MAUSAM, **67**, 3 (July 2016), 559-570

551.501.8 : 551.553.21 (540)

Spatial variation of clouding / rainfall over southeast Indian peninsula and adjoining Bay of Bengal associated with active and dry spells of northeast monsoon as derived from INSAT OLR data

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(*Received 2 March 2015, Accepted 16 July 2015*)

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सार – उत्तर पूर्व मानसून (एन ई एम) ऋतु जो अक्तूबर से दिसंबर तक होती है और कुछ वर्षों में जनवरी तक होती है, के दौरान दक्षिण प्रायद्वीपीय भारत (एस पी आई) वर्षा (आर एफ) से सबसे अधिक लाभांवित होता है। भूस्थैतिक प्रचालनात्मक भारतीय उपग्रह (इनसैट) रेडियो मीटर मे अवरक्त चैनल में विकिरण प्रेक्षणों से न्यूनतम 1° × 1° विभेदन पर बहिर्गामि दीर्घ तरंग विकिरण (ओ एल आर) के आकलनों का उपयोग करके दक्षिण प्रायद्वीपीय भारत में 2000-01 से 2012-13 के 13 उत्तर पूर्व मानसून ऋतुओं से संबद्ध मेघाच्छादन वर्षा के मुख्य पहलुओं का इसमें विश्लेषण किया गया है। वर्षा की घटना से सबंध थ्रेशहोल्ड के रूप में लिए गए 230 Wm^{-2} के मान के साथ संवहनीय गतिविधि के लिए ओ एल आर को प्रतिनिधि माना गया है एन ई एम के शुष्क, हल्के और सक्रिय चरणों के लिए अक्षांशीय और देशांतरीय परिवर्तन शीलताओं के साथ एन ई एम ऋतु के वर्ष दर वर्ष माध्य ओ एल आर पैटर्नों का विश्लेषण किया गया। 13 वर्षो से अधिक के इनसैट ओ एल आर डाटा के विश्लेषण के आधार पर यह दिखाया गया है कि एन ई एम के सक्रिय दौर में तटीय तमिलनाडु (सी टी एन) में अधिक वर्षा होती है जबकि बंगाल की खाडी (बी ओ बी) में वर्षा कम होती है और भीतरी तमिलनाडु में बहुत ही कम होती है पोलर ओरबिटिंग नोआ उपग्रहों से प्राप्त 3 वर्षो 1996-98 के ओ एल आर आंकड़ों पर आधारित पहले के अध्ययन से प्राप्त परिणाम के समान ही यह परिणाम प्राप्त हुआ है। 10.5, 12.5 और 14.5 डिग्री उत्तर अक्षांश और 75.5-85.5 डिग्री पू. देशांतर में ओ एल आर में स्थानिक परिवर्तन से पता चला है कि दक्षिण से उत्तर तक वर्षा में कमी की वजह से 10.5 डिग्री उ. के ओ एल आर मान अधिक है। दिसंबर और जनवरी में एन ई एम के शुष्क चरण के दौरान बंगाल की खाड़ी में दक्षिणी अक्षांश की तुलना में उत्तरी अक्षांश में उच्च ओ एल आर प्रेक्षित किया गया। यह पता चला है कि बंगाल की खाड़ी के दक्षिणी अक्षांश में जहाँ समुद्र सतह तापमान (एस एस टी) अधिक है, अधिक नमी उत्पन्न होती है और वायुमंडल के ऊपरी स्तरों में पहुँचती है जिससे उत्तरी अक्षांशों की तुलना में ओ एल आर के मान कम रहे।

ABSTRACT. South Peninsular India (SPI) benefits largely from the rainfall (RF) realised during the North East Monsoon (NEM) season that prevails from October to December spilling over to January in some of the years. Salient aspects of clouding / RF over SPI associated with 13 NEM seasons from 2000-01 to 2012-13 have been analysed using estimates of Outgoing Long wave Radiation (OLR) at 1° × 1° resolution derived from the radiance observations in the infra-red channel onboard the geostationary operational Indian satellite (INSAT) radiometers. OLR is considered as a proxy indicator for convective activity with the value of 230 Wm^{-2} as the threshold for RF occurrence. Year-to-year mean OLR patterns of the NEM season along with the latitudinal and longitudinal variabilities were analysed for dry, light and active phases of NEM. Based on rigorous analysis of INSAT OLR data for the above 13 years, it has been shown that during the active phase of NEM, Coastal Tamil Nadu (CTN) receives more RF while over BoB the RF is lower and decreases sharply over interior Tamil Nadu. This is a reiteration of a similar result from an earlier study based on 3 years (1996-98) OLR data from polar orbiting NOAA satellites. The spatial variation in OLR over the latitudes of 10.5, 12.5 and 14.5° N along the longitudes of 75.5-85.5° E has revealed the feature that north of 10.5° N, values of OLR are higher with decrease in RF from south to north. During dry phase of NEM in December and January, higher OLR is observed over northern latitudes of BoB than southern latitudes. It has been comprehended that in the southern latitudes of BoB, where higher sea surface temperatures (SST) are prevalent, more moisture is generated and pumped in to upper levels of the atmosphere leading to lower values of OLR compared to northern latitudes.

Key words – Active spell, Dry spell, INSAT, Northeast monsoon, Outgoing long wave radiation, Rainfall, SST.

1. Introduction

Indian North East Monsoon (NEM) is a smaller spatial scale monsoon modulating the rainfall (RF) activity over South Peninsular India (SPI). The duration of NEM is for three months, October, November and December (OND) occasionally spilling over to January of the next calendar year in one-third of the years. NEM sets in after the withdrawal of south west monsoon (SWM) season from most parts of India. Various characteristic features of the NEM and its teleconnections have been widely researched in recent years - Raj (1992, 1996, 1998a&b, 2003, 2012); Suresh and Raj (2001); Khole and De (2003); Balachandran *et al*. (2006); Pankaj Kumar (2006); Zubair and Ropelewski (2006); Asokan and Balachandran (2008); Geetha and Raj (2009); Nayagam *et al*. (2009) and Geetha (2011) to name a few. The advent of the remote sensing satellite technology in 1960s and the availability of innumerable derived products from the satellites have enabled researchers to unravel more features of the NEM.

Since the 1980s, the series of Indian satellites (INSAT) in geostationary orbit have been able to provide continuous data in the narrow band spectral channels of visible (0.55 to 0.75 μm, infra-red (IR, 10.5 to 12.5 μm) and water vapour (WV, 5.7 to 7.1 μm) through the radiometers onboard the satellites. Earth absorbs the incoming solar radiation incident on it and emits terrestrial radiation in the long wavelength or IR spectral region of 3-100 μm. Maximum intensity is at 10μm and the satellite maps the IR radiances in narrow bands. Among the many derived products available from the satellites, the outgoing long wave radiation (OLR) is potentially used as a reliable indicator of convective clouding over an area. The changes in OLR sensed by the satellite radiometers are modulated by the optical depth of the atmosphere, land-ocean temperature contrasts, moisture content in the vertical layers and cloud cover (Kelkar, 2007). Lesser values of OLR observed over an area indicate cold temperatures or presence of convective clouds and hence OLR is considered as a proxy indicator for RF activity (Rao *et al.*, 1989). Very high OLR values indicate warm surfaces and generally cloud-free conditions.

Arkin *et al.* (1989), Rao *et al.* (*loc.cit.*) and Randhir *et al.* (2007) have elaborately discussed the concepts behind OLR retrieval methodology. The algorithms initially implemented for the Indian satellite INSAT-1B to derive OLR data from the brightness temperatures of cloud tops sensed by the IR channel of the satellite were identical with those of the NOAA (National Oceanic and Atmospheric Administration) polar orbiting satellites. Later, to enhance the accuracy of derived OLR estimates, improvements were carried out by including radiances from the WV channel in the algorithms and the appropriate coefficients for varying zenith angles of the satellite to derive OLR values over Indian region. Randhir *et al.* (*loc.cit.*) have documented the methodology of estimation of OLR from the very high resolution radiometer onboard Kalpana satellite, where statistical regression methods relating OLR with the IR and WV spectral radiances through spacecraft-specific radiative transfer functions have been utilised. By and large, daily average value of OLR for the whole year varies between 160 and 300 Wm^{-2} over the Indian region, though OLR values less than 100 Wm^{-2} have been observed in association with the occurrence of intense tropical cyclones.

Taking advantage of the availability of enhanced products from INSAT, IMD has since enlarged the criteria for declaring the onset of SWM over Kerala (IMD, 2008) by including a necessary condition that INSAT derived OLR value should be below 200 Wm^{-2} in the box confined by latitudes between 5-10° N and longitudes 70-75° E. The isopleths of OLR ≤ 240 Wm^{-2} (OLR 240) generally delineate the region of SWM rains from cloud-free areas (Kelkar, *loc.cit*.). The OLR intervals 220-240, 200-220 and 180-200 Wm^{-2} are used by Raj *et al.* (2007b) to define different levels of increased cloud intensity and hence associated with convective activity. During NEM over SPI, when the clouds do not reach up to great heights like that during SWM, a higher value of OLR compared to 200Wm^{-2} to represent NEM clouding appears appropriate. Hence, Raj *et al.* (2007a) used an optimal threshold value of OLR230 to delineate and represent clouding associated with NEM over SPI. The contrasting movement of clouds from southeast to northwest towards SPI during NEM season when the low level winds are from northeast has been authenticated by Raj *et al.* (*loc.cit.*) using OLR data of 2.5° × 2.5° resolution from INSAT series of satellites obtained from India Meteorological Department (IMD), Pune and New Delhi for the 12 year period 1987-99, excluding 1992. The result was further reiterated by Amudha *et al.* (2016) for 13 NEM seasons of 2000-01 to 2012-13 using OLR data of higher resolution (1° × 1°). That the same movement from south to north repeats subsequently at the time of revival of the active phase of NEM after prolonged dry spells also is an additional finding by the authors. The recurrence of this synoptic feature has thus been validated from the analysis of OLR data for a comparatively long period of 25 years, including the period of study by Raj *et al.* (*loc.cit.*).

Suresh and Raj (*loc.cit.*) analysed OLR and precipitable water vapour (PWV) data from TIROS Operational Vertical Sounder (TOVS) of NOAA-12&14 polar orbiting satellites for the NEM seasons of the 3 year period 1996-98. Both these satellites provided two observations (morning and evening) per day over the Indian region. It was shown that during active NEM, OLR was lower over CTN compared to interior Tamil Nadu (TN) and Bay of Bengal (BoB). The study which revealed an interesting RF characteristic of NEM based as it was on a shorter data set needed further authentication to be regarded as a general feature. Actual observations

TABLE 1

Dates of onset, withdrawal and duration of Indian NEM for the period 2000-01 to 2012-13

Year	Date & month of		Duration of NEM (days)
	onset	withdrawal	
2000-01	03 Nov	2 Jan	61
2001-02	15 Oct	1 Jan	79
2002-03	09 Oct	12 Dec	65
2003-04	19 Oct	8 Dec	51
2004-05	18 Oct	16 Dec	60
2005-06	11 Oct	21 Dec	72
2006-07	17 Oct	14 Dec	59
2007-08	19 Oct	7 Jan	81
2008-09	12 Oct	21 Dec	71
2009-10	29 Oct	26 Dec	59
2010-11	29 Oct	6 Jan	70
2011-12	24 Oct	10 Jan	79
2012-13	18 Oct	11 Jan	85

Oct : October, Nov : November, Dec : December, Jan : January
NEM : northeast monsoon

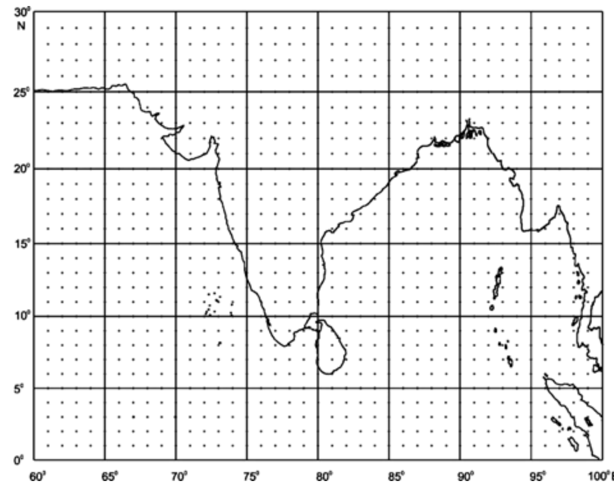


Fig. 1. Area of study and grid points at which OLR data is available

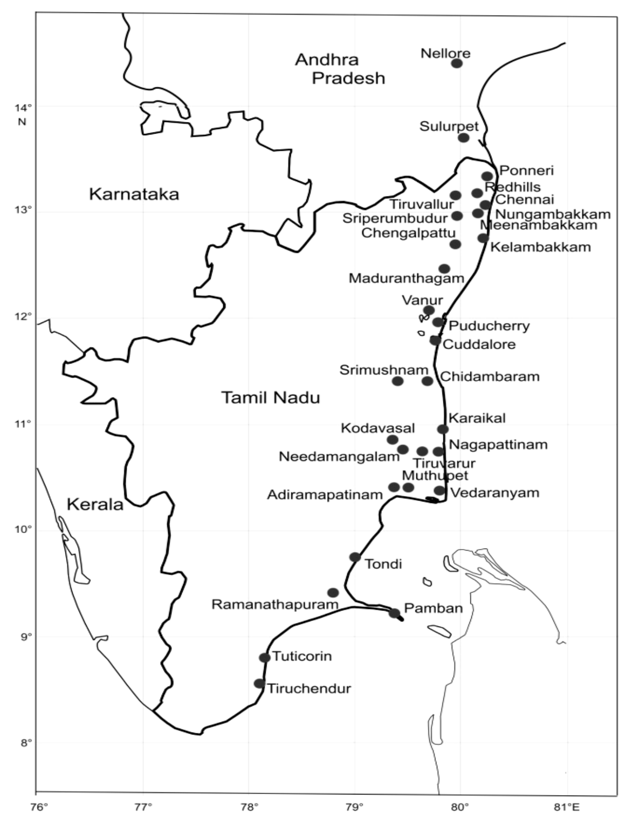


Fig. 2. Geographical locations of the 29 rain gauge stations of coastal Tamil Nadu and Andhra Pradesh considered in the study

of RF realised over the oceanic areas are normally not available. In recent times, estimates of RF over oceanic regions derived from satellites of the Tropical Rainfall Monitoring Mission (TRMM) have been extensively used in research studies. Considering OLR as a proxy indicator for RF, it is now possible to derive RF characteristics of NEM over the oceanic region also using a larger OLR data set of high resolution.

In the present study, we have analysed (a) Year-to-year seasonal mean OLR variability during NEM, (b) Spatial variation of mean OLR associated with dry, light and active phases of NEM and (c) Land-ocean contrasts in the variability in OLR along CTN during the aforementioned phases of NEM - based on INSAT OLR data thereby also authenticating the earlier results derived by Suresh and Raj (*loc.cit.*). The data used is described in Section 2 while the methodology of computation and analysis is discussed in Section 3. The outcome of the study is summarised in Section 4.

2. Data used

2.1. Dates of onset and withdrawal of NEM (Table 1) as re-determined by Geetha and Raj (2015).

2.2. The daily mean OLR data in text format for the period 1 October to 31 January for 13 NEM seasons (2000-01 to 2012-13) at 1° × 1° Long. / Lat. grid resolution over the area between 60° E - 100° E and 0° N - 30° N (Fig. 1) of parts of peninsular India and the North

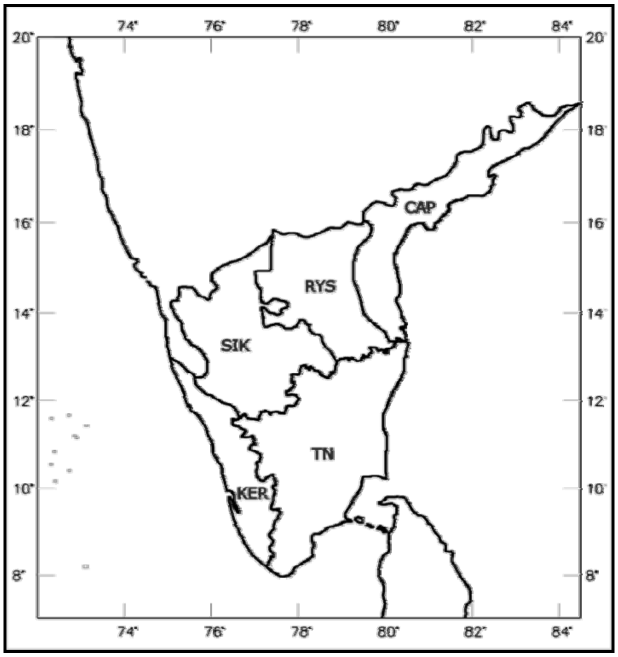


Fig. 3. Meteorological sub-divisions of south peninsular India influenced by northeast monsoon (NEM)

Indian Ocean (NIO) was obtained from the archives of National Data Centre (NDC), Pune and the Satellite Meteorology Division, IMD, New Delhi. During the initial years of the study period, the daily mean OLR of a day is the average of OLR values of eight observations, *viz*., 0000 UTC, 0300 UTC…. up to 2100 UTC. In recent years, daily OLR mean is computed based on more frequent observations since satellite data is received once in every 30 minutes. Accordingly, the averaging factor to compute the daily OLR mean has varied during the 13 year period.

2.3. Daily rainfall (DRF) data for the period 1 October to 31 January of 2000-01 to 2012-13 for 27 stations of coastal TN (CTN) and 2 of coastal Andhra Pradesh (AP) stations has been extracted from the records available at Regional Meteorological Centre (RMC), Chennai. Long term DRF normals of the period 1951-2000 for all the 29 stations (Fig. 2) have been obtained from NDC, Pune (IMD, 2010).

2.4. RF data expressed as percentage departures from normal (PDN) for the NEM season (1 October to 31 December) for five meteorological sub-divisions of SPI as shown in Fig. 3, which come under the major influence of NEM, *viz*., TN, coastal AP (CAP), Kerala (KER), Rayalaseema (RYS) and South Interior Karnataka (SIK), has been retrieved from the archives of Area Cyclone Warning Centre, RMC, Chennai. From this data set, the area weighted average RF for the combined region

TABLE 2

NEM seasonal rainfall PDN for Tamil Nadu and SPI, 2000-12

Year	Area weighted rainfall PDN	
	Tamil Nadu	SPI
2000	-29	-27
2001	-22	-2
2002	-8	-8
2003	-7	1
2004	1	-15
2005	79	71
2006	15	3
2007	20	4
2008	31	4
2009	12	1
2010	41	54
2011	22	-4
2012	-16	-7

PDN : Percentage departure from normal, SPI : South Peninsular India
Other abbreviations are as in Table 1.

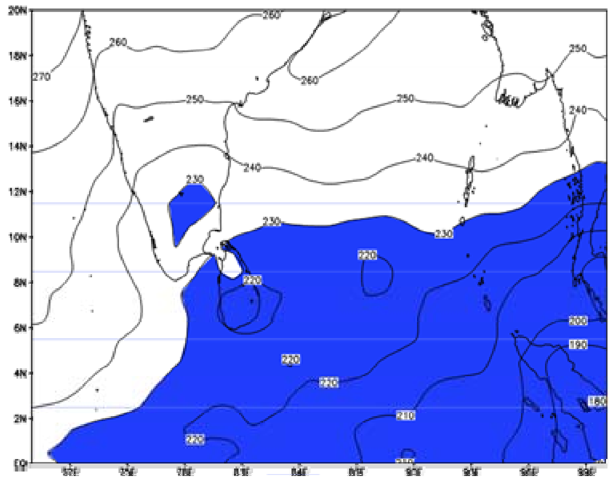
consisting of the above five sub-divisions only, henceforth called SPI, was also derived after computing the actual RF for each sub-division for each year. The NEM seasonal RF PDN values from 2000-01 to 2012-13 thus generated for TN and SPI are presented in Table 2.

3. Methodology of computation and analysis

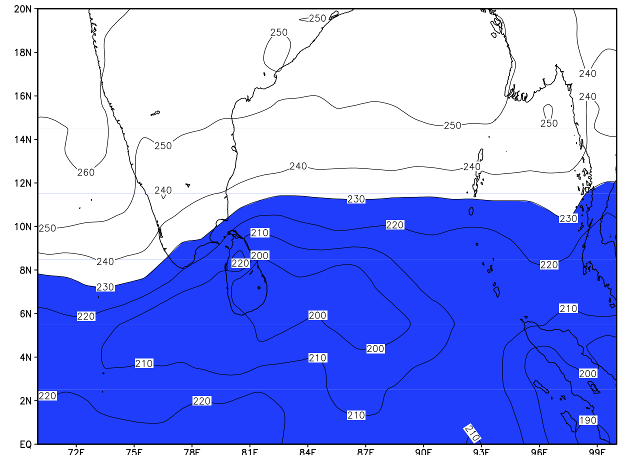
3.1. *Yearwise spatial variability in the seasonal mean OLR over SPI during NEM season*

In this sub-section, the spatial and seasonal mean variability in OLR over SPI during years of contrasting NEM performance have been analysed. As seen from Table 2, the PDN of RF of NEM was positive for many years, especially over TN where the period 2004-11 manifested continuous runs of positive PDNs with several excess years (PDN is + 20% or more). The years 2000 (PDN -29 and -27 for TN and SPI respectively), 2002 (-8, -8), 2005 (79, 71), 2010(41, 54), 2004 (1, 15) and 2011(22, -4) were chosen to study the OLR distribution. These six years by and large represent the contrasting performance of NEM over TN and SPI as the realised NEM RF was above normal in quite a number of years.

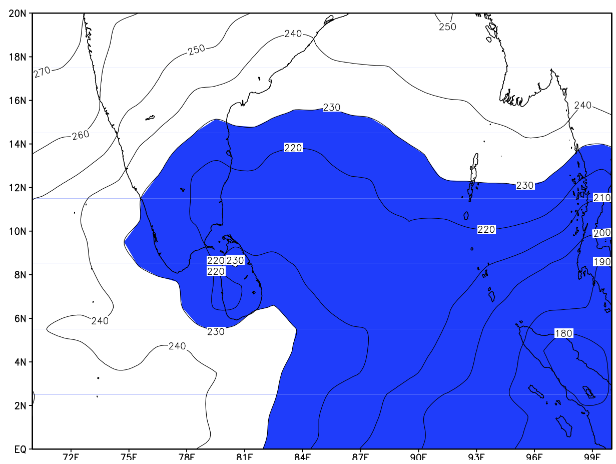
The daily mean OLR data of 1° × 1° Long. / Lat. grid resolution averaged as stated in Section 2.2 above,



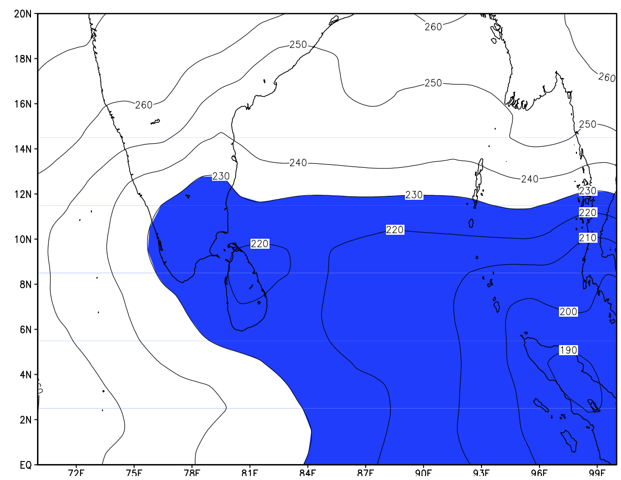
(a) 2000(-29,-27)



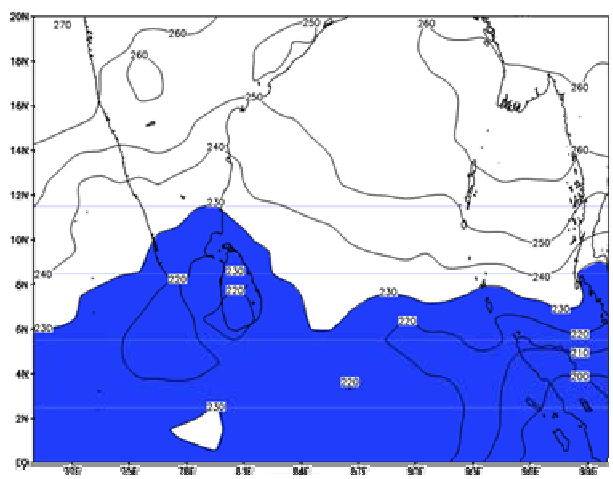
(b) 2002 (-8,-8)



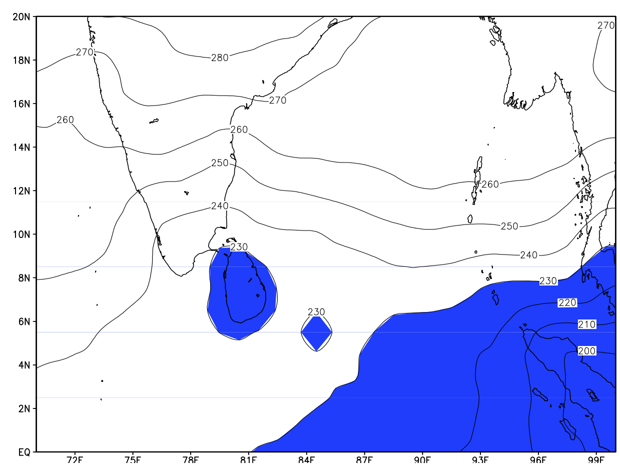
(c) 2005 (79, 71)



(d) 2010 (41, 54)



(e) 2004 (1, -15)



(f) 2011 (22, -4)

Figs. 4(a-f). Spatial variability of the seasonal mean OLR during NEM, October-December for the years 2000, 2002, 2005, 2010, 2004 and 2011 (percentage departures of rainfall from normal for Tamil Nadu and the average of five meteorological sub-divisions of SPI are provided in brackets) Shaded area : OLR $\leq$ 230 Wm^{-2}

over the area under consideration (Fig. 1) for the three months (October to December) of NEM season comprising 92 days was averaged yearwise (which is in reality seasonwise) for all the 13 years of the period 2000-12. Pictorial depiction of the yearly seasonal spatial variability of mean OLR was made using the well-known GrADS (Grid Analysis and Display System) software, for all the years. Fig. 4 depicts the mean OLR spatial variation of the six sample years (2000, 2002, 2005, 2010, 2004 and 2011) considered. It is seen that for the years of negative RF PDNs, *viz*., 2000 and 2002, except for a small area of SPI covered by contours of OLR230, rest of the region manifests higher OLR values. However, values of OLR180 to OLR230 are observed in the oceanic areas of south BoB. In the case of excess RF years 2005 and 2010 which had positive RF PDNs the whole of SPI is engulfed by contours of OLR230. During 2004, the contours of OLR230 enfold SPI up to 11° N while in the year 2011, absence of OLR230 is conspicuous over entire SPI. In both these years, PDN of TN is positive whereas that for SPI is negative.

It is quite obvious from the above description that though there is some signal from the mean spatial variation on the performance of NEM, the same is not a one-to-one relationship. In the years 2005 and 2010, low OLR values correspond to excess RF and in 2000, higher OLR values correspond to a poor monsoon. However, in 2011, despite an excess NEM over TN and a near normal monsoon over SPI, the spatial OLR distribution has not manifested the expected pattern. So, it is obvious from Fig. 4 that the seasonal average OLR variation for a given year does not exactly match with the seasonal RF realised.

Evidently, this kind of manifestation can be ascribed to the fact that extremely high OLR values are possible on cloud-free sunny days, representing the contributions to the IR channel from relatively higher temperatures of the land / ocean surfaces sensed by the satellite. Low values of OLR in regions masked by clouding and high values of OLR in cloud-free areas sensed by the satellite contribute to the temporal and spatial OLR variability during an entire NEM season. Further, it is conceded that the value of OLR at a grid point is not directly proportional to the amount of RF realised over the area since that value of OLR is modulated by the amount of WV in the vertical layer. So, OLR acts as a pointer to the extent of clouding and not necessarily to the quantum of RF actually realised over that location. Despite the contribution of low values of OLR sensed by the satellite over cloud-covered areas, in view of the high OLR values prevalent on dry days which vary from year-to-year, the spatial variability of yearly NEM seasonal mean OLR fails to exhibit the expected OLR patterns associated with the RF PDNs of SPI for a typical NEM season.

TABLE 3

Definitions for dry, light and active phases of NEM over CTN

Classification of the days in terms of rainfall during NEM	Criterion based on spatial distribution of rainfall over CTN	Strength of NEM
Dry	All stations remained dry *i.e.* 24 hours cumulative rainfall is less than or equal to 2.5 mm	-
Light	Isolated (≤25%) / scattered (26-50%) rainfall with average realised being less than or equal to 1.5 times the normal rainfall	Weak to normal
Active	At least fairly widespread (51-75%) or widespread (>76%) rainfall activity; average realised is more than 1.5 times the normal rainfall	Active to vigorous

CTN : Coastal Tamil Nadu, NEM : As given in Table 1

The analysis was continued further by identifying NEM days with different types of monsoon activity like dry, light and active phases and deriving separate OLR profiles. For CTN, dry, light and active days of NEM are as defined in Table 3. These definitions are by and large consistent with the RF categorisation used by IMD for each day of NEM. When such an analysis is taken up, the CTN region is well-suited as NEM characteristics including onset and withdrawal are clearly defined in CTN (Raj, *loc.cit.*). Therefore, the NEM strength is derived based on RF of CTN though the OLR distribution considered is for the entire region as depicted in Fig. 4.

3.1.1. *Spatial variation in OLR during dry, light and active spells of NEM*

The dates of onset and withdrawal of NEM over SPI region have been re-determined by Geetha and Raj (*loc. cit.*) based on the RF realised over CTN. For the present analysis, the period between the dates of onset and withdrawal was considered (Table 1) for each year. Based on the DRF of 29 stations, each day of the total duration of NEM season was classified among the three phases of NEM activity as defined in Table 3. There were 441 dry days, 75 light and 376 active RF days during the period 2000-12. Out of these, OLR values of 31 dry; 9 light and 26 active days were not available. In all, the OLR values of 410 dry; 66 light and 350 active days were thus

TABLE 4

Number of days of OLR data used for the three phases of NEM rainfall activity for the period 2000-12

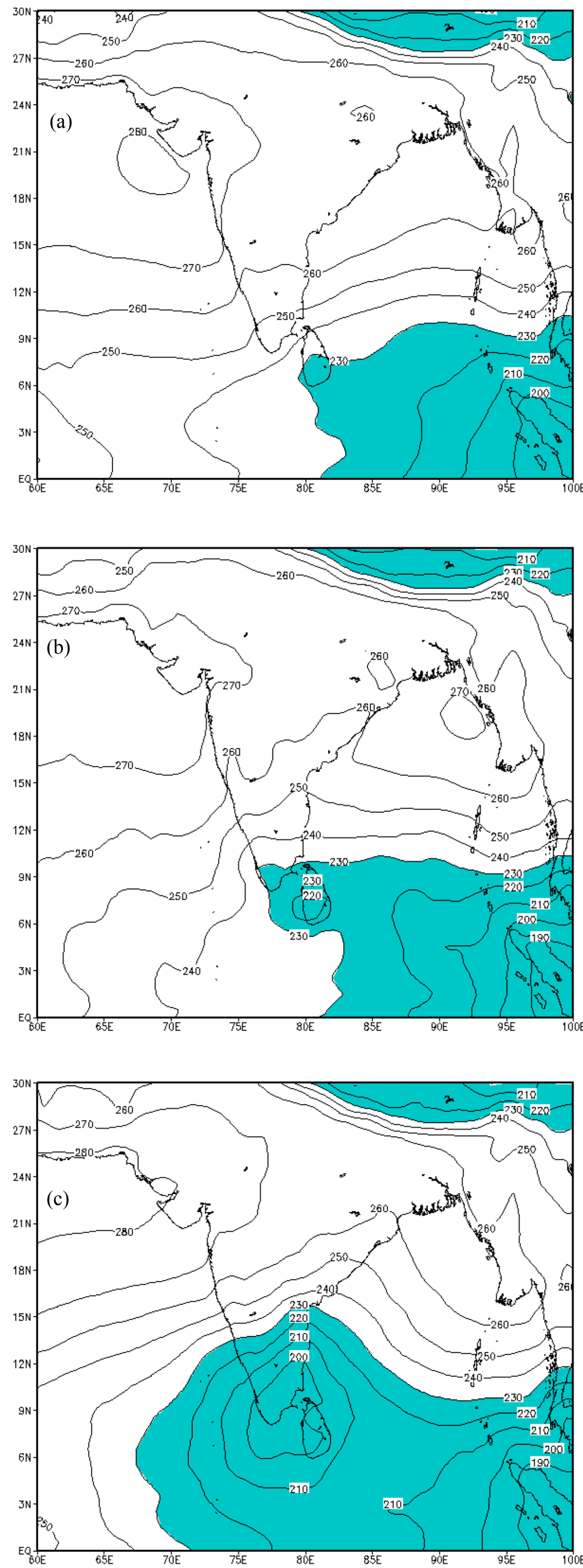
Month	Phase of NEM rainfall activity		
	Dry	Light	Active
Oct	45	8	105
Nov	167	47	179
Dec	192	17	89
Jan	37	3	3
Total	441	75	376
Missing data	31	9	26
Actual used	410	66	350

OLR : Outgoing Long wave Radiation.
Other abbreviations are as given in Table 1.

classified (Table 4) and separately averaged to generate the categorywise spatial mean OLR pattern (Fig. 5).

Such an averaging of OLR based on the above defined classifications yielded remarkably contrasting OLR patterns of dry, light and active spells of NEM. Dry spells of duration greater than 20 days were observed in three NEM seasons during 2000-12. In the dry phase of NEM, OLR values are high and vary between 240 and 270 Wm^{-2} over SPI indicating cloud free conditions whereas contours of OLR230 are seen over parts of Sri Lanka and southeast BoB. During light RF days, OLR230 is observed up to 9° N confined to south TN, Kerala and southeast sector of BoB and adjoining Comorin areas. In the case of active NEM days, the contours of OLR230 engulf SPI up to 16° N, with distinct presence of contours of OLR200 in the southern parts of TN, OLR230 in the southeast sector of BoB, adjoining Comorin area and southern parts of Sri Lanka. The trough of OLR isopleths is seen to be oriented closely along CTN and south CAP. This remarkable feature is consistent with two well-known characteristics of normal NEM RF over CTN and south CAP, *viz*., (a) north of 10.5° N, the RF decreases from south to north and (b) for a given latitude, longitudinal RF profile manifests a local maximum at the coast. These aspects would come up for further discussions in the forthcoming sections.

In the above analysis, derivation of OLR distributions by the segregation of dates into three different phases of NEM activity, *viz*., dry, light and active has brought out well-structured and contrasting OLR patterns which are amenable to easy and consistent interpretation.



Figs. 5(a-c). Spatial variability of mean OLR during (a) dry, (b) light and (c) active phases of NEM season, 2000-01 to 2012-13. Shaded area : OLR ≤ 230 Wm^{-2}

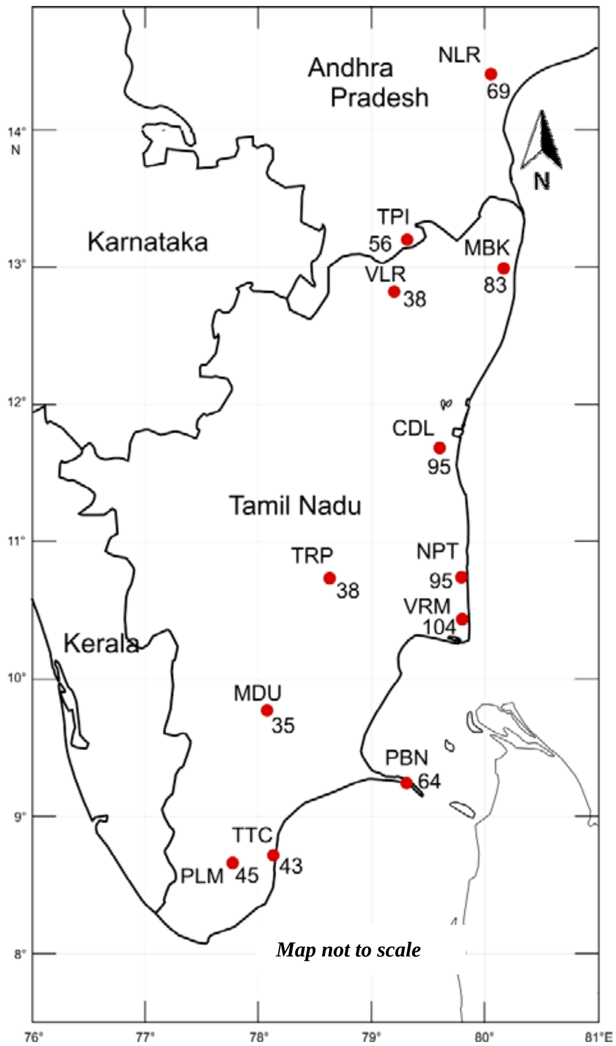


Fig. 6. Normal rainfall during NEM season (Oct-Dec) for 12 stations of south peninsular India

3.2. *Spatial variability of mean OLR over land and ocean*

In this sub-section, we analyse the longitudinal variability of the mean OLR over both land and ocean to perceive how the resulting distribution relates with the mean RF pattern. Firstly, the RF pattern over CTN and south CAP during NEM is presented.

3.2.1. *Rainfall during NEM along CTN and south CAP*

Fig. 6 presents the normal RF during NEM season (October to December) at 12 selected stations of SPI, 7 located along the coast and 5 in the interior. It is evident from Fig. 6 that the mean NEM RF sharply decreases from coast to inland. For example, Chennai-Meenambakkam (MBK) and Vellore (VLR) located more or less at 13° N receive RF of 83 cm and 38 cm respectively. Similarly, Nagapattinam (NPT) and Tiruchirapalli (TRP) at 10° N receive 95 cm and 38 cm respectively. North of 10.5° N where the coast is by and large oriented south-north, the RF also decreases south-north. It is 104 cm at 10.5° N in Vedaranyam (VRM), 83 cm at 12.5° N (MBK, 13° N) and 69 cm at 14.5° N (Nellore (NLR)). In the coastal belt southwest of VRM and up to Tuticorin (TTC), RF is relatively lower between 45-60 cm. The geographical feature of the sheltered nature of the southeastern parts of TN (Fig. 2) with Sri Lankan land mass lying to the east and Gulf of Mannar juxtaposed in between, appears to be the most plausible reason for the lower RF over CTN south of 10° N.

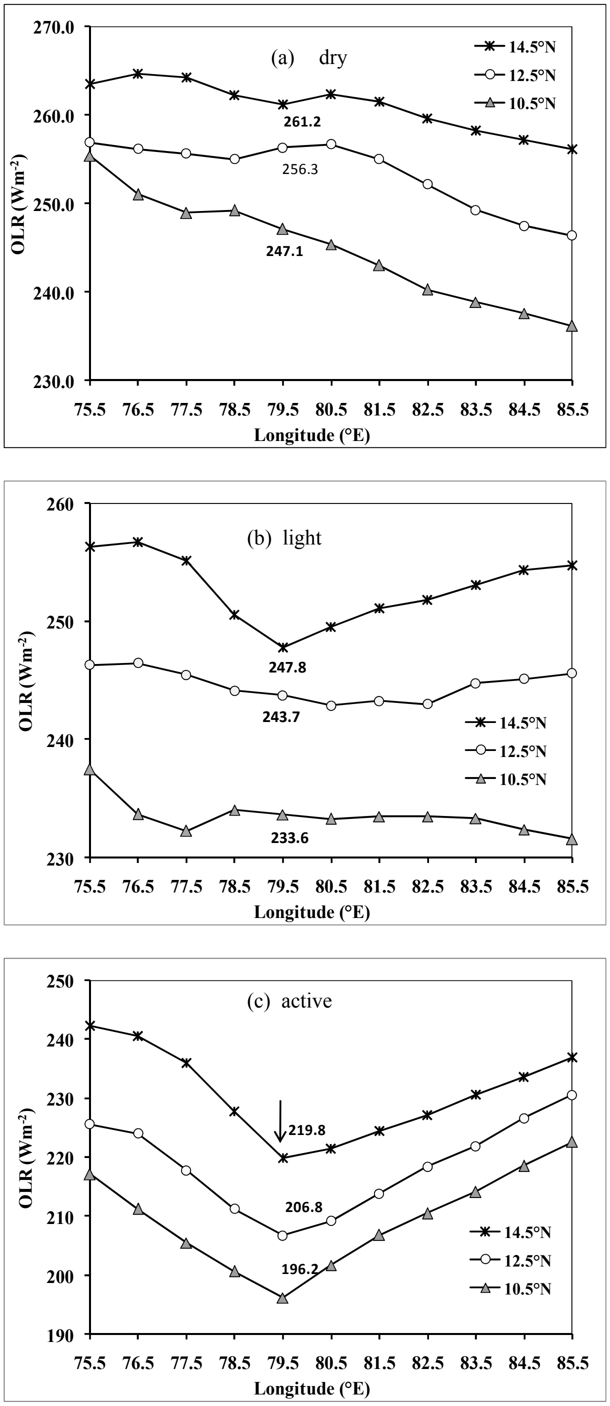
3.2.2. *Variability in OLR during various phases of NEM*

The mean OLR variability over land and oceanic areas was analysed for latitudes 10.5°, 12.5° and 14.5° N for the longitudes of 75.5, 76.5…85.5° E. The profiles for dry, light and active phases of NEM are presented in Figs. 7(a-c). The inferences drawn are as under :

(*i*) *Dry :* During dry days [Fig. 7(a)] OLR values of 240-265 Wm^{-2} are observed over the area considered, matching with rain-free days over SPI. The existence of values of OLR≥240 Wm^{-2} by and large indicates overall cloud free conditions. Lowest value of OLR is realised over the ocean at the easternmost longitude of 85.5° E for all latitudes of the area considered. Over CTN / south CAP (79.5° E), the OLR values are 247, 256 and 261 at 10.5° N, 12.5° N and 14.5° N respectively. There is slight increase in OLR values inland at 10.5° N. But in the other two latitudes OLR values remain flat, same as that obtained over the coast. OLR values increase from lower to higher latitudes for a given longitude.

(*ii*) *Light :* In the case of light RF days, OLR values of 233-255 Wm^{-2} have been observed [Fig. 7(b)]. Over CTN/ south CAP (79.5° E), the OLR values are 240, 250, 254 at 10.5° N, 12.5° N and 14.5° N respectively, slightly lesser than those in the case of dry days. At 14.5° N, a steep fall in OLR values from 75.5° E to 79.5° E (256 - 248 Wm^{-2}) and a near uniform rise (248 - 254 Wm^{-2}) eastward of BoB up to 85.5° E are observed. In the other two latitudes, the OLR profiles do not manifest any significant recognisable pattern.

(*iii*) *Active :* In all the latitudes, OLR is lowest at 79.5° E which is roughly the coastal stretch of TN and south AP, indicating that the clouding is heaviest along the coast [Fig. 7(c)]. The OLR increases eastwards indicating less



Figs. 7(a-c). Latitudinal variability in the mean OLR during (a) dry, (b) light and (c) active phases of NEM period from 2000-01 to 2012-13 along the longitudes of 75.5 to 85.5° E

clouding and justifiably less RF over the BoB oceanic region adjacent to CTN. The OLR decreases inland also at all the three latitudes, reaching 217, 226 and 242 Wm^{-2} at the longitude of 75.5° E with the decrease of OLR occurring roughly at the rate of 5-5.5 Wm^{-2}/°E. At 14.5° N, the benchmark of OLR230 representing NEM clouding is reached near 78.5° E. Thus, even during the active phase of NEM over CTN, clouding extends only up to 100 km inland from the coast at this latitude. The rate of decrease of OLR over ocean is much more gradual [Fig. 7(c)], being 4 Wm^{-2}/°E at 10.5° N and 3 Wm^{-2}/°E at both 12.5° N and 14.5° N indicating that RF over BoB adjacent to CTN though less than that over CTN, is likely to be more than that over interior TN.

The above inferences about the variability in OLR are consistent with the observed decrease of RF from CTN to inland during NEM as discussed in Section 3.2 and the presumption that by and large, OLR is a proxy indicator for RF. Whereas the decrease of RF from coast to inland during NEM is a well-known feature of RF climatology of the region, the extent of RF realised over the ocean is unknown. However, the present study based on 13 years of OLR data firmly, authenticates and reiterates the decrease of RF from coast to ocean. Study based on 3 years of TOVS data by Suresh and Raj (2001) also drew the same conclusion. As such, this important climatological conclusion derived from a fairly large OLR data set is now fully authenticated.

It is worthwhile to briefly discuss herein the physical mechanisms behind such a variation. At the time of active NEM, the northerly component in the lower tropospheric winds over BoB is less and sometimes a southerly component is present. As the easterlies approach the coast, frictional convergence develops resulting in higher vertical velocity over the coastal belt. This could be the most plausible reason for the OLR variation as derived above. In the inland areas, the sharp reduction of moisture from east-west is a likely reason for the sharp decrease in RF and as manifested in the sharp increase in the OLR values as well.

3.2.3. *Latitudinal variation of OLR vis-à-vis variation of SST and short wave radiation (SWR)*

When we reappraise the latitudinal variation of OLR as presented in Figs. 7(a-c), it is found that the OLR values are higher in the northern latitudes than in southern latitudes during all the three phases of NEM activity, *viz.*, dry, light and active. As the NEM season advances, sea surface temperature (SST) over BoB decreases in northern latitudes as compared to southern latitudes. The central parts (14° N to 10° N) of BoB are cooler than the southern parts by 0.5°C in December and by 1°C in January (IMD, 2003). Along 20° N, the SST over BoB is cooler by nearly 2°C when compared to the southern latitudes. The mean values of undepleted SWR received in December and

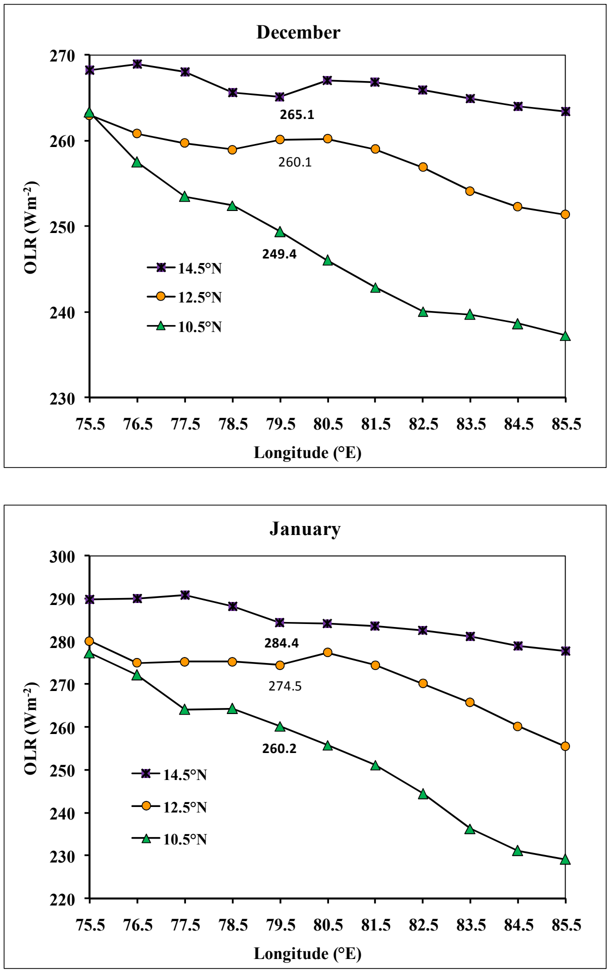


Fig. 8. Latitudinal variability in mean OLR over the longitudes of 75.5 to 85.5° E during dry days of December and January

January at 10° N are 356 and 366 Wm^{-2} respectively while at 14° N they are 332 and 344 Wm^{-2} for the same months, calculated based on a standard formula (Haltiner & Martin, 1957).

In order to further explore the latitudinal variation especially for these two months, OLR profiles were generated for 185 and 25 dry days of December and January respectively (Fig. 8). It can be reasonably expected that these days are by and large cloud-free. The same type of OLR gradient with higher OLR values in the northern latitudes and lower values in southern latitudes is evident from Fig. 8 despite lesser incoming SWR in northern latitudes and cooler SSTs. Since southern latitudes are closer to the equatorial trough and have higher SST during the two months, more moisture is generated which in turn absorbs the OLR in the vertical layers, leading to lower values of OLR. It has been comprehended that in the southern latitudes of BoB, where high SSTs are prevalent, more moisture is generated and pumped in to upper levels of the atmosphere leading to lower values of OLR compared to northern latitudes.

4. Summary and conclusions

(*i*) Year-to-year NEM seasonal mean OLR distribution over SPI derived for excess / normal / deficient RF years has not revealed any consistent relationship. The segregation of years of NEM season into dry, light and active phases of RF and averaging of the daily mean OLR values has yielded a clearly structured spatial OLR distribution for the three distinct phases of NEM.

(*ii*) The mean OLR spatial pattern of active days of NEM displayed a trough of OLR isopleths running almost parallel to CTN. This feature is consistent with two prominent normal RF characteristics of NEM, *viz*., (a) the RF generally decreases from south to north, north of 10.5° N and (b) for a given latitude, the RF is highest over the coast.

(*iii*) Longitudinal variability in OLR from 75.5-85.5° E at latitudes 10.5, 12.5 and 14.5° N indicates lowest OLR values (and hence heaviest clouding) at 79.5° E along CTN which is consistent with the observed feature of RF activity being less in interior parts of TN compared to CTN.

(*iv*) During active NEM conditions, OLR values are higher over the oceanic areas adjacent to CTN than over CTN itself. This feature clearly reiterates that the RF during NEM which is known to be heaviest over CTN compared to interior TN, also decreases east of CTN over the oceanic areas.

(*v*) The rate of decrease of OLR from coast to inland is higher than the rate of decrease of OLR from coast to ocean implying that by and large, RF over BoB adjacent to CTN is likely to be more than that over interior TN, though it is lower than that over CTN.

(*vi*) In the dry phase of NEM, OLR values vary between 240 and 270 Wm^{-2} over SPI clearly indicating cloud-free conditions.

(*vii*) During active RF days, the contours of OLR230 engulf SPI up to 16° N along CTN and CAP. OLR200 to OLR230 over SPI and OLR230 in the southeast sector of BoB and adjoining Comorin area and southern parts of Sri Lanka are also seen.

(*viii*) The OLR values are observed to be generally higher in the northern latitudes (central BoB) than in the southern latitudes (south BoB) for all types of NEM activity with such a pattern prevailing in December and January also. It has been comprehended that in the southern latitudes of BoB, where high SSTs are prevalent, more moisture is generated and pumped in to upper levels of the atmosphere leading to lower values of OLR compared to northern latitudes.

Acknowledgement

The authors thank Shri S. B. Thampi, Scientist 'F' & Deputy Director General of Meteorology, RMC, Chennai for his unstinted support during the period of this study. The authors thank Dr. R. Suresh, Scientist 'F', IMD, New Delhi for the fruitful discussions. The first author thanks Shri RM. A. N. Ramanathan, Asst. Meteorologist for his help while generating GrADS outputs. The authors sincerely thank the referee for his valuable suggestions.

References

Amudha, B., Raj, Y. E. A. and Asokan, R., 2016, "Characteristics of movement of low level clouds associated with onset / wet spells of northeast monsoon of Indian sub-continent as derived from high resolution INSAT OLR data", *Mausam*, **67**, 2, 357-376.

Arkin A. Philip., Rao, A. V. R. K. and Kelkar, R. R., 1989, "Large-scale precipitation and outgoing longwave radiation from INSAT-1B during the 1986 southwest monsoon season", *J. Clim*., **2**, 619-628.

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.

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., 2011, "Ph.D thesis, Indian northeast monsoon as a component of Asian winter monsoon and its relationship with large scale global and regional circulation features", University of Madras, Chennai

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 : 1871-2010 (Re-determination of 1901-2000), *Mausam*, **66**, 1, 7-18.

Haltiner, J. George and Martin L. Frank, 1957, "Dynamical and Physical Meteorology", McGraw Hill Book Company, Inc., USA., Ch.7.

India Meteorological Department, 2008, "Forecasters' Guide, 2008", O/o Dy. Director General of Meteorology (Weather Forecasting), Pune, 77.

India Meteorological Department, 2003, "Marine Climatological Atlas, 2003", National Climate Centre, O/o Additional Director General of Meteorology (Research), Pune.

India Meteorological Department, 2010, "Daily rainfall normals, 1951-2000", CD format, Pune.

Kelkar, R. R., 2007, "Satellite Meteorology", B. S. Publications, Hyderabad, ISBN:81-7800-137-3.

Khole, M. and De, U. S., 2003, "A study on northeast monsoon rainfall over India" *Mausam*, **54**, 2, 419-426.

Kumar, Pankaj, 2006, "Northeast monsoon rainfall prediction", Ph. D Thesis, Pune University.

Nayagam, L. R., Janardanan, R. and Mohan, H. S. R., 2009, "Variability and teleconnectivity of northeast monsoon rainfall over India", *Global and Planetary Change*, **69**, 4, 225-231.

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., 1996, "Inter- and intra-seasonal variation of thermodynamic parameters of the atmosphere over coastal Tamil Nadu during northeast monsoon season", *Mausam*, **47**, 3, 259-268.

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., Asokan, R. and Revikumar, P. V., 2007a, "Contrasting movement of wind based equatorial trough and equatorial cloud zone over Indian southern peninsula and adjoining Bay of Bengal during the onset phase of northeast monsoon", *Mausam*, **58**, 1, 33-48.

Raj, Y. E. A., Muthuchami, A. and Ramanathan, RM. A. N., 2007b, "Asymmetric structure of a severe cyclonic storm of North Indian Ocean as derived through INSAT OLR data", *Mausam*, **58**, 4, 481-500.

Raj, Y. E. A., 2012, "Monsoon Monograph", Vol. I, India Meteorological Department, Pune, Ch.13.

Rao, A. V. R. K., Kelkar, R. R. and Phillip A. Arkin, 1989, "Estimation of precipitation and outgoing long wave radiation from INSAT-1B radiance data", *Mausam*, **40**, 2, 123-130.

Singh, Randhir, Thapliyal, P. K., Kishtawal, C. M., Pal, P. K. and Joshi, P. C., 2007, "A new technique for estimating outgoing long wave radiation using infrared window and water vapour radiances from Kalpana very high resolution radiometer", *Geophys. Res. Lett*, **34**, L23815, doi:10.1029/2007/ GL031715.

Suresh, R. and Raj, Y. E. A., 2001, "Some aspects of Indian northeast monsoon as derived from TOVS data", *Mausam*, **52**, 4, 727-732.

Zubair, L. and Ropelewski, C. F., 2006, "The strengthening relationship between ENSO and Northeast monsoon rainfall over Sri Lanka and Southern India", ***J. Cli.,*** **19**, 1567-1575.