MAUSAM, **73**, 1 (January 2022), 1-18

551.577.3 : 551.553.21 (540.65)

Extent of diurnal cycle of rainfall and its intra seasonal variation over coastal Tamil Nadu during north east monsoon season

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(*Received 16 September 2020, Accepted 2 November 2021*)

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सार – चार तटीय स्टेशनों चेन्नई नुंगमबक्कम (एनबीके), चेन्नई मीनांबक्कम (एमबीके), नागपट्टिनम (एनपीटी) और पंबन (पीबीएन) द्वारा दर्शाए गए तटीय तमिलनाडु के उत्तर पूर्व मानसून वर्षा की दैनिक भिन्नता का अध्ययन बरसात के दिनों के प्रति घंटा वर्षा के आंकड़ों के आधार पर किया गया था। केवल, 1 अक्टूबर-31 दिसंबर की अवधि के लिए 47/48 वर्ष की अवधि 1969-2016/2017 के लिए। औसत ऑक्टेट वर्षा और इसकी विसंगति की गणना दिन के 8 ऑक्टेट 00-03,…, 21-24 घंटे के लिए की गई थी और विसंगति का सांख्यिकीय महत्व के लिए परीक्षण किया गया था। अक्टूबर, नवंबर, दिसंबर के अलग-अलग महीनों और अक्टूबर-दिसंबर की पूरी अवधि के लिए अलग-अलग विश्लेषण किए गए। ऑक्टेट माध्य वर्षा विसंगति के हार्मोनिक विश्लेषण द्वारा पूरक विकासवादी हिस्टोग्राम विश्लेषण की मूल तकनीक का उपयोग दैनिक चक्र संकेत का पता लगाने के लिए किया गया था। वर्षा सूचकांक की दैनिक भिन्नता और औसत निरपेक्ष ऑक्टेट वर्षा विसंगति के गुणांक के रूप में नामित दो सूचकांकों को आयामहीन संख्याओं में दैनिक भिन्नता की तीव्रता का प्रतिनिधित्व करने के लिए परिभाषित, गणना और व्याख्या की गई थी।

उपरोक्त तकनीकों पर आधारित विश्लेषण से पता चला है कि दैनिक संकेत जो सुबह की अधिकतम और देर से दोपहर को न्यूनतम अष्टक वर्षा दर्शाता है, अक्टूबर में अच्छी तरह से परिभाषित है, नवंबर में घट जाता है और सभी 4 स्टेशनों के लिए दिसंबर में और कम हो जाता है। हालांकि दैनंदिन भिन्नता दिसंबर में एक अच्छी तरह से परिभाषित पैटर्न को प्रकट करती है, ज्यादातर मामलों में संकेत सांख्यिकीय रूप से महत्वपूर्ण नहीं है। Nbk और Mbk के लिए अक्टूबर और दिसंबर में क्रमशः पूर्वाह्न और दोपहर में होने वाली ऑक्टेट वर्षा विसंगति का एक कमजोर माध्यमिक शिखर है जो वर्षा की अर्ध-दैनिक भिन्नता की उपस्थिति का सुझाव देता है। स्टेशनवार, पीबीएन में प्रत्येक महीने/मौसम के लिए दैनिक संकेत सबसे अच्छी तरह से परिभाषित है, उसके बाद एनपीटी, एनबीके और फिर एमबीके।

दैनिक संकेत के पीछे भौतिक कारणों और अक्टूबर से दिसंबर तक उत्तर पूर्व मानसून के मौसम की प्रगति के रूप में इसकी कमी पर विचार-विमर्श किया गया है। समुद्री जलवायु के साथ एक तटीय स्टेशन को प्रभावित करने वाले रात के अधिकतम समुद्री संवहन की प्रसिद्ध विशेषता और सुबह के शुरुआती घंटों में ऊपरी वायुमंडल के निचले स्तरों पर उच्च संतृप्ति को कुछ कारणों के रूप में उन्नत किया गया है। मौसम की प्रगति के साथ दैनिक सिग्नल में कमी की अधिक जटिल विशेषता के लिए, तटीय तमिलनाडु पर अक्टूबर से दिसंबर तक न्यूनतम सतह के तापमान में कमी के कारण सुबह की वैचारिक भूमि हवा के आधार पर एक संभावित कारणों में से एक के रूप में दिखाया गया है तापमान और हवा का विश्लेषण। स्वचालित मौसम स्टेशनों, मौसम उपग्रहों और डॉपलर मौसम रडारों के डेटा के आधार पर आगे के काम की गुंजाइश पर चर्चा की गई है।

ABSTRACT. The diurnal variation of north east monsoon rainfall of coastal Tamil Nadu represented by four coastal stations Chennai Nungambakkam (Nbk), Chennai Meenambakkam (Mbk), Nagapattinam (Npt) and Pamban (Pbn) was studied in detail based on hourly rainfall data of rainy days only, for the period 1 Oct-31 Dec for the 47/48 year period 1969-2016/2017. Mean Octet rainfall and its anomaly were computed for the 8 octets 00-03,…., 21-24 hrs of the day and the anomaly was tested for statistical significance. Various analysis for the individual months of Oct, Nov, Dec and the entire period Oct-Dec were separately conducted. The basic technique of evolutionary histogram analysis supplemented by harmonic analysis of octet mean rainfall anomaly was used to detect the diurnal cycle signal. Two indices named as diurnal variation of rainfall index and coefficient of mean absolute octet rainfall anomaly representing the intensity of diurnal variation in dimensionless numbers were defined, computed and interpreted.

The analysis based on the above techniques revealed that the diurnal signal which shows an early morning maximum and late afternoon minimum of octet rainfall is well defined in Oct, decreases in Nov and further decreases in Dec for all the 4 stations. Though the diurnal variation manifests a well defined pattern in Dec the signal is not statistically significant in most cases. For Nbk and Mbk there is a weak secondary peak of octet rainfall anomaly occurring in the forenoon and afternoon respectively in Oct and Dec suggesting the presence of semi-diurnal variation of rainfall. Stationwise, the diurnal signal is most well defined for each month/season in Pbn followed by Npt, Nbk and then Mbk.

The physical causes behind the diurnal signal and its decrease as the north east monsoon season advances from Oct to Dec have been deliberated. The well known feature of nocturnal maximum of oceanic convection influencing a coastal station with maritime climate and the higher saturation at the lower levels of the upper atmosphere in the early morning hours have been advanced as some of the causes. For the much more complex feature of decrease of diurnal signal with the advancement of the season, the decrease of minimum surface temperature over coastal Tamil Nadu from Oct to Dec causing an early morning conceptual land breeze has been shown as one of the plausible causes based on analysis of temperature and wind. Scope for further work based on data from automatic weather stations, weather satellites and Doppler Weather Radars has been discussed.

Key words – North east monsoon, Rainfall, Diurnal variation, Coastal Tamil Nadu, Octet, Histogram, Harmonic analysis, Land breeze.

1. Introduction

Rainfall is perhaps the most important of the numerous meteorological and hydrological parameters influencing the livelihood of humankind, which is especially so for a densely populated country like India with its agrarian economy. Rainfall data and its various derivatives are pre-requisite crucial inputs in agricultural and hydrological planning of a region. The variation of rainfall has been studied extensively in the scale of inter-, intra-seasonal, annual and also diurnal variation over a given station or a large region represented by several rain gauges. Whereas meteorological variables like surface pressure and temperature are spatially and temporally continuous, rainfall or precipitation is not so. The spatial variation of rainfall is much more complex especially over shorter time intervals. Normal rainfall derived by averaging data over a fairly long period of time, might display spatial consistency but would still need correct and careful interpretation.

In a country like India where rainfall is by and large associated with monsoons, numerous studies on rainfall over the entire India, states, meteorological sub-divisions, districts, even still smaller regions called taluk or mandal and individual stations have been carried out and results published over the last several decades. Daily Rainfall (DRF) data for several rain gauges of India for the period since 1871 available in the archives of India Meteorological Department (IMD) has been the major source of data for such studies.

The south west monsoon (SWM) is experienced in India and neighbourhood during June-September and provides the country with 75% of its annual rainfall. The north east monsoon (NEM) is another secondary and small scale monsoon affecting the south eastern parts of India mainly during October-December. The state of Tamil Nadu and surrounding regions are the major beneficiaries of NEM which is well defined and prominent over Coastal Tamil Nadu (CTN) where 75-100 cm of rainfall which is nearly 60-70% of the annual rainfall is realised during this season. Rainfall during NEM is generally lower over the inland and heavier over the coast and reaches up to more than 100 cm in a small stretch of CTN between Nagapattinam and Vedaranyam. For a general description of NEM and its various characteristics, IMD's forecasting manual on NEM by Srinivasan and Ramamurthy (1973) and Raj (2012) may be referred. The NEM sets in around 20 October over CTN and retreats during 21-31 December.

The diurnal variation is another facet of rainfall which is important and interesting. In India, summer rainfall during March-May frequently occurs in the afternoon due to convection triggered by insolation. The diurnal variation of SWM rainfall has been studied extensively. Ray *et al.*(2016) investigated the diurnal variation of rainfall over India based on hourly rainfall of 250 self recording rain gauges (SRRG) for the 20 year period 1981-2000 for all the seasons of the year. They detected early morning rain preference over NorthEast India and afternoon rain preference over North West India. Sahany *et al.* (2010) used satellite derived Tropical Rainfall Measuring Mission (TRMM) data to study the diurnal variation of summer monsoon rainfall over the Indian region. Rajan and Iyengar (2017) used the TRMM data and numerical weather prediction model outputs to analyse the diurnal scale signatures of monsoon rainfall over India.

There have been a few studies on diurnal variation of Indian NEM rainfall (NEMR) as well. Prasad (1970) while studying the diurnal variation of rainfall of selective stations of India including Chennai found that higher falls in Chennai occur in the late evening and early morning hours in all the months except in March and April. Srinivasan and Ramamurthy (1973) have commented that during NEM season, there is preference for night rain compared to daytime rain with more rain occurring during 00-09 hrs along the east coast. Rajeevan *et al*. (2012) analysed the diurnal variation of NEMR based on TRMM data for the 12 year period 1998-2009 and reported early morning rainfall peaks over Bay of Bengal (BoB) close to CTN and evening rainfall peaks over the adjoining land area.

The objectives of the present study are to (*i*) Investigate the diurnal variation of NEMR over CTN using a long period dataset based on actual hourly rainfall observations, (*ii*) Test the significance of diurnal variation using robust statistical tests, (*iii*) Study the intra-seasonal variation, *i.e*., monthwise profile of diurnal variation and (*iv*) Identify physical mechanism, if any, that can be associated with the diurnal variation of NEMR if the same existed.

2. Data

To study in detail the diurnal variation of rainfall of any station, the foremost requirement is the availability of hourly or once in 3-hourly rainfall observations of that station for a long period of time. For this study, long period SRRG rainfall data of 4 IMD observatories *viz*., Chennai Nungambakkam (Nbk), Chennai Meenambakkam (Mbk), Nagapattinam (Npt) and Pamban (Pbn) representing CTN was utilised. Nbk and Mbk represent North CTN whereas Npt and Pbn represent Central and South CTN respectively. Fig. 1 depicts the geographical locations of the 4 observatories selected for the study. For Chennai city, both Nbk located closer to the BoB coast and Mbk located slightly away from the coast were chosen to study the effect, if any, of the distance between the coast and the rain gauge location on diurnal variation of rainfall. A calendar dayis decomposed into 24 hours, *viz*., 00-01, 01-02, …, 23-24 hrs (time in IST). Hourly rainfall data for these 24 hour intervals measured by SRRG for the above 4 stations for the 92 day period 1 October-31 December for the 49 year period 1969-2017 for Nbk and Mbk and for the 48 year period 1969-2016 for Npt and Pbn was obtained from the National Data Centre, IMD, Pune. Data for certain days or few hours was missing in the dataset, but frequency of such missing data was negligibly small.

In Table 1 is presented the climatological normals of rainfall and the number of rainy days published by IMD for the months of Oct, Nov, Dec and for the season OND (Oct-Nov-Dec) for the 4 selected stations based on the 50 year period 1951-2000 (IMD, 2010a). As shown, Nov is the rainiest month for all the 4 stations. Rainfall of Dec is slightly more or equal to Oct rainfall at Npt and Pbn. For Npt, the seasonal rainfall total of 965.2 mm is the highest amongst the 4 stations selected. For this study, a day is taken as rainy if the cumulated rainfall for the 24 hr period 00-24 hrs is 2.5 mm or more. For each day, the SRRG dataset provides this cumulated rainfall figure specifically aside from the 24 hourly values.

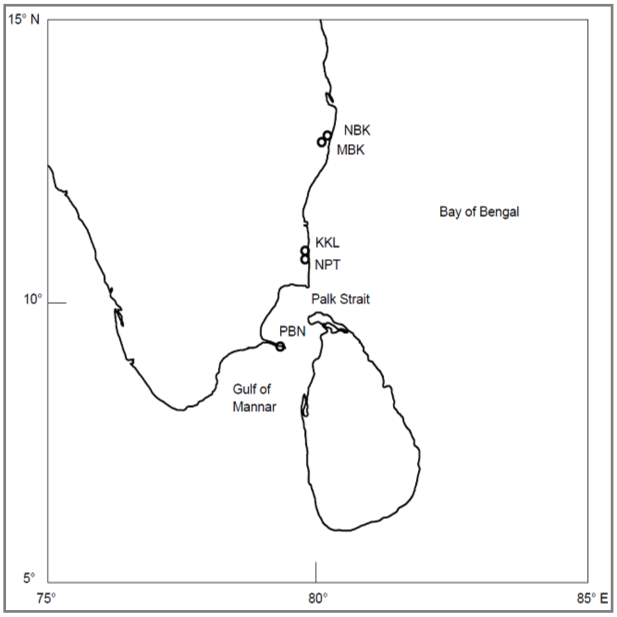


Fig. 1. Geographical locations of stations considered in the study Nbk-Nungambakkam,Mbk-Meenambakkam, Npt-Nagapattinam, Pbn-Pamban, Kkl-Karaikal

3. Computation and analysis

The diurnal variation of rainfall can be studied by employing the basic technique of computing the normal hourly rainfall for a given station for a given month or season and then by critically analysing the profiles. However, to reduce the noise inherent while studying hourly rainfall variation and to obtain smoother profiles, 3 hourly intervals or octets, *viz*., 00-03, 03-06,…, 21-24 hrs have been considered. Thus, there would be 8 values of octet rainfall (ORF) for each station and day.

It is seen from Table 1 that Nbk receives a total of 856.7 mm of normal rainfall during OND over just 26.8 rainy days out of the total length of 92 days in the season of duration 1 October-31 December. During the remaining 65 days, the station receives negligible rain and several days would remain dry with 0 mm rainfall for 24 hrs which would imply that the hourly/octet rainfall for each of the 24 hrs / 8 octets will also be 0. When diurnal variation of rainfall is studied, it is felt adequate to consider only the rainy days and omit all the non-rainy days from the analysis. The ORF values thus derived would indicate the rainfall on a rainy day and so would be more representative.

TABLE 1

Normal rainfall and number of rainy days over stations of CTN during North East Monsoon season

Month / Season ↓	Nbk		Mbk		Npt		Pbn	
	A	B	A	B	A	B	A	B
Oct	274.1	10.3	270.1	9.8	246.3	9.8	195.9	7.6
Nov	419.7	10.7	358.9	10.2	431.6	12.1	266.1	11.4
Dec	162.9	5.8	148.7	5.8	287.3	9.0	195.7	8.1
OND	856.7	26.8	777.7	25.8	965.2	30.9	657.7	27.1

Nbk- Nungambakkam, Mbk-Meenambakkam, Npt-Nagapattinam, Pbn-Pamban
CTN: Coastal Tamil Nadu, A : Rainfall in mm ; B : Number of rainy days
Source : IMD data based on 1951-2000

The analysis was carried out for the 4 stations mentioned for Oct, Nov, Dec and OND for the period indicated in Sec.2. The various computational steps carried out to derive the normal profiles of ORF and the methodology followed in the detection of significant diurnal variation are detailed below for a given station for a month/season:

(*i*) In the first step of the computational process, all the non-rainy days were excluded from the analysis. From the hourly rainfall data, the ORF was computed for each octet and if there was any missing data for a specific hour the corresponding octet data was taken as missing.

(*ii*) The mean or normal rainfall for each octet and the total mean rainfall for a day, which is the sum of the 8 ORF values were then derived. To put it mathematically, consider a month, say Oct. If n_i is the number of rainy days in Oct for the *i-th* year, then $n = \sum n_i$ is the total number of rainy days in Oct. The mean ORF x_i , i =1,8 for each octet was then computed each based on n values. The normal ORF μ based on ORF of all the 8 octas and σ the standard deviation of μ were both derived based on $8n$ values, save for missing values. As the normal ORF values for the 8 octets are $x_1, \ldots, x_8$, and μ is the normal ORF when all the octets are combined, $\mu = \sum x/8$.

(*iii*) If there was no diurnal variation then $x_1, \ldots, x_8$ all would be identical and equal to μ. But this does not generally happen and the rainfall of each octet x_i is likely to exhibit some difference from μ. The mean ORF anomaly (ORA) defined by $d_i = x_i - \mu$,i =1,8 is the difference between x_i and μ. Whether ORA is significant or not for each i and whether the ORA profile is smooth with positive (negative) anomalies displayed over a few consecutive octets resulting in a harmonious graph of ORA suggesting the presence of diurnal variation or otherwise needs to be studied and analysed.

(*iv*) If n_i is the frequency corresponding to the i-th octet then $n_i = n/8$. The standard error (SE) of x_i denoted by s_i is given by $s_i = \sigma / \sqrt{\ } n_i$. The significance of difference d_i can now be tested with standard sampling tests. The samples are however not random as meteorological samples seldom are. But as only rainy days are considered and dry days are omitted, there would be more randomness in the sample than if all the days had been included. As the samples were all very large, test for large samples based on Normal Distribution theory was applied.

(*v*) The above computational steps were carried out for the octet rainfall data of the 4 stations Nbk, Mbk, Npt and Pbn for the 4 periods Oct, Nov, Dec and OND. The mean rainfall for each octet x_i , its anomaly d_i were derived and testing was done at 5, 1 and 0.1% levels of significance (LS). Table 2(a) presents these octet profiles for the 4 stations and periods. The normal ORF μ, its standard deviation σ, the mean DRF (of a rainy day which is same as 8μ) and the approximate frequency n based on which x_i was computed are presented in Table 2(b). Fig. 2 depicts the ORA profiles in graphical histogram format.

(*vi*) The time series d_i , i =1,8 for all the 16 cases were separately subjected to harmonic analysis to detect the highs and lows in the ORA graphical profile. As the ORA profiles are by and large sinusoidal in shape, harmonic analysis can bring out such features in an objective way (Panofsky and Brier, 1958). The total number of harmonics is 4 and the first, second, third and fourth harmonics undergo 1, 2, 3 and 4 cycles within 24 hrs with periodicities of 8, 4, 2.67 and 2 octets or 24, 12, 8 and 6 hrs respectively. An ORA profile with a single maximum and minimum indicating a 24 hrs cycle would manifest as a very high percentage variation explained by the first harmonic. The presence of secondary peak/low in ORA will show up as second or third harmonics also being significant explaining high variance. If there is no

TABLE 2(a)

Mean ORF and ORA distribution on a rainy day over stations of CTN during North East Monsoon season

Octets ↓ (hrs)	October			November			December			OND		
	ORF	ORA	LS	ORF	ORA	LS	ORF	ORA	LS	ORF	ORA	LS
Nungambakkam (1969-2017)												
00-03	4.7	1.3	*	4.7	0.8	O	3.7	0.1		4.5	0.8	#
03-06	5.1	1.7	#	5.1	1.2	*	4.2	0.6		4.9	1.3	#
06-09	3.2	-0.3		3.5	-0.4		3.5	-0.1		3.4	-0.3	
09-12	3.5	0.1		3.2	-0.7		3.5	-0.1		3.4	-0.3	
12-15	2.9	-0.5		3.3	-0.6		3.8	0.2		3.3	-0.4	
15-18	2.1	-1.3	*	3.4	-0.5		3.5	-0.1		2.9	-0.7	*
18-21	2.7	-0.8		3.9	0.0		3.3	-0.3		3.3	-0.3	
21-24	3.2	-0.2		4.1	0.2		3.4	-0.2		3.6	0.0	
Meenambakkam (1969-2017)												
00-03	4.4	0.9	o	4.7	0.8	O	3.3	-0.5		4.3	0.6	o
03-06	4.1	0.6		4.4	0.5		4.7	1.0		4.4	0.7	*
06-09	3.5	-0.1		3.8	-0.2		4.1	0.3		3.7	0.0	
09-12	3.3	-0.2		3.6	-0.3		3.2	-0.6		3.4	-0.3	
12-15	4.0	0.5		3.6	-0.3		4.6	0.8		3.9	0.2	
15-18	2.6	-0.9	o	3.2	-0.7		3.3	-0.5		3.0	-0.7	*
18-21	2.8	-0.7		3.7	-0.2		3.4	-0.3		3.3	-0.5	
21-24	3.4	-0.1		4.2	0.3		3.5	-0.3		3.7	0.0	
Nagapattinam (1969-2016)												
00-03	4.7	1.6	#	5.3	1.1	*	4.0	0.5		4.7	1.1	#
03-06	4.9	1.7	#	5.0	0.8		3.8	0.4		4.7	1.0	#
06-09	3.7	0.5		4.9	0.6		3.9	0.5		4.2	0.6	o
09-12	3.1	-0.1		4.7	0.4		3.9	0.5		3.9	0.3	
12-15	1.9	-1.3	*	4.0	-0.2		2.9	-0.6		3.0	-0.7	*
15-18	2.2	-1.0	o	3.2	-1.0	O	2.8	-0.6		2.8	-0.9	#
18-21	1.9	-1.3	*	3.0	-1.2	*	2.7	-0.7		2.6	-1.1	#
21-24	3.0	-0.2		3.8	-0.5		3.4	0.0		3.4	-0.2	
Pamban (1969-2016)												
00-03	4.8	1.9	#	3.6	0.8	O	3.2	0.5		3.8	1.1	#
03-06	4.4	1.4	*	3.9	1.1	#	3.3	0.6		3.8	1.1	#
06-09	4.0	1.0	o	3.1	0.4		3.5	0.9	O	3.5	0.7	*
09-12	2.7	-0.2		2.8	0.0		2.4	-0.2		2.7	-0.1	
12-15	1.4	-1.6	*	2.0	-0.7	O	2.0	-0.7		1.8	-1.0	#
15-18	0.8	-2.1	#	1.9	-0.8	O	2.3	-0.3		1.7	-1.1	#
18-21	2.1	-0.9		2.1	-0.7	O	2.5	-0.2		2.2	-0.6	*
21-24	3.6	0.6		2.6	-0.2		2.2	-0.5		2.8	0.0	

ORF : Octet rainfall in mm , ORA : Octet rainfall anomaly in mm, Time in IST
LS : Level of Significance o : 5 % * : 1% # : 0.1%
Based on rainy days only, dry days omitted

TABLE 2(b)

Statistical parameters of ORF and ORA profiles

Month / ↓ Season	μ	σ	σ_e	Mean DRF	*n*
			Nbk		
Oct	3.4	8.9	0.41	27.3	484
Nov	3.9	8.9	0.39	31.1	521
Dec	3.6	8.1	0.50	28.8	266
OND	3.6	8.7	0.25	29.2	1271
			Mbk		
Oct	3.5	9.1	0.41	28.0	501
Nov	3.9	9.0	0.40	31.3	512
Dec	3.7	8.4	0.53	29.9	253
OND	3.7	8.9	0.25	29.7	1268
			Npt		
Oct	3.2	8.7	0.41	25.5	453
Nov	4.2	9.7	0.41	33.9	574
Dec	3.4	7.9	0.39	27.4	416
OND	3.7	8.9	0.23	29.4	1445
			Pbn		
Oct	3.0	9.1	0.50	23.8	337
Nov	2.7	7.0	0.33	21.9	461
Dec	2.7	7.0	0.40	21.4	320
OND	2.8	7.7	0.23	22.3	1119

ORF/ORA – As in Table 2a, Nbk, Mbk, Npt, Pbn - as in Table 1
μ - Normal Octet rainfall (in mm) of all 8 octets
σ - Standard deviation of μ (in mm), σ_e - Standard error (in mm)
DRF: Daily rainfall (in mm) of a rainy day
n - Number of rainy days during 1969-2016 / 2017

periodicity, same will manifest as near equal harmonics. The variance explained by each harmonic, the amplitude and the exact time at which the harmonics reached maximum and minimum values were derived. Fig. 3 presents the percentage variance explained and the amplitude corresponding to each of the 4 harmonics computed.

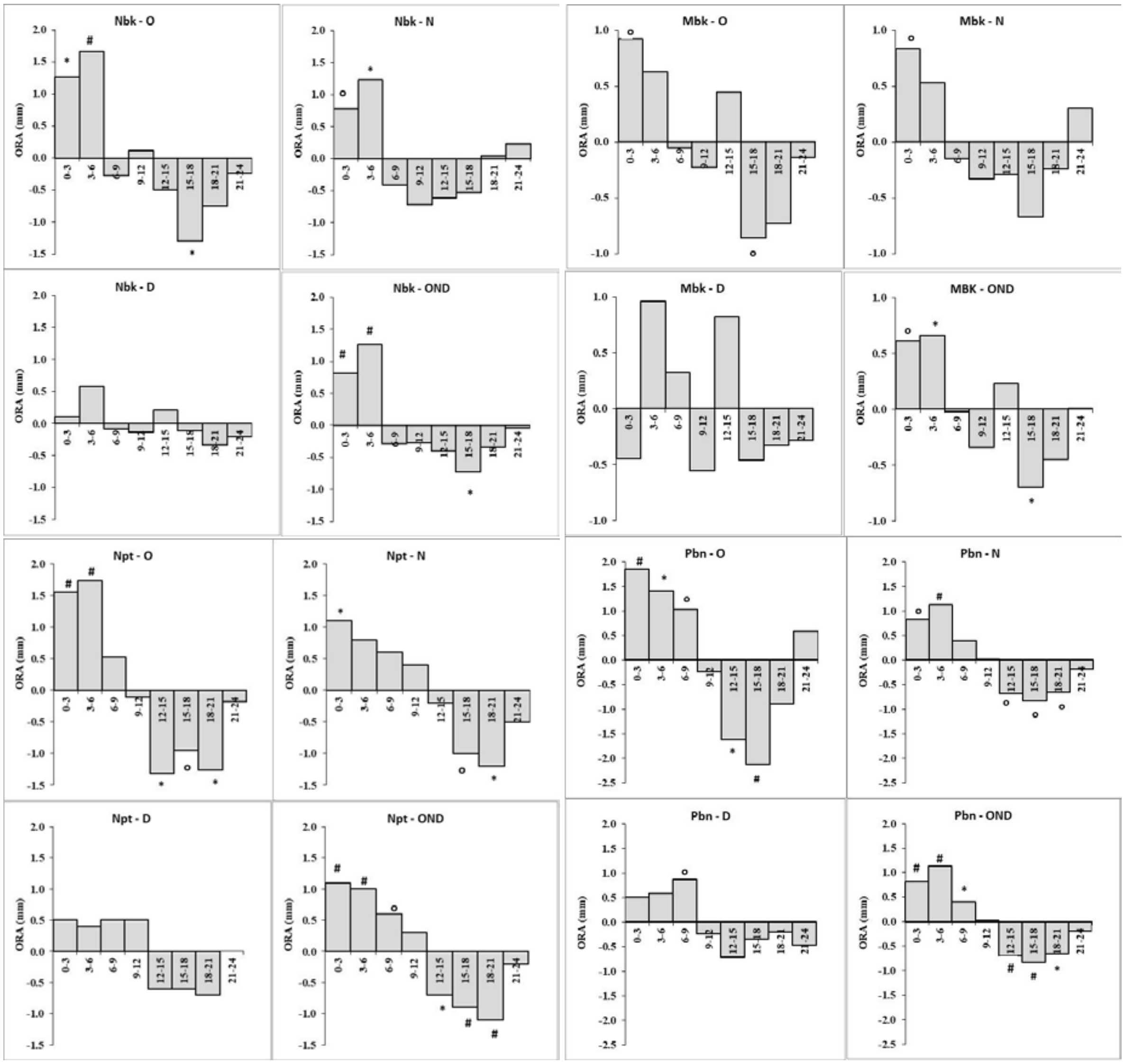
A critical analysis of the statistics depicted in Tables 2(a&b), Figs.2 and 3 and other results derived gave rise to several inferences which are presented and discussed in the forthcoming section, stationwise and periodwise. It must be noted that only rainy days have been considered and non-rainy days have been omitted in the analysis.

4. Results

4.1. *Nungambakkam*

The Nbk observatory is the northernmost of the four stations considered in the study and is located at a distance of around 3-4 km from the BoB coast (Fig.1).

Oct : The ORF normal is 3.4 mm [Table 2(b)]. During the octets 00-03 and 03-06 hrs (time in IST) the ORF (and ORA) are 4.7(1.3) and 5.1(1.7) mm which are significantly higher than the normal ORF with LS 1 and 0.1% respectively [Table 2(a)]. During 15-18 and 18-21 hrs the ORA is negative and significant for the former



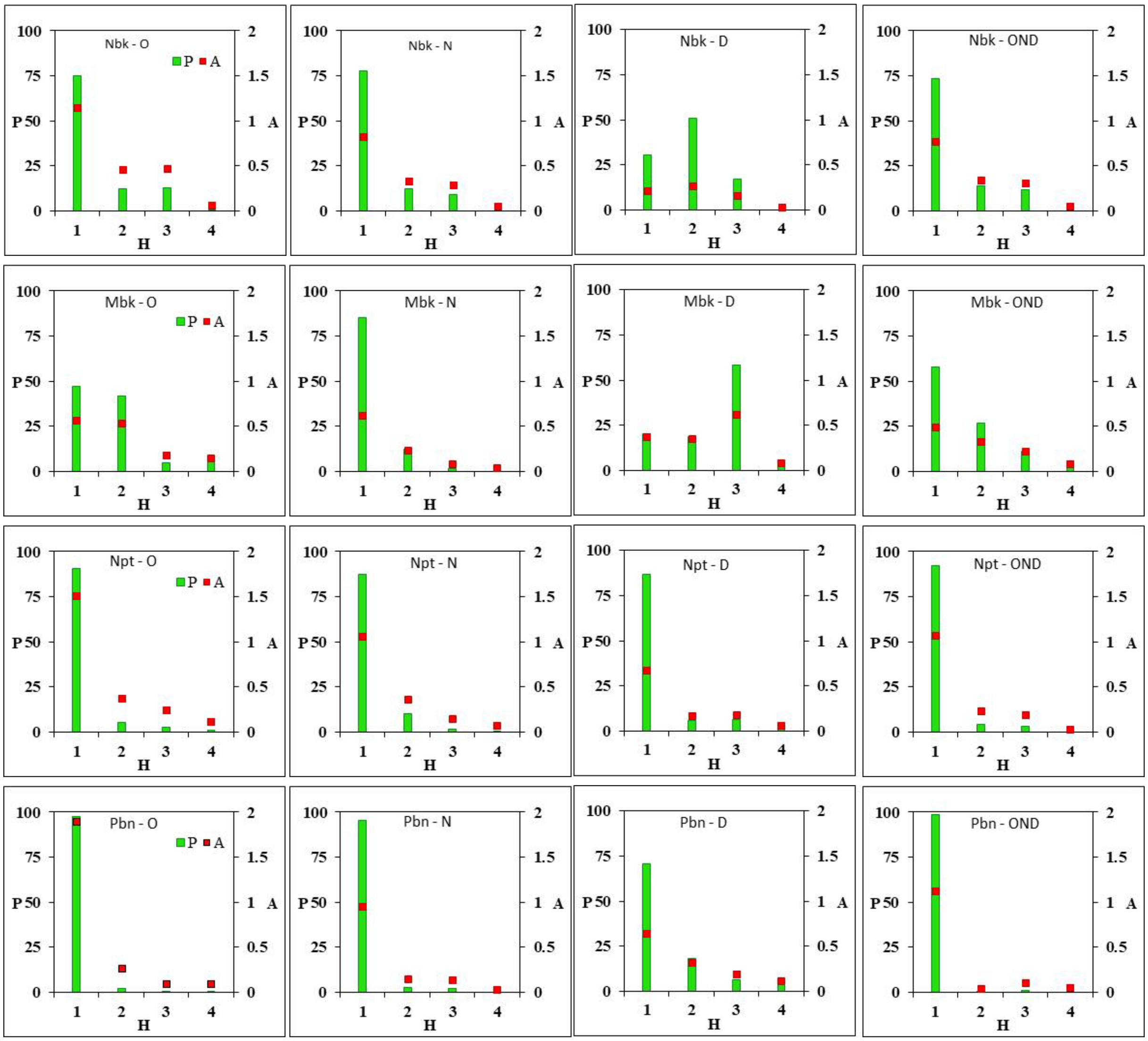
x-axis: Octets 00-03 hrs, …., 21-24 hrs (IST)
y-axis: ORA: Octet rainfall anomaly in mm (of a rainy day)
O-Oct, N-Nov, D-Dec : Station abbreviation as in Fig. 1.

Fig. 2. Histogram profiles of mean ORA for stations and months

at 2.1(-1.3) mm, LS 1%. Thus, there is a strong preference for early morning rainfall and relatively less rainfall during the late afternoon and early night hours. The first harmonic explains 75% reaching maximum and minimum amplitudes at 0400 and 1600 hrs respectively consistent with this feature (Fig.3). There is a weak secondary positive peak during 9-12 hrs with an ORA value of 0.1mm found to be associated with the third harmonic explaining 13% variance and reaching one of its maximum peaks at 0945 hrs.

Nov : The early morning rain peak is present but with reduced intensity compared to Oct. For 00-03 hrs the ORF is 4.7(0.8) mm LS 5%, 03-06 hrs 5.1(1.2) mm LS 1%. The ORA profile is very smooth with positive/zero values during 18-06 hrs and negative values during06-18 hrs though the latter is not statistically significant. The first harmonic explains 78% variance reaching maximum and minimum at 0145 and 1345 hrs respectively consistent with the ORA profile depicted in Fig. 2.

Dec : There is positive ORA during 00-06 hrs and negative ORA during 15-24 hrs but no ORA is significant During 12-15 hrs another very weak secondary positive anomaly shows up. The second harmonic explaining 50% variance is the most prominent one followed by the first



H : Number of the harmonic , P : Percentage variance (%) explained by each harmonic
A : Amplitude (mm) of the harmonic, O-Oct, N-Nov, D-Dec, Station abbreviation as in Fig. 1.

Fig. 3. Harmonic Analysis of mean ORA profiles - Periodograms for stations and months

harmonic explaining 30%. The second harmonic reaches highs at 0300 and 1500 hrs and lows at 0900 and 2100 hrs. The first harmonic peaks at 0600 hrs and bottoms at 1800 hrs. The ORA peak during 03-06 hrs is obviously the combined effect of both these peaks whereas the secondary ORA peak is associated with the peak of the second harmonic.

OND : For the two octets 00-03 and 03-06 hrs, ORF and ORA at 4.5(0.8) and 4.9(1.3) mm are significant at 0.1% LS. The octet 15-18 hrs has the lowest rainfall 2.9 (-0.7) mm and this negative anomaly is significant at 1% LS. The ORA profile is very smooth with positive values during 00-06 hrs and negative values during06-21 hrs. The first harmonic explains 73% of variation reaching maximum at 0315 hrs and minimum at 1515 hrs consistent with the histogram profile. Though Oct and Dec profiles display secondary maxima, the OND profile does not show the same.

4.2. *Meenambakkam*

The Meenambakkam observatory is located south west of Nungambakkam at a distance of 9-10 km from the Chennai city coast and is slightly more inland.

Oct : As shown in Table 2(a) and Fig.2, ORF at 4.4(0.9) mm for 00-03 hrs and 2.6(-0.9) mm for 15-18 hrs are significant at 5% LS. No other anomalies are significant. There is a secondary positive ORA peak against the octet 12-15 hrs with 4.0(0.5) mm though not significant. The first harmonic explains only 45% reaching peak and low at 0500 and 1700 hrs respectively. The second harmonic explains 39% with peaks at 0130 and 1330 hrs and lows at 0730 and 1930 hrs. The ORA peak during 00-06 hrs is associated with the peaks of both these harmonics whereas the secondary peak during 12-15 hrs is associated with the second harmonic.

Nov : The octet 00-03 hrs with 4.7(0.8) mm is the only one with a significant positive anomaly. Though anomalies during 21-06 are all positive and those during 06-21 hrs are all negative displaying a very smooth and harmonious profile, most are not significant. The first harmonic explains 85% of the variation with peak and low at 0215 and 1415 hrs respectively.

Dec : The ORA is positive during 03-09 hrs and its value for 03-06 hrs at 4.7(1.0) mm though not significant is higher than a few significant ORA values for Oct/Nov. There is an isolated positive peak at the octet 12-15 hrs with ORA 0.8 mm. The anomalies are all negative during 15-03 hrs though not significant with an isolated negative low of value -0.6 mm during 09-12 hrs. In Dec the sample size is small with less number of rainy days. The SE at 0.53 mm is high and so the ORAs fall short of being statistically significant. The first, second and third harmonics explain 20, 18 and 57% variance respectively. The first and third harmonics both reach peak at about 0730 hrs and low at about 1930 hrs which explain the morning peak and night low of ORA. The second and third harmonics are positive during 1300-1600 and 1330-1730 hrs respectively which explains the isolated positive peak. The third harmonic reaches low at 1130 hrs associated with the isolated negative peak.

Due to the reasonably organised profile of ORA, it must be concluded that the ORF/ORA profile of Mbk Dec exhibits significant morning maximum, night minimum besides secondary peak and low during the day time, despite lack of statistical significance.

OND : The octets 00-03 and 03-06 hrs have positive anomalies significant at 5% and 1% LS respectively. The octet 15-18 hrs shows negative anomaly significant at 1% LS. The octets 09-12 and 12-15 hrs display weak secondary isolated negative and positive peaks respectively. The first harmonic explaining 56% reaches maximum and minimum at 0400 and 1600 hrs respectively and is linked to the morning peak and night low. The second harmonic (26%) reaching high at 1400 hrs is linked to the secondary maximum. The secondary minimum during 09-12 hrs can be linked to the first and second harmonics assuming negative values during that period.

4.3. *Nagapattinam*

The Nagapattinam observatory is located within 1-2 km west of the BoB coast (Fig.1). It receives prodigious rainfall of nearly 97 cm during the OND NEM season.

Oct : For the 00-03 and 03-06 hrs octets, which receive ORF/ORA of 4.7(1.6) mm and 4.9(1.7) mm respectively, ORA are highly significant at 0.1% LS. The 3 octets within 12-21 hrs all have negative ORA values significant at 5 or 1% LS. The first harmonic explains 90% of the variation reaching high and low at 0400 and 1600 hrs respectively.

Nov : For the octet 00-03 hrs, ORA of 5.3(1.1) mm is significant at 1% LS. The octets 15-18 and 18-21 hrs have negative ORA of -1.0 and -1.2 mm significant at 5 and 1% LS respectively. The first harmonic explains 87% of the variation reaching maximum and minimum amplitude at 0545 and 1745 hrs respectively.

Dec : The ORA is positive during 00-12 hrs and negative during 12-18 hrs showing a smooth and harmonious profile though not statistically significant. The first harmonic explains 86% of variation reaching high at 0515 and low at 1715 hrs.

OND : The octets 00-03 and 03-06 hrs have ORA values of 4.7(1.1) and 4.7(1.0) mm respectively both significant at 0.1% LS. The octets 15-18 and 18-21 hrs have ORF 2.8(-0.9) and 2.6(-1.1) mm significant at 0.1% LS. The ORA profile is very smooth with positive ORA during 00-12 hrs and negative ORA during 12-24 hrs with 6 ORA values being significant. The first harmonic explains 92% of the variation reaching maximum and minimum values at 0500 and 1700 hrs respectively.

Overall, the ORA profiles for all the 4 periods are very smooth and continuous for Npt with no secondary peak or low which can be noted from Table 2(a) and Fig.2. The diurnal cycle is definitely present but relatively weak in Dec and is not statistically significant.

4.4. *Pamban*

The Pamban observatory is located at the western edge of the Pamban Island which lies east of the tapering tail-like landmass of the mainland protruding into the BoB and is juxtaposed between the Palk Strait and Gulf of Mannar (Fig.1). It is located nearly 2 km from the mainland and is surrounded by sea in almost all the directions.

Oct : The 00-03, 03-06 and 06-09 hrs ORF/ORA at 4.8(1.9), 4.4(1.4) and 4.0(1.0) mm are all positive and significant at 0.1, 1, 5% LS respectively. The ORF/ORA corresponding to 12-15 and 15-18 hrs are 1.4(-1.6) and 0.8(-2.1) mm, significant at 1 and 0.1% LS respectively. The ORA profile is very smooth. The first harmonic explains as much as 97% variation reaching high and low at 0330 and 1530 hrs respectively.

Nov : The ORA profile is smooth with 3.6(0.8) and 3.9(1.1) mm during 00-03 and 03-06 hrs significant at 0.1% and 5% LS respectively. The ORA is negative during 12-21 hrs significant at 5% LS.The first harmonic explains 95% variation reaching maximum at 0430 hrs and minimum at 1630 hrs respectively.

Dec : The ORA profile is smooth with positive and negative values during 00-09 and 09-24 hrs respectively. However, barring ORF/ORA at 3.5(0.9) mm during 06-09 hrs significant at 5% LS other anomalies are not significant. The first harmonic explains 67% reaching maximum and minimum at 0445 and 1645 hrs respectively. The second harmonic explains 17%.

OND : The ORA profile is very smooth with the octets within 00-06 hrs both showing positive ORA value of 3.8(1.1) mm and 12-18 hrs showing negative ORA values of 1.8(-1.0) and 1.7(-1.1) mm. Most of the ORA values are highly significant at 0.1% or at 1% LS. The first harmonic alone explains 98% of the variation reaching maximum at 0400 hrs and minimum at 1600 hrs.

Overall, the ORA profiles of Pbn are all very smooth and harmonious similar to that of Npt without any secondary positive peak or negative low.

4.5. *Inferences*

The inferences that could be drawn on the diurnal variation of NEMR over CTN based on the above description and also from Tables 2(a&b), Figs. 2 and 3 are described herein below:

(*i*) The diurnal cycle is well defined and significant in Oct characterised by early morning rainfall peak and late afternoon rainfall low for all the 4 stations. The signal persists with lower intensity in November and decreases further in December in a statistical sense. In Dec, the ORA displays positive anomalies in the early morning and negative anomalies in the evening, but statistical significance at 5% LS is absent in all the octets barring one for Pamban.

(*ii*) In Oct and Dec, the ORA profiles of Nbk and Mbk observatories situated within the city of Chennai show a weak secondary positive peak in the forenoon/afternoon though not significant displaying semi-diurnal variation. The secondary peak at Mbk is better marked for both these months. However, November ORA profiles for both the observatories are smooth and harmonious.

(*iii*) ORA profiles of Npt and Pbn observatories are smooth with continuous positive and then negative values for the 3 months and for the entire period OND with clearly defined diurnal signal of early morning peaks and evening lows. No secondary peaks or lows are present.

(*iv*) In Chennai City, Nbk observatory located closer to the sea coast displays a much clearer diurnal cycle than the slightly interior located Mbk observatory. In Pamban Island observatory, the early morning peak and afternoon low are displayed much more clearly and authentically compared to that of the other stations.

(*v*) The ORA profiles for OND are smooth with clear diurnal signal of early morning rainfall peak and late afternoon rainfall low for all the four stations. Mbk shows a weak secondary peak during 12-15 hrs. The high statistical significance of ORA of OND is also owing to the large sample size compared to that of individual months.

(*vi*) The diurnal signal is not uniform within the OND season and displays an intra-seasonal variation. It decreases as the winter season advances which has been brought out by the analysis based on individual months.

(*vii*) The various byproducts of the harmonic analysis performed on ORA provided several additional crucial inputs such as the variance explained and the time at which each harmonic reached maximum and minimum values. In the case of Nbk and Mbk, the first harmonic explains more than 70% variation in 3 and 1 out of 4 periods respectively. For Npt and Pbn, this feature is present for all the periods. For Nbk and Mbk the second and third harmonic also explain substantial variation and in two instances (Nbk and Mbk, Dec) either of them is the leading harmonic associated with the presence of secondary maximum and minimum in the ORA profile.

4.6. *Diurnal variation of rainfall index and coefficient of mean ORA*

To further authenticate the presence of diurnal signal in a more lucid fashion and to compare the strength of the various diurnal cycles, two indices were defined and derived which are detailed below:

For each station and period, two consecutive octets called quartet which together result in the highest sum of the corresponding ORF values [From Table 2(a)] were

TABLE 3

Monthly and seasonal values of DVRI and CMO over CTN during north east monsoon season

Month / Season ↓	$Q_h$hrs IST	R_hRF cm	Q_l hrs IST	R_lRF cm	Diff cm	R_mRF cm	DVRI %	MO mm	CMO %
Nbk									
Oct	00-06	472	15-21	232	240	1321	18.2	0.76	22.4
Nov	00-06	509	09-15	336	173	1612	10.7	0.57	14.6
Dec	00-06	210	18-24	177	33	766	4.3	0.22	6.1
OND	00-06	1190	15-21	789	400	3711	10.8	0.52	14.4
Mbk									
Oct	00-06	427	15-21	272	156	1403	11.1	0.50	14.3
Nov	00-06	470	12-18	351	119	1603	7.4	0.42	10.8
Dec	03-09	222	15-21	169	53	757	7.0	0.52	14.1
OND	00-06	1102	15-21	795	307	3766	8.1	0.39	10.5
Npt									
Oct	00-06	438	15-21	189	249	1155	21.6	0.96	30.0
Nov	00-06	591	15-21	357	234	1946	12.0	0.73	17.4
Dec	00-06	324	15-21	230	94	1140	8.3	0.48	14.1
OND	00-06	1355	15-21	776	579	4248	13.6	0.72	19.4
Pbn									
Oct	00-06	310	12-18	74	236	802	29.5	1.22	40.7
Nov	00-06	342	15-21	182	160	1010	15.8	0.59	21.9
Dec	03-09	206	12-18	137	68	685	10.0	0.49	18.1
OND	00-06	858	12-18	394	464	2495	18.6	0.71	25.3

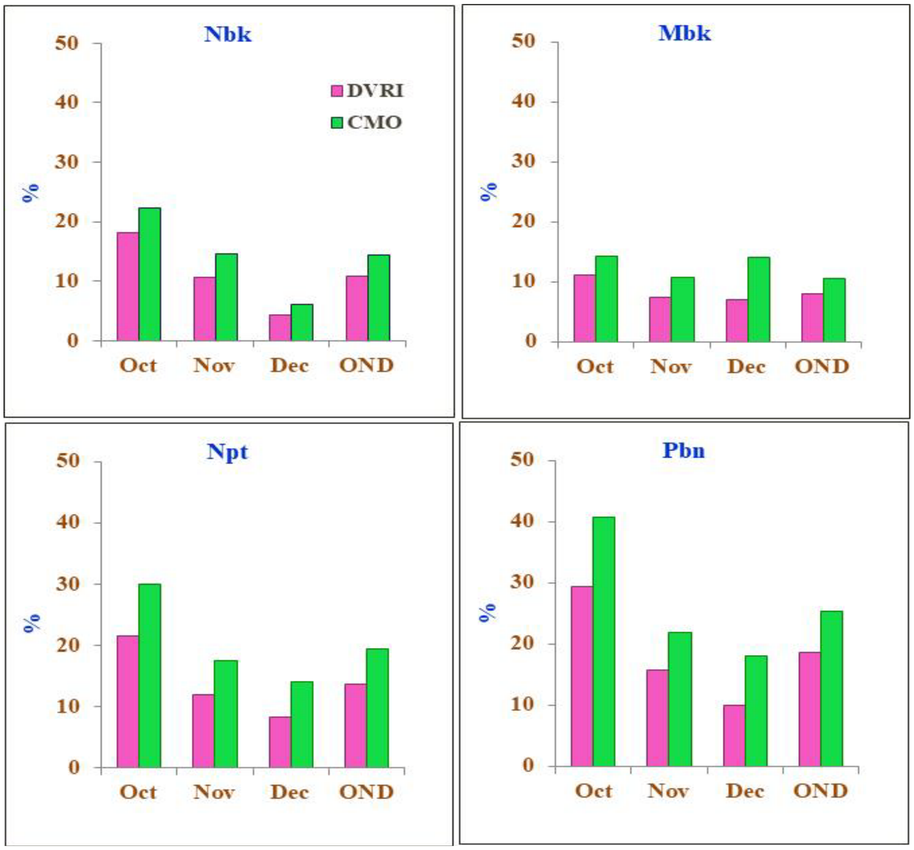
Q_h, Q_l - Quartets receiving the maximum / minimum mean rainfall
R_h RF, R_l RF - Total Rainfall (in cm) realised during the quartet for the period of data
R_m RF : Mean rainfall (in cm) for the entire period of data
Nbk, Mbk, Npt, Pbn - as in Table 1
MO – Mean absolute ORA in mm , CMO - Coefficient of MO
DVRI - Diurnal Variation of Rainfall Index
Period of data: Nbk, Mbk: 1969-2017, Npt, Pbn: 1969-2016

identified, yielding the highest quartet rainfall (QRF). Similarly, the quartet yielding the lowest QRF was also identified. The cumulative rainfall values realised corresponding to both the quartets and their differences were computed for the whole period 1969-2017/2016 and presented in Table 3 for all the stations and periods. The cumulative QRF is given by QRF multiplied by the total number of rainy days *n* [Table 2(b)] and provides a better indicative measure of the quantum of diurnal variation. Based on these parameters, a diurnal variation of rainfall index (DVRI) for each station and month / season is defined as :

$$\text{DVRI} = [(R_h - R_l)/R_m]\times 100$$

where, R_h and R_l are the highest and lowest quartet rainfall respectively as explained above and R_m is the mean rainfall for the entire period given by $R_m = n \times$Mean DRF[Table 2(b)].

The arithmetic mean of absolute ORA (MO) which is the mean size of ORA values for a given period/station was computed and based on which, coefficient of MO (CMO) is defined as $\text{CMO} = (\text{MO}/\mu)\times 100$,where,$\mu$ is the normal ORF. The definition of CMO is analogous to that of mean deviation of statistics whereas the definition of DVRI draws from that of quartile deviation but is normalised using the mean. Both DVRI and CMO are normalised indices with respect to the mean and are



DVRI - Diurnal variation of rainfall index in percentage
CMO - Coefficient of mean absolute ORA in percentage
ORA – As in Fig.2.

Fig. 4. Mean month and stationwise variation of DVRI and CMOStation abbreviation as in Fig.1.

expressed as percentage. When there is no diurnal variation, all ORA values and so MO which is the mean size of ORA must be 0 and so the extent of deviation of MO from 0 could indicate the strength of diurnal variation in most of the cases when the presence of diurnal variation is already established by other analysis. DVRI could quantify the extent of diurnal variation whereas CMO could be a supporting parameter. Both DVRI and CMO could in tandem be used to compare the strength of the diurnal cycle of the 16 cases which have been analysed.

The DVRI and CMO values computed are presented in Table 3 and depicted pictorially in Fig.4. The interpretation of DVRI is demonstrated by considering diurnal variation of rainfall at Npt for Oct. QRF is highest for the quartet 00-06 hrs which receives 438 cm of rainfall and lowest during 15-21 hrs receiving 189 cm (Table 3) yielding a difference of 249 cm for the 48 year period 1969-2016. The Mean DRF for a rainy day for Oct is 25.5 mm and there are 453 rainy days [Table 2(b)] yielding a total mean rainfall $R_m$of 1155 cm and so DVRI value of 21.6% [Table 3].

A critical perusal of the contents of Table 3 and Fig.4 yields several interesting results about the profile of diurnal variation of NEMR over CTN, which are enumerated below :

(*i*) The highest DVRI value of 29.5% is realised for Pbn for Oct and the lowest value is 4.3% for Nbk Dec. Coinciding with this, the highest CMO value of 40.7% is realised for Pbn Oct and lowest value of 6.1% for Nbk Dec. For Oct and Nov the DVRI and CMO values of Pbn, Npt, Nbk and Mbk form a decreasing sequence. For Dec, the order is Pbn, Npt, Mbk and Nbk for both the indices.

(*ii*) For a given station the DVRI values for Oct, Nov and Dec form a decreasing sequence, showing very clearly that diurnal variation signal decreases as the season advances. The CMO values also form the same pattern save for one instance when value for Mbk Dec at 14.1% is higher than the Nov value of 10.8%.

TABLE 4

Normal variation of LWC and RH over Mds and Kkl during north east monsoon season 1000-500 hPa

Month ↓	Mds 0000 UTC			Mds 1200 UTC		
	LWC mm	RH m %	RH Range %	LWC mm	RH m%	RH Range %
Oct	46	78	89-42	46	72	70-39
Nov	40	70	89-34	40	68	71-35
Dec	34	63	88-28	35	60	68-28
	Kkl 0000 UTC			Kkl 1200 UTC		
Oct	44	78	89-41	43	71	76-39
Nov	43	80	87-46	42	75	76-44
Dec	39	75	86-40	39	73	79-39

Mds : Chennai – Meenambakkam Kkl : Karaikal
0000& 1200UTC 0530 & 1730 hrs IST
LWC : Liquid Water Content 1000-500 hPa; RH : Relative Humidity
RH m - Mean RH within 1000-500 hPa
Normal data based on 1971-1990 (Mds); 1978-1990 (Kkl)

(*iii*) In Dec both DVRI and CMO are slightly higher at Mbk (7.0 and 14.1) than at Nbk (4.3 and 6.1) though diurnal variation is weak and not statistically significant at both the stations.

(*iv*) For the entire season of OND the DVRI values for Pbn, Npt, Nbk and Mbk are 18.6, 13.6, 10.8 and 8.1% and the CMO values are 25.3, 19.4, 14.4 and 10.5% respectively, both forming a decreasing sequence.

(*v*) Based on the above results, it can be concluded that by and large the strength of the diurnal variation decreases from Oct to Nov and Nov to Dec. Amongst the stations, the intensity index of diurnal variation of Pbn, Npt, Nbk and Mbk for a given period forms a decreasing sequence barring just one or two exceptions.

(*vi*) For the months, *i.e.*, Oct, Nov and Dec, in 10/12 instances the 00-06 hrs quartet receives the highest rainfall. In just 2 instances both for Mbk and Pbn in Dec it is the 03-09 quartet. There is however more variation in the quartet receiving the lowest rainfall which is 15-21 hrs in 7/12 instances, 12-18 in 3/12, 09-15 and 18-24 both each 1/12 showing wide variation. For Npt the 15-21 hrs quartet receives the lowest rainfall for all the 3 months.

(*vii*) For the entire season, *i.e.*, OND the 00-06 quartet receives the highest rainfall for all the stations. The quartet that receives the lowest rainfall is 15-21 hrs for Nbk, Mbk and Npt whereas for Pbn it is the 12-18 hrs quartet.

(*viii*) It can be noted that the mean DRF (of a rainy day) presented in Table 2(b) does not vary much within the months for a given station. However, MO decreases as the season advances (barring one exception) affirming that the lower ORA values in Dec are not due to any decrease in mean DRF but due to weakening of diurnal variation signal only.

5. Physical mechanisms behind the diurnal variation of NEMR and its intra seasonal variation

There are several references in the literature on the diurnal variation of continental and maritime type of rainfall and the physical mechanisms behind both. Most of the studies mention that summer rainfall maximum frequently occurs in the afternoon over the continent which is rather easily explained by the maximum solar heating and increased convection at that time of the day, over the land. Over the oceans more rainfall is realised in the early morning hours which however is not so easy to comprehend. A few physical mechanisms behind the nocturnal maximum of oceanic rainfall are complex features such as radiative cooling effect between cloud versus environment, absorption of solar radiation near cloud top stabilising the atmosphere during daytime, longwave cooling destabilising the atmosphere near cloud top and few others. Johnson (2011) provides a detailed description on the diurnal cycle of monsoon convection including continental and oceanic convection. There is a broad consensus that convection over oceans is maximum during late night / early morning. This feature could be reasonably expected to extend to coastal stations with a maritime climate.

TABLE 5

Normal maximum and minimum temperatures over Nbk and Npt and SST off CTN over BoB

Month↓	Nbk		Npt		BoB
	Tx	Tn	Tx	Tn	SST
Oct	31.8	24.5	31.7	25.1	28
Nov	29.6	23.0	29.7	24.1	28
Dec	28.5	21.9	28.6	23.0	27-28

Tx, Tn, SST : Max/Min Temperatures and Sea Surface Temperature in ˚C
CTN : Coastal Tamil Nadu ; BoB : Bay of Bengal
Nbk, Npt – as in Table 1

It has been established in the present study that early morning rainfall maximum is present for the 4 stations of CTN considered, though the diurnal variation itself displays varying intensity within the season. Evidently, the presence of maritime climate over CTN is the dominant factor behind the occurrence of early morning maximum of NEMR. The decrease in intensity of diurnal variation in Mbk compared to Nbk and the clear signal at Pamban which is an island station both bear testimony to the importance of proximity of station to the ocean. It is possible to explain the early morning rainfall maximum over CTN and the dropping of the diurnal variation signal towards inland in as much as CTN is a part of BoB coast.

One simple feature favouring early morning rainfall maximum over a coastal station is the higher level of saturation in the lower levels of the atmosphere at that time of the day (Haurwitz and Austin,1944). To investigate this aspect, the normal liquid water content (LWC) and the mean and range of the relative humidity in the 1000-500 hPa layer were derived for Chennai (Madras, Mds) and Karaikal (Kkl) representing CTN (Fig.1). The computations were based on normal upper air data (IMD, 2011) at 0000 and 1200 UTC (0530 and 1730 hrs IST) based on data of 1971-1990 for Chennai and 1978-1990 for Karaikal. The results are presented in Table 4. It is seen that the LWC values remain the same for both 0000 and 1200 UTC for a given station and monthbut the RH is higher by a few points at 0000UTC especially in the lower levels, obviously due to lower temperatures at 0000 UTC compared to 1200 UTC. Though these are normal values, such patterns should prevail during rainy days also which would lead to a lower lifting condensation level, more amount of cloud formation and eventually more rainfall in the morning than in the evening.

Whereas the physics behind the early morning maximum of NEMR over CTN can be explained from the above two concepts, *viz*., maritime climate and higher morning saturation at the lower levels of the upper atmosphere, the other signal detected in the study,*viz*., the decrease of diurnal variation signal as the season advances is hard to comprehend. It has been possible to detect the existence of such a feature, only by analysing the rainfall data of each month separately in this study. If the rainfall data for all the three months of the season had been clubbed together, this important feature would not have surfaced. Though there is no clear-cut physical reasoning behind the above feature, the following concept which could partly explain the same is advanced.

In Table 5 is presented the normal maximum and minimum temperatures at Nbk and Npt for Oct, Nov and Dec (IMD, 2010b) and the normal sea surface temperature (SST) of BoB adjoining CTN (IMD, 2003). As shown the minimum temperature at Nbk and Npt is lower than the SST, the gradient increasing with the season and reaching 4-6 °C in Dec. The minimum temperature drops by 2-3 °C from Oct to Dec whereas the SST decreases by 0 to 1 °C only. In all the months, the lower land surface temperature in the morning could potentially generate a solenoidal westerly land breeze circulation though shallow, blowing from the land to the sea (Holton, 2004). However due to the strong environmental low level easterlies present, the LB would not be observed as a westerly wind, but would definitely weaken the easterly wind at the lowest levels to some extent and also could change its direction. This extent would be highest in Dec which is the coldest month during Oct-Dec. It is known to the forecasters that when the NEM is very weak, NW surface wind is sometimes observed in the morning hours over CTN.

To take this proposition further, in Table 6 is presented the mean vector wind (DDD- Direction and *Vr* - resultant wind) and the mean wind speed (*Vm*) over Chennai and Karaikal at 0000 and 1200 UTC at 1000, 950, 900 and 850 hPa levels for the month of December based on 1971-90/1978-90 data (IMD, 2011). It is seen that at Chennai the *Vm* values at 0000 UTC are respectively 5.8, 7.7, 8.1 and 7.5 m/s at the above four levels. The respective values at 1200 UTC are 6.5, 7.8, 7.7

TABLE 6

Normal low level winds over Mds and Kkl in December

Level ↓ (hPa)	Mds						Kkl					
	0000 UTC			1200 UTC			0000 UTC			1200 UTC		
	DDD	*Vr*	*Vm*	*DDD*	*Vr*	*Vm*	*DDD*	*Vr*	*Vm*	*DDD*	*Vr*	*Vm*
1000	025	5.1	5.8	039	5.8	6.5	029	5.5	6.6	034	6.7	7.2
950	045	6.9	7.7	042	7.0	7.8	039	7.3	8.2	038	8.1	8.7
900	055	7.1	8.1	045	6.8	7.7	048	7.5	8.4	043	7.9	8.7
850	061	6.4	7.5	051	6.0	7.2	056	6.6	7.9	048	6.6	7.8

DDD : Wind direction in degrees
Vr/Vm : Resultant / mean wind speed in m/s
0000& 1200UTC - 0530 & 1730 hrs IST ;
Mds Kkl: Abbreviation and data period as in Table 4

and 7.2 m/s. The wind speed at 1000 hPa at 1200 UTC is 11% higher than that at 0000 UTC. At 900 and 850 hPa levels, the wind speed at 0000 UTC is higher by 4-5% when compared to 1200 UTC, thus reversing the pattern. The lower wind speed at 1000 hPa at 0000 UTC could be due to the LB factor which at Chennai is known to extend only up to 500m asl as per the study by Raj and Nageshwari (2000) for Chennai (Mbk) for Jan-Mar. The vertical extent of LB during Dec is unlikely to be substantially different from that of Jan to Mar due to similar wind pattern prevailing in the lower levels in both the periods.

The mean wind direction DDD at 1000 hPa at 0000 UTC has more northerly component than that at 1200 UTC. The mean zonal wind obtained by resolving *Vr* is -2.5 m/s at 0000 UTC and -4.1 m/s at 1200 UTC showing that the easterly speed at 1200 UTC is 64% higher than that at 0000 UTC. The difference between 0000 and 1200UTC mean winds (former-latter) is obtained as 274°/ 1.5 m/s which could conceptually be the LB wind. This perfectly matches the LB concept as the LB has to be a weak westerly wind considering that CTN is by and large oriented N-S wards (Fig. 1). Thus, it is likely that the weak westerly LB in the morning gives rise to a more northerly resultant wind also reducing its speed. At 1000 hPa the 0000 UTC speeds of both *Vr* and *Vm* at 5.1 and 5.8 m/s are lower than the 1200 UTC speeds of 5.8 and 6.5 m/s which is evidently due to the LB effect. But at 850 hPa level, 0000 UTC wind speeds of 6.4, 6.0 m/s are stronger than the 1200 UTC speeds of 6.0 and 7.2 m/s. As the LB is very shallow, it affects the wind speed up to around 950 hPa only. By and large, similar wind pattern is observed for Karaikal also.

A weak lower level NE wind with more northerly component should bring in less moisture from BoB into the coastal regions. Though this feature is present only up to 500m asl (950 hPa level), this could explain to some extent why the early morning rainfall peak observed in the month of October reduces in intensity in December and becomes insignificant as shown in Tables 2 and 3. It is also to be noted that at Pamban which is almost an island station where the LB effect would be less, the nocturnal maximum of NEMR is detected in December also though with reduced intensity.

The presence of a weak secondary maximum of octet rainfall occurring in the forenoon or afternoon at Nbk and Mbk observatories in Oct and Dec is another noticeable feature in the diurnal variation profile thereby making it rather semi-diurnal. The peaks of the Mbk rainfall profiles are more prominent than those of Nbk. Johnson (loc.cit) has adduced afternoon sea surface heating as one of the reasons for the secondary peak in the oceanic convection which could extend to coastal stations also. Another cause attributed is the convection over land especially in Oct. But why the secondary maximum is present only in Chennai and not in Npt and Pbn and in Chennai also why only in Oct and Dec and not in Nov, is not that obvious.

6. Discussions

That the NEMR over CTN displays an early morning preference has been known for a long time (IMD, 1973). However, the most authenticated and quantified profile of diurnal variation based on a reliable and long period dataset for 4 representative stations has been brought out in this study. Tables 2(a&b) and 3 enumerate all the relevant statistics including that of DVRI and CMO which are single numbers representing the diurnal variation.

In a study of this type, testing the significance of difference of the octet mean (sample mean) from its normal values is an issue due to the fact that the sample is not random. Only rainy days have been considered in the study and all the non-rainy days were omitted to have a smaller database and at the same time without in any way affecting the nature of the result. The smaller sample size is also more realistic in testing the significance of the diurnal variation and in addition removing the day to day persistence in the dataset to a considerable extent. While deciding about the existence of a cyclical pattern, not just the significance of ORA but the overall profile of ORA has to be given due importance.

The techniques employed in this study to identify the highs and lows of ORF, *viz*., the evolutionary histogram approach (Yang, 2001) and the classical harmonic analysis (Panofsky and Brier, 1958), are basic but very effective. The results derived showing the presence of diurnal variation are only for the mean ORF/ORA profiles each with just 8 octet values for a rainy day. How this normal profile will manifest on the rainfall of individual days for a given year will need careful evaluation. Sometimes rainfall may occur one day, with the next few days being dry with 0 values for all the octets and then a subsequent day may be rainy. In such a situation, the periodicity in the conventional sense will not be present in the time series of ORF but early morning maximum and evening minimum could very well be present during rainy days even if such days are isolated.

The intra seasonal variation of the diurnal variation of NEMR brought out in this study is an entirely new finding not attempted in detail in other similar studies. Prasad (1970) has provided in a matrix form the mean hourly rainfall of Chennai Mbk for all the 24 hrs for the 12 months of the year based on 15 year data from 1948. The profile given in Prasad's study displays early morning peak for both Oct and Nov besides a clear secondary maxima in the afternoon hours for Oct. For Dec, there is early morning maximum, noon minimum and a weak afternoon peak. Rajeevan *et al.* (2012) have presented in pictorial format the variation of mean TRMM rainfall over southern peninsular India for all the 8 octets of the day, based on the data for 1998-2009. The figure does show a secondary rainfall high during 1230-1530 hrs only around Chennai and surroundings and not in the southern parts of CTN where Npt and Pbn are located. The ORF profiles derived for Nbk and Mbk based on 48 years data since 1969 in the present study are similar to those generated in the above two studies thereby proving the reliability and correctness of the former.

The ORF presented in Table 2(a) is normal data and individual profiles will exhibit deviations from the normal. Some systematic deviation from the normal ORA profile could be present when subsets of ORA profiles corresponding to active and weak monsoon spells are considered. During the NEM season, depressions or cyclones affect the BoB and some of them cross the Tamil Nadu coast. When such a transient system affects the BoB coast, the diurnal variation of NEMR at a station will get considerably influenced by the location and time of its crossing. Such deviations have to be taken into consideration while interpreting the normal profiles for a specific day. The derivation and analysis of conditional ORA profiles of NEMR associated with specific patterns of monsoon activity does provide scope for further study on this topic.

Finally, the use of rainfall observations generated by the modern observing systems and scope for further studies using such data is discussed. Real time rainfall data in digital format at frequent time intervals is available to the user since around the year 2010 from a large number of automatic rain gauge stations (ARG) installed by IMD and various other agencies in India. The TRMM data has been an excellent source of remote sensed data available since the year 1998 over the oceanic regions where conventional rainfall data are not available. But its resolution of 0.25° Long./Lat. or approximately 25 km would not be able to detect precise rainfall signals over coastal land regions. The INSAT 3D imager launched in the year 2013 provides OLR data at a resolution of 2-4 km but previous versions used to provide OLR data at resolution of 1°Long./Lat. (110 km) only.

The Doppler Weather Radar (DWR) installed by IMD at Chennai in 2002 has provided good quality rainfall estimates up to a distance of 100 km from the DWR location at a very high resolution of 333m × 333m which no land based system could match. The Chennai DWR has generated more than 15 years of rainfall data since inception, during the north east monsoon season with scan interval of every 10 min. Amudha *et al.* (2016) have used such data extensively to derive several new results on the spatial variation of NEMR around Chennai. The Chennai DWR data could be a quality input to study the diurnal variation of NEMR over the oceans, at the coast and in the interior in the neighbourhood. At Karaikal, DWR was installed in the year 2016 and at least 10 years of continuous data is needed to conduct DWR data based study on diurnal variation of rainfall.

7. Summary and conclusions

The results of the study are summarised below:

(*i*) The analysis of octet/quartet rainfall data of 4 representative stations of coastal Tamil Nadu, *viz*., Nbk, Mbk, Npt and Pbn for the north east monsoon period of

Oct-Dec based on 1969-2016/2017, 47-48 year data carried out using the evolutionary histogram concept, harmonic analysis and by computing diurnal variation rainfall index and coefficient of absolute octet rainfall anomaly revealed the presence of diurnal variation of rainfall in varying intensities manifesting as early morning maximum and afternoon/evening minimum of ORF. For all the stations the diurnal variation signal is strongest in October decreasing in November and still further in December. For the entire period of OND taken together, the diurnal variation is clearly defined. For a given month/season the signal is strongest in Pbn followed by Npt, Nbk and Mbk in that order save for one instance in Dec when DVRI for Mbk is greater than that of Nbk.

(*ii*) The quartet 00-06 hrs receives the maximum QRF whereas the quartet 15-21 hrs receives the lowest QRF though there are some exceptions. For Npt the quartets 00-06 and 15-21 hrs receive the highest and lowest rainfall respectively for all the months and OND.

(*iii*) The ORA profiles of December for all the stations, display positive anomalies in the morning and negative anomalies in the evening but the anomalies are not statistically significant barring one octet for Pamban which is nearly an island station for which the diurnal variation signal is well defined in November also.

(*iv*) Within Chennai city, the diurnal variation signal is relatively weaker at Mbk located 9-10 km inward from the BoB coast compared to Nbk located 3-4 km thus testifying the role of proximity of a station to the sea coast on the strength of diurnal variation. The ORA profiles of both Nbk and Mbk display a weak secondary peak in Oct and Dec during forenoon/afternoon thus showing semi-diurnal characteristics.

(*v*) The island station of Pamban manifests the best diurnal variation signal followed by Npt, Nbk and Mbk showing the influence of maritime effect.

(*vi*) The diurnal variation signal of NEMR could be linked to the overall diurnal variation of convection over oceans which exhibits nocturnal maximum. The lower temperatures in the lower levels of atmosphere and the consequent higher amount of saturation in the atmosphere over CTN in the morning has been shown as one of the physical causes.

(*vii*) It has been shown that the decreasing surface minimum temperature over CTN compared to SST over the adjoining BoB during Oct to Dec leads to the conceptual development of weak westerly land breeze. It is also shown that the LB strength should theoretically increase as the land minimum temperature drops from Oct to Dec. These features have been adduced as some of the possible causes of the decrease of diurnal variation signal as the north east monsoon season advances from Oct to Dec.

Acknowledgements

The authors thank National Data Centre, IMD, Pune and Climatological Section, Regional Meteorological Centre, IMD, Chennai for providing the data required for the study.

Disclaimer : The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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