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Normal dates of onset/progress and withdrawal of southwest monsoon over India

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सार – देश में दक्षिण पश्चिम मानसून की शुरुआत/प्रगति और वापसी की नई सामान्य तिथियों की गणना हाल के वर्षों के दौरान भारत के मौसम विज्ञान विभाग (India Meteorological Department) द्वारा इन घटनाओं की परिचालन रूप से घोषित तारीखों के आधार पर की गई है। 1961-2019 के आंकड़ों के आधार पर सामान्य शुरुआत/प्रगति की तारीखों की गणना की गई है और निकासी की गणना 1971-2019 के आंकड़ों के आधार पर की गई है। यह अध्ययन देश के विभिन्न हिस्सों में मॉनसून की शुरुआत/प्रगति को परिभाषित करने के लिए नए उद्देश्य वर्षा मानदंड का भी सुझाव देता है। नए उद्देश्य मानदंड देश भर में 1° × 1° (अक्षांश × देशांतर) स्थानिक ग्रिड पर आईएमडी दैनिक वर्षा के आंकड़ों पर आधारित हैं। मानसून की शुरुआत/प्रगति की आईएमडी की परिचालन घोषणा को बारीकी से समझते हुए नए मानदंड तैयार किए गए है। हालांकि, वापसी की तारीखों को परिभाषित करने के लिए कोई नया मानदंड नहीं सुझाया गया है। 1961-2019 की अवधि के लिए नए मानदंडों के आधार पर इन 1° × 1° ग्रिड में से प्रत्येक में प्राप्त मानसून की शुरुआत/प्रगति की तारीखों का उपयोग भी देश में मानसून की सामान्य शुरुआत/प्रगति तिथियों की गणना के लिए किया गया था। परिचालन सेवाओं के लिए आईएमडी द्वारा वर्तमान में भारत में मानसून की शुरुआत और वापसी की जलवायु संबंधी सामान्य तिथियां 149 स्टेशनों के वर्षा विश्लेषण से प्राप्त पुराने डेटा अवधि (1901-1940) पर आधारित हैं। इस प्रस्तावित अध्ययन में मौजूदा सामान्य को बदलने के लिए मानसून की शुरुआत/प्रगति (नई वर्षा मानदंड के आधार पर) और निकासी (परिचालन आंकड़ों के आधार पर) की नई सामान्य तिथियां दिखाई गई हैं। मॉनसून की इन नई सामान्य तिथियों की तुलना और इन घटनाओं के मौजूदा सामान्य के साथ वापसी पर, दिलचस्प अंतर देखा गया। मानसून की शुरुआत/प्रगति भारतीय मानसून क्षेत्र के अधिकांश हिस्सों में मौजूदा सामान्य की तुलना में अपेक्षाकृत अधिक विलंबित है। हालांकि, लक्षद्वीप द्वीपसमूह, पूर्वोत्तर भारत के पश्चिमी भाग और दक्षिण प्रायद्वीप के पश्चिमी भागों और उत्तर और चरम उत्तर पूर्व भारत के कुछ क्षेत्रों पर मौजूदा सामान्य की तुलना में नए सामान्य में मॉनसून की शुरुआत/प्रगति से अपेक्षाकृत तेज है। नए सामान्य के अनुसार, मानसून 1 जून के आसपास केरल में स्थापित होता है, यह मौजूदा सामान्य तिथि के लगभग समान है और मौजूदा सामान्य से एक सप्ताह पहले पूरे देश में छा जाता है। हालांकि, उत्तर-पश्चिम भारत से मॉनसून की वापसी मौजूदा सामान्य तिथि (यानी 1 सितम्बर) की तुलना में 2 सप्ताह से अधिक देरी से हुई है। मानसून दक्षिण प्रायद्वीप और पड़ोसी मध्य भारत के कुछ हिस्सों को छोड़कर देश के अधिकांश हिस्सों से मौजूदा सामान्य 15 अक्टूबर तक पीछे हट जाता है और बाद में उत्तर-पूर्व मानसून दक्षिण प्रायद्वीप में स्थापित हो जाता है।

ABSTRACT. The new normal dates of onset/progress and withdrawal of southwest monsoon over the country are computed based on the operationally declared dates of these events by India Meteorological Department (IMD) during recent years. The normal onset/progress dates were calculated based on 1961-2019 data and that of withdrawal were calculated based on 1971-2019 data. This study also suggests new objective rainfall criteria to define the monsoon onset/progress over various parts of the country. The new objective criteria are based on the IMD daily rainfall data at 1° × 1° (latitude × longitude) spatial grids over the country. The new criteria were designed so as to closely simulate IMD's operational declaration of onset/progress of monsoon. However, no new criteria are suggested for defining withdrawal dates. The dates of monsoon onset/progress derived in each of these 1° × 1° grids based on the new criteria for the period 1961-2019 were also used to compute normal onset/progress dates of monsoon over the country. The climatological normal dates of onset and withdrawal of monsoon over India currently used by IMD for operational services are based on

old data period (1901-1940) obtained from the rainfall analysis of 149 stations. This study proposes the new normal dates of monsoon onset/progress (based on the new rainfall criteria) and withdrawal (based on the operational data) to replace the existing normal. On comparing the new normal dates of monsoon onset and withdrawal with the existing normal dates of these events, interesting difference were observed. The monsoon onset/progress is relatively delayed over most parts of the Indian monsoon region in the new normal compared to the existing normal. However, monsoon onset/ progress is relatively faster in the new normal than the existing normal over Lakshadweep Islands, a few grids from western part of northeast India and western parts of south Peninsula and some areas of north and extreme northwest India. As per the new normal, the monsoon sets over Kerala around 1st June, nearly same as the existing normal date and covers the entire country one week before the existing normal. However, monsoon withdrawal from northwest India is delayed by more than 2 weeks compared to the existing normal date (*i.e.*, 1st September). Monsoon retreats from most parts of the country except south Peninsula and some parts of neighboring central India by 15th October coinciding with the existing normal and subsequently northeast monsoon gets established over south Peninsula.

Key words – Normal, Onset, Withdrawal, Criteria, Rainfall, IMD.

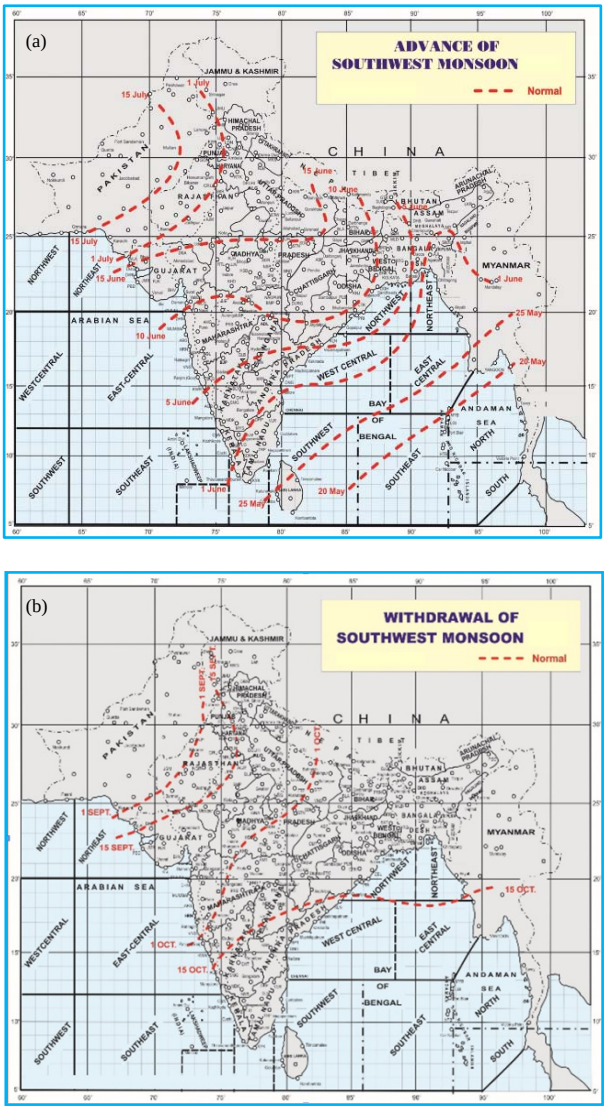
1. Introduction

For most parts of the country, 70-90% of the annual rainfall is received during the southwest monsoon season (June - September). In the Indian monsoon region, initial monsoon rains are experienced in the month of May over south Andaman Sea and the monsoon winds then advance in a north-westward direction across the Bay of Bengal. The onset and duration of this main rainy season along with the quantity of rainfall during the season are important factors in the agricultural planning, food security, and the lives of around 25 crores strong labor workforce in the agriculture and allied sectors of the country. Whereas the duration of the monsoon over many parts of south Peninsula is more than 4 months that over north-western parts of the country is only about half of that. Advance of the southwest monsoon over Indian main land is marked by monsoon onset over Kerala and is an important indicator characterizing the transition from hot and dry season to a rainy season. Associated with monsoon onset over Kerala, heavy rains lash south peninsula after the cross-equatorial low-level jet is established across the Somali coast into the near-equatorial Arabian Sea (Ramage, 1971; Rao, 1976). Similarly, withdrawal of monsoon from Indian main land is associated with the southward displacement of the surface trough, its gradual equator-ward movement and deceleration of the low-level westerly flow, establishment of dry continental air and the development of anticyclonic flow over northern and central India (Raju and Bhatla, 2013). Withdrawal of monsoon from northwest India indicates beginning of retreat of monsoon from Indian region. Delay in the retreat of monsoon from a region means a longer rainy season for that region and this has significant impact on the agriculture production of the region particularly for northwest India where the rainfall received during summer season plays a big role on the Rabi crops also.

After the advancement of southwest monsoon rains across the Bay of Bengal through May, it sets over south India in early June. Following monsoon onset, the Northern Limit of Monsoon (NLM) advances northward across the subcontinent, resulting in rainfall across India by 15th July on an average (IMD, 1943; Tyagi *et al*., 2011). Onset of the monsoon, its subsequent northward progression and withdrawal are highly variable from year to year. For example, after it sets in over Kerala (starts withdrawing from northwest India), monsoon progress (withdrawal) is rapid on some occasions and slow on other occasions. As a result, onset/progress and withdrawal of southwest monsoon over various parts of the country each year can be ahead of time, well in time or late as compared to its normal dates. There could also be prolonged stagnation in advance/retreat of monsoon. Information on the climatological dates of onset/withdrawal of southwest monsoon is therefore very important in describing the performance of the phenomenon over a region on year to year basis. In the recent global warming scenario (IPCC, 2020), it is also important to ascertain whether there have been any recent changes in the climatological patterns of onset and withdrawal of the southwest monsoon over the country.

The climatological normal dates of onset/progress and withdrawal of monsoon over India [Figs. 1(a&b)] which are being currently used by India Meteorological Department (IMD, 1943) for operational services are based on old data period (1901-1940) obtained from the rainfall analysis of 149 stations. As seen in Fig. 1(a), monsoon advances to mainland India through Kerala. The onset over Kerala is accompanied by significant transitions of large scale atmospheric and oceanic circulation patterns over the Asia-Pacific region. As per Fig. 1(a), the normal date of monsoon onset over Kerala is 1st June and then it continues to cover entire country from south to north and from east to west. It covers entire country by 15th July and starts withdrawing from the country from 1st September.

Till 2005, India Meteorological Department (IMD) used criteria based on the daily rainfall of 7 stations over Kerala suggested by Ananthakrishnan *et al*. (1967) for declaring the date of monsoon onset over Kerala operationally every year. In 2006, IMD adopted new criteria (Pai and Rajeevan, 2009) for declaring the onset of monsoon over Kerala which was based on the daily



Figs. 1(a&b). Normal dates (1901-1940) of (a) onset/progress and (b) withdrawal of southwest monsoon presently used by IMD for operational services

Rainfall of 14 stations over Kerala and neighboring area along with wind field and Outgoing Longwave Radiation (OLR) over southeast Arabian Sea. The new criteria emphasize on the sharp increase in rainfall over Kerala along with setting up of large-scale monsoon flow and extension of westerlies up to 600 hPa. In 2016, IMD adopted objective criteria nearly similar to Pai and Rajeevan (2009) for declaring monsoon onset over Andaman and Nicobar Islands, more details of which can be seen in Debnath *et al.* (2019). However, IMD declares monsoon onset/progress dates for other regions operationally in a subjective manner considering the sharp increase in rainfall and its characteristic sustenance for a few days and associated changes in the atmospheric circulation features. In the literature there are several studies (Ramdas *et al.*, 1954; Subbaramayya and Bhanu Kumar, 1978; Subbaramayya *et al.*, 1984; Deshpande *et al.*, 1986; Ananthakrishnan and Soman, 1988; Bansode *et al.*, 1991; Soman and Krishna Kumar, 1993; Mazumdar *et al.*, 2001; Fasullo and Webster, 2003; Zeng and Lu, 2004; Joseph *et al.*, 1994 and 2006; Taniguchi and Koike, 2006; Goswami and Gouda, 2007; Wang *et al.*, 2009; Cook and Buckley, 2009; Adamson and Nash, 2012; Yu *et al.*, 2015; Stolbova *et al.*, 2016; Misra *et al.*, 2017) that derived dates of monsoon onset/advance over one or a group of stations or some part of the country based on rainfall and circulation features and then examined its climatology and variability.

Like the onset criteria, the criteria for the withdrawal of monsoon have also undergone changes. The current operational criteria used by IMD for declaring the withdrawal from extreme north-western parts of the country was adopted in 2006 and consist of the following major synoptic features which will be considered only after 1st September,

(*i*) Cessation of rainfall activity over the area for continuous 5 days,

(*ii*) Establishment of anticyclone in the lower troposphere (850 hPa and below) and

(*iii*) Considerable reduction in moisture content as inferred from satellite water vapor imageries and te-phi grams.

Further withdrawal from the country is declared keeping the spatial continuity, reduction in moisture as seen in the water vapor imageries and prevalence of dry weather for 5 days. SW monsoon is withdrawn from the southern peninsula and hence from the entire country only after 1st October, when the circulation pattern indicates a change over from the south-westerly wind regime. Compared to monsoon onset/progress, there have been relatively smaller number of studies on the monsoon withdrawal (Rao, 1976; Dey *et al.*, 1985; Subbaramayya and Naidu, 1995; Syroka and Toumi, 2004).

It may be noted that most of these studies related to dates of onset and withdrawal of monsoon primarily used rainfall data to define the events because it is the one parameter that mostly affects living activities. However, there has not been any study that attempted to derive normal dates of monsoon onset and withdrawal over all parts of the country so as to replace the existing IMD normal dates based on 1901-40. The exception was Tyagi *et al.* (2011), which derived the climatology of the summer monsoon onset/progress over different parts of India using the mean pentad precipitation data of 569

stations spread all over the country for the period 1971-2000. The dates of normal onset of monsoon based on this study was 20th May for Andaman Sea, 1st June over Kerala, 5th June for northeastern parts of the country and 15th July for monsoon covering the entire country. Tyagi *et al*. (2011) also observed considerable differences in the new normal dates of onset over parts of south peninsula and western parts of central and adjoining northwest India compared to existing IMD normal dates. For last several years, IMD operational field forecasters (Annual Monsoon Reports published by IMD since 2002) have also noticed significant year to year variations in the monsoon advance over different parts of the country from the existing normal dates. Kajikawa *et al*. (2012) attributed significant warming trend found mainly in the month of May over a broad scale of the Asian Monsoon area, especially along the Tibetan Plateau for the variation in the onset dates of the Asian summer monsoon. It is well known that the elevated heating by the Tibetan Plateau plays an important role on the establishment and development of the Indian summer monsoon. The spring season heating of Tibetan Plateau is well related to the onset of the Asian summer monsoon (Wu *et al*., 2007).

In this study, the main objective was to derive the normal dates of onset/progress and withdrawal of southwest monsoon over the country using the operationally declared dates of these events by IMD in the recent years. The normal onset/progress dates were prepared based on 1961-2019 data and that of withdrawal of monsoon were calculated based on 1971-2019 data. In addition, new simple objective criteria were suggested to declare the onset/progress of monsoon over the country based on the daily rainfall. However, no such objective criteria were suggested for declaring date of withdrawal. The primary requirement for developing objective criteria to declare the onset over all parts of the country is the good quality homogeneously distributed rainfall data over the country. Due to the improved rainfall observational network in the country in the recent decades, daily rainfall data from large number of stations with an average of around 2500 stations per day are readily available for sufficiently long period for such studies. However, the station (sample point) data are often biased and distributed in homogeneously in space and time. There can be missing data, unknown errors attributed to certain observation methodologies and more importantly a change of methodology can lead to a time varying bias. Therefore, many times, point rainfall data are converted to a regular space time grid for climatological and climate variability studies. Gridded data are also preferred for the model validations, as the model outputs are generated at fixed spatial grid points. In India, homogeneous gridded rainfall data at high resolution for sufficiently long period are now readily available (Rajeevan *et al*., 2006 and 2010; Pai *et al*., 2014).In this study, IMD daily rainfall data at1° × 1°, latitude × longitude spatial grids (Rajeevan *et al*., 2010) were used to develop the new objective criteria for declaring monsoon onset/progress dates over the country. The new criteria were designed so as to closely simulate IMD's operational declaration of onset/progress of monsoon. The normal dates of monsoon onset/progress and withdrawal generated in this study using the recent data are also compared with the existing normal dates.

2. Existing normal dates of monsoon onset/progress and withdrawal

The present normal isochrones of monsoon onset/progress [Fig. 1(a)] and withdrawal [Fig. 1(b)] were derived from the pentad (5-days) rainfall normal of 149 stations for the period 1901-40. In this case, date of onset (withdrawal) of monsoon over a station was taken as the middle date of the 5 days period showing the characteristic rise (fall) in the rainfall curve. In case of onset of monsoon over a station, where the pre-monsoon thunderstorm rain merge into the monsoon rain and the transition is gradual, other factors like changes in the circulation patterns at different vertical layers were also taken into consideration. Southwest monsoon enters Indian sub-continent through Andaman and Nicobar Islands around 20th May and covers central Bay of Bengal by 25th May [Fig. 1(a)]. Subsequently, it advances in to the mainland India through Kerala. The normal date of monsoon onset over Kerala is 1st June and then it continues to cover entire country from south to north and from east to west. Once arrived in Kerala, it also covers parts of its adjacent states like Tamil Nadu and Rayalaseema and also some parts from north-eastern states like Tripura, Nagaland, Manipur and Mizoram. By 5th June, monsoon covers parts of Karnataka, Andhra Pradesh and reaches to south Maharashtra and entire north east India.

Monsoon advances up to Mumbai along with regions from West Bengal, Sikkim, Assam, Meghalaya and most parts from the Arunachal Pradesh around 10th June. It covers further north and northwest parts of the country (parts of Gujarat and Kutch, Madhya Pradesh, Bihar and east Uttar Pradesh) by 15th June. On 1st July, advancement of monsoon takes place almost over most parts of east Rajasthan, Punjab, Haryana, Delhi, Uttarakhand, west Uttar Pradesh, and Jammu and Kashmir. Climatologically, southwest monsoon covers entire country (remaining parts of northwest India) by 15th July. Southwest monsoon normally stays in the country for four months (June to September).

The monsoon starts withdrawing from extreme western parts of northwest Indian region by 1st September [Fig. 1(b)] and subsequently withdraws from most parts of

west Rajasthan and Punjab and some of the surrounding regions by 15th September. Thereafter, monsoon withdraws from most parts of the Saurashtra and Kutch, adjoining parts of Maharashtra, like, Konkan and Goa, parts of Madhya Maharashtra, west Madhya Pradesh, remaining parts of Haryana, Chandigarh and Delhi, whole of Himachal Pradesh, Jammu and Kashmir and Uttarakhand and west Uttar Pradesh at relatively faster pace. Withdrawal takes place from most parts of central, east and north east India (subdivisions like Marathwada, Vidarbha, east Madhya Pradesh, Chhattisgarh, Odisha, Jharkhand, West Bengal, east Uttar Pradesh, Bihar, Sikkim, Assam, Meghalaya and most parts from the Arunachal Pradesh as well as Nagaland, Manipur, Mizoram and Tripura (NMMT)) around 15th October. Subsequently the southwest monsoon retreats from the country and northeast monsoon get established over south Peninsula.

3. Data and methodology

In this study, the basis for preparing the normal dates of monsoon onset/progress and withdrawal is the data of these events over a 1° × 1° grid derived from the maps of monsoon onset/withdrawal isochrones prepared by IMD operationally. However, new objective criteria were developed for declaring monsoon onset based on the rainfall at the same 1° × 1° grids over the country. The new objective criteria were designed to replicate the operationally declared monsoon onset dates as close as possible. However, no new criteria are suggested for defining withdrawal dates. The normal withdrawal dates prepared in this study were purely based on IMD's operational withdrawal dates declared based on the existing IMD criteria. The normal dates of monsoon onset/progress and withdrawal over the country were prepared based on the data for the period 1961-2019 and 1971-2019 respectively. The normal dates of monsoon onset/progress derived using new objective rainfall criteria were compared with that prepared based on the operationally declared dates. Comparison of the new normal dates of monsoon onset and withdrawal prepared in this study with the existing normal dates was also made. The study also provides new normal dates of monsoon onset and withdrawal of 140important stations derived by interpolating the spatial map of new normal dates of monsoon onset and withdrawal over the country prepared in this study.

3.1. *Data used*

The main data set used in this study is the 1° × 1° gridded daily rainfall data from IMD (Rajeevan *et al*., 2010) constructed based on the fixed network of 2140 rain gauge stations that having minimum 90% data availability for the period 1951 to 2007. However, in this data set, data from several stations were unavailable for the period 2004-2007. Therefore, Pai *et al*. (2014) reconstructed the data set for this period by including point rainfall data from about 400 to 600 stations within the same fixed network but were missing in the analysis of Rajeevan *et al.* (2010). In addition, the data was extended up to 2010 using the same network of 2140 stations. Since then IMD has been updating this data set on real time basis every day and recalculating data for each year after end of that year by including all the late data available at that time. However, in this data set, the grids are only over the Indian main land and there was no data in the grids over Lakshadweep and Andaman & Nicobar Island regions of the country. Therefore, to enable to derive the normal dates of monsoon onset and withdrawal dates over Island regions also, daily gridded rainfall data over the island regions were prepared for this study following the same methodology of Rajeevan *et al*. (2010). This study used gridded rainfall data for the period 1961-2019 for developing the objective criteria for declaring the monsoon onset and to derive the normal dates of monsoon onset.

Another data used in this study is dates of the monsoon Onset over Kerala (MOK) for the period 1961-2019. MOK date for the period 1961-1970 were derived using IMD old criteria (Ananthakrishnan *et al*., 1967) and that for the period 1971-2010 were derived by existing IMD criteria (Pai and Rajeevan, 2009).

In addition, data of the operational dates of monsoon onset/progress at 1° × 1°, Latitude × Longitude grids derived from the maps of monsoon onset isochrones for the study period (1961-2019) were used. Dates of monsoon withdrawal at the same spatial resolution derived from the maps of monsoon withdrawal isochrones for the period 1971-2019 were also used. It may be mentioned that monsoon onset maps are available in the IMD records from 1961 - till the current year and withdrawal maps are available only from 1971 onwards. Out of these, the dates from 1988, till the latest were ratified by the Annual Monsoon Review meetings, by incorporating more data and analysis on a delayed mode.

3.2. *New rainfall criteria used for declaring onset, advance/progress dates of southwest monsoon*

Table 1 shows the objective criteria based on the gridded (1° × 1°, Lat. × Long. spatial grid) rainfall data used for deriving date of monsoon onset/progress over the country. In the Table 1, D1, D2 and D3 correspond to day before the operational declared date of monsoon onset over a grid, day of monsoon onset and day after the onset day respectively. For two southern most grids of the west coast, the monsoon onset date is considered as the date of

TABLE 1

Rainfall criteria mask used in this study to determine the monsoon onset over various regions of the country (Refer Fig. 2)

Region	Criteria for monsoon onset/advance
Southernmost two grids in the west coast: (Gray Shade)	For the two grids from Kerala, the monsoon onset date is taken as the date of monsoon onset over Kerala (MOK). The onset date of monsoon over the remaining grids in the main land is declared based on the rainfall criteria given below in this table but under condition that it should be same day or after the date of MOK. However, the monsoon onset over grids from Lakshadweep and Andaman Islands is declared based on the rainfall criteria only
Type - I (Blue Shade)- West coast, most parts of central India (except some western areas) Northern most parts of India, Northeast India, Lakshadweep Islands, and Andaman & Nicobar Islands	When the daily rainfalls over a grid for three consecutive days are greater than or equal to 5th percentile of rainfall of D1, D2 and D3 days respectively, the 2nd day is taken as the monsoon onset date for that grid
Type - II (Green Shade)- Northwest India, some western parts of areas of Central India, and some areas of central Peninsular India	When the daily rainfalls over a grid for two consecutive days are greater than or equal to 5th percentile of rainfall of D1 and D2 days respectively, the 2nd day is taken as the monsoon onset date for that grid
Type - III (Yellow Shade) - Southeast Peninsular India	When the daily rainfall over a grid for a day is greater than or equal to 5th percentile of rainfall of D2 day, the day is taken as the monsoon onset date for that grid

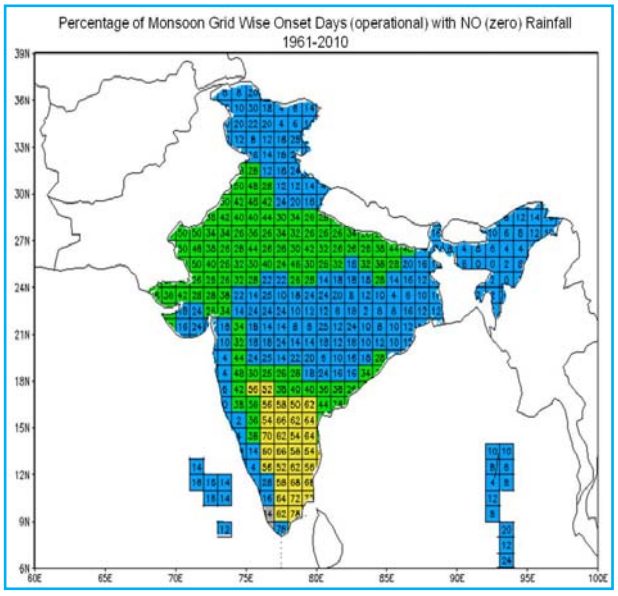


Fig. 2. Percentage of number of days when rainfall = 0(mm/day) during the onset days (D2 days) declared operationally by IMD for the period 1961-2010

monsoon onset over Kerala. The remaining grids of the country were divided into 3 categories (Fig. 2) based on the grid wise percentage of D2 days with no (zero) rainfall over the grid during the period 1961-2010. The first type (type I) of the grids are situated along the west coast, west central India and northeast India and Andaman Nicobar Islands and have the lowest zero rainfall days (<25%) on the D2 day, second type (type II) are grids from northwest, west central and central Peninsular India having the percentage of zero rainfall days between 25% and 50% and third type (type III)grids are from the rain shadow region of southeast peninsula having highest percentage of zero rainfall days (>50%). It can be seen in the Table 1 that the most stringent criteria were applied for type I grids and criteria becomes less stringent as we go from type I grids to type III grids. This is to ensure that on the day of monsoon onset (D2 day) based on the new criteria, the rainfall received is non-zero.

As seen in the Table 1, rainfall threshold values for declaring monsoon onset/advance over each of the 1° × 1° grids (total 374) in the Indian region were computed as the 5th percentile of daily rainfall (after removing zero rainfall values if any) during D1, D2 and D3 days respectively in the respective grids for the 50 years period (1961-2010).

4. Results and discussion

4.1. *Normal dates of monsoon onset/progress based on operational data*

The normal dates of grid (1° × 1°, Lat. × Long. spatial grid) wise monsoon onset/progress derived from their operationally declared dates by IMD for the period 1961-2019. [Fig. 3(a)] shows that southwest monsoon advances over Andaman and Nicobar Islands around 22nd May with a delay of about 2 days compared to existing normal date but covers central Bay of Bengal by 26th May, with a one-day delay to the existing normal date. Subsequently, it advances in to mainland India through Kerala. The Fig. 3(b) shows the difference between the normal dates of monsoon onset/progress based on

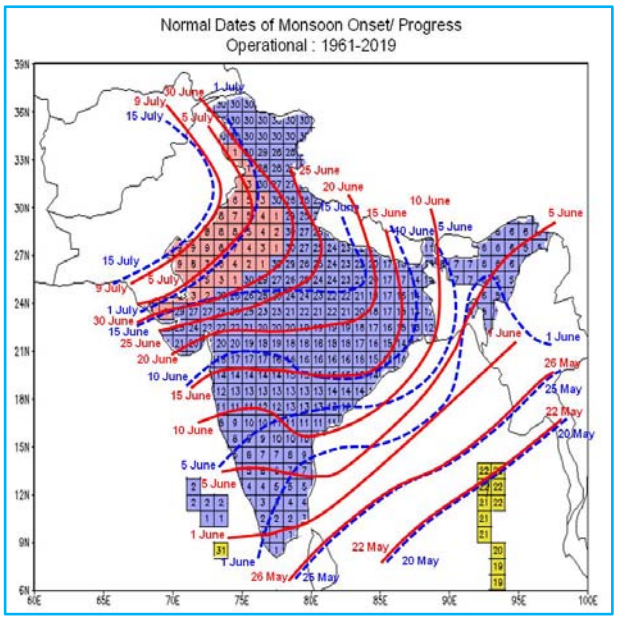


Fig. 3(a). Map showing the normal dates of monsoon onset/progress over country derived at 1° × 1° spatial grids based on the IMD declared operational dates for events during the period of 1961-2019 along with existing normal dates (base period: 1901-40). The new operational (existing) normal monsoon onset/progress dates are also shown using red solid (blue dotted) isochrones. Grids with climatological dates pertaining to May, June and July were shaded yellow, blue and brown respectively

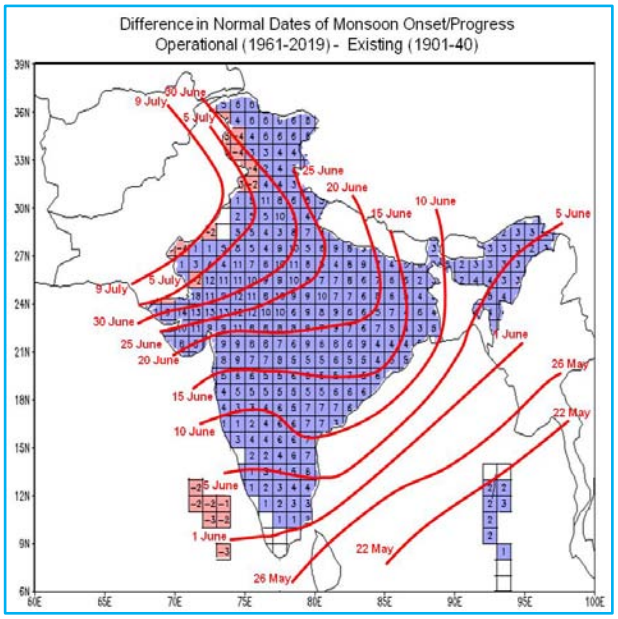


Fig. 3(b). Differences in the grid wise normal dates of monsoon onset/progress between the existing (1901-1940) and that derived based on the IMD's operationally declared dates (1961-2019) (operational-existing). The red solid isochrones represent the new operational normal monsoon onset/progress dates. Grids with negative (positive) differences are shaded brown (blue)

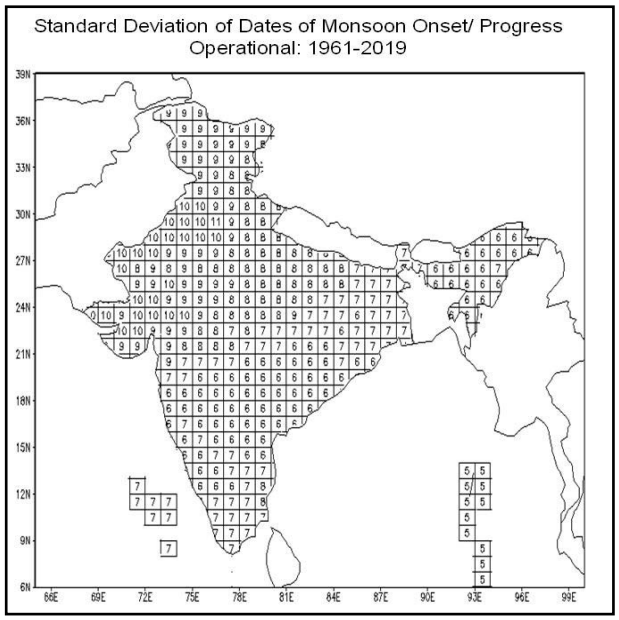


Fig. 3(c). Map showing the standard deviation of the dates of monsoon onset/progress over country derived at 1° × 1° spatial grids based on the IMD declared operational dates for events during the period of 1961-2019

operational data (1961-2019) and existing normal dates (1901-40). As seen in the Fig. 3(a), advance of monsoon over Kerala and south Tamil Nadu is also close to the existing normal date, *i.e.*, around 1st June. Monsoon covers southern parts of Karnataka state, most parts of Tamil Nadu, some parts of Northeast India by 5th June. By 10th June, monsoon enters into Goa and southern most parts of Maharashtra, covers most parts of Karnataka state and Rayalaseema, remaining areas of Tamil Nadu, some parts of Telangana, south coastal Andhra Pradesh (CAP) and Northeast India. Monsoon covers more parts of Maharashtra, most areas of Telangana, south Chhattisgarh, remaining areas of CAP, some southern and eastern areas of Odisha, most parts of West Bengal, Sikkim and some eastern areas of Bihar and Jharkhand by 15th June. Southwest monsoon advances over southern parts of Gujarat and Kutch, most parts of Maharashtra, south Madhya Pradesh state, remaining parts of Odisha and most parts of Chhattisgarh, and remaining parts of Jharkhand and Bihar by 20th June. Thereafter monsoon advances further north and westwards and by 30th June covers more parts of Gujarat, Madhya Pradesh and Uttar Pradesh, Uttarakhand, Ladakh, most parts of Jammu & Kashmir (J&K), and parts of Punjab, Haryana, Delhi and east Rajasthan. Southwest monsoon advances over remaining areas of the northwest India by 9th July. Thus, as per the new operational normal dates, monsoon covers entire country nearly one week before the existing normal date. In general, normal onset/progress of monsoon as per the operational dates in the recent years (1961-2019) is

found to be delayed compared to the existing normal in most parts of the country except over Lakshadweep area and extreme northwest India where monsoon advance earlier than existing normal. The delay is 0-4 days over Andaman & Nicobar Islands, east and northeast India, southern Peninsula and western parts of the Peninsula up to south Maharashtra. The delay is 5-8 days in the remaining parts of the Peninsula. Over central India, the duration of the delay in the monsoon onset showed increase as the monsoon progress from eastern to western parts. The delay in the normal monsoon onset in the operational data are 3-7 days over east central India, which increases to 10-14 days as the monsoon progress towards west central India & northwest India [Fig. 3(b)]. However, monsoon showed rapid progress from west central India to extreme northwest India in the operational data resulting early monsoon onset/progress over extreme northwest India by about 1-6 days compared to existing normal.

The standard deviation of the operationally derived dates of monsoon onset/progress is about 5-7 days [Fig. 3(c)] over grids from Islands, southern Peninsula, east central India, east and northeast India. For remaining grids over areas consisting of west central India and northwest India, the standard deviation of the monsoon onset/progress is about 8-10 days thus indicating relatively higher year to year variation of monsoon onset dates over these areas.

4.2. *Normal dates of monsoon onset/progress based on new rainfall criteria*

Fig. 4(a) shows the climatology of the grid wise dates of monsoon onset/advance over the country derived using new objective rainfall criteria and computed for the period 1961-2019. Fig. 4(b) shows the differences between the normal dates of monsoon onset/progress based on the new rainfall criteria (1961-2019) and existing normal dates (1901-40). Southwest monsoon arrives over Andaman and Nicobar Islands around 22nd May about 2 days delay but covers central Bay of Bengal by 26th May with only one day delay compared to existing normal date. Monsoon advanced over Kerala and south Tamil Nadu close to the existing normal date, *i.e*., around 1st June. By 5th June, it covers coastal Karnataka, most areas of south interior Karnataka (SIK) and some southern areas of north interior Karnataka (NIK), parts of Tamil Nadu, south Rayalaseema, south CAP, and Northeast India. By 10th June, monsoon enters into Goa, south Maharashtra state, most parts of NIK and Rayalaseema, south Telangana and some more areas of CAP. Within next 5 days (by 15th June) monsoon advances over more parts of Maharashtra including Mumbai, remaining areas of Telangana, south Chhattisgarh, remaining areas of CAP, most areas of Odisha, most parts of West Bengal, Sikkim and some eastern areas of Bihar and Jharkhand. Southwest monsoon advances over southern parts of Gujarat and Kutch, remaining parts of Maharashtra, south Madhya Pradesh state, remaining parts of Odisha and most parts of north Chhattisgarh, most areas of Jharkhand and Bihar by 20th June. Thereafter monsoon progresses further north and westwards and covers most parts of Gujarat and Kutch, Madhya Pradesh and Uttar Pradesh, Uttarakhand, Ladakh, most parts by Jammu & Kashmir, Punjab and Haryana, Delhi and east Rajasthan by 30th June. Monsoon advances over the remaining areas of the northwest India by 8th July and thus covers entire country nearly one week before the existing normal date. In general, there is a delay in the new monsoon onset/progress normal dates based on the objective rainfall criteria compared to the existing normal dates over most of the areas except Lakshadweep Islands, a few grids from western part of northeast India and western parts of south Peninsula, and some areas of north and extreme northwest India where monsoon advance is relatively faster in the new onset dates compared to the existing dates [Fig. 4(b)]. The delay is 0-2 days over Andaman & Nicobar Islands, 0-4 days over most grids over northeast India, southern Peninsula and western parts of the Peninsula up to south Maharashtra. The delay is 4-7 days in the remaining parts of the Peninsula. Over central India, the duration of delay showed an increase as the monsoon progress from eastern to western parts. The delay in the new normal monsoon onset based on the objective criteria is 2-5 days over east central India, which increases to 7-15 days as the monsoon progress towards Gujarat and neighboring areas [Fig. 4(b)]. However, monsoon showed rapid progress from west central India to extreme northwest India in the new normal resulting early monsoon onset/advance over extreme northwest India by about 1-9 days compared to existing normal.

The standard deviation of the dates of monsoon onset/progress based on new rainfall criteria is about 5-8 days [Fig. 4(c)] over most parts of the country except in some areas of northwest and some grids from north India where the standard deviation increases slightly to 9-10 days indicating relatively higher year to year variation of monsoon onset dates over these areas.

4.3. *Monsoon onset/progress: operational vs new rainfall criteria*

In the section 3, it was mentioned that the new objective criteria based on 1° × 1° gridded rainfall were designed so that the pattern of monsoon onset/progress over the country derived based on the new rainfall criteria each year is as close as possible to that obtained based on the IMD operational criteria. Here, attempt is made to quantify the differences in the year to year variation of

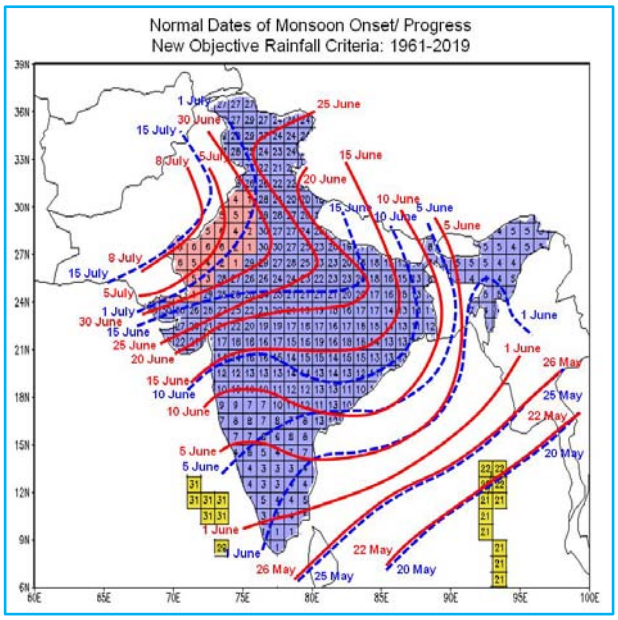


Fig. 4(a). Map showing the normal dates of monsoon onset/progress over country derived at 1° × 1° spatial grids based on the new objective gridded rainfall criteria during the period of 1961-2019 along with existing normal dates (base period:1901-40). The new (existing) normal monsoon onset/progress dates are also shown using red solid (blue dotted) isochrones. Grids with climatological dates pertaining to May, June and July were shaded yellow, blue and brown respectively

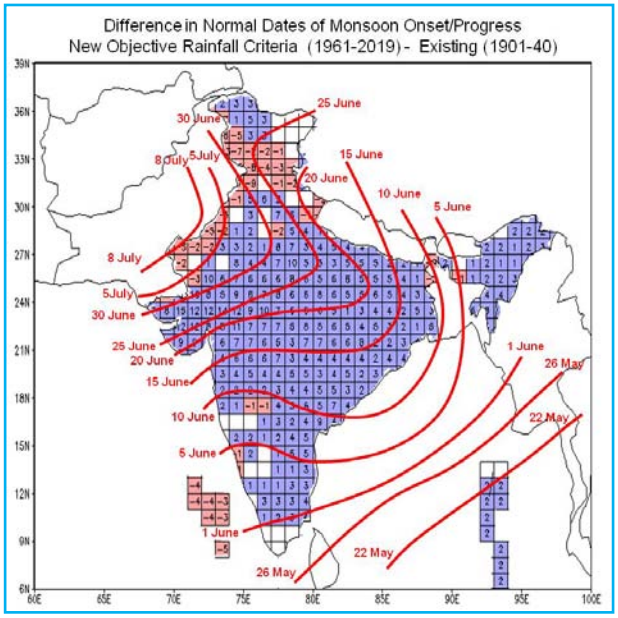


Fig. 4(b). Differences in the grid wise normal dates of monsoon onset/progress between the existing (1901-1940) and that derived based on the new objective rainfall criteria (1961-2019) (new-existing). The red solid isochrones represent the new operational normal monsoon onset/progress dates. Grids with negative (positive) differences are shaded brown (blue)

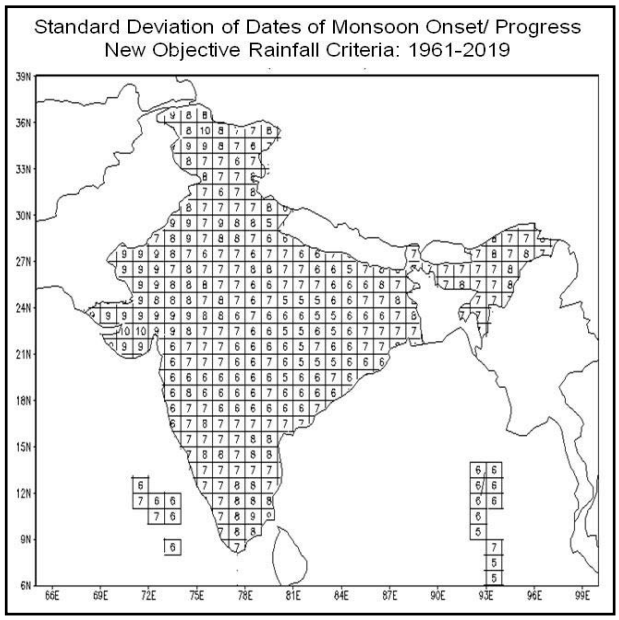


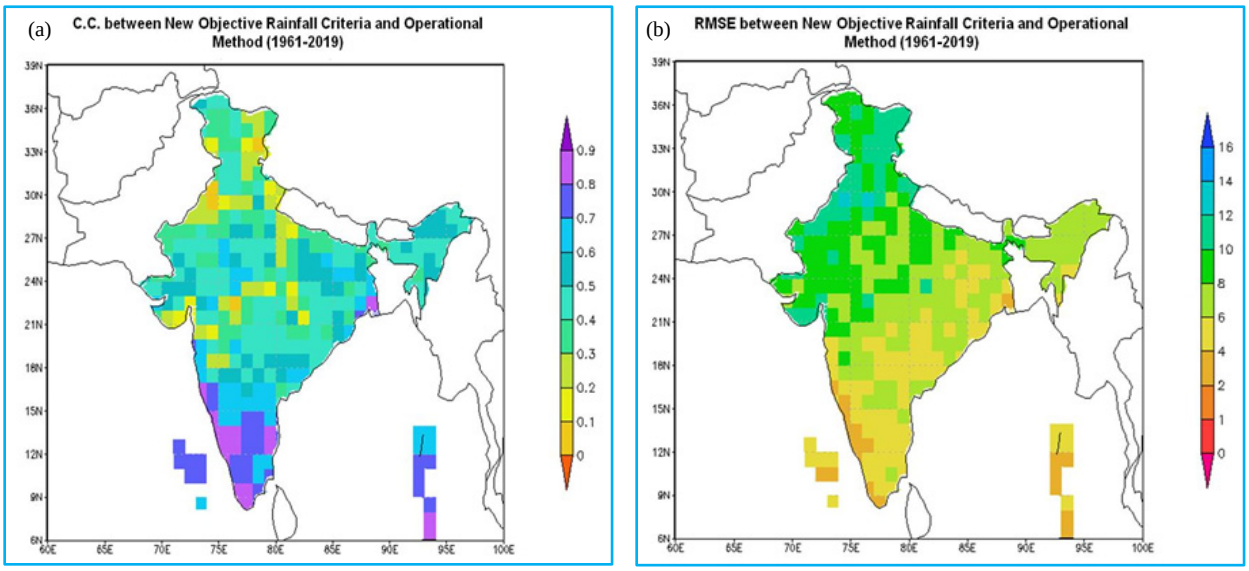
Fig. 4(c). Map showing the standard deviation of the dates of monsoon onset/progress over country derived at 1° × 1° spatial grids based on the new rainfall criteria for the period of 1961-2019

dates of monsoon progress between the new rainfall criteria and operational criteria.

Figs. 5(a&b) depict two statistical metrics, namely, grid level Correlation Coefficient (C.C.) and Root Mean Square Error (RMSE) computed between the monsoon onset/progress dates derived using the new rainfall criteria and the IMD operational criteria for the study period of 1961-2019.

The figures [Figs. 5(a&b)] exemplify the relationship between the two data series; onset dates based on new rainfall criteria and operationally declared dates. It may be noted from Fig. 5(a) that the onset dates based on new criteria and operational dates are correlated at 95% significant level (CC>0.3) in most of the grids except in some grids from northern and north western parts of the country and in few grids from central India. Correlations are relatively high (CC>0.7) in many grids from the southernmost peninsular India. The spatial distribution of RMSE [Fig. 5(b)] shows increase in the RMSE going from south to north with relatively less error (<6 days) along the west coast and some isolated grids in the peninsular and central India. However, maximum RMSE of >10 days is seen over north India and some grids from northwest India.

The year to year variation pattern correlation (grid to grid correlation each year) between onset dates derived by



Figs. 5(a&b). (a) Correlation coefficient (C.C.) and (b) RMSE between the re-determined and operational onset dates

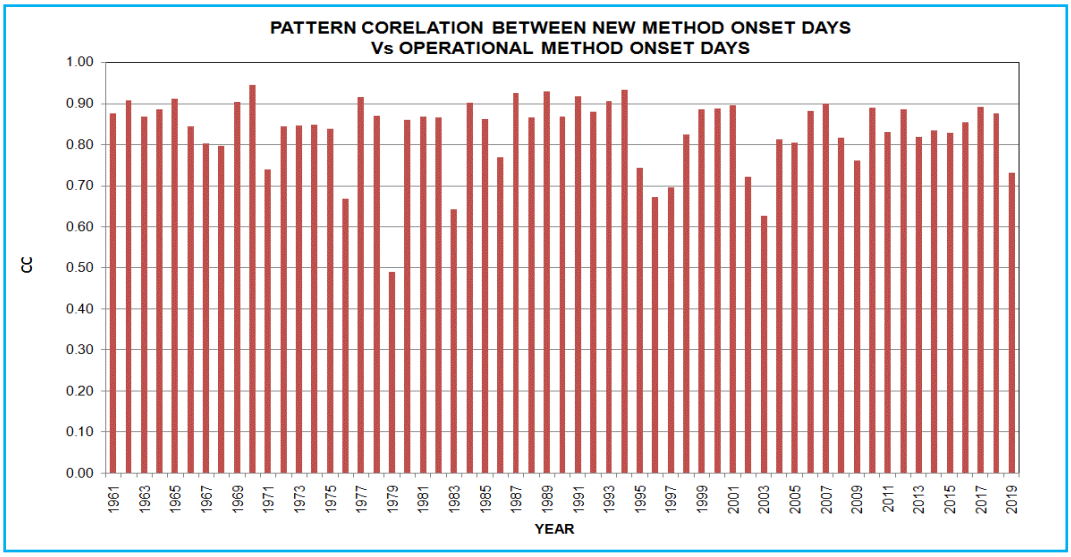


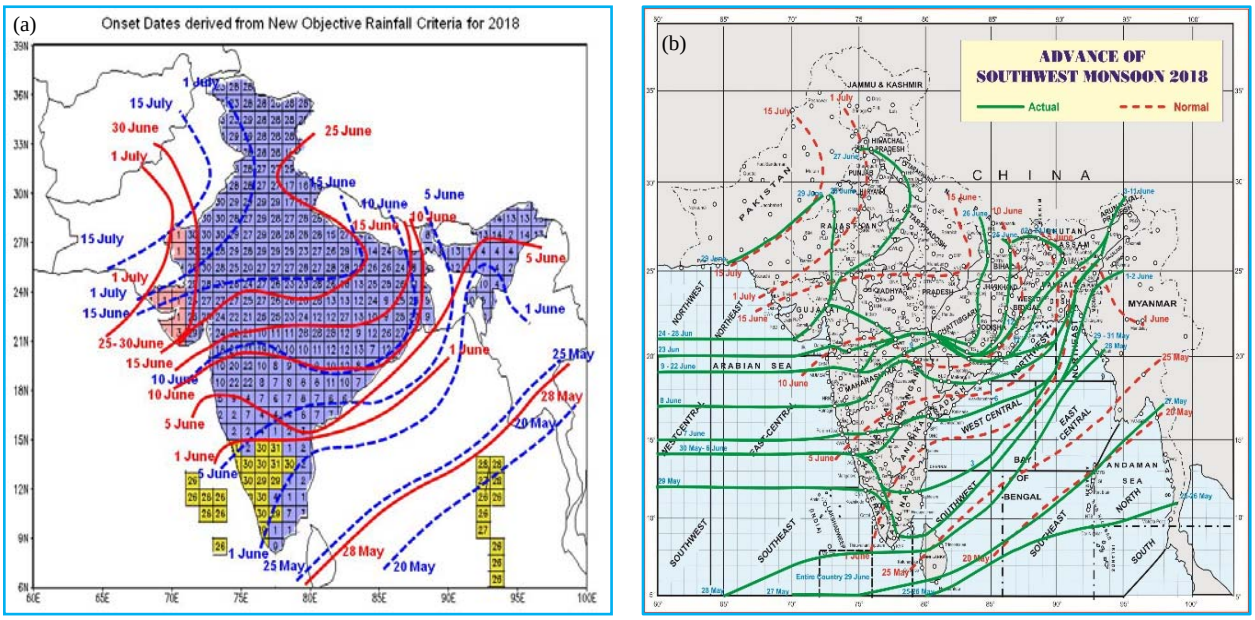
Fig. 6. Pattern correlation between re-determined onset dates and operational onset dates for the period 1961-2019

new rainfall criteria and operational criteria is shown in Fig. 6. It indicates the pattern correlation during all the years which were significant at 95% level with minimum (<0.5) during only one year (1979). During 63 of the 69 years of the study, the pattern correlation was >0.7 indicating that the methodology used for re-determining the monsoon onset and progress is nearly matching with the operationally derived dates.

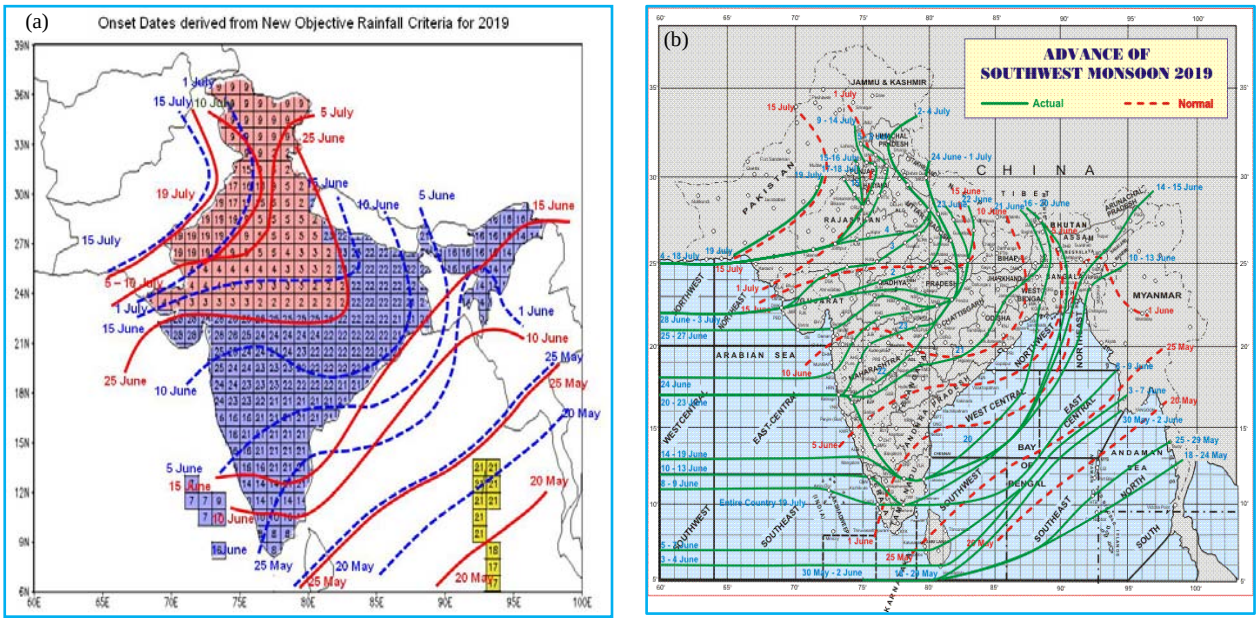
In order to highlight the utility of the new objective rainfall criteria developed in the study in deriving the monsoon onset/progress over the country during individual years, maps showing isochrones of monsoon onset/progress derived using the new objective rainfall criteria for the recent two years 2018 and 2019 are shown [Figs. (7&8)] along with the isochrones of monsoon onset prepared by IMD's present operational criteria which is subjective to some extent.

4.4. *Normal dates of monsoon withdrawal based on operational data*

Fig. 9(a) shows the normal grid wise (1° × 1° Lat. × Long. spatial grid) dates of southwest monsoon withdrawal over the country computed for the period 1971-2019 from operational declared dates of



Figs. 7(a&b). Maps showing isochrones of southwest monsoon onset/progress for 2018 derived using (a) the new objective rainfall criteria and (b) IMD's operational criteria



Figs. 8(a&b). Maps showing isochrones of southwest monsoon onset/progress for 2019 derived using (a) the new objective rainfall criteria and (b) IMD's operational criteria

withdrawal by IMD. Fig. 9(b) shows the difference between the normal dates of monsoon withdrawal based on operational data (1971-2019) and existing normal dates (1901-40). As seen in Figs. 9(a&b), monsoon start withdrawing from northwest parts of the country around 17th September with a significant delay of more than 2 weeks compared to the existing normal date of 1st September. However, thereafter monsoon withdrawal takes place much faster. Monsoon withdraws from more parts of Rajasthan and some parts of north Gujarat state, and some western areas of Punjab and Haryana by 20th September with a delay of only around 5 days compared to existing normal date of 15th September. By 1stOctober, monsoon withdraws from most areas of Gujarat, Rajasthan, Jammu and Kashmir, Ladakh, Punjab, Haryana, Delhi, Himachal Pradesh, Uttarakhand, west

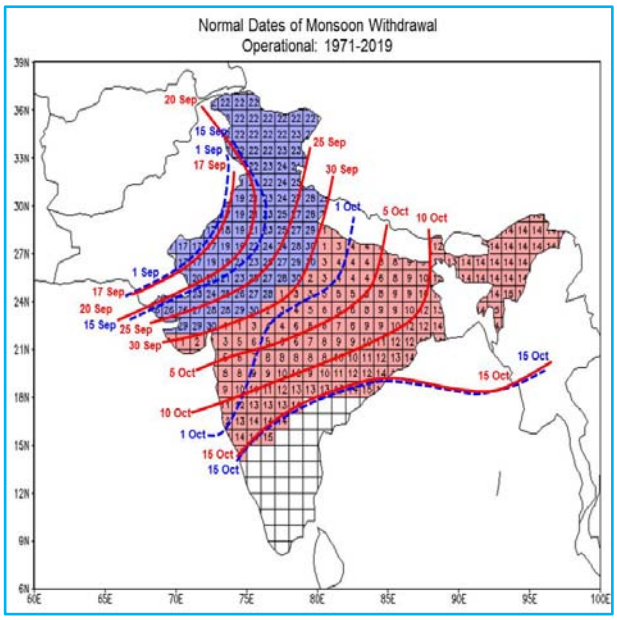


Fig. 9(a). Map showing the normal dates of monsoon withdrawal over country derived at 1° × 1° spatial grids based on the IMD declared operational dates for events during the period of 1971-2019 along with existing normal dates (base period : 1901-40). The new operational (existing) normal monsoon withdrawal dates are also shown using red solid (blue dotted) isochrones. Grids with climatological dates pertaining to September and October are shaded blue and brown respectively

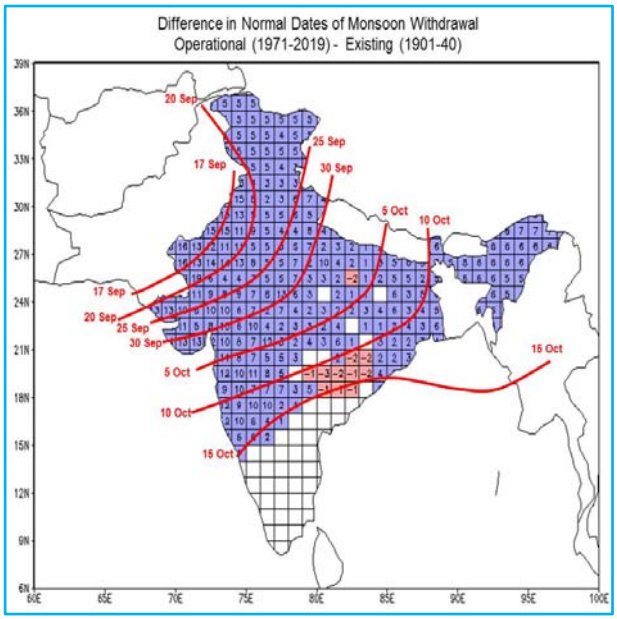


Fig. 9(b). Differences in the grid (1° × 1°) wise normal dates of monsoon withdrawal between the existing (1901-1940) and that based on the IMD's operationally declared dates (1971-2019) (operational-existing). The red solid isochrones represent the new operational normal monsoon withdrawal dates. Grids with negative (positive) differences are shaded brown (blue)

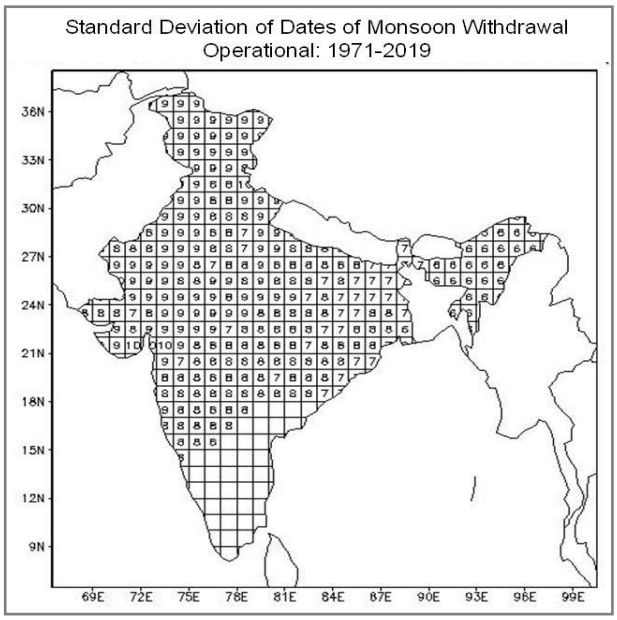


Fig. 9(c). Map showing the standard deviation of the dates of monsoon withdrawal over country derived at 1° × 1° spatial grids from IMD declared operational dates for the period of 1971-2019

Uttar Pradesh (UP) and some parts of east UP and west Madhya Pradesh (MP), with a delay of only about 2-3 days compared to existing normal dates. As on 10th October, monsoon withdrawal covers most parts of Maharashtra, east MP, north Chhattisgarh, east UP, most parts of Bihar and Jharkhand, and some parts of Odisha and Gangetic West Bengal. By 15th October, monsoon withdrawal line nearly coincides with that of existing date and withdrawal covers most parts of the country including Maharashtra, Goa, north Karnataka, some parts of coastal Karnataka, most parts of Telangana, Chhattisgarh, Odisha and entire northeast India. Subsequently southwest monsoon retreats from the remaining areas and northeast monsoon gets established over south Peninsula. Thus, it is clear that though normal date of start of withdrawal of southwest monsoon from north-western most parts of the country as per the operational data during 1971-2019 is delayed by more than 2 weeks compared to existing normal date, its further withdrawal from the country was found to be much faster with monsoon withdrawing from most parts of the country by 15th October, consistent with the existing normal date.

The new normal withdrawal dates of monsoon as per the operational data of recent years is delayed compared to the existing normal in most parts of the country except few grids over northeast part of the Peninsula where the monsoon withdrawal in the new normal [Fig. 9(b)] is early by 1-3 days (brown grids). Significant delay was observed

TABLE 2

Normal monsoon onset (1961-2019) dates based on new rainfall criteria suggested in this study and withdrawal (1971-2019) dates based on the operational data over 140 major cities of the country

Station List	New (1961-2019)	Existing (1901-1940)	New (1971-2019)	Existing (1901-1940)
South Peninsula				
Port Blair, Andaman Nicobar	21-May	19-May	*	*
Thiruvananthapuram, Kerala	01-Jun	01-Jun	*	*
Kochi, Kerala	01-Jun	01-Jun	*	*
Thrissur, Kerala	03-Jun	02-Jun	*	*
Kozhikode, Kerala	03-Jun	03-Jun	*	*
Nagercoil, Tamil Nadu	01-Jun	01-Jun	*	*
Tuticorin, Tamil Nadu	02-Jun	01-Jun	*	*
Coimbatore, Tamil Nadu	05-Jun	02-Jun	*	*
Chennai, Tamil Nadu	07-Jun	29-May	*	*
Mysuru, Karnataka	03-Jun	02-Jun	*	*
Bengaluru, Karnataka	03-Jun	02-Jun	*	*
Mangaluru, Karnataka	03-Jun	03-Jun	*	*
Medikeri, Karnataka	04-Jun	03-Jun	*	*
Shivamogga, Karnataka	04-Jun	04-Jun	*	*
Karwar, Karnataka	04-Jun	05-Jun	*	*
Gangawati, Karnataka	06-Jun	05-Jun	15-Oct	13-Oct
Belagavi, Karnataka	07-Jun	05-Jun	14-Oct	08-Oct
Gulbarga, Karnataka	07-Jun	08-Jun	13-Oct	03-Oct
Gokak, Karnataka	08-Jun	08-Jun	13-Oct	03-Oct
Bijapur, Karnataka	08-Jun	08-Jun	14-Oct	08-Oct
Anantapur, Andhra Pradesh	04-Jun	03-Jun	*	*
Ongole, Andhra Pradesh	11-Jun	03-Jun	*	*
Vishakhapatnam, Andhra Pradesh	11-Jun	08-Jun	*	10-Oct
Kalingapatnam, Andhra Pradesh	11-Jun	08-Jun	15-Oct	13-Oct
Sompeta, Andhra Pradesh	11-Jun	08-Jun	10-Oct	13-Oct
Hyderabad, Telangana	11-Jun	08-Jun	13-Oct	13-Oct
Suryapet, Telangana	12-Jun	06-Jun	*	15-Oct
Hanamkonda, Telangana	12-Jun	08-Jun	13-Oct	08-Oct
Sirkonda, Telangana	12-Jun	08-Jun	13-Oct	10-Oct
Sirpur, Telangana	14-Jun	09-Jun	09-Oct	10-Oct
East and Northeast India				
Aizwal, Mizoram	04-Jun	01-Jun	15-Oct	09-Oct
Kohima, Nagaland	04-Jun	02-Jun	14-Oct	09-Oct
Dimapur, Nagaland	04-Jun	02-Jun	14-Oct	09-Oct
Shillong, Meghalaya	04-Jun	03-Jun	14-Oct	08-Oct
Imphal, Manipur	05-Jun	01-Jun	15-Oct	10-Oct
Itanagar, Arunachal Pradesh	05-Jun	03-Jun	14-Oct	08-Oct
Agartala, Tripura	07-Jun	31-May	14-Oct	08-Oct
Gangtok, Sikkim	08-Jun	08-Jun	12-Oct	06-Oct
Sivasagar, Assam	04-Jun	03-Jun	14-Oct	08-Oct
Dibrugarh, Assam	04-Jun	03-Jun	14-Oct	08-Oct
Guwahati, Assam	05-Jun	03-Jun	14-Oct	08-Oct
Tezpur, Assam	05-Jun	03-Jun	14-Oct	08-Oct
Jalpaiguri, West Bengal	07-Jun	09-Jun	12-Oct	06-Oct
Kalimpong, West Bengal	08-Jun	08-Jun	12-Oct	06-Oct
Kolkata, West Bengal	12-Jun	07-Jun	14-Oct	08-Oct

TABLE 2 (*Contd*.)

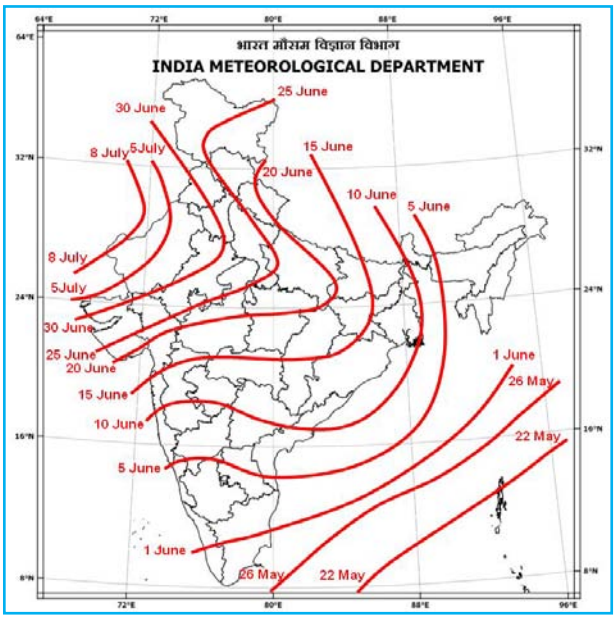
Station List	New (1961-2019)	Existing (1901-1940)	New (1971-2019)	Existing (1901-1940)
Bankura, West Bengal	13-Jun	08-Jun	12-Oct	08-Oct
Purnea, Bihar	13-Jun	12-Jun	10-Oct	08-Oct
Patna, Bihar	16-Jun	11-Jun	08-Oct	03-Oct
Gaya, Bihar	16-Jun	11-Jun	09-Oct	03-Oct
Chhapra, Bihar	18-Jun	13-Jun	06-Oct	04-Oct
Jamshedpur, Jharkhand	13-Jun	11-Jun	12-Oct	08-Oct
Bokaro Steel City, Jharkhand	13-Jun	11-Jun	10-Oct	07-Oct
Gopikandar, Jharkhand	13-Jun	10-Jun	10-Oct	05-Oct
Chakradharpur, Jharkhand	14-Jun	11-Jun	10-Oct	08-Oct
Ranchi, Jharkhand	14-Jun	10-Jun	09-Oct	03-Oct
Daltonganj, Jharkhand	17-Jun	11-Jun	08-Oct	08-Oct
Central India				
Panjim, Goa	05-Jun	05-Jun	14-Oct	30-Sep
Kolhapur, Maharashtra	08-Jun	08-Jun	13-Oct	03-Oct
Satara, Maharashtra	09-Jun	08-Jun	12-Oct	03-Oct
Baramati, Maharashtra	10-Jun	08-Jun	10-Oct	30-Sep
Pune, Maharashtra	10-Jun	08-Jun	09-Oct	30-Sep
Udgir, Maharashtra	11-Jun	08-Jun	12-Oct	05-Oct
Mumbai, Maharashtra	11-Jun	10-Jun	08-Oct	29-Sep
Ahmednagar, Maharashtra	12-Jun	08-Jun	08-Oct	28-Sep
Aurangabad, Maharashtra	13-Jun	08-Jun	09-Oct	28-Sep
Parbhani, Maharashtra	13-Jun	09-Jun	09-Oct	01-Oct
Malegaon, Maharashtra	14-Jun	08-Jun	06-Oct	28-Sep
Amravati, Maharashtra	15-Jun	08-Jun	08-Oct	03-Oct
Akola, Maharashtra	15-Jun	08-Jun	08-Oct	03-Oct
Nagpur, Maharashtra	16-Jun	09-Jun	07-Oct	03-Oct
Jalgaon, Maharashtra	18-Jun	11-Jun	06-Oct	29-Sep
Gopalpur, Odisha	11-Jun	08-Jun	14-Oct	10-Oct
Cuttack, Odisha	13-Jun	09-Jun	13-Oct	11-Oct
Bhubaneshwar, Odisha	13-Jun	10-Jun	13-Oct	11-Oct
Puri, Odisha	14-Jun	08-Jun	14-Oct	12-Oct
Sambalpur, Odisha	16-Jun	08-Jun	10-Oct	10-Oct
Jagdalpur, Chhattisgarh	13-Jun	08-Jun	12-Oct	13-Oct
Kondagaon, Chhattisgarh	14-Jun	10-Jun	11-Oct	13-Oct
Ambagarh Chowki, Chhattisgarh	15-Jun	11-Jun	08-Oct	08-Oct
Pendra Road, Chhattisgarh	16-Jun	10-Jun	07-Oct	03-Oct
Raipur, Chhattisgarh	16-Jun	10-Jun	09-Oct	03-Oct
Bilaspur, Chhattisgarh	17-Jun	12-Jun	08-Oct	08-Oct
Balrampur, Chhattisgarh	17-Jun	14-Jun	08-Oct	05-Oct
Khandwa, Madhya Pradesh	16-Jun	10-Jun	05-Oct	23-Sep
Seoni, Madhya Pradesh	18-Jun	10-Jun	06-Oct	03-Oct
Jabalpur, Madhya Pradesh	19-Jun	13-Jun	05-Oct	03-Oct
Bhopal, Madhya Pradesh	20-Jun	13-Jun	03-Oct	26-Sep
Indore, Madhya Pradesh	20-Jun	13-Jun	03-Oct	23-Sep
Satna, Madhya Pradesh	21-Jun	13-Jun	05-Oct	05-Oct
Chhatarpur, Madhya Pradesh	21-Jun	15-Jun	03-Oct	30-Sep
Sagar, Madhya Pradesh	21-Jun	15-Jun	04-Oct	30-Sep
Guna, Madhya Pradesh	23-Jun	15-Jun	01-Oct	18-Sep
Nimach, Madhya Pradesh	25-Jun	16-Jun	26-Sep	17-Sep

TABLE 2 (*Contd.*)

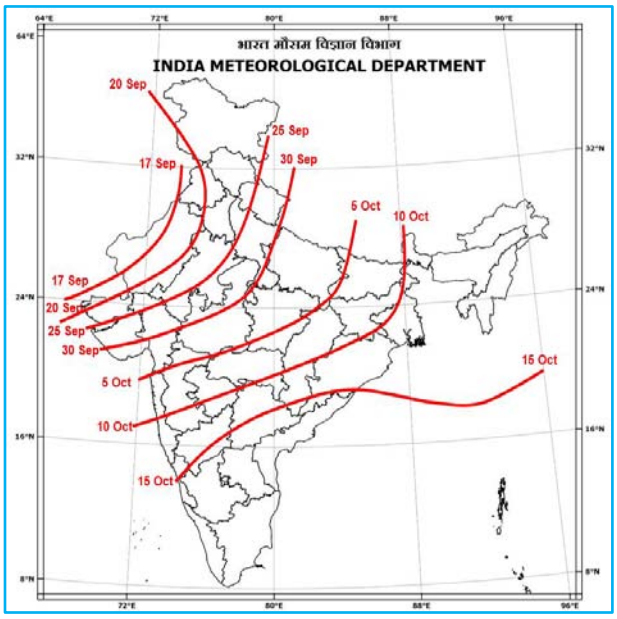
Station List	New (1961-2019)	Existing (1901-1940)	New (1971-2019)	Existing (1901-1940)
Gwalior, Madhya Pradesh	28-Jun	18-Jun	29-Sep	22-Sep
Veraval, Gujarat	18-Jun	11-Jun	05-Oct	18-Sep
Bhavnagar, Gujarat	19-Jun	14-Jun	02-Oct	20-Sep
Vadodara, Gujarat	21-Jun	13-Jun	01-Oct	18-Sep
Ahmedabad, Gujarat	26-Jun	14-Jun	28-Sep	18-Sep
Rajkot, Gujarat	27-Jun	15-Jun	29-Sep	18-Sep
Bhuj, Gujarat	30-Jun	22-Jun	26-Sep	13-Sep
Northwest India				
Gorakhpur, Uttar Pradesh	18-Jun	13-Jun	04-Oct	03-Oct
Varanasi, Uttar Pradesh	23-Jun	15-Jun	04-Oct	06-Oct
Lucknow, Uttar Pradesh	23-Jun	18-Jun	03-Oct	23-Sep
Allahabad, Uttar Pradesh	23-Jun	17-Jun	04-Oct	02-Oct
Kanpur, Uttar Pradesh	23-Jun	20-Jun	03-Oct	23-Sep
Jhansi, Uttar Pradesh	24-Jun	16-Jun	30-Sep	23-Sep
Bareilly, Uttar Pradesh	24-Jun	20-Jun	29-Sep	23-Sep
Mainpuri, Uttar Pradesh	25-Jun	22-Jun	30-Sep	23-Sep
Agra, Uttar Pradesh	27-Jun	20-Jun	28-Sep	23-Sep
Bijnor, Uttar Pradesh	27-Jun	22-Jun	27-Sep	21-Sep
Delhi, Delhi	27-Jun	29-Jun	25-Sep	21-Sep
Dehradun, Uttarakhand	20-Jun	20-Jun	27-Sep	21-Sep
Nainital, Uttarakhand	20-Jun	21-Jun	28-Sep	23-Sep
Mussoorie, Uttarakhand	20-Jun	26-Jun	27-Sep	21-Sep
Shimla, Himachal Pradesh	22-Jun	23-Jun	24-Sep	21-Sep
Palampur, Himachal Pradesh	22-Jun	26-Jun	23-Sep	18-Sep
Jalandhar, Punjab	26-Jun	05-Jul	21-Sep	17-Sep
Amritsar, Punjab	28-Jun	04-Jul	21-Sep	08-Sep
Bhatinda, Punjab	04-Jul	05-Jul	19-Sep	04-Sep
Chandigarh, Chandigarh	28-Jun	30-Jun	23-Sep	21-Sep
Sonepat, Haryana	27-Jun	29-Jun	25-Sep	21-Sep
Ambala, Haryana	28-Jun	22-Jun	23-Sep	21-Sep
Bhiwani, Haryana	30-Jun	30-Jun	23-Sep	18-Sep
Hissar, Haryana	03-Jul	30-Jun	21-Sep	16-Sep
Leh, Ladakh	24-Jun	24-Jun	22-Sep	18-Sep
Kargil, Ladakh	27-Jun	24-Jun	22-Sep	17-Sep
Anantnag, Jammu & Kashmir	25-Jun	27-Jun	22-Sep	17-Sep
Jammu, Jammu & Kashmir	28-Jun	29-Jun	21-Sep	17-Sep
Srinagar, Jammu & Kashmir	29-Jun	29-Jun	22-Sep	17-Sep
Ganderbal, Jammu & Kashmir	29-Jun	04-Jul	22-Sep	17-Sep
Jhalawar, Rajasthan	24-Jun	17-Jun	28-Sep	20-Sep
Udaipur, Rajasthan	25-Jun	20-Jun	25-Sep	17-Sep
Kota, Rajasthan	26-Jun	20-Jun	25-Sep	18-Sep
Jaipur, Rajasthan	29-Jun	25-Jun	23-Sep	15-Sep
Ajmer, Rajasthan	01-Jul	23-Jun	21-Sep	08-Sep
Jodhpur, Rajasthan	02-Jul	02-Jul	19-Sep	05-Sep
Churu, Rajasthan	04-Jul	03-Jul	19-Sep	08-Sep
Barmer, Rajasthan	05-Jul	08-Jul	20-Sep	01-Sep
Bikaner, Rajasthan	06-Jul	08-Jul	18-Sep	03-Sep
Pokhran, Rajasthan	06-Jul	08-Jul	17-Sep	05-Sep

*SW Monsoon retreats from the area and Northeast monsoon gets established

(a) New dates of normal monsoon onset/progress



(b) New dates of normal monsoon withdrawal



Figs. 10(a&b). (a) Map showing the isochrones of normal monsoon onset/progress dates over the country based on the new objective rainfall criteria for the base period of 1961-2019 and (b) Map showing the isochrones normal monsoon withdrawal dates over the country based on the IMD's declared operational dates for the base period of 1971-2019

in the new normal monsoon withdrawal over extreme northwest India (11-16 days), west central India (4-10 days), northwest Peninsula (7-12 days), north India (3-7 days) and northeast (5-8 days). Over other areas, the delay in the new normal is 1-3 days indicating close match with the existing normal.

The standard deviation of the dates of monsoon withdrawal based on IMD operational criteria is about 7-9 days [Fig. 9(c)] over most parts of the country except in some parts of Gujarat where it is 10 days and over northeast India where it is 6 days.

4.5. *Normal dates of onset/progress and withdrawal of southwest monsoon over major cities of the country*

In the earlier sections, we have discussed the normal monsoon onset dates (1961-2019) derived based on the new objective rainfall criteria and that based on the IMD's present subjective operational criteria. Similarly, normal monsoon withdrawal dates (1971-2019) derived based on IMD's present operational criteria was also discussed. In this section, normal dates of monsoon onset/progress (based on objective rainfall criteria) and withdrawal (based on operational data) over 140 major cities of the country derived by interpolating the grid point normal are shown in Table 2 along with that based on the existing climatology based on 1901-40 period.

5. Summary and conclusions

In this study, normal dates of monsoon onset/progress and withdrawal were prepared at 1° × 1° (latitude × longitude) spatial grids over the country based on the dates of these events declared operationally by IMD in the recent years. This study also suggested new objective rainfall criteria to declare monsoon onset at the same spatial resolution. However, no objective criteria could be derived for the withdrawal monsoon as the event is much more complex and variable than the monsoon onset. The monsoon onset/progress dates over the country derived each year based on these objective criteria nearly matched with that derived operationally during most of the study period of 1961-2019. The same was the case of normal dates derived based on these two methods. Differences if any were observed in some parts of north and northwest India where monsoon rains are generally experienced associated with the interaction of monsoon winds with the mid latitude westerly disturbances. Therefore, the new rainfall criteria developed in this study can be used to declare the monsoon onset dates objectively for IMD operational purpose.

This study also suggests to replace the existing IMD normal dates of monsoon onset and withdrawal dates based on very old period (1901-40) by the new normal dates of monsoon onset/progress derived based on the new rainfall criteria for the period 1961-2019 and that of withdrawal derived based on the operational data for the

period 1971-2019 for operational services [Figs. 10(a&b)]. The salient features of these new normal onset/progress and withdrawal dates of the southwest monsoon over the country are given below;

(*i*) The southwest monsoon advance over Andaman and Nicobar Islands around 22nd May with a delay of about 2 days compared to existing normal date. But it arrives over central Bay of Bengal by 26th May close to existing normal date (with a one-day delay).

(*ii*) In general, there is a delay in the new monsoon onset/progress normal dates compared to the existing normal dates over most parts of the Indian monsoon region except Lakshadweep islands, a few grids from western part of northeast India and western parts of south Peninsula, and some areas of north and extreme northwest India where monsoon advance is relatively faster in the new onset dates than the existing normal dates.

(*iii*) The Monsoon sets for Kerala around 1st June, nearly same as the existing normal date.

(*iv*) Monsoon advances over most parts of Northeast India by around 5th June with a delay of about 1-4 days compared to the existing normal.

(*v*) Monsoon covers most parts of the country except extreme northwest India by end of June close to the existing normal date. But covers the entire country by 8th July exactly one week before the existing normal date of 15th July.

(*vi*) Monsoon onset/progress over most parts of central India between 2nd week of June and early July in the new normal dates is delayed by 1-8 days compared to existing normal dates.

(*vii*) As per the new normal, monsoon start its withdrawal from northwest India around 17th September, which is a delay of more than 2 weeks compared to the existing normal date (*i.e.*, 1st September).

(*viii*) Further monsoon withdrawal is much faster. By 20th September, it withdraws from more parts of Rajasthan and some parts of north Gujarat state, and some western areas of Punjab and Haryana with a delay of only around 5 days compared to existing normal date of 15th September.

(*ix*) Monsoon withdraws from most areas of Gujarat, Rajasthan, Jammu &Kashmir, Gilgit, Baltistan, Muzzafarabad, Ladakh, Punjab, Haryana, Chandigarh, Delhi, Himachal Pradesh, Uttarakhand, west Uttar Pradesh (UP) and some parts of east UP and west Madhya Pradesh (MP) by 1st October with a delay of only about 2-3 days compared to existing normal dates.

(*x*) Monsoon withdraws from most parts of the country except south Peninsula and some parts of neighboring central India by 15th October coinciding with the existing normal dates of withdrawal.

(*xi*) After 15th October, southwest monsoon retreats from the country and northeast monsoon gets established over south Peninsula.

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