MAUSAM, **76**, 1 (January 2025), 139-162

MAUSAM

DOI : https://doi.org/10.54302/mausam.v76i1.6452
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No. 551.553.21:551.509.313.4

Understanding and prediction of Indian Northeast Monsoon over the years

Y.E.A. RAJ, S. BALACHANDRAN*, B. AMUDHA* AND B. GEETHA*

Hiranya Apartments, Raja Annamalai Puram, Chennai – 600 028

**Regional Meteorological Centre, Chennai – 600 006*

email : yearaj@gmail.com

सार– भारत के पाँच मौसम संबंधी उप-विभाग अर्थात तमिलनाडु, तटीय आंध्र प्रदेश, रायलसीमा, दक्षिण आंतरिक कर्नाटक और केरल, जिन्हें यहां दक्षिणी प्रायद्वीपीय क्षेत्र (SPR) के रूप में संदर्भित किया जाता है, अक्टूबर-दिसंबर के दौरान SPR पर हावी रहने वाले भारतीय पूर्वोत्तर मॉनसून के प्रमुख लाभार्थी हैं। इस अध्ययन में 19वीं, 20वीं और 21वीं सदी में भारतीय पूर्वोत्तर मॉनसून पर ज्ञान के आधार के विकस को प्रस्तुत किया गया। अध्ययन में दक्षिण-पश्चिम मॉनसून के मौसम से पूर्वोत्तर मॉनसून के मौसम में संक्रमण का वर्णन है। 1871-2020 के 150 साल के आंकड़ों के आधार पर SPR की पूर्वोत्तर मॉनसून वर्षा (NMR) जलवायु विज्ञान प्रस्तुत किया गया और इस पर चर्चा की गई। विभिन्न अध्ययनों में 1871-2020 के दौरान पूर्वोत्तर मॉनसून की शुरुआत और वापसी की तारीखों के निर्धारण के बारे में बताया गया। पूर्वोत्तर मॉनसून के NMR, घटकों और मौसम प्रणालियों की अंत:वार्षिक, अंत:ऋतुनिष्ठ और दैनिक विशेषताओं का वर्णन किया गया। NMR का लघु, मध्यम अवधि और ऋतुनिष्ठ पूर्वानुमान, वैश्विक दूरसंचार, NMR और भारतीय दक्षिण-पश्चिम मॉनसून वर्षा के बीच संबंध का विस्तृत रूप से वर्णन किया गया। SPR का जलवायु वर्गीकरण, पूर्वोत्तर मॉनसून पर शोध और श्रीलंका के पूर्वोत्तर मॉनसून का संक्षिप्त संदर्भ शामिल किया गया।

ABSTRACT. The five meteorological sub-divisions of India *viz*. Tamil Nadu, Coastal Andhra Pradesh, Rayalaseema, South Interior Karnataka and Kerala which together are defined as the Southern Peninsular Region (SPR), are the major beneficiaries of Indian northeast monsoon which prevails over SPR during Oct-Dec. In this article how the knowledge base on Indian northeast monsoon evolved in the 19th, 20th and 21st centuries is presented. The transition from southwest monsoon season to northeast monsoon season is described. The northeast monsoon rainfall (NMR) climatology of SPR based on 150 year data of 1871-2020 is presented and discussed. How the onset and withdrawal dates of northeast monsoon for 1871-2020 have been determined in various studies is set out. The inter-annual, intra-seasonal and diurnal variation features of NMR, components and weather systems of northeast monsoon are described. Short, medium range and seasonal forecasting of NMR, global teleconnections, relation between NMR and Indian southwest monsoon rainfall, research on northeast monsoon are elaborated.

Key words – Indian northeast monsoon, ENSO, Bay of Bengal, Cyclone, Easterly wave.

1. Introduction

The monsoon is a planetary scale phenomenon which is associated with a large geographical region. The beginning of the monsoon season is characterized by noticeable reversal of surface and low level winds which for the remainder of the season blow from a near constant direction. However, the most important weather parameter which is associated with monsoon is rain or precipitation. The Indian sub-continent experiences the southwest monsoon which prevails during the period Jun-Sep. Rao (1976), Das (1986), Asnani (2005), Kelkar (2009), India Meteorological Department (IMD) (2012) present detailed description of the various aspects of Indian southwest monsoon. Whereas the southwest monsoon affects the entire India, the southeastern parts of India are also affected during Oct-Dec by another small and sub-planetary scale monsoon which is the Indian northeast monsoon. The IMD forecasting manual by Srinivasan *et al*. (1973) is a classic treatise which contains an elaborate description of several aspects of northeast monsoon. Das (1986) and Asnani (2005) also contain description of various monsoons of the

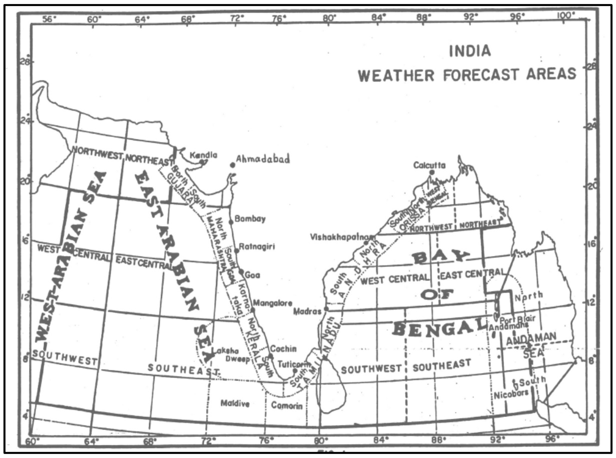

Fig. 1a. Map depicting North Indian Ocean and its littoral states.

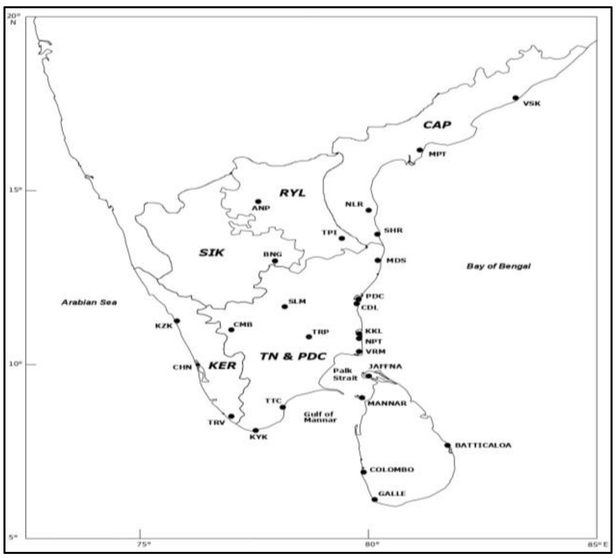

Fig. 1b. Five meteorological sub-divisions of Southern Peninsular India and Sri Lanka and geographical locations of several stations.

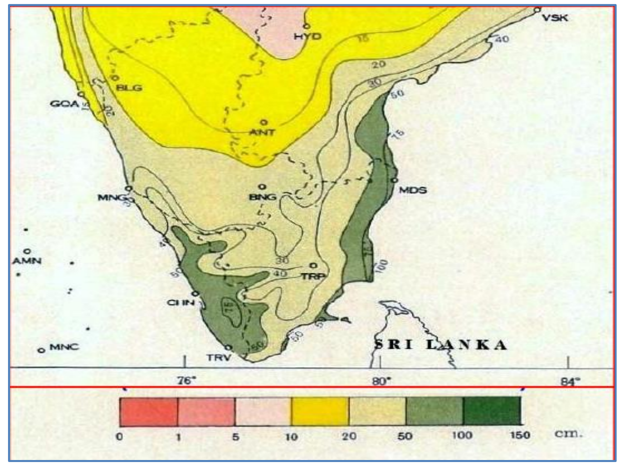

Fig. 2. Spatial distribution of normal rainfall over southern peninsular India during the northeast monsoon season Oct-Dec.

world including the Indian and South East Asian northeast monsoons. Raj (2012) and Rajeevan *et al*. (2022) brought into focus the manifold features of Indian northeast monsoon which have emerged from the research studies of the past 50 year or so based on data from modern observational platforms such as Satellite, Radar and output from Numerical Weather Prediction (NWP) models.

In this article the various characteristics and features of Indian northeast monsoon especially as to how the knowledge base on this monsoon expanded over the decades are briefly described. The geography and rainfall climatology of the region, climatic classification, synoptic features, weather systems that give rise to rainfall, inter and intra-seasonal variation of rainfall, diurnal variation, forecasting of its various features, relationship with global forcings, seasonal forecasting, research work on Indian northeast monsoon- are the topics which are elaborated.

2. Geography and rainfall climatology

Fig. 1a presents the weather forecast areas of India, the Bay of Bengal and Arabian Sea both of which together constitute the North Indian Ocean (NIO) (IMD, 2003). It also depicts the various ocean areas and the coastal belts. Fig. 1b shows the geographical locations of the five meteorological sub-divisions of India that benefit from the northeast monsoon, *viz*. Tamil Nadu, Coastal Andhra Pradesh, Rayalaseema, South Interior Karnataka and Kerala which together are defined in this article as the Southern Peninsular Region (SPR). The geographical area shown as Tamil Nadu also includes Puducherry and Karaikal which come under the Union Territory of Puducherry. The respective areas of the above 5 sub-divisions in sq. km are 130522, 93045, 69043, 93171 and 38864 respectively and the total area of SPR is 424645 sq. km.

Table 1a presents the normal rainfall of the above five sub-divisions and SPR for the months of October, November, December, northeast monsoon rainfall (NMR) of Oct-Dec besides the annual rainfall, based on 1971-2020, 50 year data. Table 1b presents similar data of 11 representative stations of the 5 sub-divisions of SPR. Fig. 1b depicts the locations of these stations. Fig. 2 shows the spatial variation of Oct-Dec seasonal rainfall of the southern peninsular India. The salient rainfall features during northeast monsoon season over SPR as shown in the tables and depicted in Fig. 2 are briefly presented below.

In Coastal Andhra Pradesh, Rayalaseema, South Interior Karnataka and Kerala, October rainfall is substantially higher than the November rainfall. For Tamil Nadu, both October and November rainfall figures are almost identical. The rainfall of November is highest in Tamil Nadu at 181.9 mm amongst the 5 sub-divisions. In

TABLE 1a

Normal monthly, seasonal and annual rainfall of five meteorological sub-divisions of SPR of India

Month / Season	Rainfall (mm) Sub-division					Rainfall mm
	TN	CAP	RYS	SIK	KER	SPR
Oct	172.0	182.2	132.1	137.2	306.4	172.2
Nov	181.9	113.1	78.4	51.2	153.1	118.3
Dec	89.4	27.6	25.9	10.6	32.4	42.8
OND	443.3	322.9	236.4	199.0	491.9	333.3
Annual	921.3	1042.7	733.2	1025.9	2890.7	1118.1
Rainfall as % of OND rainfall						
Oct	38.8	56.4	55.9	68.9	62.3	51.7
Nov	41.0	35.0	33.2	25.7	31.1	35.5
Dec	20.2	8.6	11.9	5.4	6.6	12.8
Rainfall as % of annual rainfall						
OND	48.1	31.0	32.2	19.4	17.0	29.8
CV	30	39	40	37	29	26

Based on 1971-2020 data. TN – Tamil Nadu, CAP – Coastal Andhra Pradesh, RYS –Rayalaseema, SIK – South Interior Karnataka, KER- Kerala, SPR- Southern Peninsular Region, OND- Oct-Dec, CV – Coefficient of variation of OND rainfall

the remaining four sub-divisions except for Tamil Nadu, the month of October accounts for more than 50% of the seasonal total. The decrease of rainfall from October to November is very sharp over Rayalaseema and South Interior Karnataka. The December rainfall figures are substantial in Tamil Nadu and Kerala only. The Oct-Dec seasonal total is highest in Kerala at 491.9 mm but this is only 17 % of the annual total as Kerala receives copious rainfall in the preceding southwest monsoon season. Tamil Nadu receives 443.3 mm during Oct-Dec which is 48.1% of its annual rainfall of 921.3 mm and further it is higher than the 317.2 mm rainfall realised during the southwest monsoon season of Jun-Sep. In fact, Tamil Nadu is the only one of the 36 meteorological sub-divisions of India which receives more rainfall during the northeast rather than the southwest monsoon season. The NMR is therefore very important for the agricultural and hydrological needs of Tamil Nadu. For the entire SPR, the normal rainfall figures of October, November and December are 172.2, 118.3 and 42.8 mm which are 51.7, 35.5 and 12.8% respectively of the Oct-Dec seasonal total of 333.3 mm which itself is 29.8% of the annual total of 1118.1 mm.

The Indian states of Odisha and West Bengal located along the east coast of India, north of Coastal Andhra Pradesh (Fig. 1a) receive normal rainfall of 144.1 mm and 185.3 mm respectively during Oct-Dec which could be partly attributed to the effect of cyclonic disturbances which cross or move closer to the coasts of above two states. Such occurrences are isolated and it is reasonable to assume that the activity of Indian northeast monsoon is confined to SPR.

The rainfall statistics of Table 1b and the spatial distribution of Fig. 2 reveal several other interesting features. In Tamil Nadu, Coimbatore and Tiruchirappalli located in the interior parts receive NMR of 300-400 mm most of it in Oct-Nov. Chennai located in the northern Tamil Nadu coast receives 856.7 mm in Oct-Dec including 162.9 mm in December. Along the Coromandel coast, the north - south belt stretches slightly south of Vedaranyam and at Point Calimere the coast takes an east to west orientation with Palk Strait of Bay of Bengal located southwards (Fig. 1b). The coastal station Vedaranyam receives normal rainfall of 1038.3 mm during Oct-Dec which is the highest rainfall realised by any rain gauge station in India during this season. Tuticorin (or Thoothukudi) located further south with Gulf of Mannar to the east receives relatively lower Oct-Dec rainfall of only 439.9 mm with an annual total of 630.5 mm.

The port city of Visakhapatnam located in the northern parts of Coastal Andhra Pradesh receives most of the Oct-Dec rainfall in October which is 219.1 out of 302.1 mm, 72.5% of seasonal total. Nellore in south Coastal Andhra Pradesh receives maximum rainfall in November with a seasonal total of 659.5 mm. Tirupathi in Rayalaseema receives 468.9 mm during Oct-Dec with both October and November contributing almost same quantum. Bangalore in South Interior Karnataka receives 248.7 mm during Oct-Dec with 170.6 mm or 68.6 % realised in October itself. In Kerala the northern station of Kozhikode and the southernmost station of Thiruvananthapuram receive 438.4 and 527.7 mm respectively during Oct-Dec. Thiruvananthapuram receives more rainfall in Nov-Dec than Kozhikode.

As shown in Fig. 2 parts of Kerala and Coastal Tamil Nadu receive more than 50 cm rainfall during Oct-Dec, a belt of Coastal Tamil Nadu realises more than 75 cm with a small strip receiving close to 100 cm rainfall. It must be noted that not all the rainfall of October could be attributed to northeast monsoon and that in the first half of October the continuation of southwest monsoon from September also contributes to the rainfall realisation. It has been shown by Geetha and Raj (2014) that the contribution of southwest monsoon rainfall in October is nearly 15% of Oct-Dec rainfall of SPR. For the state and sub-division of Tamil Nadu the Oct-Dec northeast monsoon season is the major rainy season besides manifesting several well defined characteristics of this monsoon. A noticeable climate feature within SPR is that the feature of winter rainfall of Oct-Mar exceeding the summer rainfall of Apr-Sep is realised over most parts of Coastal Tamil Nadu and south Coastal Andhra Pradesh. As such these regions experience the Koppen’s climate classification designated as Aw', a distinct and unique climate feature specific to this region only, within India.

TABLE 1b

Normal monthly seasonal and annual rainfall (in mm) of selected stations of the five meteorological sub-divisions of SPR (based on 1951-2000 data)

Month / Season	Station and sub-divisions										
	MDS	VRM	TTC	CMB	TRP	NLR	VSK	TPT	BNG	KZK	TRV
	TN	TN	TN	TN	TN	CAP	CAP	RYS	SIK	KER	KER
Oct	274.1	254.6	149.3	146.6	165.2	260.0	219.1	195.0	170.6	273.1	270.1
Nov	419.7	436.3	198.3	116.5	134.1	295.1	75.5	183.0	57.2	131.7	192.0
Dec	162.9	347.4	92.3	45.8	93.8	104.4	7.5	90.9	20.9	33.6	65.6
OND	856.7	1038.3	439.9	308.9	393.1	659.5	302.1	468.9	248.7	438.4	527.7
Annual	1402.7	1477.0	630.5	613.8	872.3	1062.5	993.1	953.7	977.4	3175.8	1792.0
Rainfall as % of OND RF											
Oct	32.0	24.5	33.9	47.5	42.0	39.4	72.5	41.6	68.6	62.3	51.2
Nov	49.0	42.0	45.1	37.7	34.1	44.7	25.0	39.0	23.0	30.0	36.4
Dec	19.0	33.5	21.0	14.8	23.9	15.8	2.5	19.4	8.4	7.7	12.4
OND Rainfall as % of Annual RF											
OND	61.1	70.3	69.8	50.3	45.1	62.1	30.4	49.2	25.4	13.8	29.4

TN, CAP, RYS, SIK, KER, OND - As in TABLE 1a. For station locations Fig.1b may be referred.

3. Historical references

In the Tamil literary epic Tholkappiyam considered to be more than 2000 years old, there is a reference to the Tamil months Aippasi and Karthigai which by and large correspond to the period 15 Oct - 15 Dec, as a distinct season. In another Tamil epic Agananooru which belongs to the time period of B. C, there is a reference to cold north winds and rain occurring simultaneously. In another epic Kurunthogai, considered to be more than 1800 years old, the poet's description of the cold northerly winds chasing the rain clouds towards south is an apparent reference to northeast monsoon, the major monsoon for Tamil Nadu. In Tamil Sangam literature there is an age old adage saying that 'Aippasi maadham adai mazhai and Karthigai maadham gana mazhai' (In Aippasi month there is heavy rain, in Karthigai month there is very heavy rain) connoting the occurrence of heavy rainfall during northeast monsoon season.

Blanford (1886) in his memoirs has used the term northeast monsoon and described the rainfall as Carnatic rains as quoted by Srinivasan *et al*. (1973). In the early years of 20th century IMD publications such as Indian Daily Weather Report took the period up to 15 October as the southwest monsoon season and the period subsequent to that as post-monsoon or retreating southwest monsoon or northeast monsoon over the southern peninsula.

4. Definitions of certain terminologies used by IMD

The definitions, acronyms and terminologies used in IMD's bulletins are presented in this section as given in the various publications of IMD (IMD, 2003 and Glossary).

The daily rainfall of a station is defined as the cumulated rainfall of 24 hrs ending at 0830 hrs IST of that day. If the daily rainfall of a station is more than or equal to 2.5 mm, the day is called a rainy day. For a region such as state or meteorological sub-division, IMD describes the rainfall distribution of a day in terms of the percentage of number of stations of that region receiving 2.5 mm daily rainfall or more. The distribution over a region is described as widespread (WS) if the percentage is 76-100, fairly widespread (FWS) if 51-75, scattered if 26-50, isolated if 1-25 and dry if it is 0. If the daily rainfall of a station is 64.5-115.5 mm it is defined as heavy rainfall (HRF), if 115.6-204.4 mm as Very HRF (VHRF) and if $\geq$ 204.5 mm as extremely heavy rainfall (EHRF). The daily rainfall of a meteorological sub-division is computed as the mean daily rainfall of the various stations it represents and expressed as the percentage of the long period average (LPA). During monsoon season if the daily rainfall is 0.5-1.5 LPA, monsoon is described as normal and weak if it is below 0.5. If the daily rainfall distribution is WS or FWS over a region and if the realized rainfall is 1.5-4 LPA, monsoon is described as active and if more than 4 LPA as vigorous. The seasonal rainfall of a sub-division is described in terms of the percentage departure from normal (PDN) of the realised rainfall which is defined as excess if PDN $\geq$ 20, normal if it is -19 to 19, deficient if $\leq$ -20, and scanty if $\leq$ -60. For Jun-Sep Indian southwest monsoon rainfall (ISMR) of entire India, ISMR is defined as excess if the PDN is $\geq$ 10, normal if it is -10 to 10 and deficient if it is $\leq$ -10. Oct-Dec northeast monsoon rainfall of Tamil Nadu and SPR are abbreviated as NMR TN and NMR SPR respectively.

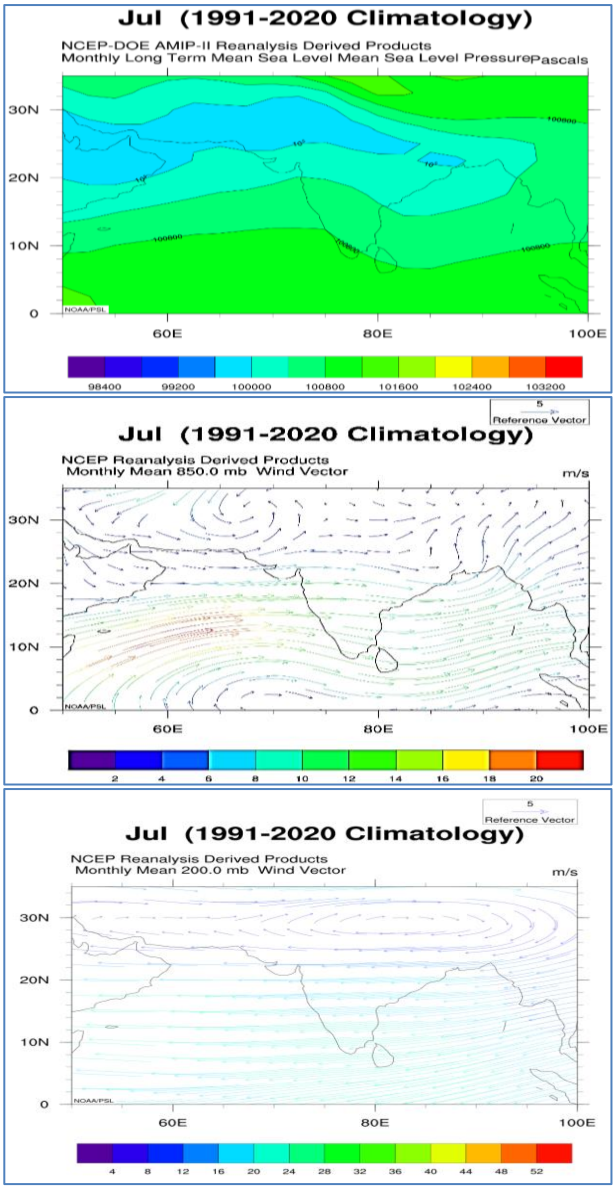

Fig. 3a. Normal July mslp, 850 hPa and 200 hPa winds.

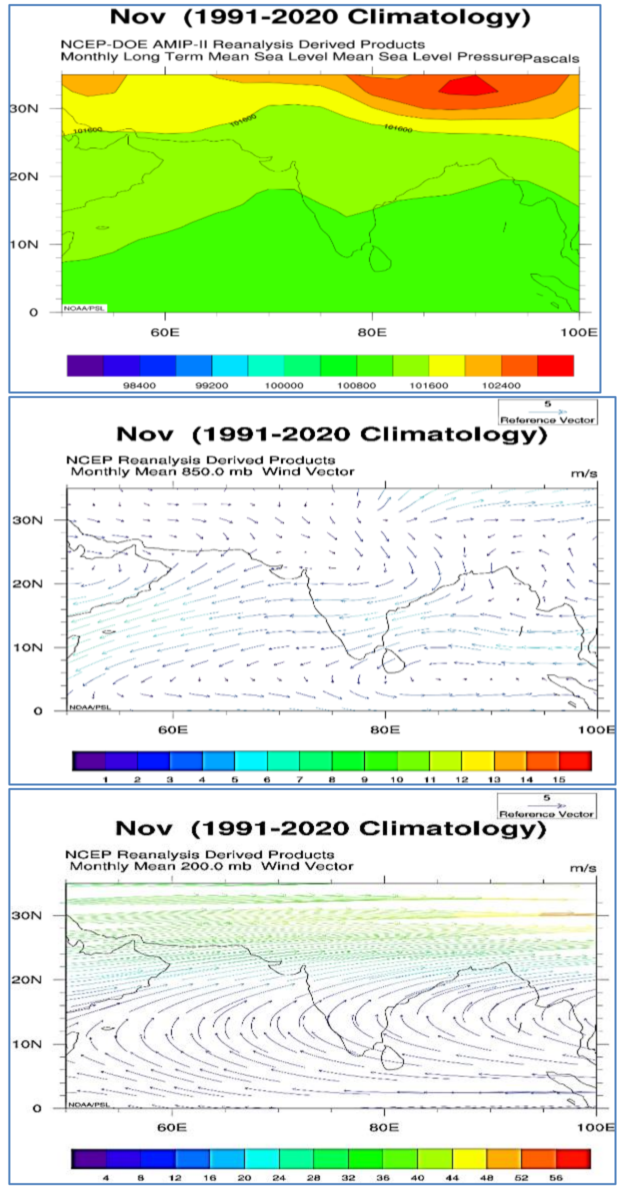

Fig. 3b. Normal November mslp, 850 hPa and 200 hPa winds.

Cyclonic disturbances when they are over sea are categorised based on the maximum sustained wind speed at the sea surface level in the vicinity of the system. If maximum sustained wind speed is below 17 knots the system is called as low pressure area (lopar), 18-27 knots as depression (D), 28-33 as deep depression (DD), 34-47 as cyclonic storm (CS), 48-63 as severe cyclonic storm (SCS), 64-89 as very severe cyclonic storm (VSCS), 90-119 as extremely severe cyclonic storm (ESCS) and if 120 knots and above as Super cyclonic storm (SuCS).

5. Various features of northeast monsoon

In the sub-sections of this section several aspects of northeast monsoon which are based on the various IMD publications, reports, published books and research papers are presented.

5.1. *Reversal of pressure gradient and wind pattern over India from summer to winter*

Figs. 3a and 3b show the normal msl pressure distribution, wind flow at 850 hPa and 200 hPa levels over the extended Indian region for the months of July and November which could be taken as the representative months of southwest and northeast monsoon seasons respectively. As shown, in July msl pressures are lowest over northwest Indian region and the adjoining Pakistan reaching less than 1000 hPa. The pressure increases as one moves to the southern latitudes. At 850 hPa level the winds

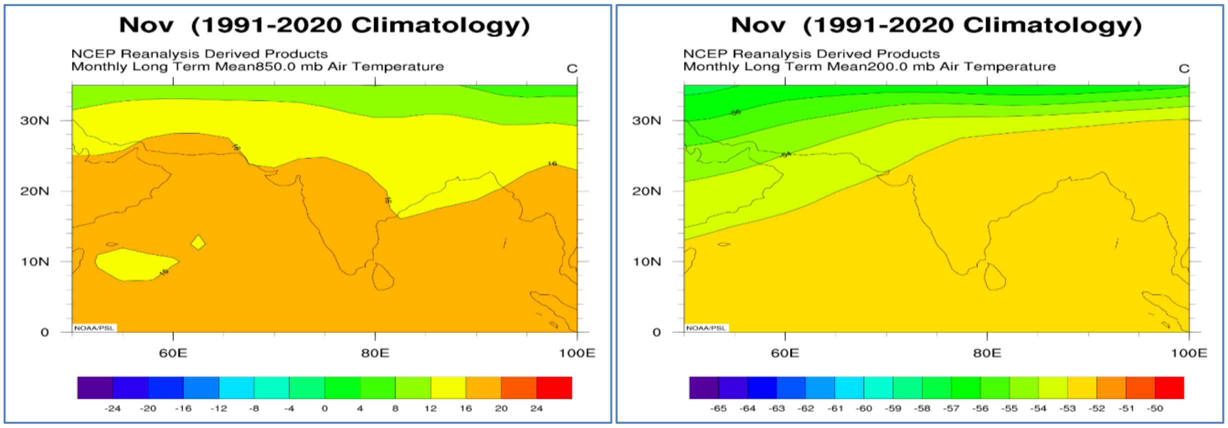

Fig. 4. November climatology of temperature at 850 hPa and 200 hPa levels.

are strong southwesterlies with speeds reaching up to 10-12 m/s (20-24 knots) over the peninsula which tend to become easterlies in the higher latitudes north of the trough which is the monsoon trough. In the upper troposphere at 200 hPa level, the winds are strong easterlies reaching speeds of 25 m/s or nearly 50 knots which is the Tropical Easterly Jet, an important southwest monsoon component with its core at 150 hPa level.

In November the July pattern gets reversed. The msl pressure is higher over northwest India reaching close to 1020 hPa and decreases towards south to around 1008 hPa south of 10º N. At 850 hPa level, winds are easterlies or northeasterlies over the peninsula and over south and central Bay of Bengal. Over northern latitudes westerlies prevail resulting from the transposition of the high pressure area over the northwest region. Winds reverse to westerlies again south of the Inter Tropical Convergence Zone or the equatorial trough lying close to the equator roughly along 4º N. In the upper troposphere, winds are strong westerlies over the northern parts with speeds up to 30-40 m/s (60-80 knots) forming the Sub-Tropical Westerly Jet Stream. Over the peninsula the east-west sub-tropical ridge is present with easterlies to the south. As the northeast monsoon season advances from October to December this ridge moves southwards. The movement of the equatorial trough from higher latitudes in July to near equator in November is by and large in synchronisation with the movement of the sun from north to south. Rao (1976) presents a detailed description of wind flow during southwest monsoon season. Srinivasan *et al*. (1973) and Rajeevan *et al*. (2022) describe in detail monthly surface pressure distribution and upper wind flow at various pressure levels during northeast monsoon season.

5.2. Upper air temperature and thermodynamic features

Fig. 4 presents the normal temperature distribution over India at 850 and 200 hPa levels in November. At 850 hPa level the temperature is 8-12 ºC over extreme north and is more than 16 ºC over the peninsula. At 200 hPa level the temperature is -56 ºC over the northern parts and is around -52 ºC over the peninsula. The cooling of the atmosphere over the northern latitudes compared to southern latitudes at both lower and upper tropospheric levels is evident. The sea surface temperature (SST) over Bay of Bengal off Tamil Nadu coast varies from 28-26 ºC during Oct-Dec. It drops over higher latitudes reaching around 25 ºC over head Bay of Bengal in December. The mean liquid water content over the peninsular India and adjoining Bay of Bengal during Oct-Dec is shown to vary from 40-50 mm with higher values over the ocean, based mainly on remote sensed data (Rajeevan *et al*., 2022). Overall the northeast monsoon is a shallow monsoon with lower moisture depth when compared to the preceding southwest monsoon.

5.3. *Onset and withdrawal of northeast monsoon*

The southwest monsoon normally withdraws from entire India by 15 October when rainfall shows a marked decrease in most sub-divisions of peninsular India. In SPR the rainfall continues in the first half of October also in association with low level westerlies. At 13º N the lower level winds including the surface winds over Bay of Bengal reverse to northeasterlies around 15 October. After this episode there is a marked and well defined increase in rainfall especially over Coastal Tamil Nadu and South Coastal Andhra Pradesh which is called the onset of northeast monsoon.

It is interesting to note that the phrase northeast monsoon onset was used by IMD in its daily bulletins as early as in 1923, the Indian Daily Weather Report of this year on 15 October contains a statement that 'northeast monsoon has set in over Tamil Nadu'. Subsequently mention about northeast monsoon onset could be found in some years and not found in other years. From 1981, northeast monsoon onset declaration was regularly done by

IMD. As per Srinivasan *et al*. (1973) IMD had no well defined criteria to declare northeast monsoon onset and this status continued up to the late 1980s. The Forecasting Officers' Conference of IMD held in 1987 laid out a few requirements (IMD, 1987) for the onset declaration. The gist of the recommendations is that after the withdrawal of southwest monsoon over the entire India and firm establishment of low level easterlies over the Chennai latitude and the adjoining Bay of Bengal, the first date of fairly widespread rainfall (Sec.4) would be the date of northeast monsoon onset. By and large based on these recommendations the onset dates of northeast monsoon over Coastal Tamil Nadu were determined for each year of 1901-90 based on the analysis of daily rainfall of 4-6 stations for the period 1 Sep-28 Feb in Raj (1992) and the dates were given for each year in tabular format.

The withdrawal of northeast monsoon is not as well defined as that of the onset which is preceded by the reversal of low level winds from southwesterlies to northeasterlies over the peninsular India. There is no similar well defined synoptic event associated with withdrawal. The low level winds which establish during October over the peninsula continue to blow up to mid-April of next calendar year though rains by and large cease during Dec-Jan. The withdrawal of northeast monsoon was not specifically mentioned in IMD's bulletins up to 1989 but from 1990 withdrawal was announced based mainly on rainfall considerations though there have been no clear and firm guidelines published by IMD on the declaration of withdrawal dates.

In Raj (1998b) the determination of withdrawal dates of northeast monsoon for the period 1901-90 based on daily rainfall data of 4-6 stations was carried out by defining a Daily Rainfall Index for a pentad. The Daily Rainfall Index varies between 0 and 100 and is defined as the percentage of rainy days in an aggregate of daily rainfall data of 4-6 stations of Coastal Tamil Nadu in a 5 day overlapping pentad during 1 Nov - 28 Feb. If Daily Rainfall Index ≥ 40, then northeast monsoon is taken as prevailing during that pentad. The last pentad with Daily Rainfall Index ≥ 40 is the withdrawal pentad and the date of withdrawal then fixed by studying the daily rainfall distribution for the 5 days. The process of determination of withdrawal date is not as precise as that of onset. This methodology based on Daily Rainfall Index can be invoked only after the season is over and the rainfall data for the entire season becomes available.

In subsequent studies onset and withdrawal dates were determined for 1991-2000 and presented in Raj (2003) along with statistics for the century period 1901-2000. In Geetha and Raj (2015) the onset and withdrawal dates were re-determined by using daily rainfall data of 25 stations, extending the period backwards into 1871-1900 and further into 2001-10 and listing the dates for the 140 year period 1871-2010. Satyanarayana *et al*. (2020) determined onset dates of northeast monsoon over SPR for the period 1994-2014 by analysing pentad rainfall, outgoing long wave radiation (OLR) data and circulation features. In Rajeevan *et al*. (2022), determination has been carried out using a slightly different methodology also using OLR data for 1981-2020. In Raj and Amudha (2023) the methodology earlier followed in Raj (1992, 1998b and 2003) was employed to determine onset and withdrawal dates for 2011-20 based on data of 16 stations, to derive dates which were homogenous to the earlier set of dates. The IMD dates of onset have been available since 1981 and withdrawal dates from early 1990s both of which were declared on real time basis. As such in some years there could be difference between IMD dates and other dates determined in a diagnostic study which in a few years is substantial in respect of withdrawal.

Table 2 presents the normal and standard deviations of onset and withdrawal dates determined in the various studies, in a consolidated fashion. As shown the normal date of easterly onset is 14 October and that of northeast monsoon onset is 20 October both with standard deviations of 7-8 days for the 100 year period 1901-2000. The withdrawal date is determined as 27 December with standard deviation of 13-14 days. During 1901-2000 the earliest onset was on 4 October 1999 and the most delayed withdrawal was on 28 January 1934. The study by Geetha and Raj (2015) based on 1871-2010 data yielded normal onset date of 19 October, withdrawal date of 28 December, normal date of withdrawal from north Coastal Tamil Nadu as 17 Dec and that over central and south Coastal Tamil Nadu as 31 December, the latter taking place 14 days after the former. Satyanarayana *et al*. (2020) derived 19 October as the normal onset date. Rajeevan *et al*. (2022) obtained 22 October as the normal date with standard deviation of 6-7 days. The IMD onset dates declared on real time basis, for 1990-2020 yielded normal onset and withdrawal dates of 22 October and 5 January respectively.

Taking into consideration the results from all the studies, the normal date of northeast monsoon onset could be taken as 20 October over South Coastal Andhra Pradesh and Coastal Tamil Nadu and withdrawal as taking place during the pentad 26-30 December. If withdrawal from sub-Coastal Tamil Nadu level is considered the northern parts experience 2 week early withdrawal than the central and southern parts. The standard deviation of date of withdrawal is higher at 12-14 days compared to onset dates. Though the duration of northeast monsoon is taken as the period 1 Oct- 31 Dec, it has been shown that the monsoon spills over to the January of next calendar year in one third of the years (Raj, 1998b).

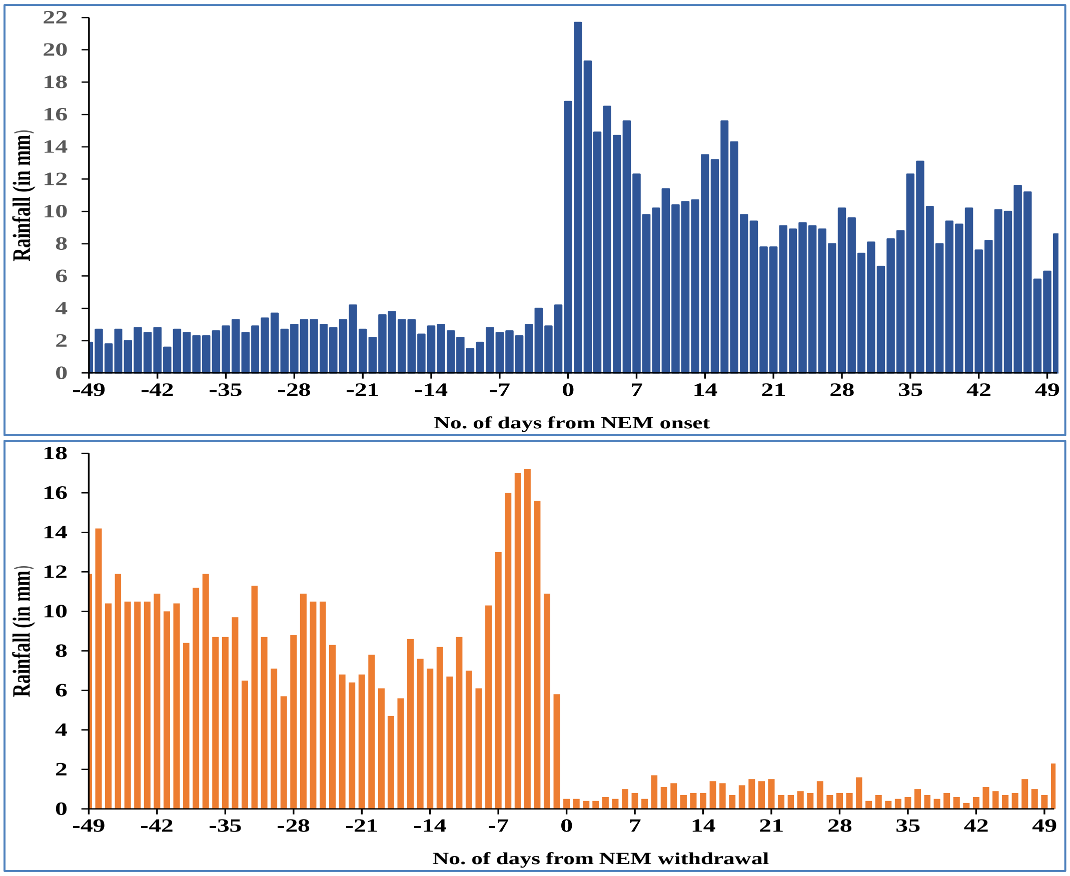

Fig. 5. Mean daily rainfall over coastal Tamil Nadu with respect to northeast monsoon onset/withdrawal dates. Superposed epoch analysis based on 1901-2000 data (0 – date of onset / withdrawal).

TABLE 2

Normal onset and withdrawal dates of northeast monsoon as derived in various studies (1871-2020)

Study	Period	Region	Parameter	Normal Date	SD (days)
Raj (1992, 1998, 2003)	1901-2000	CTN	EO	14 Oct	7-8
			O	20 Oct	7-8
			W	27 Dec	13-14
Geetha and Raj (2015)	1871-2010	CTN & SCAP	O	19 Oct	7-8
		CTN & SCAP	W	28 Dec	13-14
	1961-2010	NCTN	W	17 Dec	15
		SCCTN	W	31 Dec	13
Satyanarayana *et al*. (2020)	1994-2014	SPR	O	19 Oct	
Rajeevan *et al*. (2023)	1981-2020	CTN & SCAP	O	22 Oct	6-7
Raj & Amudha (2023)	2011-20	CTN	EO	20 Oct	
			O	23 Oct	
			W	31 Oct	
		NCTN	W	23 Dec	
		SCCTN	W	05 Jan	
IMD	1990-2020	TN	O	22 Oct	6-7
			W	05 Jan	10-11

TN – Tamil Nadu, CTN - Coastal TN , SPR- Southern Peninsular Region, NCTN – North CTN, SCAP – South Coastal Andhra Pradesh, SCCTN - South and Central CTN, EO – Easterly onset, O/ W – Northeast monsoon onset / withdrawal IMD : India Meteorological Department SD- Standard Deviation

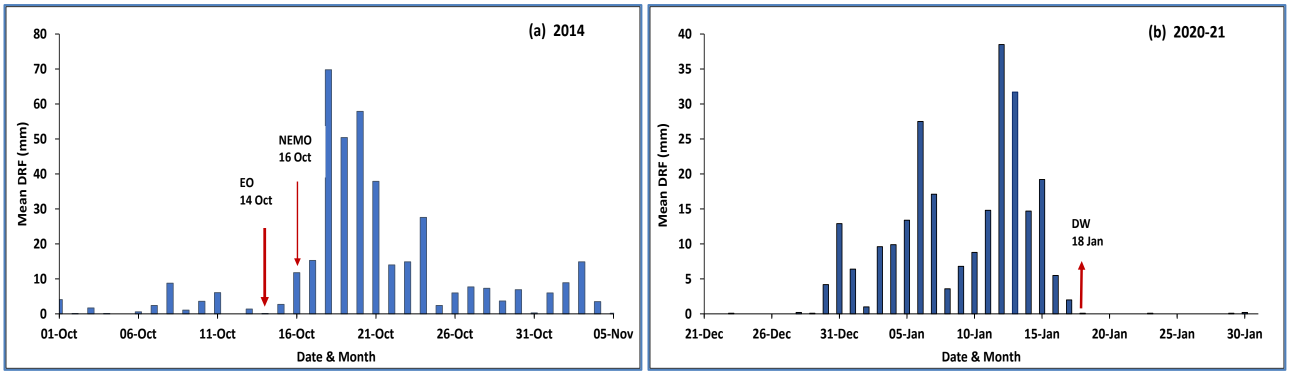

Fig. 6. Mean daily rainfall over Coastal Tamil Nadu and south coastal Andhra Pradesh showing **a.** Onset of northeast monsoon in 2014 and **b.** Withdrawal of northeast monsoon during 2020-21 EO- Onset of low level easterlies, NEMO- Northeast monsoon onset DW- Date of withdrawal.

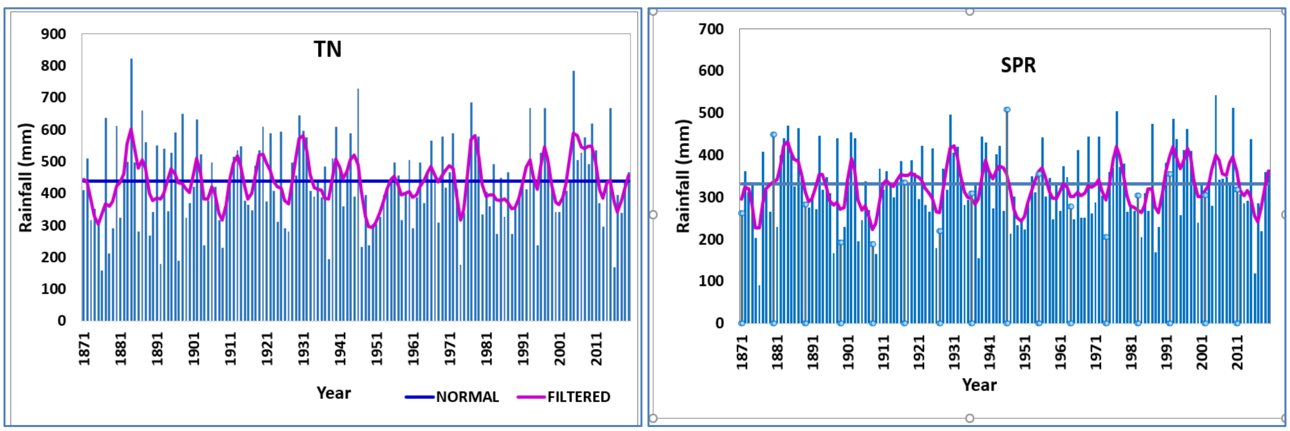

Fig. 7. Time series of northeast monsoon Oct-Dec rainfall over Tamil Nadu and Southern Peninsular Region for 1871-2020. *Bars* : actual rainfall, *Continuous line*: filtered value.

Over Coastal Tamil Nadu the onset of northeast monsoon heralds a dramatic increase in daily rainfall. This is shown by the superposed epoch analysis of daily rainfall of 4-6 stations of Coastal Tamil Nadu for 1901-2000 in which onset date is taken as 0 for each year. Fig. 5 presents the mean daily rainfall profile for 50 days before and after onset and withdrawal dates. The daily rainfall which is 2-4 mm before onset rises to nearly 14 mm after onset which persists for nearly a week but remains close to 10 mm for the 50 day period. After withdrawal the mean daily rainfall is about 1 mm per day.

The onset and withdrawal dates determined in most of the studies listed in Table 2 are for Coastal Tamil Nadu and South Coastal Andhra Pradesh where both the events are well defined. In other regions of SPR the events may not be clearly defined in all the years. In North Kerala and South Interior Karnataka, rainfall in the first half of October is higher than that of the second half. Here northeast monsoon onset could be a subdued process and withdrawal could occur much earlier than the withdrawal over Coastal Tamil Nadu.The normal rainfall in December for Visakhapatnam, Bangalore and Kozhikode (Table 1b) are: 7.5, 20.9 and 33.6 mm respectively alluding to cessation of rains much earlier.

Examples of a well-defined onset and withdrawal are now presented. In the year 2014, low level easterlies established at Chennai latitude on 14 October. IMD declared withdrawal of southwest monsoon and simultaneous onset of northeast monsoon on 18 October. The study by Raj and Amudha (2023) fixed the onset day as 16 October. Fig. 6 presents the mean daily rainfall of South Coastal Andhra Pradesh and Coastal Tamil Nadu based on 16 stations for 1 Oct- 5 Nov. As shown there was sporadic rainfall during 1-15 October. On 16 October FWS rainfall commenced over the coastal belt with isolated HRF and the spell continued beyond 24 October. During 16-24 October the northeast monsoon rains were FWS / WS on 9 days with several occurrences of HRF and VHRF.

Fig. 6 also presents the daily rainfall of 21 Dec 2020-31 Jan 2021. As shown there was little rainfall during 21-29 December. A fresh spell of rainfall which commenced on 30 December continued up to 17 January. During this period there were 9 days of FWS/WS rainfall with several instances of heavy and very heavy rainfall. During 18-31 January there was little rain and so 18 January 2021 was fixed as the date of withdrawal of northeast monsoon 2020-21. However, in this year northeast monsoon withdrew on

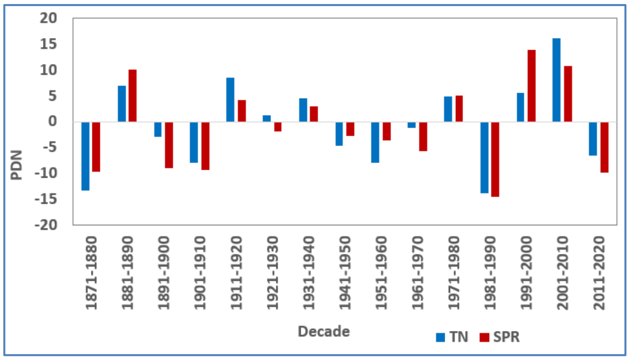

Fig. 8. Decadal means of Oct-Dec northeast monsoon rainfall during 1871-2020. TN - Tamil Nadu, SPR – Southern Peninsular Region, PDN - Rainfall percentage departure from normal.

TABLE 3

Frequency of various categories of Oct-Dec northeast monsoon rainfall (1871-2020)

Category	TN		SPR	
	Frequency No. of years	Percentage frequency (%)	Frequency No. of years	Percentage frequency (%)
Deficient (PDN ≤ -20%)	42	28	36	24
Negative side of normal (-19% <PDN ≤ 0 %)	36	24	40	27
Positive side of normal (0%<PDN≤+19%)	34	23	39	26
Excess (PDN≥ +20%)	38	25	35	23
Total	150	100	150	100

PDN, TN, SPR – As in Table 1a.

10 January itself from northern parts as shown in Raj and Amudha (2023). IMD declared withdrawal on 19 Jan 2021.

5.4. *Inter-annual and decadal variation of rainfall*

In India several rain gauges were installed in the 19th century and daily rainfall data of adequate number of representative stations were available since 1871. Rainfall data of nearly 4000 stations of India has been utilised in the preparation of the Rainfall Atlas of India (IMD, 2023).

To derive the time series of NMR TN and SPR for Oct-Dec for the 150 year period 1871-2020 some basic data analysis was carried out. For 1871-1900, data from Kothwale and Rajeevan (2017), for 1901-2000 sub-division rainfall data provided by National Data Centre, IMD, Pune and for 2001-2020 data available in various IMD reports were retrieved. The data was made homogenous based on the normal rainfall of 1971-2020 Table 1a. The Oct-Dec rainfall time series thus derived for 1871-2020 are presented as bar charts in Fig. 7. Both the series were smoothed with weights (1, 4, 6, 4, 1) and the filtered series are displayed as smooth continuous lines.

The LPA of NMR TN based on the 1871-2020 data, and coefficient of variation are 435.2 mm and 29.8% and similar values for NMR SPR are 326.7 mm and 26.3% respectively. This LPA could slightly differ from the normal values given in Table 1a. The coefficients of variation of Oct-Dec rainfall of the five subdivisions are also given in Table 1a. The figures vary from 29-40% for the five subdivisions. The high variability is indicative of the wide fluctuation the seasonal rainfall experiences from year to year. The correlation coefficient (CC) between NMR TN and NMR SPR based on 150 year data was 0.83 highly significant at 0.1% level of significance. The power spectrum for NMR TN showed periodicities of 14.3, 3.7 and 2.3 years respectively. The periodicity of around 14 years could be a manifestation of the sunspot cycle and that of 2-3 years is normally interpreted as quasi-biennial oscillation. NMR SPR also manifested similar periodicities.

The CC between the NMR TN series and the linear trend line series was 0.05 and same for NMR SPR as well. Thus both the rainfall time series for 150 years displayed no increasing or decreasing trend which definitely is a remarkable feat. But there have been epochs of low and high rainfall as shown in Fig. 8 which displays means of NMR TN and SPR for the 15 decades 1871-80,..,2011-20 in terms of PDN of LPA. For NMR TN the decades 1871-80 and 1981-90 showed deficiency of 13% and 14% respectively. In the decade 2001-2010 rainfall was in excess by 16%. During the 8 year period of 2004-11 NMR TN was in the positive side of normal with as many as 5 excess rainfall years which was a unique occurrence in the long time series. A low rainfall epoch took place during the 8 year period 1947-54 when NMR TN was in the negative side of normal with 5 deficient years (Fig. 7). In Table 3 is presented the statistics on the number of years of excess rainfall, positive departure, negative departure and deficient rainfall. As shown the NMR PDN values are evenly distributed amongst the four categories. For Tamil Nadu that as many as 28% of years could end up with deficient rainfall is a noteworthy feature.

Overall NMR times series for TN and SPR are trend free but manifest secular variations with positive and negative epochs, non -randomness with weak 12-17 and 2-3 year periodicities.

5.5. *Intra-seasonal and diurnal variation*

The northeast monsoon season is interspersed with dry and wet spells and intermediate spells which are neither fully dry nor fully wet. The mean frequencies of vigorous and active northeast monsoon are 9%, 4% and 3% of total number of days for October, November and December respectively for SPR and 16%, 14% and 12% for Tamil

Nadu (Srinivasan *et al.*, 1973). Thus active and vigorous monsoon conditions are more common over Tamil Nadu than over SPR. In December such conditions are confined mainly to Tamil Nadu. The frequencies of weak monsoon or completely dry weather days are 43%, 51% and 60% for Tamil Nadu and 58%, 74% and 80% for SPR respectively. Northeast monsoon dry spells could sometimes last so long in Tamil Nadu which is generally not the case even for southwest monsoon season. That the former is a winter monsoon and the latter summer monsoon appears to be a reason for such long dry spells.

Rajeevan *et al*. (2022) have reported the presence of 30-40 day periodicity in NMR. Sreekala *et al*. (2018) have suggested that such intra -seasonal variation is influenced by the well-known Madden-Julian Oscillation. In Raj (2003) it is shown that the daily rainfall anomalies of Coastal Tamil Nadu for 1-Sep-28 Feb exhibit a 30-40 day periodicity as revealed by harmonic / spectral analysis and that there is some clear signal of south to north movement. The rainfall anomalies took 2-3 days to travel from Pamban (9.2º N) to Chennai (13.0º N).

The northeast monsoon rainfall displays a significant diurnal variation signal. Srinivasan *et al*. (1973) reported that northeast monsoon rainfall occurrence is more in the night and early morning than during the day. Rajeevan *et al*. (2022) based on conventional rainfall data over land and remote sensed rainfall data over Bay of Bengal reported that NMR displays early morning maximum over oceans and coastal areas whereas interior stations display late evening and early night peak. Raj and Amudha (2022) studied the diurnal variation of Oct-Dec rainfall of Chennai, Nagapattinam and Pamban observatories (Fig. 1b) all located over Coastal Tamil Nadu, based on more than 45 years of hourly rainfall data. Early morning rainfall peak in all the stations with strong signal in October decreasing in November and further in December was detected. The signal was strong in Nagapattinam and Pamban than in Chennai where there was a secondary afternoon peak. Generally oceanic convection reaches maximum in the early morning and stations with a maritime climate manifest this feature which partly explains the morning peak. The secondary peak could be attributed to afternoon convection (Haurwitz and Austin, 1944 and Johnson, 2011).

5.6. *Frequency of occurrence of heavy rain*

Once the northeast monsoon is established, rainfall is generally heavier over Coastal Tamil Nadu and South Coastal Andhra Pradesh than over interior parts during wet spells. Occurrence of HRF, VHRF and sometimes EHRF is common during the season especially over Coastal Tamil Nadu. It is found from climatic data (IMD, 2022) that the Coastal Andhra Pradesh and the Coastal Tamil Nadu belt of Chennai to Nagapattinam has recorded instances of EHRF. For *e.g*. for Nagapattinam the heaviest daily rainfall figures are 397.8, 365.5 and 402.6 mm for October, November and December respectively. For Thoothukudi located in the extreme south these are 167.4, 183.4 and 188.2 mm respectively. For Nellore (444.0, 523.4 and 189.2 mm) and Visakhapatnam (371.2, 201.6 and 114.7 mm) such high rainfall figures are associated with cyclone landfall. In Coastal Tamil Nadu however, EHRF has been frequently realised without being associated with Bay of Bengal cyclones or their crossing the coast.

Raj and Amudha (2023) have studied the HRF occurrences during northeast monsoon season for the 10 year period 2011-20 based on the data of 16 well distributed stations of South Coastal Andhra Pradesh and Coastal Tamil Nadu. The frequencies of HRF and higher categories are 128, 180 and 121 for the months of October, November and December respectively for 10 years and 16 stations. The total frequency of HRF from 1 October up to the previous day of northeast monsoon onset is just 15. It is 427 from date of onset to withdrawal with 15 EHRF occurrences. The frequency of HRF for a single station for 1 October to the preceding day of onset date increases from 0.42% to 8.42% during the 7 day period commencing from the onset date. The frequency is 3.62% from onset to withdrawal date. These figures clearly testify to the higher probability of HRF over south Coastal Andhra Pradesh and Coastal Tamil Nadu during northeast monsoon especially during the post-onset rain spell.

5.7. *Components that influence northeast monsoon activity*

The southwest monsoon is associated with several semi-permanent synoptic systems called monsoon components. Easterly Jet Stream over the peninsular India (150 hPa level) and Mascarene High over Indian Ocean adjacent to Madagascar Island (surface level) are two such components. The transpositions and strength of these semi-permanent systems are known to influence the activity and strength of monsoon (Rao, 1976, Das,1986 and Asnani, 2005).

According to Krishnamurthy (1979) and Das (1986), the northern hemispheric Sub-tropical winter Westerly Jet Stream of upper troposphere with core at 200 hPa level and the Siberian High pressure area at surface level over the Siberian land mass of Russia could be considered as components of South Asian northeast monsoon and that these two features are respectively analogous to the Easterly Jet Stream and the Mascarene High of southwest monsoon. An intense Siberian High is associated with colder temperature anomalies over the Siberian region and could trigger cold surges travelling towards equator

TABLE 4a

Normal monthly position of formation of depressions during northeast monsoon season

Basin/Month	BoB		AS	
	Lon (ºE)	Lat (ºN)	Lon	Lat
Oct	87.7	13.9	68.9	13.7
Nov	89.0	10.2	68.1	11.1
Dec	87.9	7.7	71.3	7.7

Based on 1961-2010 data BoB- Bay of Bengal, AS – Arabian Sea

TABLE 4b

Frequency of cyclonic disturbances formed over North Indian Ocean for various intensities during Oct-Dec 1971-2020

Basin	BoB			AS			Land
Intensity Month	A	B	C	A	B	C	A
Oct	67	29	15	29	17	11	2
Nov	70	53	38	23	8	7	1
Dec	31	18	12	10	3	2	1
OND	168	100	65	62	28	20	4

A-D+CS+SCS B: CS+SCS C: SCS D –Depression, CS Cyclonic Storm, SCS -Severe Cyclonic Storm BoB- Bay of Bengal, AS-Arabian Sea

TABLE 4c

Frequency of landfall of cyclonic disturbances that formed over North Indian Ocean during Oct-Dec 1971-2020

Coast / Basin Intensity (At crossing)	Bay of Bengal and Land							
	TN	CAP	Odisha	WB	BD	Arakan	SL	All
D+CS+SCS	33	47	13	9	22	1	12	137
CS+SCS	18	25	9	5	13	1	5	76
SCS	14	15	7	4	9	1	2	52

Coast/ Basin Intensity (At crossing)	Arabian Sea					
	CK	K&G	Gujarat	Pakistan	IAA	All
D+CS+SCS	2	1	7	1	10	21
CS+SCS	0	1	4	0	5	10
SCS	0	0	3	0	1	4

TN – Tamil Nadu, CAP – Coastal Andhra Pradesh, WB- West Bengal, BD- Bangladesh, SL – Sri Lanka, CK- Coastal Karnataka, K&G – Konkan and Goa, IAA – Iran, Arabia & Africa.

strengthening the northeast monsoon over Southeast Asia. Raj and Geetha (2008) showed that surface pressure over Siberian High in September exhibits positive relation with NMR TN, higher pressure associated with more rainfall. A strong Westerly Jet which is conceptually associated with colder temperatures over northern latitudes must favour good South Asian northeast monsoon which might reflect on Indian northeast monsoon as well.

5.8. *Weather systems that cause rainfall during northeast monsoon season*

The weather systems that give rise to rainfall during northeast monsoon could be broadly categorised as: cyclones and depressions, low pressure areas trough of lows and easterly waves. Strong northeasterly winds over Bay of Bengal in the lower levels of the atmosphere can also cause active northeast monsoon conditions. These systems are discussed briefly in this section.

5.8.1. *Cyclones and Depressions*

Cyclones are the most important weather systems during northeast monsoon season. Nearly 10% of the Oct-Dec seasonal rainfall over SPR could be attributed to cyclones and depressions that cross SPR coasts or come closer and affect the region (Geetha and Raj, 2014). A cyclonic disturbance forms as a feeble low-pressure area along the equatorial trough, becomes a well-marked low and then as a depression with a clearly defined centre. The online application, Cyclone eAtlas-IMD (2008) can generate tracks and statistics of cyclones and depressions which formed and moved over North Indian Ocean since the year 1891. The tracks of cyclonic disturbances prepared by IMD since 1964 have been based on satellite imageries and are very accurate. Since 1982, INSAT imageries have been available which not only give precise location of the cyclone centre on a continuous basis but also provide estimates of several other parameters within the cyclone field.

Bay of Bengal and Arabian Sea are the major basins of formation of cyclonic disturbances which affect India during Oct-Dec. In Table 4a is presented the normal longitudinal and latitudinal positions of formation of depressions over both the basins based on 1961-2010 data (Raj, 2011). As shown, over Bay of Bengal the longitude of formation is 88-89º E but the latitude which is 13.9º N in October shifts south to 11.1º N in November and further down to 7.7º N in December. Once a system forms over Bay of Bengal, it normally moves towards higher latitudes in various directions. The system then crosses one of the coasts of the littoral states of Bay of Bengal (Fig. 1a) and dissipate over land or in less number of cases dissipates over the ocean itself. Over Arabian Sea the longitude of formation is 68-71º E but the latitudinal position shifts southwards from 13.7º N in Oct to 11.1º N in Nov and thence to 7.7º N in Dec. The normal speed of movement of a cyclonic disturbance during Oct-Dec in North Indian Ocean is 12-14 kmph though this varies with basin, month, longitude and latitude.

Table 4b shows the statistics of frequency of cyclonic disturbances that formed over Bay of Bengal and Arabian Sea in Oct, Nov, Dec and Oct-Dec for the 50 year period 1971-2020 generated from Cyclone eAtlas – IMD. As shown 168 depressions formed over Bay of Bengal out of which 100 and 65 intensified to CS and SCS categories respectively.

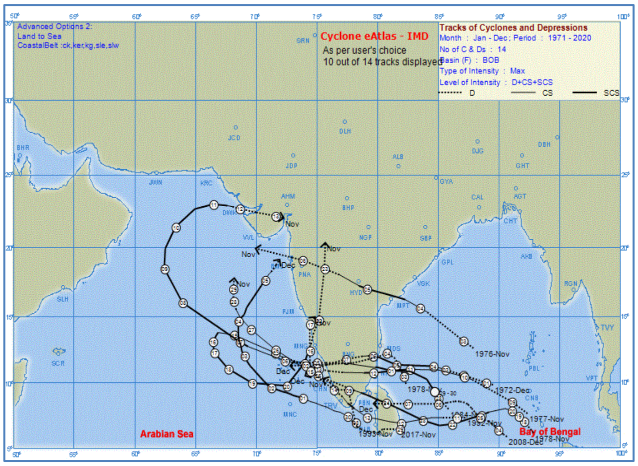

Fig. 9. Tracks of 10 cyclones and depressions that formed over Bay of Bengal and moved over to Arabian Sea.

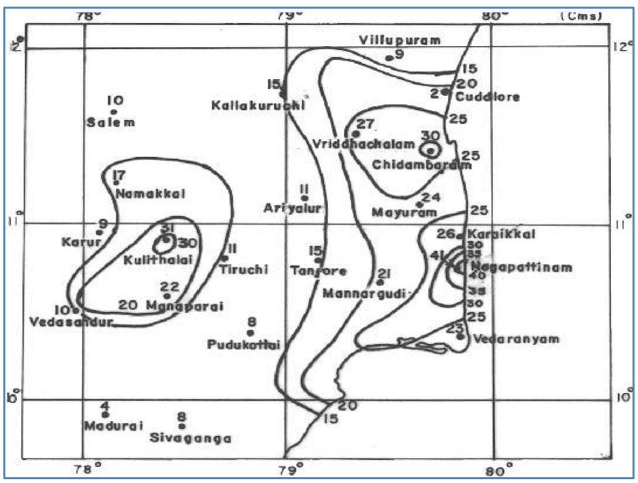

Fig. 10. Distribution of 2-day rainfall (cm) 12-13 Nov 1977 over TN.

Similar figures for Arabian Sea are 62, 28, 20 respectively. As such 3-4 systems form over Bay of Bengal on an average every year with 2 and 1-2 occurrences of CS and SCS respectively. The figures for Arabian Sea are much lower at 1.2, 0.5 CS and 0.4 SCS per year.

In Table 4c frequencies of cyclonic disturbances that crossed the various coasts during Oct-Dec 1971-2020 are given. Taking the intensity at the time of coastal crossing, the frequencies of D+CS+SCS, CS+SCS and SCS which formed in Bay of Bengal or Sri Lankan land mass and crossed Tamil Nadu coast are respectively 33, 18 and 14 thus less than one cyclonic disturbance per year and one SCS for 3-4 years. The frequencies for Coastal Andhra Pradesh are higher at 47, 25 and 15 respectively. There is another peak corresponding to Bangladesh coast for which the frequencies are 22, 13 and 9 respectively. The frequencies of landfall for coasts of Arabian Sea are 7, 4 and 3 for Gujarat, 10, 5 and 1 for combined Iran, Arabia and African coasts. For all the coasts combined the frequencies are 137, 76 and 52 for Bay of Bengal and Land and 21, 10 and 4 for Arabian Sea respectively. During Oct-Dec, the chance of a cyclonic disturbance which forms over Bay of Bengal to cross coast is 81.5% whereas similar figure for an Arabian Sea cyclonic disturbance is 32.3% only. Most of the cyclonic disturbances forming over Arabian Sea dissipate over the sea itself.

Whether there is any trend in the frequency of cyclonic disturbances forming over North Indian Ocean and crossing coasts is a question which could be raised. The frequencies of the cyclonic disturbances formed over North Indian Ocean during Oct-Dec for the decades 1971-80, 1981-90, 1991-2000, 2001-10 and 2011-20 are 58, 48, 43, 36 and 49 respectively. The frequencies of coastal crossing are 38, 32, 32, 22 and 30 respectively. Thus 234 cyclonic disturbances developed over North Indian Ocean and 154 crossed coast during Oct-Dec 1971-2020. There appears to be no significant trend in the decadal frequencies of formation as well as coastal crossing.

In Fig. 9 the tracks of 10 cyclonic disturbances that formed over Bay of Bengal crossed coast and re-emerged into Arabian Sea during 1971-2020 are presented. Out of these 10, 3 crossed west coast again and entered into Indian land mass. The Nov 1977 cyclone executed an anti-clockwise loop over Arabian Sea and crossed west coast again. Over west coast of India, Coastal Karnataka was crossed by 2 cyclonic disturbances with depression intensity which are the only cyclonic disturbances crossing this coastal belt. Frequency of cyclonic disturbances forming over Arabian Sea and crossing Coastal Karnataka or Kerala is nil. There have been 8 instances of cyclonic disturbances crossing Kerala coast from land area and emerging into the Arabian Sea.

The three important weather phenomena which cause extensive damage in association with the landfall of a cyclonic disturbance are: strong gale force surface winds, heavy rainfall and storm surge. But sometimes a very intense cyclone is associated with light rainfall only whereas a not so intense cyclone can cause torrential rainfall over a large region. A few examples illustrating the rainfall distribution associated with cyclone landfall are presented below.

Fig. 10 presents the rainfall distribution for 2 days during 12-13 Nov 1977 corresponding to the landfall of an SCS that crossed Tamil Nadu coast near Nagapattinam during 11-12 Nov 1977 (Raghavan *et al*., 1979) (Fig. 9). Rainfall in the range of 30-40 cm occurred in the vicinity of landfall. Secondary maxima of 25-30 cm rainfall is observed northwards near Chidambaram and up to 30 cm is observed westwards near Kulithalai. The rainfall associated with the landfall of a northeast monsoon cyclonic disturbance extends considerably towards northern latitude and less towards southern latitudes. Fig. 10 provides an example of this climatic feature.

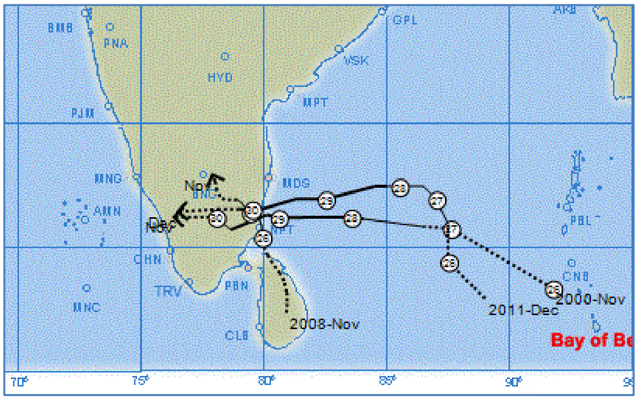

Fig.11. Tracks of Nov 2000 cyclone, Nisha (2008) and Thane (2011).

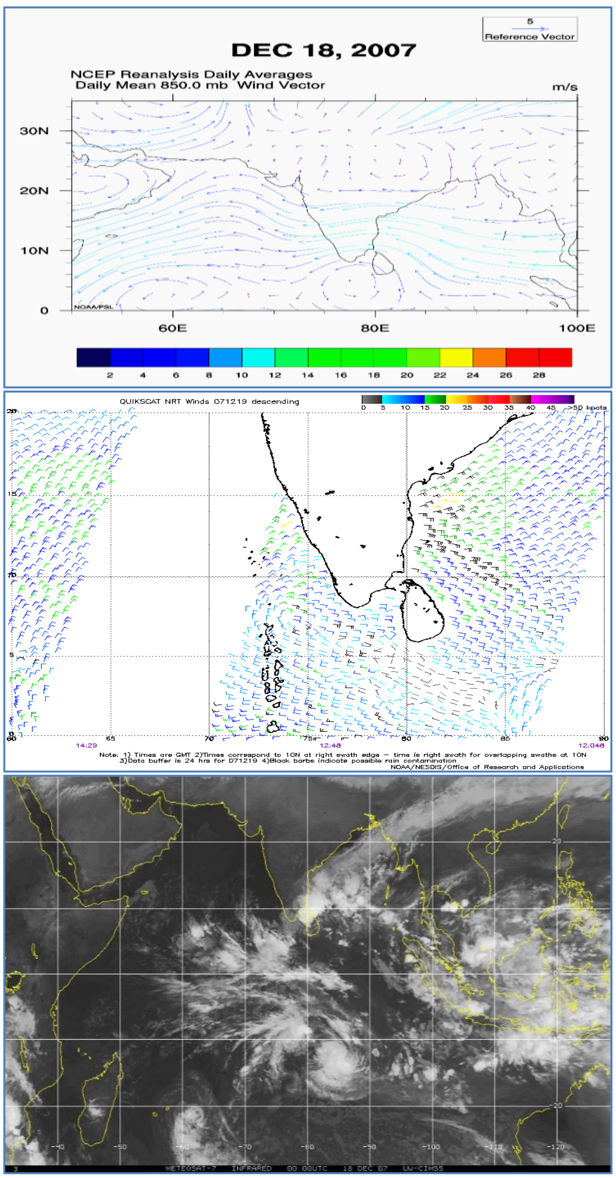

Fig. 12. 850 hPa flow pattern over India, QuikSCAT sea surface winds over Bay of Bengal and Meteosat-7 IR Cloud image on 18 Dec 2007.

Fig. 11 presents the track of cyclone Nisha of 25-28 November 2008. Nisha formed over Sri Lankan land mass entered Palk Strait, reached maximum intensity of only 45 knots and crossed coast near Vedaranyam during 26-27 November. The cumulative rainfall figures during 25-28 Nov 2008 are: Nagapattinam (57 cm), Thiruvarur (56), Thanjavur (58), Cuddalore (44) and Ariyalur (44) (IMD, 2009). Fig. 11 also presents the track of an ESCS of 26-30 November 2000 which reached maximum intensity of 102 knots, crossed north Tamil Nadu coast near Cuddalore and caused considerable damage but the rainfall realised was meagre. During 29-30 November 2000, 4 stations of Coastal Tamil Nadu and South Coastal Andhra Pradesh reported daily rainfall 7-9 cm, 6 stations reported 4-6 cm (IMD, 2001).

In some cases, a cyclonic storm may cause severe weather over Indian land area even if it has not crossed Indian sea coast. The cyclone Ockhi (Fig. 9) formed just east of Sri Lanka as a depression on 29 Nov 2017, crossed both east and west coasts of Sri Lanka moved south of Kanyakumari and intensified into a CS. It gave rise to severe weather over the sea and extreme southern parts of Tamil Nadu, Kerala and caused nearly 300 deaths in India and Sri Lanka. Nearly 500 fishermen who went into the sea were reported missing. Ockhi reached VSCS intensity and weakened off Konkan coast on 5 Dec, 2017 (IMD, 2018).

Unlike the Atlantic and Pacific Oceans which are open in the north, the North Indian Ocean is a sheltered basin bound by land mass in the northern direction. Despite this sheltered geography, cyclones forming over North Indian Ocean especially Bay of Bengal have reached very high intensities reaching up to SuCS level. The list of 22 cyclones which formed over North Indian Ocean during Oct-Dec, 1961-2020 and reached ESCS intensity level (Sec.2) is enumerated in Table 5. Out of these 22, 15 formed over Bay of Bengal and 7 over Arabian Sea. The coasts of Tamil Nadu, Andhra Pradesh, Odisha, West Bengal and Bangladesh were crossed by 3, 4, 4, 1 and 3 ESCS respectively. There were only 2 ESCS over Arabian Sea during 1961-82 but since the year 2014 it has experienced 5 ESCS though most have weakened off coast or moved away towards western direction.

5.8.2. *Low pressure areas, Easterly waves and Upper air circulations*

The normal latitudinal positions of surface equatorial trough over Bay of Bengal in October, November and December are 11.7º N, 6.2º N and 0.7º N respectively (Geetha and Raj, 2009). The lopars generally form just north of the equatorial trough, some oscillate along the trough and some move westwards. A well marked lopar whose centre could be fixed with the help of satellite imageries, can move like a depression and might have a

TABLE 5

Brief history of a few ESCS / SuCS that affected NIO during Oct-Dec, 1961-2020

S.No	Duration and name of ESCS / SuCS	Basin of occurrence	Location of landfall, if crossed coast	Highest MWS (knots)
1	17-24 Dec 1964	BoB	Sri Lanka and Pamban, Tamil Nadu	**150**
2	27 Oct – 1 Nov 1971	BoB	Paradeep, Odisha	**91**
3	14-20 Nov 1977	BoB	Chirala, Andhra Pradesh	**140**
4	18-29 Nov 1978	BoB	Sri Lanka and Pamban, Tamil Nadu	**150**
5	5-11 Dec 1981	BoB	West Bengal	**90**
6	10-14 Nov 1984	BoB	Sriharikota, Andhra Pradesh	**119**
7	15-21 Nov 1992	BoB	Bangladesh	**102**
8	21-25 Nov 1995	BoB	Bangladesh	**102**
9	4-7 Nov 1996	BoB	Kakinada, Andhra Pradesh	**135**
10	15-19 Oct 1999	BoB	Gopalpur, Odisha	**91**
11	25-31 Oct 1999	BoB	Paradeep, Odisha	**140**
12	26-30 Nov 2000	BoB	Cuddalore, Tamil Nadu	**102**
13	11-16 Nov 2007, Sidr	BoB	Bangladesh	**115**
14	08-14 Oct 2013, Phailin	BoB	Gopalpur, Odisha	**115**
15	07-14 Oct 2014, Hudhud	BoB	Visakhapatnam, Andhra Pradesh	**100**
16	19-23 Oct 1975	AS	Porbandar, Gujarat	**90**
17	4-9 Nov 1982	AS	Kodinar, Gujarat	**90**
18	25-31 Oct 2014, Nilofar	AS	Weakened off Gujarat coast	**110**
19	28 Oct -04 Nov 2015, Chapala	AS	Yemen (south of Riyan)	**115**
20	05-10 Nov 2015, Megh	AS	Yemen	**90**
21	24 Oct – 02 Nov 2019, Kyaar	AS	Weakened off Somalia coast	**130**
22	30 Oct – 07 Nov 2019, Maha	AS	Weakened off Gujarat coast	**100**

NIO – North Indian Ocean, MWS – Maximum wind speed (knots), ESCS – Extremely Severe Cyclonic Storm (MWS 90-119) SuCS – Super Cyclonic Storm (MWS 120 and above). BoB and AS – As in Table 4

clear track as well. It may also give rise to good amount of rainfall over SPR especially over the southern areas.

During November and December, the equatorial trough over Bay of Bengal is frequently located south of the Comorin latitude. In the prevalent easterly flow north of the trough at the surface and lower levels, sinusoidal perturbations move from east to west which are called easterly waves. These can be identified and tracked by analysing surface pressure and its 24 hrs change over coastal stations, low level winds of upper air stations, remote sensed surface winds over Bay of Bengal, satellite imageries and NWP model generated charts. The easterly wave can give rise to widespread and heavy rainfall and cause active to vigorous northeast monsoon conditions especially over Coastal Tamil Nadu. Geetha and Balachandran (2014) analysed 3 easterly waves that moved over Bay of Bengal during the northeast monsoon of 2010 and estimated that the mean life cycle was 4.2 days, wavelength was 2800 km and the speed of movement was 7.3 m/s (nearly 15 knots). Upper air cyclonic circulation and troughs over SPR are another set of synoptic systems

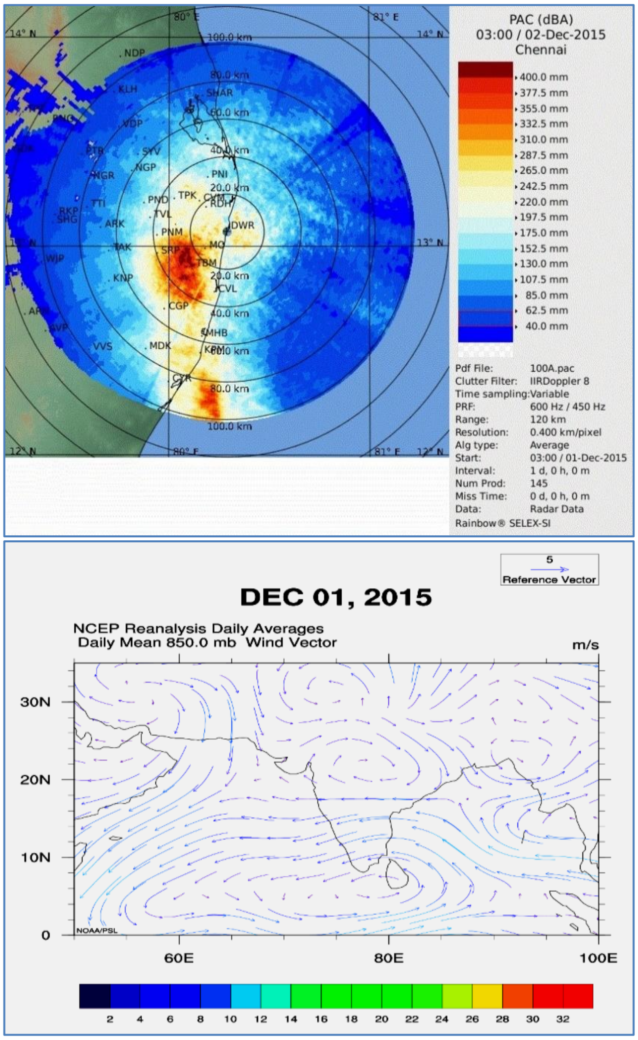

Fig.13a. PAC24 product of Chennai DWR for 24 hrs ending 2 Dec 2015 0830 hrs IST and 850 hPa flow pattern over India on 1 Dec 2015.

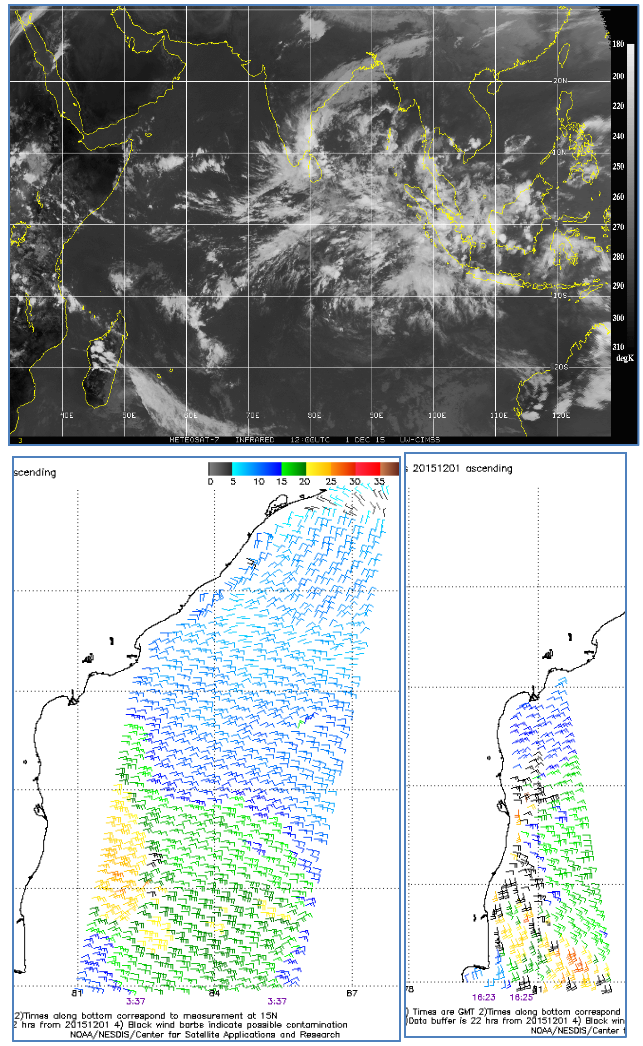

Fig.13b. Meteosat-7 IR Cloud image and ASCAT sea surface winds over Bay of Bengal on 1 Dec 2015.

which can cause intensification of northeast monsoon over SPR. Another synoptic scale system which could cause active northeast monsoon conditions is the trough in easterlies or trough of low which forms east of the peninsular coast and remains quasi-stationary. Rajeevan *et al*. (2022) who have compiled the statistics on lopars, easterly waves and upper air cyclonic circulations during the northeast monsoon season of Oct-Dec based on 2000-2021 data obtained the mean seasonal frequencies per year of the above three synoptic systems as: 2.7, 13.7 and 8.6 respectively.

5.8.3. *Well marked equatorial trough and strong low level winds*

In addition to the above mentioned transient systems, stationary weather features such as well marked and active equatorial trough also can cause active monsoon conditions over SPR especially over the coastal regions. The pressure gradient over Bay of Bengal in November (Fig. 3b) and December is not that strong but on occasions it could increase strengthening the surface and low level winds over Bay of Bengal resulting in coastal convergence and transporting more moisture into SPR causing active to vigorous monsoon. Srinivasan *et al*. (1973) have pointed out that during active northeast monsoon conditions low level upper winds off Coastal Tamil Nadu can reach speeds of up to 40 knots even without the presence of any well marked low pressure system such as Depression or CS.

5.8.4. *Illustration of two active northeast monsoon episodes without any depression or CS*

In this sub-section two episodes of active to vigorous northeast monsoon conditions experienced over north Coastal Tamil Nadu resulting from strong low level easterly winds or active equatorial trough or passing of an easterly wave are presented.

The first episode was during 18-21 Dec 2007 when Tamil Nadu experienced active to vigorous monsoon conditions. On 18th, 7 stations of Coastal Tamil Nadu reported HRF. On 19th 9, 37 and 57 and on 20th 2, 14 and 35 stations reported EHRF, VHRF and HRF respectively. On 20th, 4 stations reported HRF (IMD, 2008). Fig. 12 shows the 850 hPa level wind pattern over India on 18th. The north-south oriented trough in easterlies located off Coastal Tamil Nadu and the strong winds at 850 hPa level reaching up to 10-12 m/s (20-24 knots) are observed. The QuikSCAT satellite pass on 19th shows ESE winds over Bay of Bengal off Coastal Tamil Nadu with speeds of 15-35 knots and a lone 50 knot wind. Obviously the active to vigorous monsoon conditions have been substantially influenced by strong surface and low level winds and the intensity of well marked easterly trough. Satellite image on 18th (Fig. 12) shows the intense north to south oriented cloud cover over and off Coastal Tamil Nadu.

The next episode presented was the wet spell over Tamil Nadu especially that over Chennai city and surrounding areas during 30 Nov - 7 Dec 2015. The SPR experienced intense northeast monsoon in 2015 with several active and vigorous spells during Oct-Nov. On 30 November 19 stations of Tamil Nadu reported HRF. On 1 Dec, 5 and 22 stations reported HRF and VHRF respectively. However, on 2nd, 5 stations reported rainfall in excess of 40 cm. Tambaram (49 cm), Chennai Meenambakkam (35) and 24 stations reported EHRF, 11 stations VHRF and 20 stations HRF. Most of the stations reporting VHRF were from north Tamil Nadu and some from South Coastal Andhra Pradesh. Fig. 13a presents the 24 hrs rainfall, *i.e*. PAC24 product of Doppler Weather Radar (DWR) Chennai on 2nd at 0830 hrs IST. As seen the heaviest spell of 40-50 cm is realised in the southwestern sector of Chennai city (IMD, 2016). The heavy rainfall led to severe flooding in the Adyar river inundating vast stretches of areas closer to the river. The HRF episode continued after 2 December also but shifted to southern latitudes. Fig. 13b presents the 850 hPa level wind pattern, ASCAT satellite passes and cloud imagery on 1 December. The 850 hPa level wind flow shows that the equatorial trough is located south of Comorin, a north-south oriented trough in the easterlies off the coast is present and the wind speeds are 20-24 knots. The strong sea surface winds reaching up to 20-25 knots can be observed. The satellite imagery at 12 UTC shows the intense clouding.

In both the cases that have been presented the heavy to very heavy rainfall and severe weather have not been due to any intense and transient weather systems such as depression or CS. Features such as strong surface easterly winds, trough in the low level easterlies and well marked and active equatorial trough have been able to cause such heavy rainfall over several days.

6. Evolving of short, medium range and cyclone forecasting during northeast monsoon

6.1. *Short and medium range forecasting*

Weather forecasts valid for 1-3 and 4-10 days are defined as short and medium range forecasts respectively. Up to early 1960s short range forecasting by IMD especially of rainfall was by and large based on weather charts, climatology and persistence. By early 2000's IMD had high speed computers with NWP models providing rainfall forecast output charts for up to 10 days lead time besides forecast products of other parameters such as surface pressure, winds, temperature and humidity at all levels of the atmosphere. For short range forecasting of northeast monsoon which is volatile in nature, NWP products are a boon and events such as monsoon onset could be predicted 7 days ahead with almost 100% accuracy. The occurrence of HRF and VHRF could also be forecasted with much higher precision.

During 1970-90 experimental medium range forecasts of weekly rainfall of Tamil Nadu were prepared on research mode during northeast monsoon season based on 500 hPa level flow pattern as the input using contingency table technique De (1982). The forecasts with two intervals *viz.* Excess/ Normal or Deficient/Scanty (Sec.4) displayed moderate skill. In 2000s medium range forecasts of rainfall with lead period of up to 4 weeks were generated by IMD based on multimodel ensemble models and made available to the users. With such advancements an accurate forecast outlook on northeast monsoon rainfall with 1-4 weeks lead time can be provided.

6.2. *Cyclone forecasting*

The first Cyclone Detection Radar was installed by IMD in Visakhapatnam in the year 1969. Subsequently more radars were installed and from 2002 the Cyclone Detection Radars have been upgraded to DWRs in a phased manner. As of now 7 DWRs have been installed within SPR. The DWR can track cyclonic storms more accurately and provide estimates of their intensity. DWRs generate several products in digital format which are very useful in general forecasting and also in providing nowcasting (1-3 hrs prediction) services in major cities. The cyclone forecasts - both track and intensity have become more accurate with the availability of products from high resolution NWP models, DWR, satellite outputs and other remote sensed observations.

An example of such accurate prediction was the track forecasting of VSCS Thane which formed over Bay of Bengal on 25 December 2011, crossed coast near Cuddalore and dissipated over land on 31 December. The track of Thane is presented in Fig. 11. Thane reached intensity of VSCS with 75 knots as the maximum wind speed. It moved along 12.5º N during 27-28 and then started moving slightly towards lower latitudes and reached up to 11.6º N, crossed the coast and caused extensive damage. But its movement towards lower latitudes was correctly predicted by IMD and the landfall location was forecast well in advance. With such precise forecasts the local administration was able to take preventive action over a core area, manage evacuation of people which considerably minimised the loss of lives and after the landfall, organise efficient relief work.

One of the major disastrous features associated with a cyclone landfall is storm surge defined as the rise in sea water level caused by strong surface winds in the cyclone field. The probable maximum storm surge (without tide and wave effects) is 8.0 metres at Tondi in Tamil Nadu, 2.5 m at Chennai, 7.6 m at Bapatla of Coastal Andhra Pradesh (Kalsi *et al*., 2007). The high storm surge generated by the 18-24 December 1964 Pamban cyclone almost wiped off the entire island of Dhanushkodi. The 14-20 November 1977 Chirala cyclone caused more than 12000 fatalities mainly due to high storm surge. IMD currently issues storm surge forecasts, based on nomograms developed after considerable research and on NWP based storm surge models.

7. Indian northeast monsoon-Teleconnections and relation with Indian southwest monsoon

7.1. *Relation with ENSO*

The southwest monsoon of India is known to exhibit relation with preceding and concurrent atmospheric phenomena that occur both closer to and farthest from India. El Nino and Southern Oscillation or ENSO, are shown to be related to ISMR in several studies. SST over Nino 3.4 region is negatively and Southern Oscillation Index (SOI) is positively correlated with Indian southwest monsoon rainfall both in concurrent and antecedent modes. Though ENSO is considered as a very important global forcing influencing ISMR the CC is only around 0.4 in the antecedent mode and 0.6 in the concurrent mode explaining around 15-35% of the variation (Rajeevan, 2012).

On the relation between ENSO and NMR, Geetha and Raj (2008), based on more than 100 year data have shown that SOI is negatively related to NMR TN with CC of -0.38 to -0.47 in antecedent and concurrent modes respectively and that the relation changes sign in December to become slightly positive in January. Rajeevan *et al*. (2022) identified significant CCs between SST of other oceanic regions including Bay of Bengal and NMR but such CCs have not remained stable, some of them even changing sign with time. Kripalani *et al*. (2004), Rajeevan *et al*. (2012), Sengupta *et al*. (2019) studied the relation between NMR and ENSO.

The relation between NMR and ENSO has not been very stable and has shown inconsistency in the recent past which has been pointed out by Rajeevan *et al*. (2022). In 1997 NMR TN was more than 50% of normal which was in harmony with antecedent and concurrent negative SOI (Aug-Sep, -17.3, Oct-Nov, -16.5) and positive Nino 3.4 SST anomalies (Aug-Sep, 2.02 ºC, Oct-Nov, 2.36 ºC). In 2015 with more than 50% excess rainfall the SOI values were -18.8 and -12.8, SST anomalies were 1.94 ºC and 2.49 ºC for the same periods. But in 2005 which also registered more than 50% excess NMR TN, similar values were -3.5, 4.5 for SOI and -0.6 ºC, -0.3 ºC for SST providing no signal. In the years 2007, 08, 10, 11 and 21, during which NMR TN was 20-59% above normal, the SOI was substantially positive and SST negative providing contradictory signals. In 2021 the SOI values were 7.0, 9.6 and SST values -0.44 ºC, -0.83 ºC indicating mild La Nina but NMR TN was 59% above normal. In 1988 Aug-Sep and Oct-Nov experienced La Nina conditions with positive SOI and NMR TN was 38% deficient. But the deficit of 1982 (-18%), substantial deficit of 1995 (-46%) were not associated with similar ENSO events. Thus overall there is still the conceptual and moderate relationship of El Nino / negative SOI associated with good NMR and La Nina / positive SOI with poor NMR, established as it was with a long data set, despite the relationship not maintaining consistency in recent years.

7.2. *Relation with IOD and Bay of Bengal SST*

The Indian Ocean Dipole (IOD) is defined by the difference in SST between two ocean areas - a western pole in the western Indian Ocean and an eastern pole in the eastern Indian Ocean south of Indonesia (Asnani, 2005). According to Kripalani *et al*. (2004) IOD is positively related to NMR. Geetha and Balachandran (2021) have studied the 2015 excess and 2016 deficient northeast monsoons and brought into focus the role played by ENSO and IOD. Singh (1995) studied the contrasting northeast monsoons of 1987 (normal to good) and 1988 (poor) and the SST over Bay of Bengal and showed that in the month of September just preceding the northeast monsoon, SST and evaporation over Bay of Bengal were higher in 1987 than in 1988.

7.3. *Relation between ISMR and NMR*

The relation between ISMR Jun-Sep with NMR TN Oct-Dec is deliberated in this section, based on the 150 year data of 1871-2020, the latter presented in Fig. 7. The CC based on 150 values was obtained as -0.15 which falls short of being significant at 5% level. But the scatter diagram

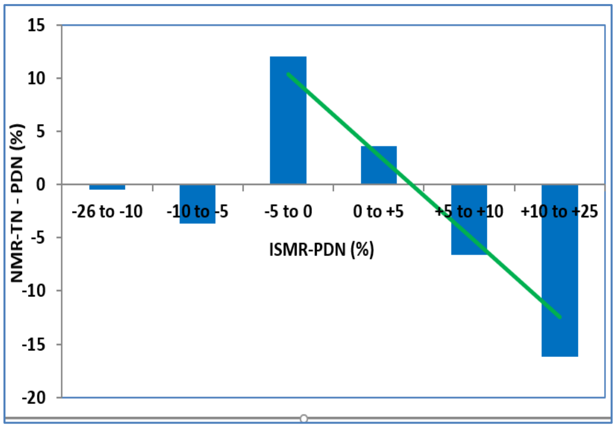

Fig. 14. Conditional means of NMR TN given ISMR (NMR TN – Northeast monsoon Oct-Dec rainfall of Tamil Nadu, ISMR- Southwest monsoon rainfall over India, Jun -Sep) Data base: 1871-2020.

revealed a different type of relation. This led to classification of 5 intervals of ISMR (*x*) defined as: < -10, (-10, -5), (-5, 0), (0, 5), (5,10) and >10 where both *x* and *y* are expressed as PDN values. As the coefficient of variation of *x* is nearly 10%, the above 6 intervals could be defined as corresponding to deficient, slight deficient, negative side of normal, positive side of normal, slight excess and excess rainfall respectively. The conditional means of *y* were computed for the above *x* intervals and are shown in Fig. 14. The conditional means of *y* for the *x* intervals (-5, 0), (0, 5), (5, 10) and >10 are 12.0, 3.6, -6.6 and -16.2 respectively displaying negative relationship which breaks down when *x* lies in (-10, -5) or < -10 for which the mean values of *y* are -3.7 and -0.5 respectively.

The conclusion is that the negative relation that is manifested when $x > -5$ disappears when $x < -5$. Thus when IMSR is just below / above normal we can expect PDN of NMR TN to be positive. If ISMR is slight excess NMR PDN mean is negative and if ISMR is excess, NMR TN is 16% below normal, a fairly strong signal. During the 17 years of excess ISMR of 1871-2020 there were 8 deficient NMR TN years and only in 1893 NMR TN was excess ($y \geq 20\%$). In all the other years and for the last 125 years or so an excess ISMR (PDN ≥ 10) and an excess NMR TN (PDN ≥ 20) have not occurred in the same year. But during the 28 years when ISMR was deficient NMR TN was excess in 6 years and deficient in 7 years thus showing no clear pattern. The CC between *x* and *y* leaving aside years when $x < -5$, was -0.29 (1% Level of Significance) based on 105 values. The regression line based on these 105 pairs is shown in Fig. 14. Thus ISMR and NMR exhibit some sort of negative relation but in a restricted range of the former. A good ISMR may be associated with not so good NMR but the converse, *viz*. poor ISMR associated with good NMR does not hold. Relation between ISMR and NMR SPR was found to be not well defined and so not discussed here.

8. Seasonal forecasting of northeast monsoon rainfall

8.1. Seasonal forecasting of ISMR

In meteorology, long range forecast (LRF) is the seasonal outlook of a weather parameter issued around one month in advance. IMD has been a pioneer in the field of LRF of monsoon rainfall. The first LRF by IMD was issued in the year 1886 on southwest monsoon rainfall over India and Burma (now Myanmar) based on the relation between Himalayan snow cover in the winter season and ISMR (Blanford, 1886). In the early parts of 20th century Gilbert Walker did considerable work in this field which have been quoted and briefly reviewed in Das (1986). Thapliyal and Rajeevan (2003), Pai (2012) may be referred for a detailed exposition of LRF of ISMR which has been an important activity and mandate of IMD for the past several decades.

8.2. *LRF of NMR – Research studies*

For the SPR, Oct-Dec northeast monsoon rains have been important as shown in Sec 2. Both NMR TN and SPR have high coefficients of variation. Due to the high inter annual variability of NMR, LRF of the same would be important as well as useful for planners and farmers. For Tamil Nadu the northeast monsoon season is the primary rainfall season. As such researchers have shown more interest in seasonal forecasting of NMR TN. The first known work in this field was by Doraisamy Iyer (1941) who derived regression equations based on South American pressure during Jun-Aug and September upper winds of Agra and obtained a multiple CC of 0.59 to predict NMR TN. Subsequently there have been several research studies conducted on this topic.

In Raj (1989) based on data of 1951-83, mean upper air winds of June, July, August and September of 9 stations of India were taken as potential predictors and were correlated with NMR of Tamil Nadu, Coastal Andhra Pradesh, Rayalaseema and Kerala. Most of the significant CCs were obtained from the winds of upper troposphere and the absolute values of such CCs ranged from 0.48 to 0.77. The resulting regression equations were tested in an independent sample. It emerged that upper tropospheric zonal winds over India during Jun-Sep were positively correlated with NMR. As the normal winds are strong easterlies over most parts of India at that level during Jun-Sep, it means that strength of Tropical Easterly Jet which is a southwest monsoon component, is related to NMR, weaker (stronger) jet favouring good (poor) NMR. The best predictor was Aug-Sep 150 hPa level mean zonal wind of Thiruvananthapuram of south Kerala which exhibited a CC

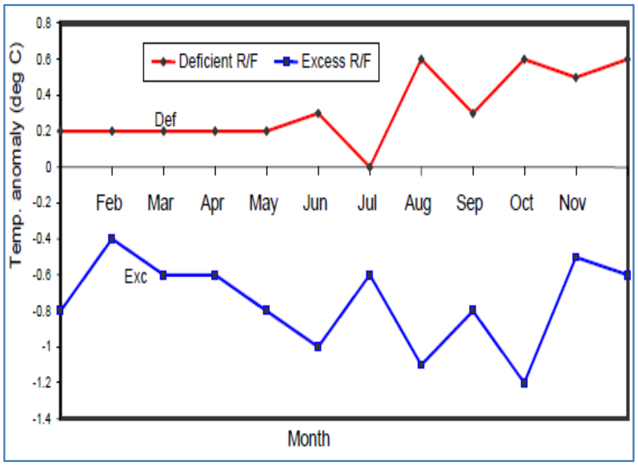

Fig. 15. Mean monthly temperature anomalies (averaged over India) over 200 hPa in years of 25% deficient / excess northeast monsoon rainfall over Tamil Nadu.

of 0.77 and the regression equation performed well in the test sample of 1976-87.

In another study based on data of 1965-94, upper air wind and temperature over India during pre-monsoon and monsoon months were taken as potential predictors of NMR TN and 6 predictors with absolute CC values ranging from 0.47 to 0.80 were identified (Raj,1998a). The mean April zonal wind of 5 stations of Indian peninsula had a CC of 0.61 (1% level of significance) implying that some signals were available even 5 months in advance. The 150 hPa level Jun-Sep temperature of two stations yielded a CC of -0.80 (1% level of significance) which could be interpreted as colder upper troposphere over India during the southwest monsoon season favouring a good subsequent northeast monsoon. The final forecast equation based on all the 6 equations yielded a system explaining 77% variance equivalent to a multiple CC of 0.88 with forecast error of 18% compared to 27 % of coefficient of variation of NMR TN for the period of study. In Raj *et al.* (2004) it was shown based on 35 year 1963-98 data that 200 hPa level zonal westerlies over India during pre-monsoon and monsoon months were correlated negatively with ISMR but positively with NMR. The monthly mean temperature anomaly at 200 hPa level over India during deficient NMR TN years was positive from January to December in the range of 0.2 ºC to 0.4 ºC. In excess NMR TN years this was -0.4 ºC to -1.2 ºC (Fig. 15).

Balachandran *et al.* (2006) and Asokan and Balachandran (2008) identified global surface temperature and pre-monsoon temperature anomalies over India as potential predictors for NMR based on 104 year grid point temperature data over India. Balachandran and Geetha (2012) have developed a model which could forecast in advance the cyclonic activity over North Indian Ocean. Singh *et al*. (2011), Onkari Prasad *et al*. (2022 and 2023) have developed seasonal forecasting models for NMR at sub-division and even at district level. The major predictor in their models is the position, intensity and movement of South Indian Ocean Convergence Zone. The late or early onset of northeast monsoon can also be foreshadowed from the above data according to the authors.

8.3. *LRF of NMR – A conceptual model*

A list of 10 parameters manifesting conceptual antecedent relations with potential to be used as predictors in a seasonal forecasting scheme of NMR is presented in a consolidated form in Table 6 along with the period of study. As shown negative temperature and positive zonal wind anomalies at upper troposphere over India in winter, pre-monsoon and monsoon seasons favour good NMR and opposing patterns favour poor NMR. Weak Tropical Easterly Jet at 150 hPa level over India during Jun-Sep and intense Siberian High in September favour good NMR, strong Tropical Easterly Jet and weak Siberian High favour poor NMR. El Nino and negative SOI during Aug-Sep favour good NMR whereas La Nina and positive SOI favour poor NMR. The IOD and South Indian Ocean Convergence Zone are also shown to be related. The ISMR also provides some signal during some years. It must be noted that some of the results of Table 6 were derived from data sets available at that time which might need updating and it is possible that some predictors may not be keeping the same level of intensity of relation as of now. But as a concept, results of Table 6 should by and large hold good.

8.4. *Real time LRF of NMR, Past and Present Status*

Since 1998, IMD has been preparing and issuing experimental seasonal forecasts of NMR for SPR and TN. For preparing quantitative and probabilistic forecasts of NMR over the south Peninsula, a 5-parameter Principle Component Regression model was used. Similarly, a 4-parameter Principle Component Regression model was used for forecasting seasonal rainfall over Tamil Nadu (IMD, 2016). In recent years South Asian Climate Outlook Forum (SASCOF) has come out with consensus forecast outlook on NMR which has been developed through an expert assessment of the prevailing global climate conditions and forecasts from different climate models from around the world (SASCOF, 2020). In the year 2021 IMD adopted a new strategy based on existing statistical techniques and newly developed Multimodal Ensemble system based on coupled global climate models and IMD's monsoon mission climate forecasting system, based on which seasonal forecasts for NMR were issued for 2021-23 (IMD, 2023).

TABLE 6

Conceptual relations for seasonal forecasting of Indian northeast monsoon rainfall

	Parameter	Parameter Status	Northeast monsoon rainfall Oct-Dec
1	200 hPa temperatures over India in the preceding months Jan- Sep 1963-98	Colder Warmer	Good Poor
2	200 hPa Zonal winds over northern India in Summer – April representative month 1963-98	Positive anomalies (Strong westerlies) Negative anomalies (Weak westerlies)	Good Poor
3	150 hPa Zonal winds over south Peninsular India Aug-Sep 1951-83	Positive anomalies (Weak Easterly Jet) Negative anomalies (Strong Easterly Jet)	Good Poor
4	150 hPa temperatures over Peninsular India Jun-Sep 1965-94	Colder Warmer	Good Poor
5	Nino 3.4 SST Aug-Sep 1948-2021	Strongly positive- El Nino Strongly negative -La Nina	Good Poor
6	Southern Oscillation Index Aug-Sep 1901-2004	Strongly Negative Strongly positive	Good Poor
7	Surface Pressure over Siberian High area – September 1971-2004	High – Good Low – Poor	Good Poor
8	Indian Ocean Dipole 1871-2001	Strongly positive Strongly negative	Good Poor
9	South Indian Ocean Convergence Zone 1982-2021 Jul-Sep		Depends on position and movement
10	ISMR 1871-2020	Good Sub-normal Poor	Sub-normal Positive side of normal No clear signal

For the past several years the Agromet division of Tamil Nadu Agricultural University, Coimbatore has provided seasonal forecasts of NMR over the entire Tamil Nadu and at district levels based on Australian Rainman software which is based on a sole predictor, the SouthernOscillation Index (TNAU, 2023). Also seasonal rainfall forecasts based on NWP models for the entire globe are hosted on their websites by organisations such as NCEP and ECMWF. Forecasts for Oct-Dec rainfall for the Indian region based on NWP models could thus be had in September itself from which the forecast for NMR region could be downscaled.

Overall, seasonal forecasting of NMR has come a long way in the last 2-3 decades. Despite the volatile nature of northeast monsoon, it is possible to provide a reasonably accurate outlook on NMR in the beginning of the season.

9. Research work on Indian northeast monsoon and gap areas

In India, up to around 1980s synoptic, statistical and weather charts based research was the most common type in meteorological research. For a researcher, getting access to computing facilities was another major challenge. By 1980s data collected by IMD's various observatories were archived at the National Data Centre, IMD, Pune in digital form which were available to the users and researchers. In 1980s personal computers of the most basic version were available providing direct access to higher level of computation. By 2000s remote sensed data, INSAT and DWR products, data on parameters such as El Nino, SOI, IOD *etc*. were easily available. Organisations such as NCEP and ECMWF gave free access to the facility of retrospective generation of weather charts and grid point data for any given period, time and customised area. NWP models such as WRF (Weather Research and Forecasting) could be installed in personal computers and researchers could run the models and conduct experiments by ingesting locally available data. Large volume of data could be handled and intense statistical applications such as multiple regression, principal component analysis, spectral analysis could be executed.

With such easy data availability and matching computational ability, large number of research students and university faculty showed interest in pursuing research on northeast monsoon. There have been several research works on Indian northeast monsoon based on large volume of data and model outputs, which could not have been attempted before half a century. In India, a good number of research students pursued their doctorate studies on northeast monsoon and earned doctorate degrees. The Indian northeast monsoon has found its place in textbooks of Meteorology. During the last 30 years or so nearly 150 research papers have been published in peer reviewed journals, but due to space constraints only a few could be referenced in this article.

There are several new areas of research on northeast monsoon which need to be explored. The atmospheric features behind extreme northeast monsoon performance such as occurrence of severe drought and large excess rain are not fully understood. Seasonal forecasting of northeast monsoon rainfall is another area which calls for more research. Energetics, moisture flux budget, SST over North Indian Ocean and its relation with northeast monsoon rainfall are other areas of potential and useful research. Studies on such topics will usher in further understanding of this small scale monsoon.

10. Concluding Remarks

The sub-planetary scale Indian northeast monsoon has remained as an enigmatic phenomenon for a long time though this monsoon has been known to the Indian meteorologists for nearly 150 years. It can be considered as the antithesis of Indian southwest monsoon and is a shallow, dry and cold current but owing to its travel over Bay of Bengal the maritime states get rainfall. Our understanding of Indian northeast monsoon, its components, features, climatology, the associated synoptic systems, relation with global parameters, forecasting aspects - are much better known and understood than was the case before 50 years. These have substantially benefitted the user community- the Governments at various levels, the people and the farmers and several other users. India Meteorological Department which was established in 1875 and understood the uniqueness of this monsoon has played a very important and pivotal role in establishing the science behind this monsoon and will surely continue to do so in future as well.

Acknowledgements

The authors thank the Director General of Meteorology, India Meteorological Department for having provided this excellent opportunity to contribute an article on Indian Northeast monsoon for the special issue of Mausam Journal. The constructive comments made by the learned referee has helped to improve the manuscript substantially and the same is gratefully acknowledged.

Disclaimer: The contents and views presented in this research article/paper are the views of the authors and do not necessarily reflect the views of the organizations they belongs to.

References

Asnani, G. C., 2005, ‘Tropical Meteorology’ Pune, India.

Asokan, R. and Balachandran, S., 2008, “A pre-monsoon precursor for foreshadowing of northeast monsoon rainfall over Tamil Nadu”, *Mausam*, **59**, 4, 445-452.

Balachandran, S., Asokan, R. and Sridharan, S., 2006, “Global surface temperature in relation to northeast monsoon rainfall over Tamil Nadu”, *J. Earth. Syst. Sci.*, **115**, 3, 349-362.

Balachandaran, S. and Geetha, B., 2012, “Statistical Prediction of Seasonal Cyclonic Activity over North Indian Ocean”, *Mausam*, **63**, 1, 17-28.

Blanford, H. F. 1886, “On the connection of Himalayan snowfall and seasons of drought in India”, *Proc. R. Soc. London*, **37**, 3-22.

Das, P. K., 1986, “Monsoons”, *IMO lecture*, WMO-No. 613, Geneva.

De, U. S., 1982, “Recent studies in medium range forecasting for agromet advisory service”, *Mausam*, **33**, 4, 499-502.

Doraiswamy, Iyer V., 1941, “Forecasting of northeast monsoon rainfall of south Chennai”, *India Met. Dep.*, Sci. Notes, 8, 98.

Geetha, B. and Balachandaran, S., 2014, “An analytical study of easterly waves over southern peninsular India during the northeast monsoon, 2010”, *Mausam*, **65**, 4, 591-602.

Geetha, B. and Raj, Y. E. A., 2009, “Role and impact of Siberian High on the temporal variation of Indian northeast monsoon rainfall”, *Mausam*, **60**, 4, 505-520.

Geetha, B. and Raj, Y. E. A., 2014, Spatial patterns of northeast monsoon rainfall over sub-regions of southern peninsular India and Sri Lanka as revealed through empirical orthogonal function analysis, *Mausam*, **65**, 2, 185-204.

Geetha, B. and Raj, Y.E.A., 2015, “A 140 year data archive of dates of onset and withdrawal of northeast monsoon over Coastal Tamil Nadu”, *Mausam*, **66**, 1, 7-18.

Geetha, B. and Balachandaran, S., 2021, "Diagnostic analysis of two dos-a-dos extreme northeast monsoon seasons with dipolar rainfall performance", *Theor. Appl. Climatol.,* **144**, 675-690.

Haurwitz, B. and Austin, J. M., 1944, "Climatology", McGraw-Hill Book Company, Incorporated, New York, London.

India Met. Dep., 2009, "Weather over India, Oct-Dec 2008", *Mausam*, **60**, 4, 549-574.

India Met. Dep., 2019, "Weather over India, Oct-Dec 2018", *Mausam*, 70, **4**, 853-876.

India Met Dep., 1987, Report of 10th conference of forecasting officers, 43-46.

India Met. Dep. 2001, Weather over India, Oct-Dec, 2000, *Mausam*, **52**, 4, 749-764.

India Met. Dep., 2003, "Cyclone Manual", 1-469.

India Met. Dep., 2008, Cyclone eAtlas – IMD

India Met. Dep., 2008, Weather over India, Oct-Dec, 2007, *Mausam*, **59**, 4, 541-570.

India Met. Dep., 2010, "Daily rainfall normals, 1951-2000", CD format.

India Met Dep., 2012, Monsoon Monograph, Vol. I & Vol. II Ed., Ajit Tyagi, Asnani, G. C., De, U. S., Hatwar, H. R. and Mazumdar, A.B., 1-670 and 1-559.

India Met. Dep., 2016, "LRF bulletin for northeast monsoon-2016".

India Met. Dep., 2016, Weather over India, Oct-Dec, 2015, *Mausam*, **67**, 4, 955-972.

India Met. Dep., 2022, Climatological Tables of Observatories in India, 1991-2020.

India Met. Dep., 2023, Rainfall Atlas of India, 1971-2020, Met. Monograph.

Johnson, R. H., 2011, "Diurnal cycle of monsoon convection, The global monsoon system : Research and Forecast (2nd Edition)", World scientific series on Asia-Pacific weather and climate, 5, 257-276.

Kalsi, S. R., Jayanthi, N., Raj, Y. E. A. and Bhowmik, S. K. R., 2007, "Probable maximum storm surge heights for the maritime districts of India", Met. Monograph No.: Synoptic Meteorology – 5/2007, *India Met. Dep*.

Kelkar, R. R., 2009, "Monsoon Prediction", B.S. Publications, Hyderabad.

Kothawale, D.R. and Rajeevan, M., 2017, "Monthly, Seasonal and Annual Rainfall Time Series for All India, Homogeneous Regions and Meteorological Subdivisions: 1871-2016". IITM Research Report No. RR-138.

Kripalani, R. H. and Kumar, P., 2004, "Northeast monsoon rainfall variability over south peninsular India vis-a-vis the Indian Ocean Dipole Mode", *Int. J. Climatol.,* **24**, 1267-1282.

Krishnamurti, T. N., 1979, "Tropical Meteorology", Compendium of Meteorology, WMO, Geneva, II, p.428.

Onkari Prasad, Singh, O.P. and Prasad, K., 2022, "Development of northeast monsoon and its long range forecast, Part I – Development", *J. Ind. Geophys. Union,* **26**, 6, 521-540.

Onkari Prasad, Singh, O. P. and Prasad, K., 2023, "Development of northeast monsoon and its long range forecast, Part II - Subdivision level forecast", *J. Ind. Geophys. Union,* **27**, 4, 292-310.

Pai, D. S., 2012, "Long Range Forecasting of Monsoon", Monsoon Monograph, Vol.II, Ch. 11, *India Met. Dep.,* Pune, 468-540.

Raghavan, S. and Veeraraghavan, K., 1979, "Radar synoptic study of the Nagapattinam cyclone of 12 November 1977", *Mausam,* **30**, 1, 21-30.

Raj, Y. E. A., 1989, "Statistical relations between winter monsoon rainfall and the preceding summer monsoon", Mausam, **40,** 51-56.

Raj, Y. E. A., 1992, "Objective determination of northeast monsoon onset dates over Coastal Tamil Nadu for the period 1901-90", *Mausam*, **43**, 3,272-282.

Raj, Y. E. A., 1998a, "A scheme for advance prediction of northeast monsoon rainfall of Tamil Nadu", *Mausam,* **49**, 2, 247-254.

Raj, Y. E. A., 1998b, "A statistical technique for determination of withdrawal of northeast monsoon over Coastal Tamil Nadu", *Mausam,* **49**, 3, 309-320.

Raj, Y. E. A., 2003, "Onset, withdrawal and intraseasonal variation of northeast monsoon over Coastal Tamil Nadu, 1901-2000", *Mausam*, **54**, 3, 605-614.

Raj, Y. E. A. and Geetha, B., 2008, "Relation between Southern Oscillation Index and Indian northeast monsoon as revealed in antecedent and concurrent modes", *Mausam*, **59**, 1, 15-34.

Raj, Y. E. A., 2011, "Climatology and Forecasting based on climatology of Tropical Cyclones of Indian Seas", *India Met. Dep.*, Met. Monograph No. Cyclone warning 9/2011.

Raj, Y. E. A., 2012, "Northeast monsoon over India", Monsoon Monograph, Vol. I, Ch.13, *India Met.Dep.,* Pune, 606-670.

Raj, Y. E. A. and Amudha, B., 2022, "Extent of diurnal cycle of rainfall and its intra seasonal variation over Coastal Tamil Nadu during north east monsoon season", *Mausam*, **73**, 1, 1-18.

Raj, Y. E. A. and Amudha, B., 2023 "A re-assessment study on the onset and withdrawal dates of Indian northeast monsoon for the decade 2011-20", *Mausam*, **75**, 3, 747-758.

Rajeevan, M., 2012, "Teleconnections of Monsoon", Monsoon Monograph, Vol.II, Ch. 3, *India Met. Dep.,* Pune, 78-128.

Rajeevan, M., Mohapatra, M, Unnikrishnan, C. K., Geetha, B., Balachandran, S., Sreejith, O. P., Mukhopadhyay, P., Pattanaik, D. R., Guhathakurta, P., Pankaj Kumar., Niranjan Kumar, K., Jyoti Bhate., Rohini, P., Monica Sharma, Ashrit, R., Ashim Mitra and Karuna Sagar, 2022, "Northeast Monsoon over South Asia", *India Met. Dep.,* Met. Monograph, 1-216.

Rajeevan, M., Unnikrishnan, C. K., Bhate, J., Kumar, K. N. and Sreekala, P. P., 2012, "Northeast monsoon over India: variability and prediction", *Meteorol. Appl. Roy. Meteor. Soc.* UK., 19, 226-236.

Rao, Y. P., 1976, "Southwest Monsoon", Meteorological Monograph, IMD, Pune.

SASCOF, 2020, Consensus statement of forecast for Oct-Dec rainfall of Southeast Asia.

Satyanarayana, G. C., Naidu C. V., Bhaskara rao D. V., Umakantha N, Naveena N,2020, "Onset of northeast monsoon over South Peninsular India", *Mausam,* **71**,3,501-512.

Sengupta, A. and Nigam, S., 2019. "The northeast winter monsoon over the Indian subcontinent and Southeast Asia: Evolution, interannual variability, and model simulations", *Journal of Climate*, **32**, 1, 231-249.

Singh, O. P., 1995, "Influence of Bay of Bengal on winter monsoon rainfall, *Mausam*, **46**, 3, 307-312.

Singh, O. P. and Onkari Prasad, 2011, "District level forecast of northeast monsoon rainfall over Tamil Nadu using Indian Ocean dipole mode index", *Mausam*, **62**, 2, 229-234.

Sreekala, P.P., Rao, S.V.B., Rajeevan, K. and Arunachalam, M. S., 2018, "Combined effect of MJO, ENSO and IOD on the intraseasonal variability of northeast monsoon rainfall over south peninsular India", *Clim. Dyn.* **51**, 3865–3882.

Srinivasan, V. and Ramamurthy, K., 1973. "Northeast monsoon", Comprehensive articles on selected topics, *India Met. Dep.*, FMU Report No. IV-18.4.

Thapliyal, V. and Rajeevan, M., 2003, "Updated operational models for long range forecasts of Indian Summer Monsoon Rainfall, **54**, 2, 495-504.

Tamil Nadu Agricultural University,2023, Seasonal rainfall forecast of Northeast monsoon.