1	29 Aug 81	567.0	9.3	61	25 Jun 98

(SD_{AI} = 176.6 mm), and the rainfall intensity 1.04 times (SD_{AI} = 3.4 mm day^{-1}) than that of the actual WS. The duration increases from the northwest to extreme southeast peninsula; however, the rainfall amount and rainfall intensity is higher over highlands and low over plains. It starts around 30 June along the west coast and northeast, during July over areas north of 18°N, mid-August over the central peninsula (SRs 6 and 7), and 10–25 September over the southeast peninsula. The SD_{AI} is about 24.7 days, suggesting the occurrence of extreme WS anywhere during the period of seasonal rainfall activities. The longest wet spell on record occurred over ESEP, starting on 28 June 2005 with a duration of 91 days, rainfall amount of 1645.2 mm, and rainfall intensity of 18.1 mm day^{-1}.

In general, the different extreme wet spells are lengthier (2.16 times), wetter (2.09 times), and more intense (1.14 times) than the actual.

c. *Climatological features of the dry spells*

The total duration of intervening DSs (3–10 in number) is shorter (45 days) over WCI and WIGP, increases to 59 over NNWI, to 81 over ENI, to 101 over ENI, and to 173 days over the ESEP. At subregional scale across the country, the interannual variation (SD) in total duration of DSs is 17–61 days; the SD is larger where rainfall occurrences are spread over a long period of the year and the rainfall intensity is relatively low. Total rainfall as a result of DSs is high over higher (annual) rainfall areas and low over lower rainfall areas—over NEI 553 mm, along the west coast 291–509 mm, and over CEC, NEC, and EIGP 222–291 mm, and decreases to 28 mm over NNWI. The DS is shorter (11–12 days) over WCI, ECI, EIGP, and CIGP (SRs 12, 13, 14 and 17), increases to 22 days over NNWI, and to 19 days over ESEP (Table 5). The SD_{AI} is about 7.9 days, suggesting a large interannual variation in the duration on subregional scales. Mean rainfall amount of an individual DS is 10 over the northwest, increases to 14 over ESEP, to 37 over ENI, to 70 over NEI, and to 116 mm along the west coast. The mean rainfall intensity during the DS is 1–2 mm day^{-1} over the northwest and eastern south peninsula, 3–6 mm day^{-1} over almost all northern India, and 6–10 mm day^{-1} along the west coast. The interannual variation in rainfall intensity during dry spells across the country is only about 1 mm day^{-1}. The CC of the DS rainfall intensity with the DS rainfall amount and annual rainfall is almost negligible. But the total duration and total rainfall of the DSs are also important contributors to the respective annual rainfall. The correlation (CC) between total duration and total rainfall of the DSs is in the range of 0.55–0.89, between total duration and respective annual rainfall of 0.47–0.90, and between total rainfall and respective annual rainfall of 0.47–0.97 across the 19 subregions. The DS rainfall contributes about 17% to the respective annual total.

The first dry spell starts around 24 March over ESEP; 28 April over the northeast (SR 18); during May over ESWP, CSEP, and CEC, and extreme north (SR 19); and during June over most parts of the country except

TABLE 5. Mean and SD of nine parameters of the dry spells for the 19 subregions. From left, $\overline{DS}$ indicates mean number, $DS_{\overline{TRAIN}}$ is mean total rainfall, and $DS_{\overline{TDUR}}$ is mean total duration of the DSs; $DS_{\overline{RI}}$ is mean rainfall intensity, $DS_{\overline{RAIN}}$ is mean rainfall amount, and $DS_{\overline{DUR}}$ is mean duration of the individual DS; $DS_{\overline{START}}$ is mean starting date of the first DS; $DS_{\overline{END}}$ is mean ending date of the last DS; and $DS_{\overline{\%age}}$ is mean percentage contribution of the DSs rainfall to the annual total.

Subregion	$\overline{DS}$ (SD)	$DS_{\overline{TRAIN}}$ (SD) (mm)	$DS_{\overline{TDUR}}$ (SD) (in day)	$DS_{\overline{RI}}$ (SD) (mm)	$DS_{\overline{RAIN}}$ (SD) (mm)	$DS_{\overline{DUR}}$ (SD) (day)	$DS_{\overline{START}}$ (SD (day)	$DS_{\overline{END}}$ (SD (day)	$DS_{\overline{\%age}}$ (SD) (%)
ESWP	5.9 (1.9)	509.1 (172.4)	89.5 (31.6)	5.8 (1.0)	86.3 (32.3)	15.2 (6.3)	30 May (21.5)	15 Oct (28.1)	19.4 (7.5)
ESEP	9.7 (2.1)	130.9 (29.5)	172.5 (41.4)	0.8 (0.1)	13.5 (4.7)	17.8 (7.2)	24 Mar (33.2)	6 Dec (17.2)	14.9 (6.7)
SCWC	4.0 (1.4)	459.4 (219.5)	50.7 (31.5)	9.8 (2.1)	114.9 (48.0)	12.7 (6.1)	13 Jun (16.9)	11 Sep (30.5)	15.1 (8.1)
CSEP	8.0 (2.2)	144.8 (32.5)	135.5 (34.6)	1.1 (0.2)	18.1 (5.9)	16.9 (6.9)	8 May (32.3)	26 Nov (17.6)	17.8 (6.0)
NCWC	3.8 (1.2)	358.7 (149.8)	53.3 (29.6)	7.2 (1.5)	94.4 (48.2)	14.0 (8.3)	20 Jun (14.8)	13 Sep (30.0)	16.6 (7.6)
SCP	6.3 (1.9)	119.1 (40.4)	92.1 (31.5)	1.3 (0.3)	18.9 (9.2)	14.6 (7.0)	3 Jun (27.5)	17 Oct (24.6)	17.5 (6.8)
CEC	7.3 (1.9)	221.8 (77.1)	108.1 (44.4)	2.2 (0.5)	30.4 (12.3)	14.8 (7.8)	28 May (36.3)	31 Oct (21.3)	22.3 (8.2)
NWC	3.6 (1.3)	291.0 (104.7)	47.6 (17.3)	6.2 (1.2)	80.8 (38.2)	13.2 (6.5)	26 Jun (12.9)	8 Sep (20.8)	16.7 (6.6)
NCP	5.1 (1.7)	175.6 (60.1)	67.7 (35.3)	2.9 (0.9)	34.4 (15.8)	13.3 (7.1)	17 Jun (30.1)	30 Sep (27.3)	18.1 (7.5)
NEC	7.1 (1.7)	302.7 (103.0)	78.7 (33.7)	4.0 (0.8)	42.6 (17.7)	11.1 (4.7)	14 Jun (25.4)	14 Oct (22.4)	21.6 (7.6)
SNWI	3.1 (1.5)	69.3 (36.6)	53.4 (29.0)	1.5 (0.7)	22.4 (11.7)	17.2 (11.5)	29 Jun (17.8)	10 Sep (32.4)	11.7 (6.3)
WCI	3.8 (1.3)	143.7 (62.9)	44.9 (32.3)	3.8 (1.3)	37.8 (17.7)	11.8 (8.9)	1 Jul (21.9)	13 Sep (32.5)	13.7 (6.3)
ECI	4.6 (1.6)	191.3 (82.6)	47.6 (30.7)	4.4 (1.1)	41.6 (21.5)	10.3 (5.6)	28 Jun (30.6)	17 Sep (22.8)	15.8 (7.2)
EIGP	5.8 (1.6)	291.2 (84.2)	65.6 (21.4)	4.5 (0.8)	50.2 (18.6)	11.3 (4.0)	14 Jun (23.9)	25 Sep (15.8)	21.0 (7.1)
NNWI	3.1 (1.4)	27.5 (18.6)	58.8 (40.8)	0.6 (0.3)	8.9 (8.8)	19.0 (25.0)	27 Jun (32.4)	7 Sep (34.8)	9.5 (7.5)
WIGP	3.7 (1.5)	102.0 (55.9)	44.5 (33.9)	2.6 (0.9)	27.6 (12.9)	12.0 (6.6)	4 Jul (34.7)	12 Sep (21.7)	14.0 (8.2)
CIGP	5.5 (1.5)	185.1 (66.6)	57.8 (31.9)	3.4 (0.7)	33.7 (11.2)	10.5 (4.3)	21 Jun (31.4)	20 Sep (15.4)	16.5 (6.1)
NEI	8.2 (2.1)	553.1 (129.6)	101.0 (30.2)	5.6 (0.8)	67.5 (20.8)	12.3 (4.3)	28 Apr (26.9)	5 Oct (23.3)	26.8 (6.8)
ENI	4.7 (1.6)	173.7 (86.8)	80.9 (61.3)	2.8 (1.1)	37.0 (15.1)	17.2 (11.3)	23 May (61.4)	13 Sep (31.1)	20.3 (10.0)
INDIA	5.4 (1.6)	234.2 (84.9)	76 (33.8)	3.7 (0.9)	45.3 (19.5)	14 (7.9)	8 Jun (28)	2 Oct (25)	17.0 (7.3)

TABLE 6. Climatology (mean) of rainfall amount (mm), rainfall intensity (mm day^{-1}), duration (days), and starting date of the extreme DSs concerning rainfall amount, rainfall intensity, and duration. Parameters $\tilde{DS}^{RAIN}$, $\tilde{DS}^{RI}$, and $\tilde{DS}^{DUR}$ indicate extreme DS concerning lowest rainfall amount, lowest rainfall intensity, and longest duration, respectively. Parameters $\tilde{DS}^{RAIN}_{RAIN}$, $\tilde{DS}^{RAIN}_{RI}$, $\tilde{DS}^{RAIN}_{DUR}$, and $\tilde{DS}^{RAIN}_{START}$ indicate mean rainfall amount, mean duration, mean rainfall intensity, and mean starting date of the extreme DS concerning rainfall amount, respectively. Parameters $\tilde{DS}^{RI}_{RAIN}$, $\tilde{DS}^{RI}_{RI}$, $\tilde{DS}^{RI}_{DUR}$, and $\tilde{DS}^{RI}_{START}$ indicate mean rainfall amount, mean rainfall intensity, mean duration, and mean starting date of the extreme DS concerning rainfall intensity, respectively. Parameters $\tilde{DS}^{DUR}_{RAIN}$, $\tilde{DS}^{DUR}_{RI}$, $\tilde{DS}^{DUR}_{DUR}$, and $\tilde{DS}^{DUR}_{START}$ indicate mean rainfall amount, mean rainfall intensity, mean duration, and mean starting date of the extreme DS concerning duration, respectively.

	$\tilde{DS}^{RAIN}$				$\tilde{DS}^{RI}$				$\tilde{DS}^{DUR}$			
Subregion	$\tilde{DS}^{RAIN}_{RAIN}$	$\tilde{DS}^{RAIN}_{RI}$	$\tilde{DS}^{RAIN}_{DUR}$	$\tilde{DS}^{RAIN}_{START}$	$\tilde{DS}^{RI}_{RAIN}$	$\tilde{DS}^{RI}_{RI}$	$\tilde{DS}^{RI}_{DUR}$	$\tilde{DS}^{RI}_{START}$	$\tilde{DS}^{DUR}_{RAIN}$	$\tilde{DS}^{DUR}_{RI}$	$\tilde{DS}^{DUR}_{DUR}$	$\tilde{DS}^{DUR}_{START}$
ESWP	24.4	5.7	4.9	14 Jul	84.3	3.2	22.3	3 Aug	193.0	4.8	40.8	13 Aug
ESEP	1.2	0.3	5.8	8 Sep	2.9	0.1	13.3	23 Aug	44.1	0.8	57.7	15 May
SCWC	48.7	10.7	5.3	9 Jul	154.0	7.5	23.1	19 Jul	219.8	9.0	28.1	30 Jul
CSEP	2.1	0.6	4.6	11 Sep	6.9	0.3	16.2	21 Sep	49.3	1.0	47.5	15 Jun
NCWC	39.0	7.3	6.3	16 Jul	91.9	5.0	19.2	17 Jul	173.3	6.5	29.2	4 Aug
SCP	4.4	0.9	5.8	22 Aug	9.4	0.5	15.3	14 Aug	37.7	1.2	32.1	14 Jul
CEC	7.1	1.7	5.9	28 Aug	17.6	0.8	19.4	22 Aug	62.9	1.8	37.7	21 Jul
NWC	39.4	6.6	6.3	20 Jul	72.1	4.4	16.1	18 Jul	144.8	5.9	24.9	26 Jul
NCP	14.6	2.5	6.4	6 Aug	26.6	1.7	18.5	9 Aug	64.9	2.5	31.1	4 Aug
NEC	10.9	3.2	4.5	10 Aug	28.3	1.9	18.0	31 Aug	88.4	3.5	28.7	3 Aug
SNWI	12.1	1.6	10.5	27 Jul	28.3	1.9	18.0	31 Aug	35.4	1.3	31.2	27 Jul
WCI	14.6	3.9	4.3	4 Aug	40.6	2.5	21.7	2 Aug	70.8	3.3	27.8	27 Jul
ECI	17.3	3.2	4.4	9 Aug	39.6	2.6	17.5	5 Aug	78.5	4.1	23.8	2 Aug
EIGP	14.2	3.7	4.1	2 Aug	32.1	2.7	10.9	12 Aug	109.2	4.3	26.1	22 Jul
NNWI	5.4	0.4	15.7	27 Jul	6.6	0.3	26.4	25 Jul	13.1	0.4	35.7	6 Jul
WIGP	12.5	2.6	5.5	14 Aug	29.6	1.7	20.1	8 Aug	48.1	2.3	25.9	28 Jul
CIGP	8.8	2.7	3.7	1 Aug	17.9	1.8	10.0	29 Jul	71.2	3.3	24.2	31 Jul
NEI	14.0	4.8	3.7	10 Jul	50.6	3.0	17.6	15 Jul	149.8	4.9	31.9	5 Jul
ENI	10.7	3.1	4.7	31 Jul	43.0	1.7	36.6	18 Jun	78.2	2.4	50.0	13 Jun
INDIA	15.9	3.4	5.9	4 Aug	41.2	2.3	19	5 Aug	91.2	3.3	33.4	18 Jul

over WIGP, where it starts 4 July. The SD of the start of the first DS is shortest (15–18 days) along the west coast and SNWI (SRs 3, 5, 8, and 11), longer (32–35 days) along the east coast (SRs 2, 4, and 7) and over the north–northwest (SRs 15 and 16), and longest (61 days) over the extreme north (SR 19). The last dry spell ends around 7–10 September over the northwest (SRs 11 and 15), and the date progressively shifts to 6 December over ESEP, following the normal withdrawal pattern of the summer monsoon. The SD of the end of the last DS is shortest (17–21 days) along the south and central east coast, and longest (28–35 days) along the west coast (SRs 1, 3, and 5) and central and northwestern India (SRs 11, 12, and 15). In general, the SD of the start and end of DSs is lowest toward the windward side of orographic barriers for large-scale moist monsoon flows and high elsewhere. The percentage contribution of rainfall as a result of DSs to the respective annual total varies from 10% over NNWI to 27% over NEI.

The CC between the total duration of WSs and that of DSs is in the range of −0.55 to 0.02 across the 19 subregions; it is mostly negative and weak. Similarly, the CC between total rainfall as a result of WSs and DSs is mostly negative and weak and in the range of −0.40 to 0.02. The time distribution of rainfall during a year into wet and dry spells over most parts of the country is such that its partitioning on the ground surface will produce more green water flow (actual and potential evapotranspiration) and green water storage (soil moisture) and less blue water flow (reservoir storage and water yield) and blue water storage (deep aquifer recharge). Under Indian condition partitioning of rainfall into green water and blue water is two-thirds and one-third, respectively (Ranade et al. 2008). Therefore, rainfall occurrences across the country are more suitable for practicing rain-fed agriculture rather than developing water resources for hydroelectric power generation, irrigation, industrial usage, and domestic consumption.

d. *Climatological features of the extremes of dry spells*

Extreme dry spells are identified based on three conditions: extremely low rainfall amount, extremely low rainfall intensity, and extremely long duration. For the period of 1951–2007, the time series of extreme DS concerning (i) rainfall amount has been obtained by yearly picking the DS with the lowest rainfall amount (mm), (ii) rainfall intensity by yearly picking the DS with lower rainfall intensity (mm day^{-1}), and (iii) duration by yearly picking the DS of the longest duration (days). The climatology of the duration, rainfall amount, rainfall

TABLE 7. The most extreme dry spell over the 19 subregions during 1951–2007. RI and Dur same as in Table 4, and units are rainfall (mm), RI (mm day^{-1}), and Dur (days).

	Concerning rainfall amount				Concerning rainfall intensity				Concerning duration			
Subregions	Rainfall	RI	Dur	Period	Rainfall	RI	Dur	Period	Rainfall	RI	Dur	Period
ESWP	0.6	0.3	2	12 Sep 75	0.6	0.3	2	12 Sep 75	483.9	4.5	107	22 Aug 65
ESEP	0.0	0.0	2	24 Dec 65	0.0	0.0	2	24 Dec 65	80.2	0.6	139	6 Mar 79
SCWC	1.8	0.9	2	8 Jul 05	3.1	0.2	17	25 Sep 05	379.7	3.5	108	24 Aug 65
CSEP	0.0	0.0	2	16 Nov 64	0.0	0.0	2	16 Nov 64	179.6	1.3	138	4 May 68
NCWC	0.5	0.5	1	8 Aug 92	0.5	0.5	1	8 Aug 92	229.4	2.1	107	25 Aug 65
SCP	0.0	0.0	1	13 Sep 60	0.0	0.0	8	15 Oct 84	51.8	0.6	82	12 Mar 89
CEC	0.1	0.1	1	13 May 69	1.2	0.1	19	24 Oct 80	53.0	0.4	121	18 Feb 72
NWC	3.4	3.4	1	20 Jun 70	13.7	2.0	7	16 Aug 71	216.1	3.3	65	11 Aug 51
NCP	0.1	0.1	1	1 Aug 92	0.1	0.1	1	1 Aug 92	85.4	0.6	142	2 Feb 05
NEC	0.2	0.2	1	25 Aug 97	2.5	0.2	12	5 Oct 80	140.3	1.2	117	9 Feb 61
SNWI	0.8	0.8	1	10 Jul 00	2.0	0.1	24	25 May 99	24.5	0.3	93	15 Aug 51
WCI	1.3	0.7	2	11 Jul 86	18.5	0.3	72	23 Sep 62	186.5	1.3	140	12 Mar 06
ECI	0.3	0.3	1	21 Aug 84	0.3	0.3	1	21 Aug 84	214.5	1.5	140	14 Feb 07
EIGP	0.9	0.9	1	26 Sep 71	1.3	0.4	3	12 Jun 70	164.5	2.1	80	1 Apr 98
NNWI	0.0	0.0	1	31 Jul 83	0.0	0.0	1	31 Jul 83	56.3	0.3	168	8 Jul 80
WIGP	1.1	1.1	1	24 Sep 58	1.5	0.2	9	26 Sep 85	155.8	1.2	134	13 Feb 07
CIGP	0.1	0.1	1	27 Jun 75	0.1	0.1	1	27 Jun 75	185.8	1.2	156	31 Jan 59
NEI	0.4	0.4	1	29 Jun 82	8.2	0.2	38	22 Oct 88	304.3	3.8	80	18 Aug 55
ENI	1.0	1.0	1	29 Jul 86	13.2	0.2	69	16 Sep 51	140.9	0.9	156	3 Feb 54

intensity, and starting date of the extreme dry spell parameters is given in Table 6. A description of spatial features of the parameters of different extreme DSs is provided in comparison with actual dry spells (Table 5).

1) EXTREME DRY SPELL CONCERNING RAINFALL AMOUNT

The duration is 11–16 days over northern India and 4–7 days over all other subregions. The rainfall amount is 24–49 over the west coast, 1–7 over the southern peninsula, and 9–17 mm elsewhere. The rainfall intensity is near zero (0.4–2 mm day^{-1}) over hot, dry regions of the northwest and southern peninsula; 6–11 mm day^{-1} along the west coast; and 3–4 mm day^{-1} over other places. Broadly, the duration of extreme DSs is shorter (0.42 times) than the actual DS; the rainfall amount is lower (0.34 times), and the rainfall intensity is slight weaker (0.96 times). Such extreme DSs occur during July over western India (SRs 1, 3, 5, 8, 11, and 15) and the northeastern parts, during August over the central and eastern parts, and during 8–11 September over the southeastern peninsula (SRs 2 and 4). The most extreme DS of zero rainfall occurred over dry regions of ESEP during 24–25 December 1965, SCP on 13 September 1960, and NNWI on 31 July 1983 (Table 7).

2) EXTREME DRY SPELL CONCERNING RAINFALL INTENSITY

The duration of extreme DSs is shortest (10 days) over CIGP, and it increases in all directions: 37 over ENI, 26 over NNWI, 23 over SCWC, and 13 days over ESEP. The rainfall amount is 7 over NNWI, 3–9 over SCP and SEP, 72–154 along the west coast and 18–51 mm elsewhere. The rainfall intensity is near zero (<2 mm day^{-1}) over NNWI, SCP, CEC, CSEP, and ESEP; 3–8 mm day^{-1} along the WC; and 2–3 mm day^{-1} elsewhere. For the country as a whole, the duration of extreme DS is 1.28 times than that of actual DS; rainfall amount 0.87 times and rainfall intensity 0.64 times. Such extreme DS occurs around 18 June over ENI, during July along the west coast and SNWI (SRs 1, 3, 5, and 11), CIGP and NEI, during August over almost the entire area of central India and ESEP and around 21 September over CSEP. The most extreme DS with the lowest rainfall intensity (0.0 mm day^{-1}) occurred over ESEP during 24–25 December 1965 and over NNWI on 31 July 1983 (Table 7).

3) EXTREME DRY SPELL CONCERNING DURATION

The duration is shortest (24 days) over CIGP and ECI, and it increases to 32 over NEI, 36 over NNWI, 50 over ENI, and 58 days over ESEP. The rainfall amount is lowest (13 mm) over NNWI, and it increases to 220 along the west coast, 89 over NEC, 150 over ENI, and 78 mm over ENI. The rainfall intensity is near zero (<2 mm day^{-1}) over NNWI and the southeast peninsula, 5–9 mm day^{-1} along the west coast, and 2–5 mm day^{-1} elsewhere. Broadly, the duration of extreme DSs is 1.28 times the duration of an actual DS, rainfall amount 1.93 times, and rainfall intensity 0.89 times. It occurs around 15 May over ESEP, during June over CSEP and

ENI, and during July–August over the remaining areas. The most extreme dry spell occurred over NNWI starting from 8 July 1980; the duration was 168 days, the rainfall amount was 56.3 mm, and the rainfall was intensity 0.3 mm day^{-1} (Table 7).

To comprehend the broad spatial climatological features of the dry and wet spells across the country, a generalized description of the parameters in five categories is provided.

- The number and total duration of wet–dry spells and the duration of actual and different extreme wet–dry spells—the highest value is in the extreme southeast peninsula, and it decreases toward the north–northwest as the tropical and oceanic influences decrease.
- The total rainfall of the wet–dry spells, and the rainfall amount and the rainfall intensity of actual and extreme wet–dry spells—the high value in the orographic regions (the west coast and central, northeast, and extreme north India), and the lowest value over the plains (peninsula, Indo-Gangetic Plains, and northwest dry provinces).
- The start of the first wet spell—the earliest is in the extreme southeast peninsula and the latest in northwestern India.
- The end of the last wet spell—the earliest is from northwestern India and the latest is from the extreme southeast peninsula.
- The occurrence of the different extreme wet–dry spells—during June through August over most parts of northern India and during September through December over the south peninsula.

It is interesting to note that normally 68% of the annual rainfall occurs during WSs and 17% during DSs (the intervening period of subdued and/or no rainfall activities) identified by the present objective criteria. So, 85% of the annual rainfall occurs between the first WS and the last WS and only 15% as isolated random convection spread over the remaining parts of the year. It is consistent with the known rainfall climatology that about 80% of the annual rainfall over the country is seasonal. The spatial variation of this seasonal contribution over most subregions is between ~80% and ~90%, which is relatively small. Hence, the identification of the wet and dry spells can be regarded as robust. To get these robust results, it is essential to use a variable rainfall threshold for different subregions. Arbitrarily, a fixed choice of the threshold and its uniform application (Ananthakrishnan and Soman 1988; Ananthakrishnan et al. 1967; Aviad et al. 2004; Bai et al. 2007; Cook and Heerdegen 2001; Deni et al. 2008; Raman 1974; Stern et al. 1981) will produce unrealistic results for the subregions. If the rainfall threshold is larger than the DMR of the subregion, then in low-rainfall areas there will be fewer and shorter WSs, broad and longer DSs, some or most years without any WSs, a late start of the first WS, and an early end of the last WS; whereas the opposite will be the features of rainfall occurrences in high-rainfall areas. And if the rainfall threshold is smaller than the DMR, then in high-rainfall areas there will be broad and longer WSs, fewer and shorter DSs, some or most years without any DS, an early start of the first WS, and a late end of the last WS; whereas the opposite will be the rainfall features in low-rainfall areas.

e. Fluctuation features of the wet and dry spells and their extremes

In this section fluctuations of wet and dry spells and their extremes across the country are reported. Each of the 760 time series (40 parameters multiplied by 19 subregions) has been examined at the following three levels:

1) visual examination of time series plots of the actual and 5-point binomial low-pass-filtered values;
2) Mann–Kendall rank test of randomness (τ) against trend (Mitchell et al. 1966); and
3) Wilcoxon–Mann–Whitney rank-sum test for two independent samples (Wilks 2006).

From the visual examination, each of the 40 parameters is found to exhibit a wide range of fluctuation characteristics across the country, such as short-term–long-term rising–falling trend, stationary, among others. The Mann–Kendall rank test of τ against trend (Mitchell et al. 1966) has been applied to each of the 760 series to determine the broad nature (+ve and −ve) of the long-term trend, and an abstraction of the results is as follows: 399 series show increasing tendency (42 of which are significant at the 5% level and above) and 361 series show decreasing tendency (34 of which are significant at the 5% level and above). To determine if there is any change in the mean of the recent 30-yr period (1978–2007) compared to the previous 27 years (1951–77), the Wilcoxon–Mann–Whitney rank-sum test for two independent samples (Wilks 2006) has been applied and the results are that 349 series show an increase in the recent 30-yr period (7 of which are significant at the 5% level and above) and 411 series show a decrease (36 of which are significant at the 5% level and above). The detailed results for wet spells are presented in Fig. 2 and for dry spells in Fig. 3. The exercise is repeated and the mean of the recent 20-yr period of 1988–2007 is compared with the mean of the previous 37-yr (1951–87) period, and the results are 363 series show a positive tendency (20 of which are significant at the 5% level and above) and 397 series show a decrease (29 of which are significant at

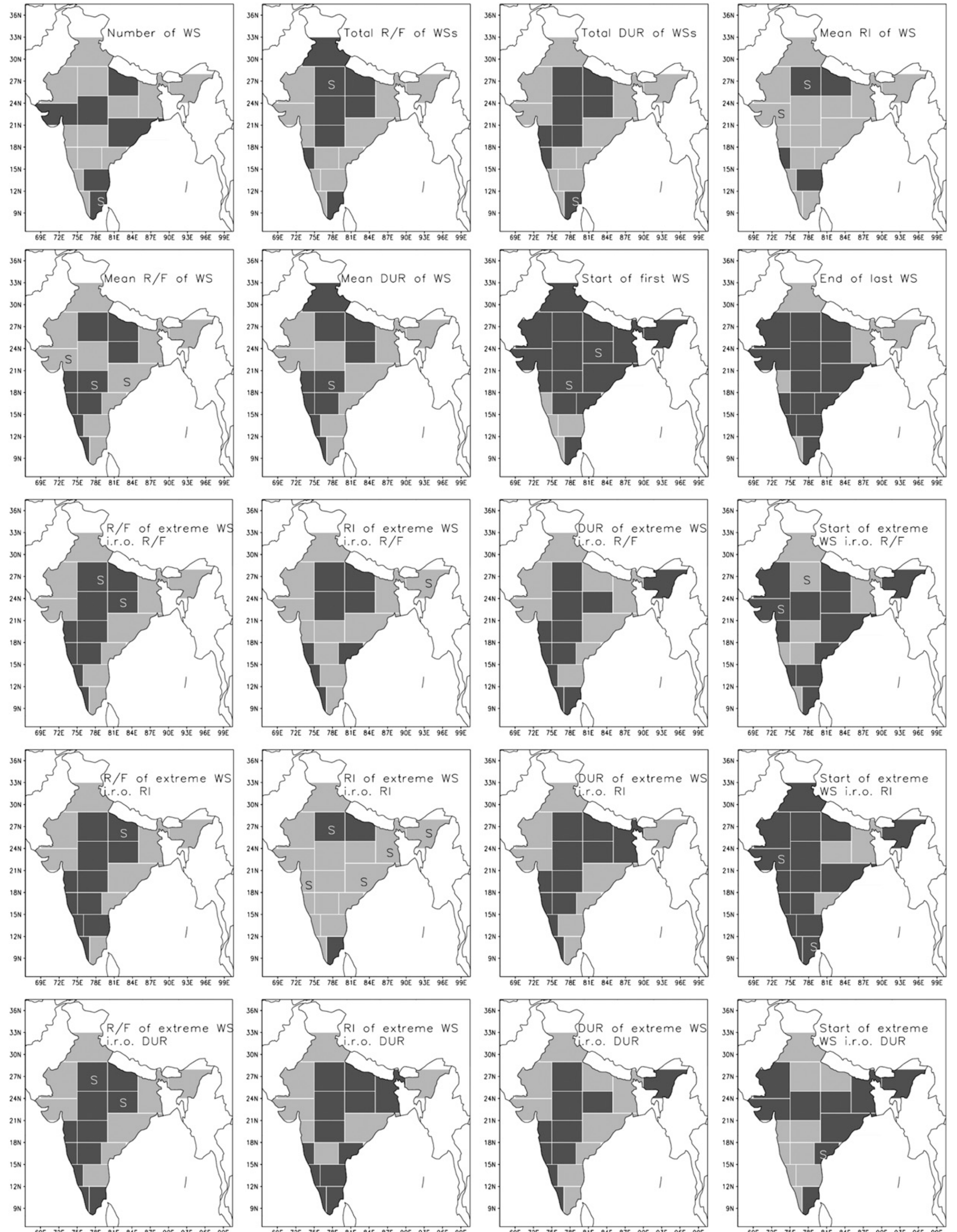

FIG. 2. Map showing the tendency–change (at the 5% level and above) in the mean of the indicated parameter of the wet spell and its extremes during the 20-yr period of 1988–2007 compared to 1951–87. Gray shading indicates the positive tendency–change and black the negative tendency–change. The letter "S" denotes that the change is significant at the 5% level and above (Wilcoxon–Mann–Whitney test).

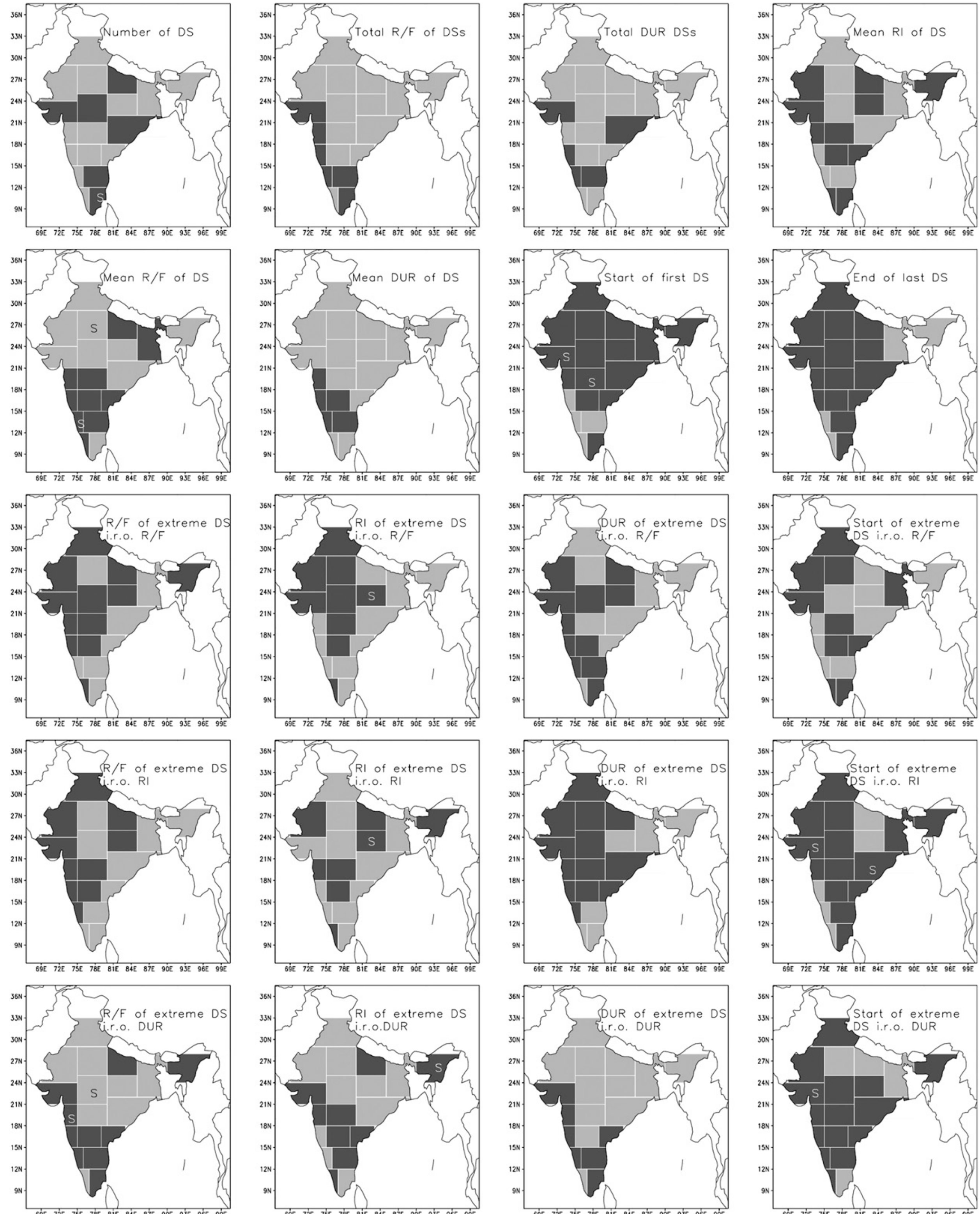

FIG. 3. Same as in Fig. 2, but for the dry spells.

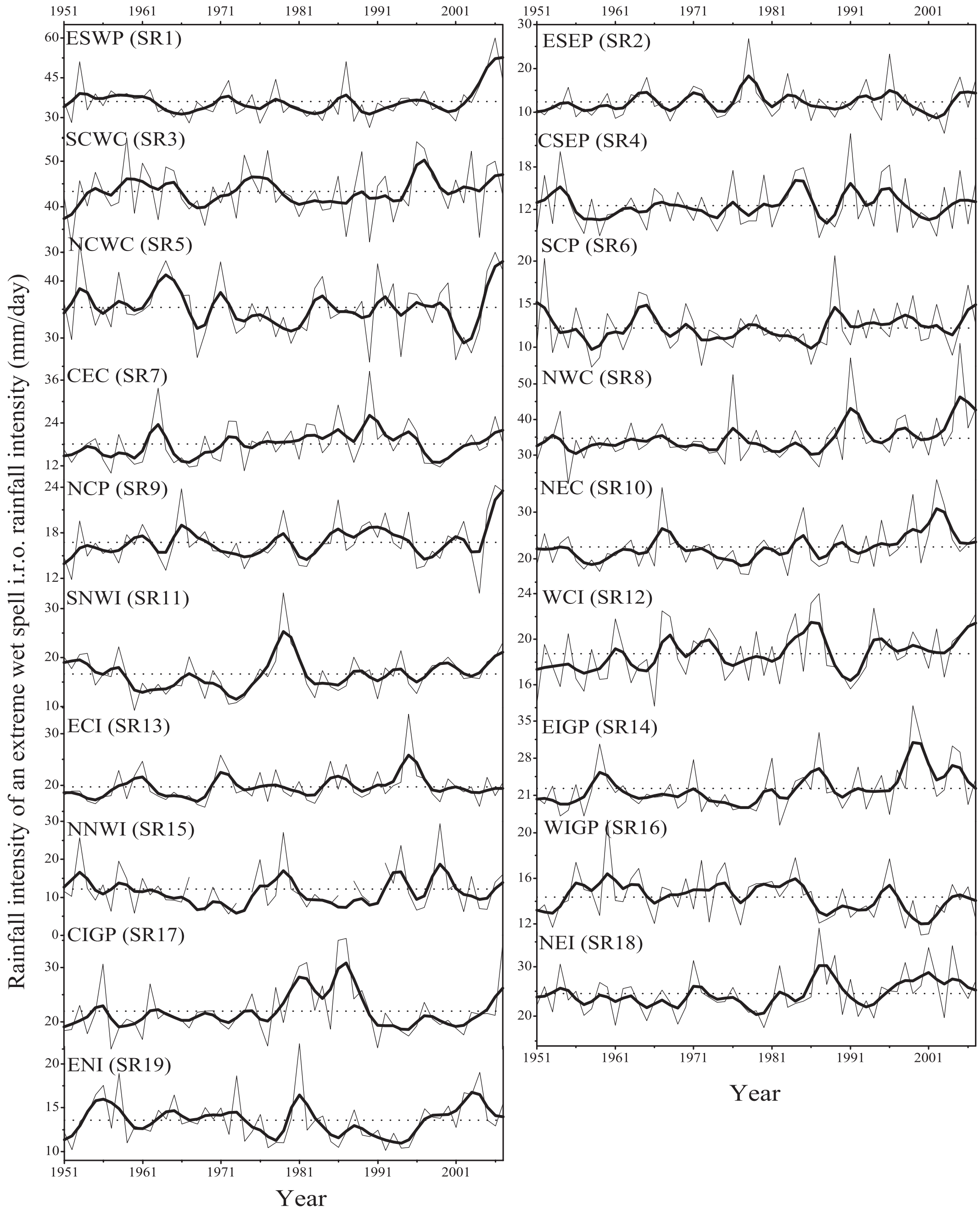

FIG. 4. Time series plots of actual (thin curve) and 5-point binomial low-pass-filtered values (dark curve) of the rainfall intensity for the extreme wet spell concerning rainfall intensity for the period of 1951–2007 in the 19 subregions.

the 5% level and above). Further, the mean of the recent 10-yr period (1998–2007) is compared with the previous 47 years (1951–97), and the results are that 361 series show an increase (26 of which are significant at the 5% level and above) and 399 series show a decrease (35 of which are significant at the 5% level and above). A spatially coherent, robust long-term trend is not seen in any of the 40 WS/DS parameters during 1951–2007. However, persistent positive–negative tendencies spread over 11 or more subregions are seen in some of the parameters. Notable among them are a decreasing tendency in duration and an increasing tendency in rainfall intensity of actual and extreme WSs (Fig. 4), and an increasing tendency in duration and a decreasing tendency in rainfall intensity of actual and extreme DSs. These changes in rainfall time distribution appear to be related to changes in the frequency, duration, and intensity of rain-producing weather systems. Over the country, the number and duration of low pressure areas (LPA; central pressure difference of 2 mb from surrounding areas and surface wind speed $<$17 kt) show an increasing trend since 1961 of 1.4–8.1 days per 10 yr, and the number and duration of depressions/storms (DDS; central pressure difference $>$2 mb from surrounding areas and surface wind speed $>$17 kt) shows a significant decreasing trend of 1.5–6.0 days per 10 yr (Jadhav and Munot 2008). Further, it appears there is some change in middle tropospheric (850–500 hPa) circulations (trough, convergence zone, and cyclonic circulations) due to a warmer environment. In random occurrences, if surface and middle tropospheric circulations were coherent (both the lower- and upper-troposphere is warmer), then shorter, intense WSs would occur; otherwise (the lower- and/or upper-troposphere is cooler) longer, severe DSs would occur. But this proposition requires further investigation, which can be done in a separate study.

Compared to 1951–1987, during 1988–2007 the first WS started about six days earlier and the last WS ended about two days earlier. Over most parts of the country, the first WS starts during May–June and the last WS ends during September–October. It may be noted that the July–September rainfalls show a declining tendency in recent years–decades over the country. But the April–June rainfalls show a rising tendency. Therefore, the first WS is starting slightly earlier (approximately six days). Similarly, because of a rising tendency in October rainfall and declining tendency in November–January rainfall, the last WS is ending approximately two days earlier. Consequently, the period between the start of the first WS and end of the last WS is approximately four days longer in recent years.

Two additional tests have been applied to see if the results discussed earlier are robust:

1) fitting least squares linear trend to different time series of the period 1951–2007 and
2) Student's t test for the difference between the means of two subperiods.

These tests produced broadly the same results as obtained by the two earlier tests, that is, the Mann–Kendal Rank test and the Wilcoxon–Mann–Whitney rank-sum test. Hence, the results reported in this paper are robust.

f. Limitations

The rainfall threshold derived from the local climatology is used to understand the broad climatology of WSs and DSs and their climatic and hydroclimatic variability; however, depending upon practical problems (agriculture, hydrology, among others) and meteorological conditions (evaporation/evapotranspiration), a regional threshold independent of the present framework can be adopted. But its application will be limited to the particular region. Even in the CMRR (between parallels 18° and 32°N, and between meridians 68° and 88°E), the standard deviation of onset and withdrawal date is ~7 days (5–9 days), but the standard deviation of the start of the first WS is ~21 days and the end of the last WS is ~23 days. This suggests that for determining the onset and withdrawal dates, rainfall alone is not sufficient. Other parameters such as meteorological conditions over the particular area [geopotential height of selected isobaric levels, precipitable water, cloud amount, outgoing longwave radiation (OLR), among others], the strength of large-scale monsoon flow (meridional wind along the Somali coast, zonal wind over the central Arabian Sea, meridional wind over the Bay of Bengal, resultant wind over the South China Sea and so on), intensity of subtropical high–anticyclone (Tibetan anticyclone, northwest Pacific subtropical high, Mascarene high, and Australian high) and the state of the tropical easterly jet (TEJ) should also be considered. This is being done as a separate study.

In the subregional rainfall analysis, the station rainfall amount is highly suppressed. Therefore, subregional extreme rainfall cannot be used for estimating the probable maximum precipitation (PMP) and the standard project storm (SPS). Using the longest instrumental monthly–seasonal–annual rainfall, Sontakke et al. (2008a) reported that mean annual rainfall over the country during 1965–2006 was less by 4.23% compared to the period of 1931–64. Most of the daily rainfall data (1951–2007) used in the present analysis is from the dry epoch (1965–2007). Therefore, if 20–30 years of data prior to 1951 are included in the present study, the results may be somewhat different.

5. Summary and conclusions

A summary of the main results is as follows:

1) Climatologically, the number of WSs (DSs) decreases from 11 (10) over the south/southeast peninsula to 4 (3) over northwest India. The total duration of the WSs (DSs) decreases from 100.4 (172.5) to 29.2 (44.5) days. The duration of an individual WS (DS) decreases from 13 (19) to 8(11) days—the values of the parameters decrease as the tropical and oceanic influences decrease.
2) The total rainfall of the WSs–DSs, and rainfall amount and rainfall intensity of actual and extreme WSs–DSs are high over orographic regions (west coast, central India, and northeast India) and low

over the peninsula, Indo-Gangetic plains, and northwest dry province.

3) The country as a whole gets more than six WSs from 31 May through 8 October, each with a duration of 8.8 days and a rainfall amount of 152.8 mm. The duration of the intervening DS is 14 days, and the rainfall amount 45.3 mm. The total rainfall and the total duration of the WSs (DSs) and the respective annual rainfall are highly correlated; the CC between the total rainfall and total duration is ~0.91 (~0.77), between total rainfall and annual rainfall is ~0.87 (~0.86), and between total duration and annual rainfall is ~0.84 (~0.70). The WSs contribute ~68% and the DSs ~17% to the respective annual rainfall.
4) The first WS starts the earliest over ESEP on 19 March and the latest over NNWI on 22 June. Over most parts the first WS starts about five days earlier than the onset of the monsoon; over the peninsula, northeast, extreme north, and northwest, the first WS starts 11–55 days earlier. The SD of the first WS is much larger (25 days) than the monsoon onset (7 days). Hence, the onset date is more reliable than the start of the first WS.
5) The last WS ends the earliest (12 September) over NNWI and the latest (16 December) over ESEP. Over the CMRR the last WS ends approximately nine days earlier than withdrawal of the monsoon; over the northeast, east coast, and south peninsula about 4–58 days later. The SD of the withdrawal date is much smaller (6.5 days) than the end of the last WS (22 days), suggesting robustness of the withdrawal date also.
6) The mean starting date of different extreme WSs/DSs is June–August over most parts of northern India and September–November over the northeast, east coast, and south peninsula. But high values of standard deviation (16–111 days) suggest that extremes can occur anywhere between the first WS and the last WS.
7) In recent years–decades, the WSs are slightly shorter and the rainfall intensity is higher, and the DSs are slightly longer and the rainfall intensity is weaker over a majority of the subregions.
8) There is a weak tendency (not significant) for the first WS to start approximately six days earlier and the last WS to end approximately two days earlier; consequently, the period of rainfall activities is approximately four days longer in recent years over most of the subregions.
9) A spatially coherent, significant long-term trend is not seen in any of the 40 WS–DS parameters over the period of 1951–2007 that were examined in the present study.

In the tropical monsoon environment of India, seasonally occurring rainfall with relatively shorter WSs (~9 days) and longer DSs (~14 days) is more favorable for agricultural and ecological activities than for hydrological and water resources purposes. The characteristics of wet and dry spells across India provide some evidence for the hypothesis that the ''hydrological cycle is supposed to be intensified under global climate change background'' (Houghton et al. 1996). Though the lower troposphere (surface–600 hPa) shows a warming trend across the globe, the upper troposphere (400–150 hPa) shows a cooling trend, resulting in a weaker Tibetan anticyclone and weaker southwest monsoon flow and a diminuendo phase in rainfall over India (Sontakke et al. 2008b).

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