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A re-assessment study on the onset and withdrawal dates of Indian northeast monsoon for the decade 2011-20

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सार – वर्ष 2011-20 के दशक के प्रत्येक वर्ष के लिए तटीय तमिलनाडु और दक्षिण तटीय आंध्र प्रदेश में भारतीय पूर्वोत्तर मॉनसून के आरंभऔर वापसी की तारीखों को अक्टूबर-जनवरी की अवधि के लिए 16 स्टेशनों के दैनिक वर्षा डेटा पर पूर्वनिर्धारित वस्तुनिष्ठ मानदंडों के एक सेट को लागू करके फिर से निर्धारित किया गया है। 2011-20 के लिए प्राप्त औसत आरंभ और वापसी की तारीखें क्रमशः 23 अक्टूबर और 31 दिसंबर हैं, जबकि इसी अवधि के लिए उत्तरी और दक्षिणी तटों के लिए प्राप्त औसत वापसी की तारीखें क्रमशः 23 दिसंबर और 5 जनवरी हैं। 16 स्टेशनों की दैनिक वर्षा पर किए गए अध्यारोपित युग विश्लेषण में पूर्वोत्तर मॉनसून केआरंभ के समय वर्षा में तेज वृद्धि और वापसी के बाद कमी देखी गई है। आरंभ के समय दैनिक वर्षा 1-4 मिमी से बढ़कर 10-33 मिमी हो गई है और वापसी के बाद 4-16 मिमी से घटकर 0-2 मिमी हो गई है।

दक्षिण तटीय आंध्र प्रदेश तथा उत्तर, मध्य और दक्षिण तटीय तमिलनाडु जैसे 4 उप-क्षेत्रों में अक्टूबर-जनवरी, 2011-12 से 2020-21 की पेंटाड वर्षा पर किए गए अनुभवजन्य दोलन फ़ंक्शन विश्लेषण से पता चला है कि पहला प्रमुख घटक जो पूर्वोत्तर मॉनसून की समग्र सक्रियता से जुड़ा हो सकता है, उसने 78.3% भिन्नता को दर्शायाहै जो सभी क्षेत्रों के लिए सकारात्मक है वह उत्तर और मध्य तटीय तमिलनाडु के लिए अधिक है।संभाव्यता पर आधारित भारी वर्षा सूचकांक को परिभाषित किया गया है और सितंबर-फरवरी की अवधि के लिए गणना किए गए मानों का उपयोग कई उप-अवधिओं में भारी वर्षा की घटनाओं की तुलना करने के लिए किया गया है। 10 साल की अध्ययन अवधि के दौरान अक्टूबर-दिसंबर के दौरान 16 स्टेशनों पर भारी वर्षा की 429 घटनाएं हुईं।यह दिखाया गया है कि 16 स्टेशनों पर 10 वर्षों के दौरान आरंभचरण के पश्चात भारी वर्षा की घटनाओं की आवृत्ति 91 है, जो कि आरंभ चरण के पूर्व की तुलना में 19 गुना अधिक है और पूर्वोत्तर मॉनसून की वापसी के बाद भारी वर्षा दुर्लभ है।

ABSTRACT. The onset and withdrawal dates of Indian northeast monsoon over Coastal Tamil Nadu and South Coastal Andhra Pradesh for every year of the decade 2011-20 have been re-determined, by invoking a set of pre-defined objective criteriaon the daily rainfall data of 16 stations for the period October-January. The mean onset and withdrawal dates for 2011-20 derived are 23 October and 31 December respectively, while for the same period the mean withdrawal dates for the northern and southern coasts obtained are 23 December and 5 January respectively. The superposed epoch analysis performed on the daily rainfall of the 16 stations has shown sharp increase of rainfall at the time of northeast monsoon onset and decrease after withdrawal. The daily rainfall has increased from 1-4 mm to 10-33 mm at the time of onset and has decreased from 4-16 mm to 0-2 mm after withdrawal.

The empirical orthogonal function analysis conducted on the pentad rainfall of October-January, 2011-12 to 2020-21 of 4 sub-regions, *viz.*, South Coastal Andhra Pradesh, North, Central and South Coastal Tamil Nadu revealed that the first principal component which could be associated with the overall strength of northeast monsoon has explained 78.3% of the variation and that the loadings which are positive for all the regions are higher for North and Central Coastal Tamil Nadu. A heavy rainfall index based on probability has been defined and the values computed for the period September-February have been utilised to compare the occurrence of heavy rainfall incidences over several sub-periods. There are 429 heavy rainfall events over 16 stations during October-December of the 10 year study period. It has been shown that the frequency of heavy rainfall occurrences in the post-onset phase is 91 for the 16 stations for 10 years,

which is 19 times more compared to the pre-onset phase and that, occurrence of heavy rainfall is rare after the withdrawal of northeast monsoon.

Keywords –Northeast monsoon, Onset, Withdrawal, Tamil Nadu, Andhra Pradesh.

1. Introduction

The Indian northeast monsoon is a small-scale monsoon benefitting the southeastern peninsular region of India comprising the meteorological sub-divisions of Tamil Nadu, Rayalaseema, Coastal Andhra Pradesh, Kerala and South Interior Karnataka. The northeast monsoon prevails during the period October-December, sometimes spilling over to January of the next calendar year. It sets in over the southern peninsula after the cessation and withdrawal of southwest monsoon from India around mid-October. The forecasting manual on Indian northeast monsoon by Srinivasan and Ramamurthy (1973) published by India Meteorological Department (IMD) was a classic treatise which detailed various diverse aspects of this monsoon. Raj (2012) summarised several new characteristics of northeast monsoon based on results of research work carried out subsequent to the publication of the 1973 manual. In the recent past, more studies have been published which have thrown further light on some of the characteristics of Indian northeast monsoon. The digital remote sensed data generated by modern observing systems such as weather satellites and radars have been extensively used in several such studies. Onkari *et al.* (2022) have linked northeast monsoon activity including that of onset and withdrawal to the convergence zone in the South Indian Ocean. A detailed monograph on Indian and Asian northeast monsoon incorporating the findings of several contemporary studies has been recently authored by Rajeevan *et al*. (2022).

The onset and withdrawal dates are important features of northeast monsoon. In this paper, re-determination of the dates of onset and withdrawal for every year of the decadal period 2011-20 is addressed. In Raj (1992 and 1998), the dates of onset and withdrawal of northeast monsoon over Coastal Tamil Nadu were determined for the 90 year period 1901-90 based on daily rainfall (defined as the 24 hrs cumulative rainfall of a station ending at 0830 hrs IST, 0300 hrs UTC of that date) data of 4-6 stations. The dates of onset and withdrawal of northeast monsoon were determined in Raj (2003) for the period 1991-2000, thereby generating such a data set for the entire 20th century. The long period average (LPA) obtained for the date of onsetis 20 October and the pentad of withdrawal is 26-30 December for the period 1901-2000.

The re-determination of dates of onset and withdrawal of northeast monsoon was carried out by Geetha and Raj (2015), based on daily rainfall data of 25 rain gauges located over Coastal Tamil Nadu and South Coastal Andhra Pradesh for the period 1871-2010, thereby extending the study period backwards into the 19th century and including the first decade of the 21st century. This resulted in the generation of a more robust and homogeneous historical data set of dates of onset and withdrawal of northeast monsoon for the 140-year period. The LPA of date of onset as 20 October and date of withdrawal lying within the pentad 26-30 December obtained in the earlier studies persisted in this study also. Based on the 50 year data of 1961-2010, it was further shown that the LPA of northeast monsoon withdrawal date is 17 December over South Coastal Andhra Pradeshand North Coastal Tamil Nadu whereas over the Central and South Coastal Tamil Nadu it is 31 December, a fortnight later than its withdrawal date from the northern parts.

In all the above mentioned studies, objective to semi-objective techniques were invoked to fix the dates for each year. Tables of dates derived were presented and several statistical parameters were computed to interpret the data sets. The onset process of northeast monsoon was found to be well defined and the date of onset could be fixed with reasonable certainty. The phenomenon of withdrawal, however, was less well defined and there was an extent of ambiguity in the determination of date of withdrawal for some years. The above-said studies were all diagnostic and the dates were determined in a retrospective fashion, *i.e*. after the northeast monsoon season was over and all the data became available.

Historically, the onset of northeast monsoon was first declared by IMD in the year 1923, and the same was included in IMD's Daily Weather Report (Raj, 1992). Subsequently, the onset was declared in some years and not mentioned in other years. The practice of IMD declaring the onset of northeast monsoon every year, on a real time basis commenced in the 1980s and that of withdrawal in the 1990s. Criteria for declaration of onset of northeast monsoon by IMD were set out in IMD (1987), whereas no such criteria appears to have been formulated for withdrawal. The real time declaration of northeast monsoon onset by IMD could be earlier or later than the actual date which could happen due to operational reasons. In the case of withdrawal, real time declaration might become complex due to various constraints such as, withdrawal of northeast monsoon based on daily rainfall is not clearly defined every year, occurrence of prolonged dry spell in between northeast monsoon rain spells and absence of major synoptic patterns associated with withdrawal. In nearly one-third of the years, northeast

monsoon spills over to the next calendar year, resulting in withdrawal occurring in the month of January.

With this background, the purpose of the present study, which is essentially a sequel to the research studies mentioned above is set out. The objective is to retrospectively derive afresh the dates of onset and

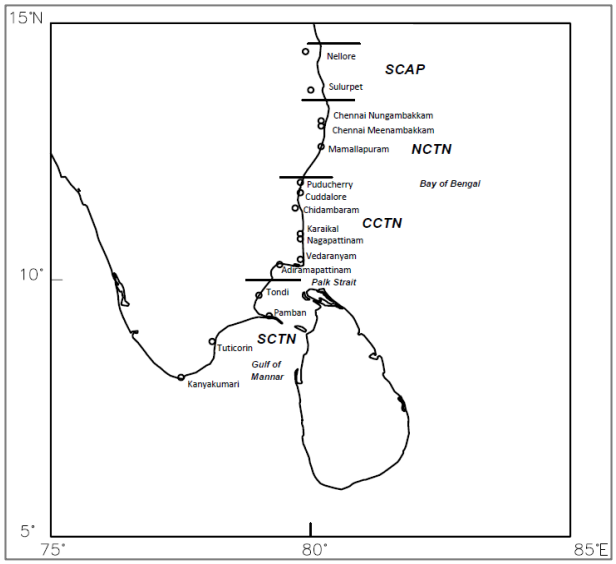


Fig. 1. Geographical locations of 16 rain gauge stations and 4sub-coasts : SCAP- South Coastal Andhra Pradesh, NCTN, CCTN, SCTN - North, Central, South Coastal Tamil Nadu ; Northern Coast : NC-SCAP & NCTN, Central and Southern Coasts : CSC-CCTN & SCTN, Entire Coast : NC&CSC

withdrawal of northeast monsoon over Coastal Tamil Nadu and South Coastal Andhra Pradesh, for the 10 year period 2011-20 based on daily rainfall data of a well distributed and adequate network of rain gauge stations. This short term dataset when appended with the 140 year dataset of 1871-2010 already derived, would result in a homogeneous and reliable data archive for a long 150 year period 1871-2020 of northeast monsoon onset and withdrawal dates, which could serve as a handy input for researchers of northeast monsoon. The superposed epoch technique has been performed to derive the mean daily rainfall profile, to demonstrate the sharp increase and decrease of rainfall after the onset and withdrawal respectively for 2011-20. The process of onset and withdrawal for a few individual years has been illustrated and presented. The technique of Empirical Orthogonal Function (EOF) has been employed to study the spatial variation of rainfall within the region of study. The frequency of occurrence of heavy rainfall and the influence of northeast monsoon onset and withdrawal over such events has been studied, based on a normalised index of heavy rainfall and a few interesting results have been derived.

2. Data and methodology

2.1. *Definition of various sub-coasts*

For the study, Coastal Tamil Nadu is subdivided into 3 sub-coasts, *viz*., North Coastal Tamil Nadu lying within 12.0-13.5° N, Central Coastal Tamil Nadu, 10-12° N and South Coastal Tamil Nadu, 8.1-12.0° N. South Coastal Andhra Pradesh is taken to be the coastal belt within 13.5-14.5° N. The Northern Coast is defined as the combined South Coastal Andhra Pradesh and North Coastal Tamil Nadu. The Entire Coast is defined as the combined North, Central and South coasts. For this study, 16 coastal rain gauge stations located along the Entire Coast were chosen. The sub-coastal belts South Coastal Andhra Pradesh, North, Central and South Coastal Tamil Nadu are represented by 2, 3, 7 and 4 rain gauge stations respectively. The belts North Coast and Central South Coast are represented by 5 and 11 stations respectively. Fig.1 presents the geographical locations of the 16 stations and the sub-coastal belts defined and delineated as above.

2.2. *Rainfall data*

Daily rainfall data for the 16 stations for the 181 day period 1 Sep - 28 Feb (of succeeding year) from 2011-12 to 2020-21 was obtained from the National Data Centre, IMD, Pune. A few missing values for South Coastal Andhra Pradesh stations were filled up by extracting the same from IMD's daily grid point rainfall data (Pai *et al*., 2014).

2.3. *Criteria for determination of date of onset of northeast monsoon*

The major conditions to be satisfied are (*i*) The southwest monsoon should have withdrawn from India (*ii*) Surface and lower level easterly winds should have set in over the Bay of Bengal adjacent to Coastal Tamil Nadu (*iii*) Rainfall data for a year is monitored from 1 October and if the first two conditions are satisfied, the first date of fairly widespread or higher category rainfall (*i.e*., 50% or more stations should have received daily rainfall data of at least 2.5 mm) over the Entire Coast can be taken as the northeast monsoon onset date. For declaration on real-time basis, there are some more guidelines, not required for the present study which is essentially retrospective.

2.4. *Criteria for determination of date of withdrawal*

For a given day say *n-th* day, the set of pentad days with *n-th* day as the central date is taken into consideration. Daily rainfall data for the 5 days and 16 stations are considered and the percentage of rainy days

out of total number of 80 days is defined as the daily rainfall index for the *n-th* day. Daily rainfall index which varies from 0-100, is an apt parameter representing the spatial and temporal persistence of rainfall. If its value is more than 40, northeast monsoon is taken as prevailing during the pentad concerned. For a specific year, the last pentad during November-January with an index value of less than 40 is taken as the withdrawal pentad, and the date of withdrawal is fixed within this pentad. In some years, aside from the index value, the quantum of rainfall also may have to be taken into consideration. After the date of withdrawal, a significant rain spell corresponding to an index value of 40should not have occurred up to 31 January. A fresh rain spell commencing in February is not taken as northeast monsoon rain spell.

TABLE 1

Onset and withdrawal dates of northeast monsoon determined for the period,2011-12 to 2020-21

Year	DWSWM (IMD)	EOOver 15 °N (Study)	DONEM (IMD)	DO NEM (Study)	DW NEM (IMD)	DW NEM (Study)	DW NEMNC (Study)	DW NEMCSC (Study)
2011-12	24 Oct	21 Oct	24 Oct	24 Oct	10 Jan	3 Jan	3 Jan	31 Dec
2012-13	18 Oct	16 Oct	19 Oct	18 Oct	11 Jan	1 Jan	1 Jan	11 Jan
2013-14	21 Oct	17 Oct	21 Oct	19 Oct	18 Jan	14 Dec	14 Dec	10 Jan
2014-15	18 Oct	14 Oct	18 Oct	16 Oct	4 Jan	3 Jan	31 Dec	3 Jan
2015-16	19 Oct	16 Oct	28 Oct	28 Oct	7 Jan	14 Dec	11 Dec	21 Dec
2016-17	28 Oct	30 Oct	30 Oct	30 Oct	4 Jan	29 Jan	14 Dec	29 Jan
2017-18	25 Oct	25 Oct	27 Oct	28 Oct	15 Jan	5 Dec	2 Dec	24 Dec
2018-19	21 Oct	20 Oct	1 Nov	21 Oct	2 Jan	26 Dec	7 Dec	25 Dec
2019-20	16 Oct	13 Oct	16 Oct	15 Oct	10 Jan	07 Jan	08 Jan	03 Jan
2020-21	28 Oct	28 Oct	28 Oct	29 Oct	19 Jan	18 Jan	10 Jan	18 Jan
Mean	21 Oct	20 Oct	24 Oct	23 Oct	10 Jan	31 Dec	23 Dec	5 Jan
LPA		14-16 Oct		20 Oct		26-30 Dec	17 Dec	31 Dec

IMD – Dates declared on real time mode byIndia Meteorological Department
Study – Dates determined in the study in retrospective mode
EO- Date of easterly onset, DO/DW- Date of onset/withdrawal
SWM - Southwest monsoon, NEM - Northeast monsoon
NC - Northern Coast, CSC - Central and Southern Coasts
LPA- Long period average

For further details about the criteria for onset and withdrawal of northeast monsoon, Raj (1992 and 1998) and Geetha and Raj (2015) could be referred. Remote sensed satellite images and outgoing long wave radiation (OLR) data could provide valuable inputs for the determination of the onset date. But in a diagnostic study of this type, the need for using the OLR data was not felt since rainfall which is the primary index of monsoon activity is taken as the most important parameter.

3. Retrospective determination of onset and withdrawal dates for 2011-20

The daily rainfall data of the 16 stations, from 1 September - 28 February for each year for the period from 2011 - 2012 to 2020 - 2021 was processed and analysed. For each day, (*i*) Mean rainfall, (*ii*) Spatial distribution of rainfall indicated by the percentage of number of stations reporting at least 2.5 mm of daily rainfall, (*iii*) Rainfall categorisation as Dry (No station receiving rainfall), Isolated (ISOL, 1 - 25% stations receiving rainfall), Scattered (SCT, 25 - 50%), Fairly Widespread (FWS, 50 - 75%) and Widespread (WS, 75 - 100%), (*iv*) Frequencies of occurrence of heavy, very heavy and extremely heavy rainfall (HRF, VHRF and EHRF, daily rainfall of 65-125, 125-200 and more than 200 mm respectively) amongst the stations and (*v*) Daily rainfall index as defined in Sec.2 were all determined.

The dates of withdrawal of southwest monsoon, as declared by IMD were extracted from various publications of IMD such as monsoon reports and articles published in IMD's MAUSAM Journal. The date of onset of easterlies, which is the date of firm establishment of surface easterly and lower level winds over Bay of Bengal at about Chennai latitude 13° N, was determined based on

the re-analysed charts of NCEP (National Centre for Environmental Prediction, USA). In some years, when the date of withdrawal of southwest monsoon as declared by IMD was found to be later than the easterly onset date, which might have happened due to operational constraints, the former was taken to coincide with the latter insofar as the present study is concerned. The northeast monsoon onset date could be fixed easily, once the onset date of easterly winds was determined. In all the 10 years, the date of onset for each year could be fixed without any ambiguity.

The date of withdrawal of northeast monsoon from the Entire Coast was determined for each year, by critically studying the daily rainfall index and the spatial distribution of daily rainfall. By and large, the dates of withdrawal could be determined with reasonable certainty, though not to the level of onset dates. The dates of withdrawal of northeast monsoon from both North Coast and South Central Coast were fixed separately also by following the same methodology which was adopted for the Entire Coast.

The following sets of dates for each year of 2011-20 were extracted or derived, *viz*., (*i*) Southwest monsoon withdrawal date from Tamil Nadu, (*ii*) Firm date of onset of surface level easterlies over Bay of Bengalat about Chennai latitude 13° N, (*iii*) IMD declared onset date of northeast monsoon, (*iv*) Onset date of northeast monsoon as determined in the study, (*v*) Withdrawal date of northeast monsoon as per IMD records, (*vi*), (*vii*) and (*viii*) Withdrawal dates of northeast monsoon from Entire Coast, North Coast and South Central Coast respectively. These sets of dates are listed in Table 1. Here (*i*), (*iii*) and (*v*) were extracted from IMD records and all the other sets of dates were determined in the study.

4. Analysis and results

4.1. *Dates of onset and withdrawal*

The mean dates of onset and withdrawal of northeast monsoon were computed and are presented in Table 1. The LPA based on 1901-2000 data is given for most of the categories of dates listed in Table 1. The mean date of onset of northeast monsoon for 2011-20 is derived as 23 October, whereas the mean of IMD declared date is 24 October. The LPA onset date of northeast monsoon over the Entire Coast is 20 October with a standard deviation of 7.5 days. The differences of means were tested using Student's *t*-test and found not significant at both 5% and 1% levels, for both IMD declared dates of onset and the dates derived in the study. For the year 2018, the difference of 12 days between IMD onset date (1 November) and the study onset date (21 October) is substantial. The onset of northeast monsoon which took place on 21 October as per the study, though a bit subdued satisfied the criteria fully. The rainfall was FWS with isolated HRF on 21 October and continued as SCT/ISOL up to 31 October.

Rajeevan *et al*. (2022) have re-determined the onset dates of northeast monsoon for 1981-2020, using almost the same criteria followed in the present study along with an additional condition based on OLR data. During 2011-20, the difference between the two sets of dates is 0-2 days only except for the year 2018.

The mean date of withdrawal obtained for the Entire Coast is 31 December, which is close to the LPA pentad of 26-30 December. The withdrawal occurred in December in 4 years and in January in 6 years of the study period. In all the years, the IMD date of withdrawal is later than the withdrawal dates determined in the study, the difference ranging from 1 day to 35 days. The mean IMD date of withdrawal is 10 January, which is 11 days later than the study mean of 31 December. For North Coast, the mean date of withdrawal is 23 December and for Central South Coast, it is 5 January. The LPA dates of withdrawal for the above two coasts based on 1961-2010 data are 17 and 31 December respectively. The mean date of withdrawal during 2011-20 for both the coasts is later by around 6 days compared to the LPA, but the time lag of withdrawal between North Coast and Central South Coast has remained as 14 days during both the periods.

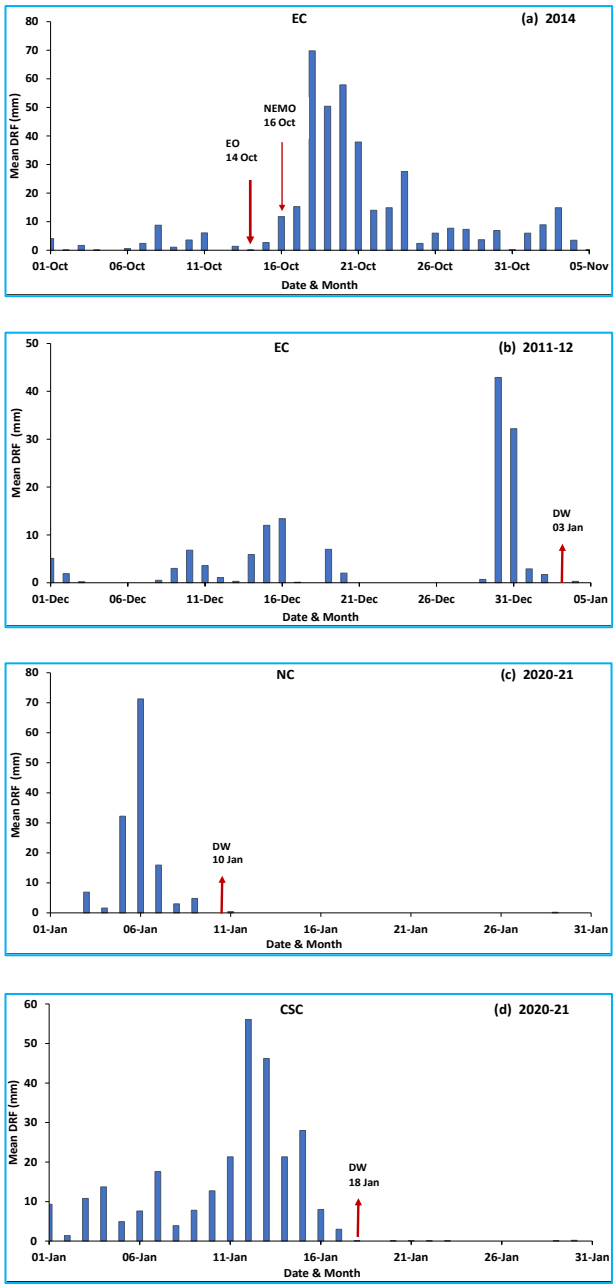
The presumption that the northeast monsoon prevails over Central and South Coastal Tamil Nadu for a longer duration than over the northern parts was first mentioned by Srinivasan and Ramamurthy (1973). This was validated by Geetha and Raj (2015) through a rigorous analysis wherein the dates of withdrawal were derived separately for North Coast and Central South Coast for 1961-2010, based on which the LPA was computed. This characteristic of northeast monsoon that prevailed in the period 1961-2010, persisted during 2011-20 also as shown in the present study. But in 2011 and 2019, the northeast monsoon first withdrew from the Central South Coast and then from North Coast, showing that there are individual exceptions.

4.2. *A few illustrations of northeast monsoononset and withdrawal*

In this section, the determination of northeast monsoon onset and withdrawal dates is illustrated for a few years.

In the year 2014, the onset of surface and low level easterly winds took place on 14 October. The northeast

monsoon onset date has been fixed as 16 October. Fig. 2(a) presents the mean daily rainfall of 16 stations over the Entire Coast for the period 1 Oct-5 Nov. As shown, the onset is very well defined and the onset spell of rain lasted up to 4 November. The cumulative mean rainfall of Entire Coast during 16-24 October is 304 mm, with occurrences of 20 and 2 instances of HRF and VHRF days respectively amongst the 16 stations.



Figs. 2(a-d). Illustration of northeast monsoon onset in 2014 and withdrawal in 2011-12 and 2020-21 (EO, DO, DW – As in Table 1) EC/ NC/CSC – As in Fig. 1

For the year 2011-12, the mean daily rainfall of the Entire Coast for the period 1 Dec 2011 to 5 Jan 2012 is presented in Fig. 2(b). A good spell of rain occurred during 9-16 December. The next rain spell of shorter duration occurred during 30 Dec-2 Jan when the Entire Coast received 79.7 mm of cumulative rainfall. There were 7 days of HRF and two days of VHRF during 30-31, December when FWS rainfall was realised. The date of withdrawal of northeast monsoon from the Entire Coast was therefore taken as 3 January 2012.

For the year 2020-21, the daily rainfall for 1-31 January 2021 for North Coast, based on 5 station data is depicted in Fig.2(c). During the rain spell of 3-9 January, there were 3 instances of HRF and one instance of VHRF (amongst the 5 stations) with 136 mm as the realised cumulative mean daily rainfall. The northeast monsoon withdrew from the North Coast on 10 January. There was no rainfall over the North Coast, during the period 10-31 January 2021. For the same year 2020-21, the daily rainfall for 1-31, January 2021 for Central South Coast, based on data of 11 stations is depicted in Fig. 2(d). During 1-17 January, almost continuous rainfall occurred. The cumulated mean daily rainfall (based on 11 stations) was 264 mm with 5 and 4 instances of HRF and VHRF respectively amongst the 11 stations. The northeast monsoon withdrew from Central South Coast, on 18 January. Only 0.8 mm of rainfall occurred during 18-31, January. The year 2020-21 provides an illustration of clear northeast monsoon withdrawal from North Coast first and then from Central South Coast after 8 days.

During 2016-17 the northeast monsoon withdrew on 14 December from the North Coast but persisted for a further period of 45 days over Central South Coast, with withdrawal occurring on 29 January 2017 only. The cumulative mean daily rainfall received over the North Coast during 15 Dec-31 Jan was 4 mm. The Central South Coast, which received 16.9 mm daily rainfall from 15 Dec-9 Jan, received 104 mm of cumulated mean daily rainfall during 20-28 January and experienced 5 days of FWS/WS rainfall, interspersed with 4 HRF/VHRF occurrences amongst the 11 stations. This rain spell happened several days after the cessation of rainfall over North Coast and substantially later than the LPA date. Since the duration of the rain spell was long and the quantum of rainfall was large, this was taken as a northeast monsoon spell and the date of withdrawal was fixed as 29 January. For the Entire Coast also, the date of withdrawal was determined as 29 January, which is the most delayed withdrawal of northeast monsoon since the year 1871. The previous most delayed northeast monsoon withdrawal occurred on 28 January 1934, for the 1933-34 northeast monsoon season.

4.3. *Superposed epoch analysis*

The superposed epoch analysis (Panofsky and Brier, 1958) can be performed on daily rainfall data to bring out the spike in rainfall at the time of northeast monsoon onset, and the near cessation of rainfall activity, just after northeast monsoon withdrawal. For this study, such an analysis has been performed for onset of northeast monsoon over the Entire Coast, withdrawal from Entire Coast, North Coast and Central South Coast. The date of the event, *viz*., onset or withdrawal, is taken as 0, the days prior to this date are assigned -1,-2,-3,… and days succeeding are assigned 1,2,3,…*etc*. Then, the corresponding mean daily rainfall values of stations considered are averaged over the years. The superposed epoch rainfall profiles for the 4 events mentioned above are presented in Figs. 3(a-d). In Fig. 3(a), the dramatic and sharp increase at the time of onset is clearly brought out. The mean daily rainfall, which is 1-4 mm for 10 days before onset, rises to 10-33 mm after onset. In the case of withdrawal, the mean daily rainfall depicted in Fig. 3(b), which varies from 4-16 mm for 10 days before withdrawal, drops to 0-2 mm after withdrawal. For the North Coast, the withdrawal profile of daily rainfall is very sharp. The mean daily rainfall, which is 3-24 mm for 10 days before withdrawal, drops to near 0 after withdrawal as shown in Fig. 3(c). The withdrawal profile depicted in Fig. 3(d), for Central South Coast is also sharp, though minor spikes in daily rainfall are observed after withdrawal. The superposed epoch profile has clearly brought out the sharp increase (decrease) of mean daily rainfall at the time of onset (withdrawal) during the period of study.

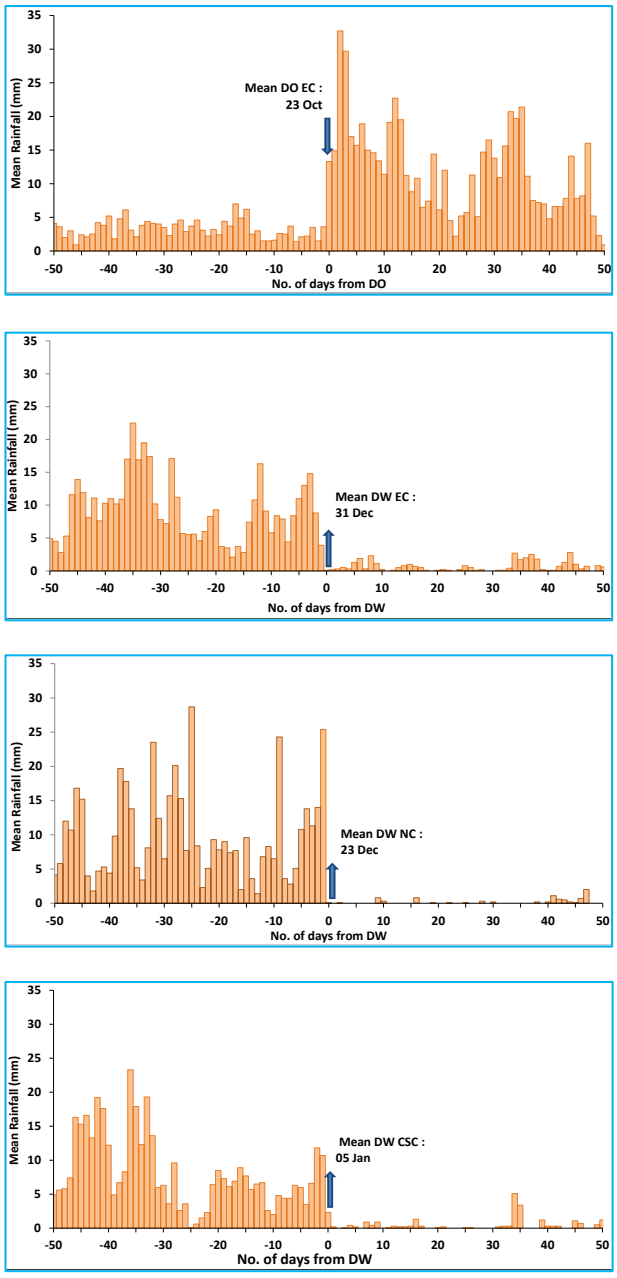


Fig. 3. Mean daily rainfall with reference to northeast monsoon onset and withdrawal dates – Superposed epoch analysis DO, DW – As in Table 1, EC, NC, CSC – As in Fig. 1 Period : 2011-20

4.4. *Analysis based on Empirical Orthogonal Function*

The EOF analysis which can be invoked to study the spatial variation of atmospheric parameters (Wilks, 2010), has been performed to study the spatial variation of rainfall of the four sub-coasts and to interpret the products, especially in relation to northeast monsoon onset and withdrawal. To reduce the noise which is likely to be present if daily rainfall is used, pentad rainfall series of the four sub-regions of the sub-coasts defined in Sec.2, *viz*., South Coastal Andhra Pradesh, North, Central and South Coastal Tamil Nadu (Fig. 1) were derived. For each year, rainfall of 25 pentads commencing from 1-5 October and ending with 29 Jan-2 Feb (of next year) for the 10 year period was computed.

Initially, the EOF analysis was performed for each year separately using the covariance matrix. The yearly variation of the first and second principal components (PC1 and PC2) is depicted in Fig. 4(a). The first component PC1 which explains the maximum variation has the range 71-96%. The second component PC2 has a range of 3-24%. Together, the first two principal components account for 90-98% of the variation, showing that when the pentad rainfall of the 4 sub-regions is considered, the spatial variation can be explained by just two variables.

To further simplify the analysis and to obtain an overall profile, the pentad rainfall series for the 10 year period were all composited and combined into a single a series. The 250 pentad series for 4 sub-coasts resulting in 250×4 matrix was subjected to covariance based EOF analysis. Fig. 4(b) presents the variance explained by

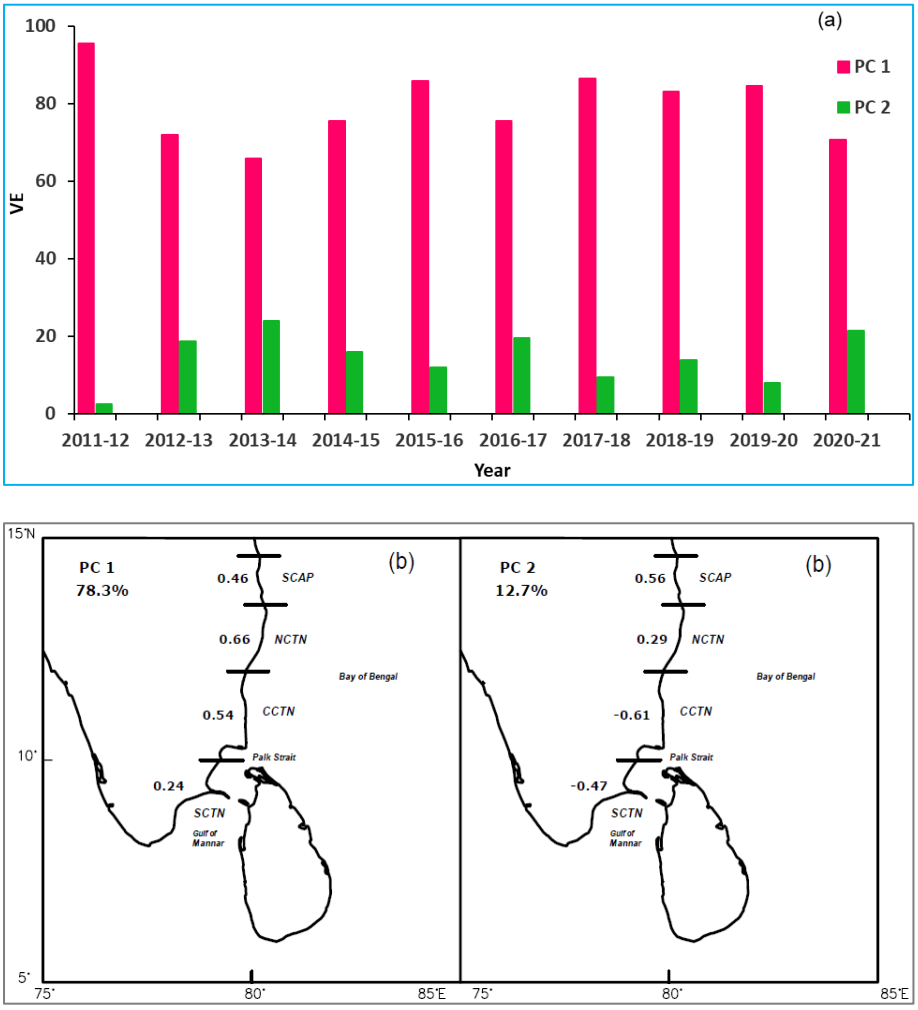


Fig.4. EOF analysis of pentad rainfall of Oct-Jan, 2011-12 to 2020-21 for four sub-coasts. PC1 and PC2- First and second principal components (a). Variance explained (VE in %) yearwise by PC1 and PC2 (b). VE by PC1 and PC2 and loadings of the same for the four sub-coasts for 2011-20 (Coasts as defined in Fig.1)

PC1 and PC2 along with the loadings for each sub-coast.

It is seen that PC1 and PC2 explain 78.3% and 12.7% variation respectively and together both explain 91% variation. The remaining two components explain 9% only. The loadings corresponding to PC1, for South Coastal Andhra Pradesh, North, Central and South Coastal Tamil Nadu are 0.46, 0.66, 0.54 and 0.24 respectively. Thus, North Coastal Tamil Nadu is associated with the highest variation, followed by Central Coastal Tamil Nadu, South Coastal Andhra Pradesh and South Coastal Tamil Nadu in that order.

The first component PC1 which explains 78.3% of the variation with positive loadings for all the four sub-coasts, can be considered to be associated with the overall strength of northeast monsoon, when daily/pentad rainfall anomalies are likely to be positive or negative simultaneously in all the four regions. The loadings represent the level of importance of each sub-coast. This feature could be factored in, while the onset date of northeast monsoon is fixed, albeit in some instances. When there is an ambiguity about the northeast monsoon onset date for a specific year, the rainfall of North and Central Coastal Tamil Nadu could be given more importance.

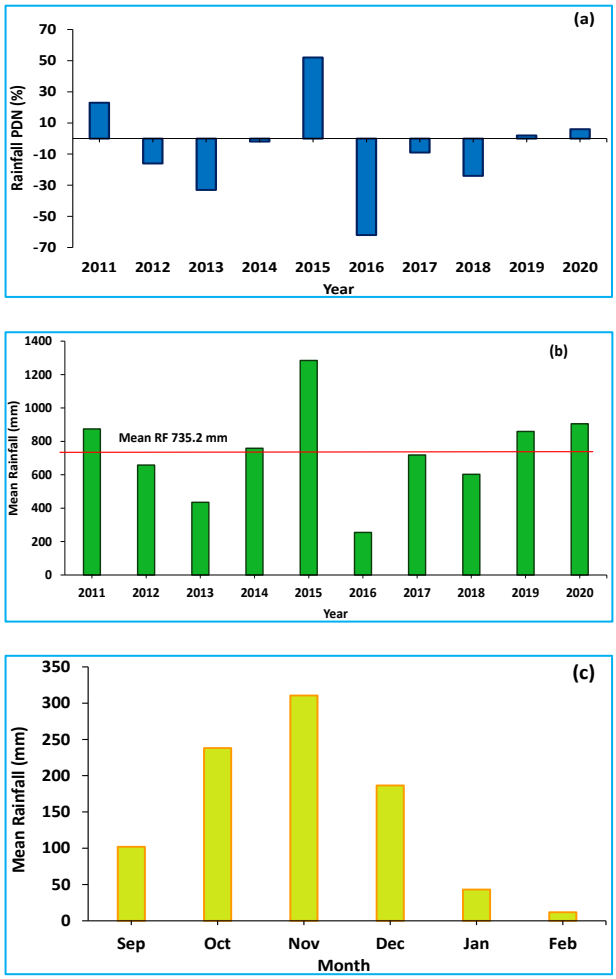
The second component PC2, which explains nearly 12.7% of the variation, has loadings of 0.56, 0.29, -0.61 and -0.47 for South Coastal Andhra Pradesh, North, Central and South Coastal Tamil Nadu respectively. The loadings are positive for the two northern coasts and negative for the central and southern coasts [Fig. 4(b)]. This type of pattern is associated with the event of positive (negative) daily/pentad rainfall anomalies over North Coast and negative (positive) anomalies over Central and South Coasts occurring together. Such a rainfall pattern could happen within the season also, but it is likely to happen towards the end of the season. The feature of northeast monsoon withdrawal from the two northern coasts, happening two weeks earlier, compared to the two southern coasts, explained in Sec.4.1 is definitely one of the reasons for the PC2 having loadings which are of opposite signs for the respective coasts.

The following examples illustrate the effect of the magnitude of the variations explained by PC1 and PC2, on the withdrawal process in certain individual years. In the year 2011, northeast monsoon withdrew almost simultaneously from North Coast and Central South Coast (Table1) with PC1 and PC2 explaining 96% and 3% respectively [Fig. 4(a)]. In 2015, the difference is 10 days with PC1 at 86% and PC2 at 12%. In 2019, the difference is 5 days, PC1 is 85% and PC2 is 8%. In these years, closer withdrawal dates are associated with larger PC1 and smaller PC2 values. In 2013, the difference is 27 days while PC1 is 66% and PC2 is 24%. In 2016, the difference is 46 days, PC1 is 76% and PC2 is 20%. In these two years, the northeast monsoon withdrawal dates for North Coast and Central South Coast are far apart and this feature is associated with relatively smaller PC1 and larger PC2 values.

It may be pointed out that, such a clearly defined EOF pattern in association with withdrawal may not manifest every year, as the northeast monsoon withdrawal process is not the only factor behind the loadings of PC2. Though the EOF analysis can be carried out only after the northeast monsoon season is over and the entire season's rainfall data is available, it can be an effective diagnostic tool to understand and comprehend some of the features of onset and withdrawal of northeast monsoon.

4.5. *Rainfall related features*

The Oct-Dec rainfall of Tamil Nadu, which is frequently taken as the best index of the seasonal performance of northeast monsoon, is presented for each year for the period 2011-20 in Fig. 5(a), in terms of percentage departure from the LPA which is 443.2 mm (IMD, 2010). The rainfall of the Entire Coast, based on the 16 station data for Oct-Dec of 2011-20, was computed for each year and the time series is presented in Fig. 5(b). The mean rainfall during Oct-Dec for the Entire Coast is 735.2 mm as shown in Fig. 5(b), with lowest of 254.6 mm in the year 2016 and highest of 1284.4 mm in 2015. The 10 year average monthly rainfall based on the 16 station data is depicted in Fig. 5(c). As shown, the mean rainfall figures for each month from September to February are 102.1, 238.1,310.4, 186.6, 43.2 and 11.8 mm respectively. When the Entire Coast is considered, there is



Figs. 5(a-c). (a).Oct-Dec rainfall of Tamil Nadu as % departure from normal (443.2mm) for 2011-20, (b).Oct-Dec rainfall of EC for 2011-20 and (c). Mean monthly rainfall of Sep-Feb of EC for2011-12 to 2020-21 EC-Entire Coast as defined in Fig. 1

a sharp rise of rainfall from September to October, that November is the rainiest month and that there is a reasonable quantum of rainfall in January as well. The month of January received the highest rainfall of 231.0 mm in the year 2021 for the period of consideration. In November 2015, Entire Coast received 707.1 mm, which is the highest monthly rainfall during 2011 - 2020.

The occurrence of HRF, VHRF and EHRF (defined in Sec.3) is common during northeast monsoon season. To investigate such instances further, especially in relation to the northeast monsoon onset and withdrawal dates, the frequencies of HRF, VHRF and EHRF were derived from the daily rainfall data of 1 Sep-28 Feb for the 16 stations for the period 2011-12 to 2020-21 for each month. The frequencies were also derived for the following periods /

TABLE 2

Frequency / probability of heavy rainfall during various sub-periods associated with northeast monsoon season

Month/Period	HRF	VHRF	EHRF	Total	Total number of days	PHRin %
Sep	33	1	0	34	300	0.71
Oct	103	24	1	128	310	2.58
Nov	124	44	7	180	300	3.75
Dec	83	32	6	121	310	2.44
Jan	13	5	1	19	310	0.38
Feb	2	2	0	4	280	0.09
Oct - Dec	315	100	14	429	920	2.91
Oct -Jan	328	105	15	448	1230	2.28
Sep -Feb	363	108	15	486	1810	2.01
1 Oct- DO1	12	3	0	15	225	0.42
DO+ 6 days	71	19	1	91	70	8.12
DO-DW1	310	102	15	427	737	3.62
DW- 28 Feb	8	2	0	10	225	0.11

Frequency derived from daily rainfall of 16 stations, 10 year data, 2011-12 to 2020-21
DO, DW – As in Table 1 ; DO1, DW1 – The preceding day of DO, DW
HRF /VHRF / EHRF – Heavy /Very Heavy / Extremely heavy (one day) rainfall
PHR – Probability of (HRF + VHRF + EHRF) expressed in %

sub-periods, *viz*., (*i*) northeast monsoon season of Oct-Dec, (*ii*) Extended northeast monsoon period of Oct-Jan, (*iii*) The entire period Sep-Feb, (*iv*) 1 Oct-Pre-onset date (*v*) Date of onset+6 days, (*vi*) Date of onset-Pre-withdrawal date and (*vii*) Date of withdrawal-28 Feb. For *e.g*., for the year 2013, the dates of northeast monsoon onset and withdrawal are 19 October and 14 December respectively. The periods (*iv*) to (*vii*) as defined above for 2013 are : 1-18 Oct, 19-25 Oct, 9 Oct-13 Dec, and 14 Dec- 28 Feb respectively.

The derived and total frequencies are given in Table 2. However, the interpretation is based on total frequency only. The monthly frequencies of each month from September to February are by and large comparable. The frequencies of other sub-periods are, however, not comparable due to the varying length of the defined sub-periods. To effect such a comparison, the probability of one station receiving heavy rainfall (PHR) on one day is defined as: $PHR=a/b$, where a is the total number of HRF/VHRF/EHRF days for all the 16 stations and b = 16 (number of stations) × Total number of days of the sub-period. As the denominator in the above expression contains the number of stations and the total number of days of the sub-period, PHR is a normalised index and could be conveniently expressed in percentage. The PHR values given in Table 2 are all comparable amongst the 13 different sub-periods. For *e.g*., the total HRF days is 429 for October-December, total number of days is 920 and so PHR is 2.91%. The interpretation is that, during October-December in any station, on any given day, the probability of occurrence of HRF is 0.0291. Suppose there are 100 evenly distributed rain gauge stations, the frequency of HRF occurrences would be 2.91 on a given day.

Some of the results based on the statistics of heavy rainfall presented in Table 2 are enumerated below:

(*i*) The total monthly frequency of heavy rainfall days in all the categories (for 10 years and 16 stations), rises sharply from 34 instances in September to 128 in October, reaching a peak of 180 in November, then falling to 121 in December, dropping sharply to 19 in January and further reducing to just 4 in February. These frequencies are closely comparable.

(*ii*) During Oct-Dec, Oct-Jan and Sep-Feb, the total frequencies of heavy rainfall days are 429, 448 and 486

days and the corresponding PHR values are 2.91, 2.28 and 2.01 respectively. As the season gets extended, the total frequency increases, but the PHR drops due to the increasing length of the season but without a proportionate increase in the frequency of HRF.

(*iii*) During September, the frequency of heavy rainfall events is 34 while the PHR is 0.71. During Oct-pre-onset date, the frequency is only 15 and PHR is 0.42 based on 225 days. This shows that the incidences of HRF decrease from September to the pre-northeast monsoon onset period of October.

(*iv*) The 7 day period commencing from the onset date of northeast monsoon for each year of 2011-20 and consisting of a total of 70 days, experienced 71 HRF, 19 VHRF and 1 EHRF instances adding up to 91 corresponding to a PHR of 8.12. Thus, the HRF frequency increases nearly 19 times from the pre-onset phase to the immediate post-onset phase, which shows the remarkable influence of northeast monsoon onset on the occurrence of HRF.

(*v*) During the period from onset to pre-withdrawal date which is in fact the actual northeast monsoon duration, there are 427 instances of heavy rainfall out of a total of 737 days with a PHR of 3.62.

(*vi*) During the period from the date of withdrawal to 28 February, which is the post-northeast monsoon period, there are 10 heavy rainfall occurrences out of 225 days yielding a PHR value of just 0.11.

The influence of northeast monsoon onset phase, its duration and withdrawal, on the occurrence of heavy rainfall events over the Entire Coast is thus well established and quantified.

5. Discussions

During the decade 2011 - 2020, the northeast monsoon set in around 3 days late in an overall sense, compared to the LPA date. In 4 years, the onset was on or after 28 October, which could be termed as substantial delay. The withdrawal also slightly shifted to be later than the LPA date. As shown in Table 1, the mean date of surface to low level easterly onset is 20 October, which is 4 - 6 days later than the LPA date of 14 - 16 October, obtained in earlier studies. The late onset of easterlies and northeast monsoon can be partly attributed to the late withdrawal of southwest monsoon from the entire India, during most of the years of the study period. The onset of northeast monsoon has been intense in most of the years, as evidenced from the superposed epoch analysis. The Central South Coast experienced late withdrawal by nearly 2 weeks than from North Coast during 2011 - 2020 also, which was a new feature first identified by Geetha and Raj (2015). This characteristic also results in significant variation of PC2, in which the North Coast and Central South Coast behave differently, as shown through the EOF analysis.

The incidences of HRF/VHRF/EHRF associated with northeast monsoon onset have been studied and it is shown that the onset spell experiences very high frequencies of HRF compared to the pre-onset phase and that HRF is rare after northeast monsoon withdrawal. During 2011 - 2020, the withdrawal of northeast monsoon spilled over to January of next year in 6/10 years, a ratio which is much higher than the1/3, which was obtained for the very long period 1901 - 2010. The determination of withdrawal dates is not as precise as that for the onset dates and further, the rainfall data for the entire extended season is needed to correctly fix the withdrawal date of northeast monsoon. The normal pentad of northeast monsoon withdrawal is 26 – 30, December, with a standard deviation of around 13 - 14 days. Thus, there is more than 98% chance that the northeast monsoon days are all encompassed within January and it is reasonable to assume that a fresh rain spell commencing in February is not northeast monsoon activity. However, as shown in the present study, the northeast monsoon season extended up to 29 January during 2016 - 2017. A significant northeast monsoon rain spell commencing in the last few days of January may be difficult to foresee in the beginning of January, even with the guidance provided by the numerical weather prediction models. The declaration of northeast monsoon withdrawal on a real time basis, is therefore, fraught with this type of uncertainty and as such, a retrospective fixing of the withdrawal date of northeast monsoon, after the entire rainfall data of January becomes available, appears to be a better option.

6. Conclusions

The major results of the study are summarised below:

(*i*) The onset and withdrawal dates of the northeast monsoon season over the combined region of Coastal Tamil Nadu and South Coastal Andhra Pradesh, for the 10 year period 2011 - 2020 have been determined, based on daily rainfall data of 16 stations, by following certain objective criteria. The derived dates when appended with the past set of dates for 1871 - 2010, fixed by following a similar methodology, has resulted in a homogeneous data set of onset and withdrawal dates of northeast monsoon for 150 years, *viz*., 1871 - 2020.

(*ii*) The mean onset / withdrawal dates of northeast monsoon for the period 2011-20 are obtained as 23 October and 31 December respectively, which are 3 and 4 days later than the corresponding long period average dates.

(*iii*) The mean withdrawal date of northeast monsoon is obtained as 23 December, for South Coastal Andhra Pradesh and North Coastal Tamil Nadu. For Central and South Coastal Tamil Nadu, the mean withdrawal date of northeast monsoon is 5 January. The two week late withdrawal over the Southern Coast, compared to the Northern Coast, which was identified in an earlier study, based on 50 year data for the period 1961-2010, has persisted in 2011-20 also.

(*iv*) The superposed epoch analysis performed on the daily rainfall data of the 16 stations, has shown a very sharp increase in rainfall at the time of onset of northeast monsoon and a sharp decrease after its withdrawal. The daily rainfall increases from 1-4 mm to 10-33 mm with northeast monsoon onset and decreases from 4-16 mm to 0-2 mm at withdrawal.

(*v*) The empirical orthogonal function analysis conducted on the pentad rainfall of Oct-Jan for 4 sub-coasts South Coastal Andhra Pradesh, North, Central and South Coastal Tamil Nadu has revealed that the first principal component, which could be associated with the overall strength of the northeast monsoon, explains 78.3% of the variation and that the loadings are positive for all the regions and higher for North and Central Coastal Tamil Nadu. The second principal component, which explains 12.7% of the variation, has positive loadings in South Coastal Andhra Pradesh and North Coastal Tamil Nadu and negative loadings in Central and South Coastal Tamil Nadu. Such a pattern manifestation, resulting from opposite types of rainfall anomalies in the two sub-regions could be partly attributed to the late withdrawal in the southern sub-coasts compared to the northern sub-coasts.

(*vi*) An analysis of the frequencies of heavy/very heavy/extremely heavy rainfall derived for several sub-periods, has revealed the occurrence of 429 heavy rainfall events for the 16 stations and 10 years during October-December. The computation of a normalised index of heavy rainfall has revealed that the number of incidences of heavy rainfall occurrences commencing from the onset date is 91, which is 19 times more during the onset phase compared to the pre-onset phase. The occurrence of heavy rainfall is rare, after the withdrawal of northeast monsoon.

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Disclaimer: The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organisation which the second author belongs to.

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