MAUSAM, **58**, 1 (January 2007), 33-48

551.511 : 551.462.54 : 551.553.21

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

Y. E. A. RAJ, R. ASOKAN and P. V. REVIKUMAR

Regional Meteorological Centre, Chennai, India

(*Received 18 May 2005, Modified 25 August 2006*)

e mail : yearaj@satyam.net.in

सार – दक्षिणी पष्चिमी मॉनसून की वापसी के उपरान्त भूमध्यरेखीय द्रोणी के दक्षिण दिशा में आगे बढ़ने के साथ–साथ भारतीय प्रायद्वीप के दक्षिणी भाग में उत्तरी पूर्वी मॉनसून का आगमन होता है। इनसैट उपग्रह से लिए गए पिछले अनेक वर्षों के चित्रों की जाँच करने से पता चला है कि उत्तरी पूर्वी मॉनसून के आगमन के समय मेघ–पुँज दक्षिणी खाड़ी से दक्षिणी प्रायद्वीप की ओर बढ़ते हैं। यह विषेषता भूमध्यरेखीय द्रोणी की उत्तर से दक्षिण की ओर बढ़ने के विपरीत है। इस षोध पत्र में 1981–2000 तक की अवधि के 20 वर्षों के प्रायद्वीप के उपरितन वायु के निचले स्तर के पवन आंकड़ों, वर्षा आंकड़ों तथा ओ. एल. आर. आंकड़ों के आधार पर इस तथ्य की जाँच की गई है। उत्तरी पूर्वी मॉनसून के आगमन की तिथियों के संदर्भ में क्षेत्रीय पवनों के उच्च कालावधि के पार्ष्व चित्र तैयार किए गए हैं तथा भूमध्यरेखीय द्रोणी की अक्षांषीय स्थिति का पता लगाया गया है और उसका अध्ययन किया गया है। जिस क्षेत्र में ओ. एल. आर. के मान 230 W/m^2 से कम थे उसे भूमध्यरेखीय मेघ क्षेत्र कहा गया है तथा भूमध्यरेखीय मेघ क्षेत्र के उत्तर की ओर आगे बढ़ने की सीमा का अध्ययन पाँच दिवसीय सामान्य ओ. एल. आर. आंकड़ों तथा उच्च कालावधि के पार्ष्व चित्रों के आधार पर किया गया है। इन विष्लेषणों से यह पता चला है कि उत्तरी पूर्वी मॉनसून के आगमन के समय पवन पर आधारित भूमध्यरेखीय द्रोणी कोमोरीन के दक्षिण की ओर बढ़ती गई है जबकि बंगाल की खाड़ी में बना मेघ– क्षेत्र दक्षिण से उत्तर की तरफ गतिमान होता है। तमिलनाडु के तटीय क्षेत्र में निम्नस्तर की पूर्वी पवनों की उत्तर से दक्षिण की तरफ बढ़ने की गति में कमी, मॉनसून के आगमन के समय चेन्नै एवं तिरूवनंतपुरम के तापमान प्रवणता का विपरीत होना और 40 दिनों के दोलन में गत्यात्मकता इस प्रकार की परस्पर विरोधी घटनाओं के मुख्य कारण हैं। तमिलनाडु के तटीय क्षेत्र में उत्तर पूर्व मॉनसून गतिविधियाँ इस क्षेत्र के निम्न स्तर क्षेत्रीय पवनों से ऋणात्मक रूप से संबंधित रही हैं। उत्तर से दक्षिण की तरफ इनके संबंधों के परिणाम में गिरावट हुई है और यह स्थिति अक्तूबर से दिसम्बर तक रही है। इस अध्ययन में प्राप्त हुए परिणामों तथा उत्तर पूर्वी मॉनसून की अन्य ज्ञात विषेषताओं के आधार पर उत्तरी पूर्वी मॉनसून के आगमन का थिमैटिक मॉडल तैयार किया गया है जिसके मुख्य तत्व मॉनसून के आगमन और उसकी वापसी की घटनाएँ हैं।

ABSTRACT. The northeast monsoon sets in over southern parts of peninsular India after the retreat of southwest monsoon and in association with the southward movement of equatorial trough. The INSAT satellite imageries scrutinised during the past several years revealed that the cloud bands at the time of northeast monsoon onset moved from south Bay into the southern peninsula, a feature that contrasts with the north to south movement of the equatorial trough. The paper investigates this aspect based on a dataset of lower level upper winds of the peninsula, rainfall data and INSAT OLR data for the 20 year period 1981–2000. The super epoch profiles of zonal winds, latitudinal position of equatorial trough with reference to northeast monsoon onset dates have been derived and studied. The region with OLR values less than 230 W/m^2 was defined as the equatorial cloud zone and the movement of northern limit of ECZ was studied based on the normal pentad OLR data and also the superposed epoch profiles. From these analysis it has been established that at the time of northeast monsoon onset, the wind based equatorial trough moves south of Comorin whereas the cloud zone in the Bay of Bengal moves from south to north. Reasons for the occurrence of such a contrasting feature have been ascribed to features such as decreasing strength of lower level easterlies from north to south over coastal Tamil Nadu, reversal of temperature gradient between Chennai and Thiruvananthapuram at the time of onset and the dynamics of 40-day oscillation. The northeast monsoon activity over coastal Tamil Nadu has been found to be negatively correlated with the low level zonal winds over the coast, the degree of relation decreasing from north to south and also from October to December. Based on the results derived in the study and also the other known features of northeast monsoon a thematic model of northeast monsoon onset listing the events that precede and succeed the onset has been postulated.

Key words – Northeast monsoon, Southwest monsoon, Onset, INSAT, OLR, Equatorial cloud zone, Thematic model, Equatorial trough, 40-day oscillation.

1. Introduction

The Indian northeast monsoon is a monsoon of smaller spatial scale experienced in the southern parts of peninsular India, in the aftermath of retreat of southwest monsoon from most parts of India. This retreat is associated with the southward movement of equatorial trough in September, from its semi permanent orientation

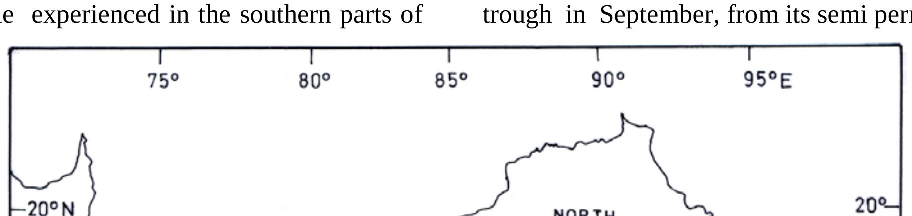


Fig. 1. Geographical location of 6 stations and 3 upper air stations and the demarcated areas of Bay of Bengal

along the Head Bay of Bengal to Ganga Nagar axis in July–August (Rao, 1976). In October it moves further southwards to about 15° N and is located south of Comorin by 1 November. The passage of equatorial trough over southern peninsula from north to south is associated with reversal of low level winds from southwesterlies to northeasterlies. The subsequent increase in rainfall over the southern peninsula is taken as the northeast monsoon onset. A detailed account on northeast monsoon onset along with listing of onset dates for 1901-2000 could be found in Raj (1992 & 2003). The normal date of northeast monsoon onset is 20 October with a standard deviation of 7-8 days. India Meteorological Department (1973) provides a general description of northeast monsoon. The low level winds over southeast coast of India and southern Bay of Bengal, during northeast monsoon onset are generally northeasterlies. During the northeast monsoon season of October–December stations located in the southeast peninsula receive normal rainfall in the order of 35–100 cm, with the northeast monsoon being most prodigious over north coastal Tamil Nadu, which receives 80–100 cm of rainfall.

Aside from the rainfall and the transition of equatorial trough, another interesting and visible feature associated with the northeast monsoon onset is the movement of cloud bands from the Bay of Bengal into the peninsula. When such a feature is studied, it is logical to look into the pattern of cloud movement during the onset of the large scale and well organised southwest monsoon as well and to effect a comparison between the two patterns of cloud movement. The onset of southwest monsoon which takes place over Kerala around 1 June is associated with movement of clouds from southwest Arabian sea towards the west coast of India (Rao, 1976). By a similar analogy and logical necessity, the cloud bands at the time of northeast monsoon onset should be expected to approach the southeast coast of peninsular India from the northeast Bay of Bengal.

However in reality this does not appear to be the case. During the last two decades INSAT (Indian National Satellite) cloud pictures over Indian region have been extensively available to Indian meteorologists. Observing such cloud imageries for days before and after the northeast monsoon onset for several years gave the impression that the cloud bands at the time of northeast monsoon onset moved by and large from the southern Bay of Bengal into the southeast coast of Indian peninsula. If objectively proved, such a phenomenon would adduce to the concomitant but contrasting movement of low level wind based equatorial trough with the movement of equatorial cloud zone (ECZ), the former moving from north to south and the latter from southeast to northwest.

TABLE 1

Yearly onset dates of northeast monsoon over coastal Tamil Nadu, 1981-2000

Year	Onset date	Year	Onset date
1981	23	1991	19
1982	18	1992	02 N
1983	24	1993	13
1984	03 N	1994	18
1985	25	1995	23
1986	26	1996	10
1987	20	1997	13
1988	03 N	1998	28
1989	29	1999	04
1990	18	2000	05 N

N – November , Otherwise – October

This interesting but seemingly dissonant feature has been investigated and results presented in this paper. A few other related noteworthy synoptic features associated with northeast monsoon onset also have been identified and will be discussed.

2. Data

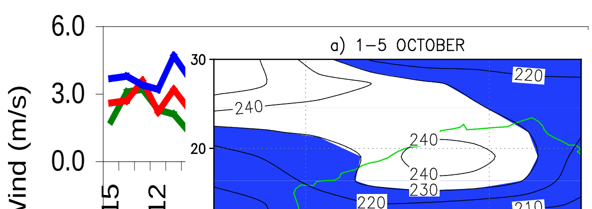
The study is based on the following data sets :

2.1. The onset dates of northeast monsoon over coastal Tamil Nadu for the period 1981 - 2000 (Raj, 1992, 2003).

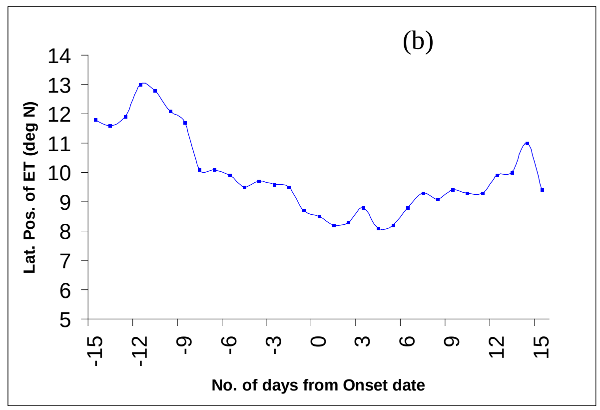
2.2. The 0000 UTC (0530 hrs IST) winds and temperature at 1000, 900 & 850 hPa levels at Chennai, Karaikal and Thiruvananthapuram for each day of 1 October – 31 December for the 15 year period 1981-95 [*Source* : National Data Centre (NDC), India Meteorological Department (IMD), Pune].

2.3. Daily rainfall data of 6 stations located along coastal Tamil Nadu *viz.*, Chennai, Cuddalore, Nagapattinam, Vedaranyam, Pamban and Tuticorin for the period 1981-2000 (*Source* : NDC, IMD)

2.4. Outgoing longwave radiation (OLR) data for 1 October – 31 December, for the 12 year period 1987-91 and 1993-99. (OLR data was unavailable for 1992) for the Indian region based on INSAT products (*Source* : NDC, IMD). For this study we used the data over the region bounded by the longitudinal and latitudinal circles of 75 - 95° E and 0 - 30° N repectively. The OLR values were available at the centre of the 2.5° × 2.5° grids over the above region.



(a)



Figs. 2(a&b). Superposed epoch profiles with reference to northeast monsoon onset dates of (a) 900 hPa zonal winds over Chennai, Karaikal and Thiruvananthapuram and (b) latitudinal position of wind based equatorial trough at 900 hPa at 80° E

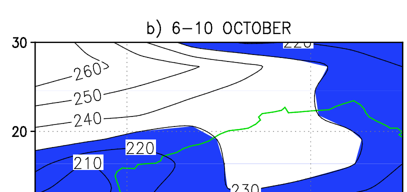
2.5. Surface pressure charts available at Regional Meteorological Centre, Chennai and charts published by IMD in the Indian daily weather report for October & November 1981-2000.

2.6. INSAT and NOAA cloud imageries available at the Regional Meteorological Centre, Chennai.

Fig. 1 presents the geographical locations of southern Indian peninsula, the three upper air stations and the six rain gauge stations considered and also the various demarcated areas of the Bay of Bengal.

3. Onset and activity of northeast monsoon as related to low level winds over the southeast Indian peninsula

In this section we study the reversal of winds and movement of equatorial trough over southern Indian peninsula, at the lower levels at the time of northeast monsoon onset and also the relation between low level



Figs. 3(a-f). Spatial variation of normal OLR data for the pentads of October (OLR values in W/ m^2 and shaded area OLR < 230 W/ m^2)

winds and northeast monsoon activity. The superposed epoch analysis (Panofsky & Brier, 1968) has been used to derive the profiles of the various parameters with reference to the onset dates.

3.1. *Onset of northeast monsoon*

The low level easterlies establish at the latitude of 13° N around 14 October, roughly one week ahead of the normal onset date. After the southwest monsoon has retreated and the low level easterlies have firmly set in, the first day of fairly widespread rainfall over Tamil Nadu and adjoining sub-divisions is taken as the date of northeast monsoon onset (Raj, 1992). In the present study the onset dates for the 20 year period 1981-2000 have been considered, the dates are listed in Table 1.

3.2. *Profiles of lower level zonal winds*

The 900 hPa (or 0.9 km asl) level could be taken as the ideal level representing the low level wind flow. The daily 900 hPa 0000 UTC winds of Chennai, Karaikal and

TABLE 2

CCs between DRI over coastal Tamilnadu and daily 900 hPa zonal wind of Chennai, Karaikal and Thiruvananthapuram, October - December 1981-95

Month → Parameter	October		November		December		OND	
	Mean	CC	Mean	CC	Mean	CC	Mean	CC
u CHE	-0.3	-0.52	-4.2	-0.39	-5.8	-0.33	-3.4	-0.33
u KKL	1.0	-0.39	-3.3	-0.31	-6.0	-0.26	-2.8	-0.22
u TRV	3.0	-0.33	0.0	-0.19	-1.6	-0.20	-0.2	-0.18
ET 900	10.9	-0.43	8.8	-0.28	7.5	-0.10#	9.1	-0.19
N	465		450		465		1380	

u - zonal wind (m/s), ET900 - Lat position of equatorial trough in °N , CC Correlation Coefficient, DRI - Daily rainfall index, CCs - Significant at 0.1 % level, # Significant at 5 % level.

Thiruvananthapuram [Fig. 2(a&b)] for the period 1 October–31 December, 1981-95 were subjected to superposed epoch analysis with reference to the northeast monsoon onset dates. The profiles are presented in [Fig. 2(a&b)] from which the following inferences are drawn:

(*i*) At Chennai and Karaikal, the 900 hPa zonal winds reverse to easterlies 6-7 days before the northeast monsoon onset.

(*ii*) At Chennai the zonal easterlies which establish roughly one week before onset and maintain a speed of 1-2.5 m/s intensify to 5-6 m/s at the time of onset. At Karaikal the easterly strength after onset is slightly weaker than that of Chennai.

(*iii*) At Thiruvananthapuram, westerly zonal winds prevail almost up to the time of onset and revert to weak easterlies just on the onset date. This easterly regime continues for nearly 6 days from the onset date where after westerlies establish again.

3.3. *Movement of wind based equatorial trough at 900 hPa*

The latitudinal position of equatorial trough at 900 hPa for every day of 1 October - 31 December, 1981-95 at about 80° E was determined from the zonal winds of the three stations. [Fig. 2(a&b)] presents the superposed epoch profile of equatorial trough with respect to the onset dates. The equatorial trough which is located at about 10° N one week prior to northeast monsoon onset is located at about 8.5° N at the time of onset and at nearly 8° N, 4 days after the onset whereafter there is a slight northward shift. It is evident that the wind based equatorial trough moves from north to south and is located closer to the southern tip of the peninsula at the time of northeast monsoon onset.

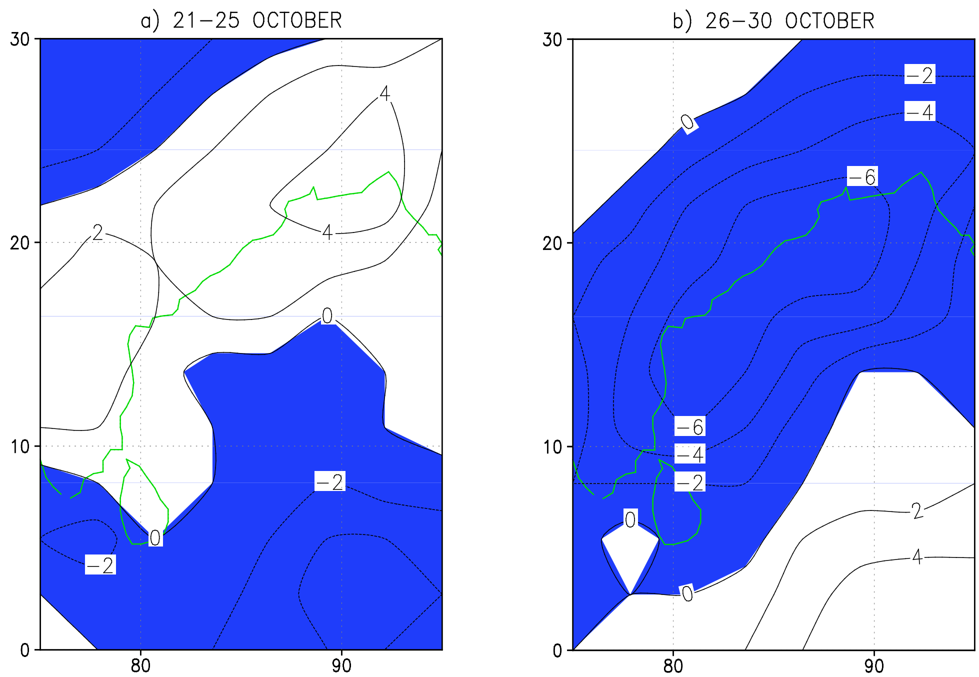
3.4. *Correlation between low level zonal winds / equatorial trough and northeast monsoon activity*

The daily northeast monsoon activity over coastal Tamil Nadu could be objectively expressed based on a daily rainfall index (DRI) as defined and used in Raj (1998). The DRI is the percentage of rainy days in an aggregate containing 5 days and 6 stations of coastal Tamil Nadu (Fig. 1) and represents the rainfall activity on the mid date of the pentad. The correlation coefficient (CC) between the daily 900 hPa 0000 UTC zonal winds of the three stations and the DRI values were computed based on data of 1981-95. The CCs between the daily latitudinal positions of equatorial trough as derived in Sec. 3.1 and DRI were also computed. In both the cases CCs were derived for individual months *viz*., October, November and December and also for the whole season October-December. Table 2 presents the various values of the CCs along with the normal values of zonal winds and the trough position. From the table following inferences could be drawn:

(*i*) The CCs between zonal winds and DRI are all negative and highly significant. Thus easterly anomalies are associated with good northeast monsoon activity.

(*ii*) For a given station, the absolute value of the CC is higher in October (0.52-0.33) and decreases in November (0.39-0.19) and decreases further in December (0.33-0.20).

(*iii*) For a given month or for the whole season the absolute value of the CC is highest for Chennai and decreases for Karaikal and decreases further for Thiruvananthapuram.



Figs. 4(a&b). Spatial variation of day to day changes of normal OLR data for the pentads 21–25 & 26 – 30 October (OLR24 values in W/ m^2 and shaded area OLR24 < 0 W/ m^2)

(*iv*) The CCs between latitudinal position of ET and DRI also manifested the same pattern of relationship as existed between zonal wind and DRI. The CCs for October, November and December are -0.43, -0.28 and -0.10 respectively.

(*v*) The normal easterly strength at 900 hPa level increases as the season progresses, the highest speeds are realised in December for all the three stations.

It is evident from the above inferences that strong easterly anomalies in the lower troposphere and a southern position of equatorial trough favour heightened northeast monsoon activity. Scrutiny of data of individual years/months revealed that this broad based postulate held true barring a few exceptions. When intense low pressure systems such as depressions or cyclonic storms moved across southern peninsula, the equatorial trough would be located in a northern latitude and would be associated with increased rainfall activity as well. In the period of study 1981-95, the CCs were not significant in 3 years *viz*., 1982, 1986 and 1995. During 1981-2000, the onset of northeast monsoon was generally not associated with the movement of a migratory cyclonic disturbance moving from Bay of Bengal towards the coast save for the year 1982. As such, generally the onset of northeast monsoon is not associated with presence of westerlies in the lower levels over the southeast coast.

4. Movement of ECZ during northeast monsoon onset as derived from OLR data

4.1. *OLR data from INSAT geostationary satellites*

The OLR values can be derived from the products of both polar orbiting and geostationary satellites, but the methodology based on the latter carries considerable advantages. The INSAT based OLR data is derived by IMD using observations at 3-hour intervals using a single radiometer. The methodology used in the OLR derivation has been described in detail in Rao & Phillip, 1987 and Kelkar *et al*. (1989 & 1993).

The INSAT OLR daily mean data over the Indian region obtained from NDC, IMD, provides a single value of OLR for a calendar day derived as mean of 8 observations taken at 3 hourly intervals, at numerous grid points spread over the Indian region. The OLR value is expressed in W/m^2 (Watts/metre^2), the values generally ranging from 100 to 280. OLR is frequently taken as an index of convective activity and clouding over the tropics.

4.2. *Analysis of OLR data*

The OLR data for the 12 year period 1 October – 31 December, 1987-91 & 1993-99 at 2.5° × 2.5° grids over the region 75° E - 95° E & 0° N - 30° N were processed.

TABLE 3

Approximate mean latitudinal positions of 220, 230 & 240 W/m^2 isopleths of OLR at 81.3 & 83.8° E for the pentads of October and for the triads with reference to northeast monsoon onset date

OLR → threshold	220		230		240	
Pentad ↓	81.3° E	86.3° E	81.3° E	86.3° E	81.3° E	86.3° E
1 – 5 Oct	15.3	14.0	20.8	15.2	24.6	-
6 – 10 Oct	-	10.0	19.6	13.4	21.2	25.0
11 – 15 Oct	9.1	10.2	13.2	13.4	19.4	18.0
16 – 20 Oct	7.5	7.5	-	-	20.8	23.0
21 – 25 Oct	8.4	7.8	10.2	10.1	12.2	13.3
26 – 30 Oct	13.8	13.8	16.5	17.2	19.0	21.2
Days *w.r.t.* onset date						
-4	6.6	5.3	8.4	9.9	22.5	23.8
-2	6.8	8.5	9.4	11.2	18.8	14.6
0	12.0	7.8	15.2	10.9	18.2	18.1
2	15.4	5.9	18.0	16.8	20.4	21.2

OLR in W/ m^2, Latitude in °N - could not be determined

The centre of the square grid was taken as the representative grid point. From this data set the following two sets of mean OLR data were computed.

(*i*) Mean OLR data for each day for the period 1 October – 31 December were computed and the data values thus obtained were temporally smoothed by means of a filter. From this series normal OLR data for the 6 pentads of 1-5, 6-10,…, 26-30 October were derived, for each grid point. The spatial and temporal variation of the normal pentad OLR data is presented in Figs. 3(a-f).

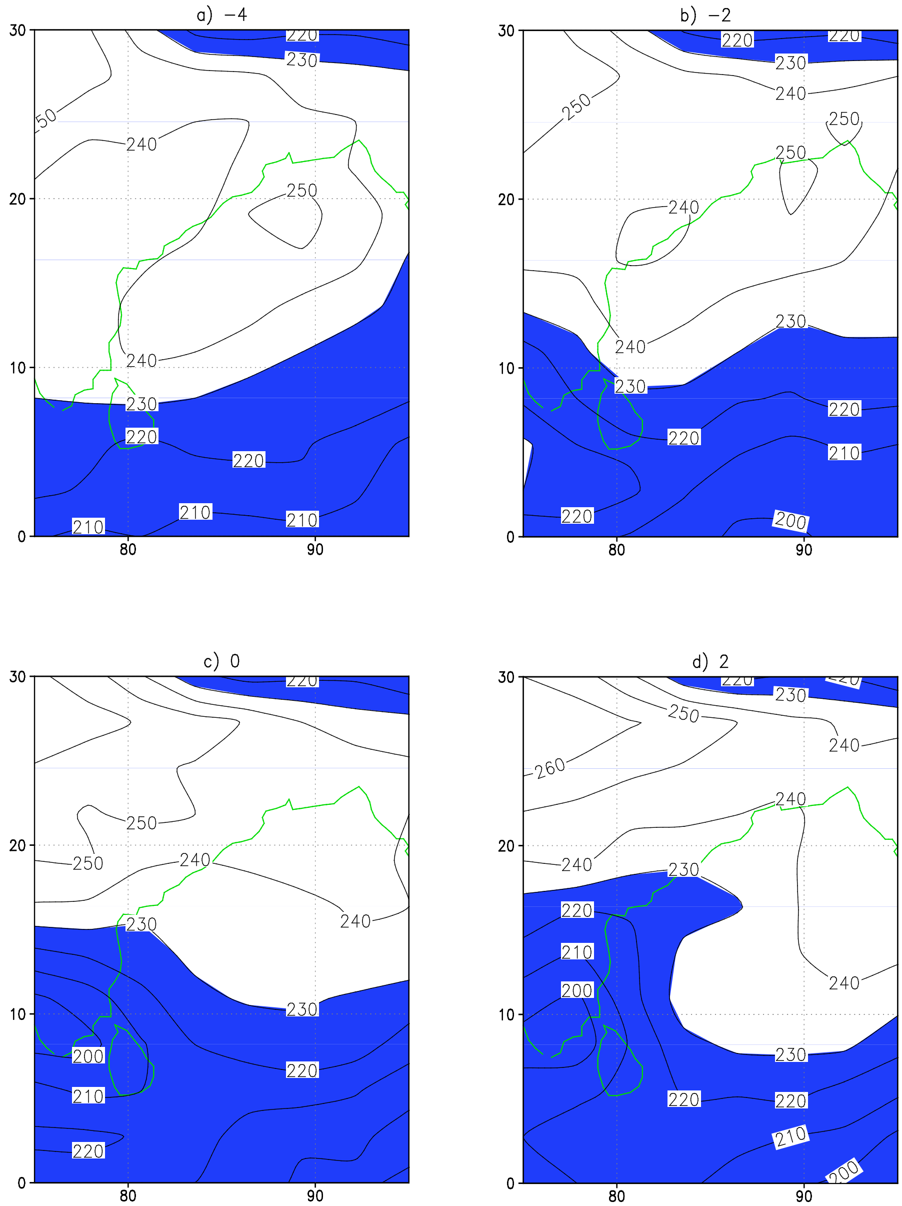
(*ii*) Similarly the day to day changes of OLR, were computed and averaged over the pentads. The same is presented in Figs. 4(a&b) for two pentads *viz.*, 21-25 & 26–30 October.

(*iii*) A super epoch analysis of the temporal variation of OLR with reference to the onset dates was performed. For this the onset date for each year (Table 1) was taken as 0 and the calendar dates preceding onset dates assigned -1, -2,… and succeeding dates assigned 1,2,…. The OLR values for each grid were thus arranged as corresponding to -7 to +7 days with reference to the northeast monsoon onset date for each year and then averaged across the 12 years. Figs. 5(a-d). presents the spatial variation of OLR for the dates -4, -2, 0 and 2 with reference to the onset date.

4.3. *Inferences from the analysis of OLR data*

Reference to literature on OLR over the tropics reveals that values of OLR greater than 240 W/m^2 can be taken as associated with no convection , 220-240 W/m^2 with moderate convection and 200-220 W/m^2 with intense convection. From a preliminary analysis of OLR pattern presented in Figs. 3(a-f) an OLR threshold of 230 W/m^2 appeared to be the best and optimal value which could define the northern limit of ECZ (NLECZ). The mean OLR distribution is presented in Figs. 3(a-f). Table 3 presents the latitudinal positions of the 220, 230 & 240 W/m^2 isopleths over the 81.3 & 86.3° E longitudinal circles the former located just off the southeast coast of the peninsula and the latter representing the median longitudinal belt of Bay of Bengal. From a critical study of Figs. 3(a-f) and Table 3 the following inferences are drawn.

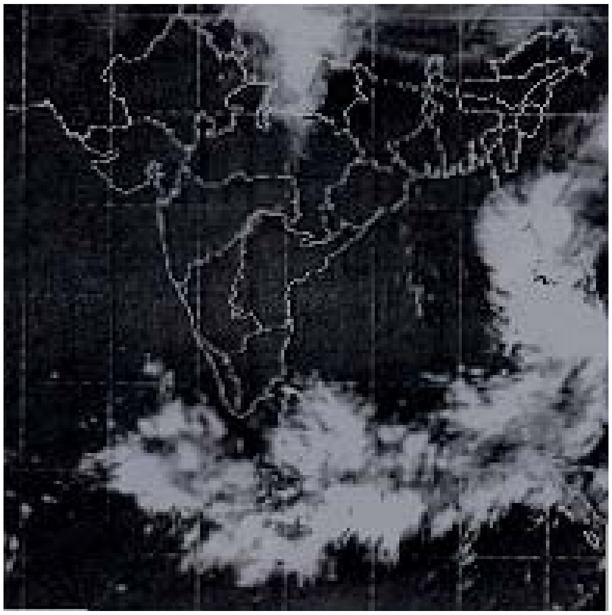
During the pentads 1-5 to 21-25 October the isopleths of three designated OLR values generally shift southwards from pentad to pentad, the southern most position realised during 16-20 / 21-25 October. However during the pentad 26-30 October there is a conspicuous and unmistakable shift of all the isopleths towards north. From the 21-25 to 26-30 October pentad the south to north shift is 6-8° latitude over both the belts.



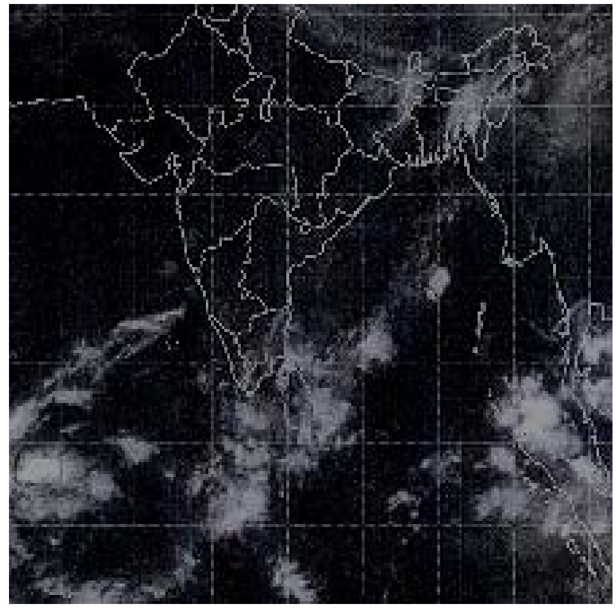
Figs. 5(a-d). Spatial variation of mean OLR data for -4, -2, 0 & -2 days with respect to the northeast monsoon onset dates based on superposed epoch analysis(OLR values in W/m^2 and shaded area < 230 W/m^2)

The normal day to day change of OLR presented in Fig. 4, reveals that the negative values are confined to south of 9° N in the western sector and to south of 13° N in the eastern sector during the pentad 21-25 October. During 26–30 October, the region with negative departures move northwards covering 6° N to 24° N, the decrease of values are in the order of 5 - 8 W/m^2. Over the south eastern region OLR values have risen by nearly 4 W/m^2. The analysis based on normal values and day to day changes clearly shows that normal isopleths of OLR and so the normal latitudinal position of NLECZ move from south to north just after northeast monsoon onset whose normal date is 20 October. This normal feature is expected to reflect in most of the individual years as well.

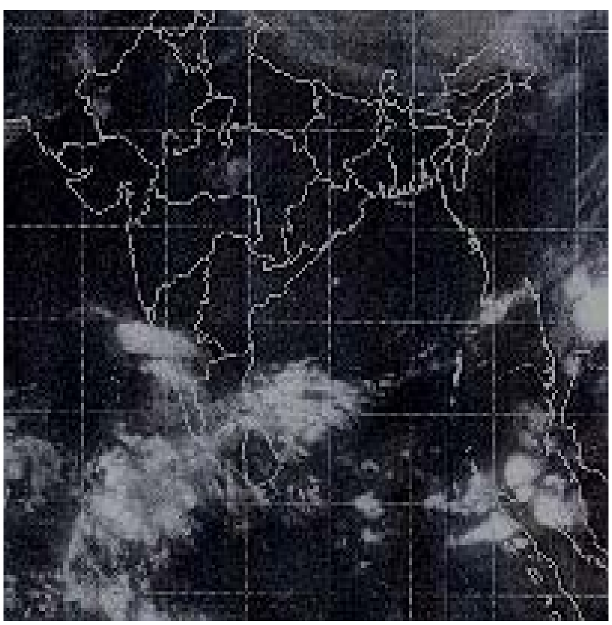
The above conclusion gets reaffirmed much more authentically from the superposed epoch profiles of OLR for the -4, -2, 0 & 2 days presented in Fig. 5 and the



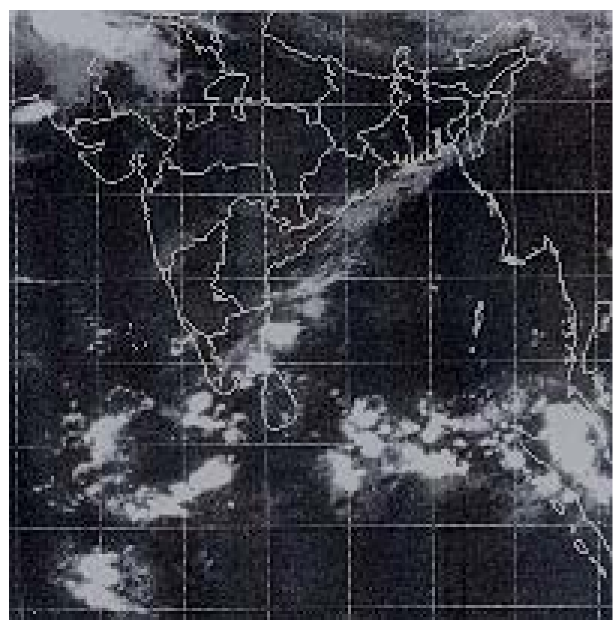
6 October (0000 UTC)



9 October (0000 UTC)



13 October (0300 UTC)

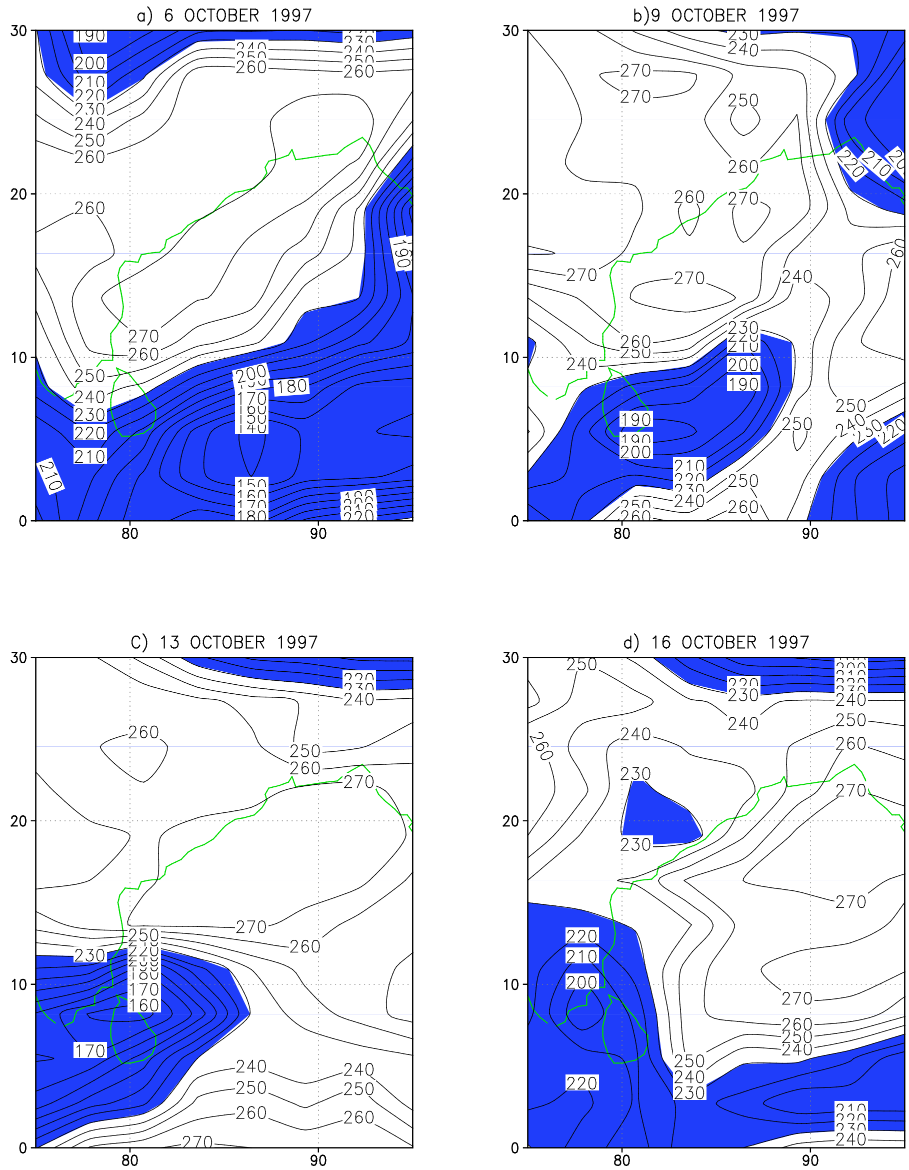


16 October (0300 UTC)

Fig 6. INSAT Cloud Imageries, 1997

latitudinal positions of the isopleths presented in Table 3. The 220 W/m^2 isopleth shifts consistently from south to north from 6.6 to 15.4° N during the above period at 81.3° E, *i.e.*, close to the coast. The 230 W/m^2 isopleth shifts from 8 to 18° N over 81.3° E and 10 to 17° N over 86.3° E. The 240 W/m^2 isopleth manifests an initial shift from north to south but after the onset shifts by 2–3° latitude northwards over both the longitudes.

The spreading of ECZ from south to north at the time of northeast monsoon onset has thus been well established.



Figs. 7(a-d). OLR distribution for 6, 9, 13 & 16th October (OLR values in W/m^2 and shaded area < 230 W/m^2)

5. Illustration of south to north movement of ECZ during the onset phase in 1997

The south to north movement and also the west to east movement of ECZ is illustrated for the year 1997 for which the north east monsoon set in on 13 October (Table 1). Fig. 6 presents the INSAT IR imageries at 0000/0300 UTC for 6, 9, 13 & 16 October and Figs. 7(a-d) depicts the mean OLR distribution for the same set of dates. From the figures it can be observed that the ECZ which is located at about 6-7° N over the south Bay of Bengal on 6th is confined to 9-10° N over the southwest Bay of Bengal on 9th. On 13th, the cloud zone shifts both west and northwards to be located at 10-11° N over the east coast. The OLR values reach upto 160 W/m^2 over parts of southwest Bay Of Bengal. On 16th the NLECZ has shifted north of 13° N.

The sequence of cloud imageries and OLR distributions presented for 1997 has shown that the ECZ shifted northwards as well as westwards at the time of onset. By and large similar movement of ECZ was detected for other years also. Though assigning a latitudinal value to the ECZ position was rather

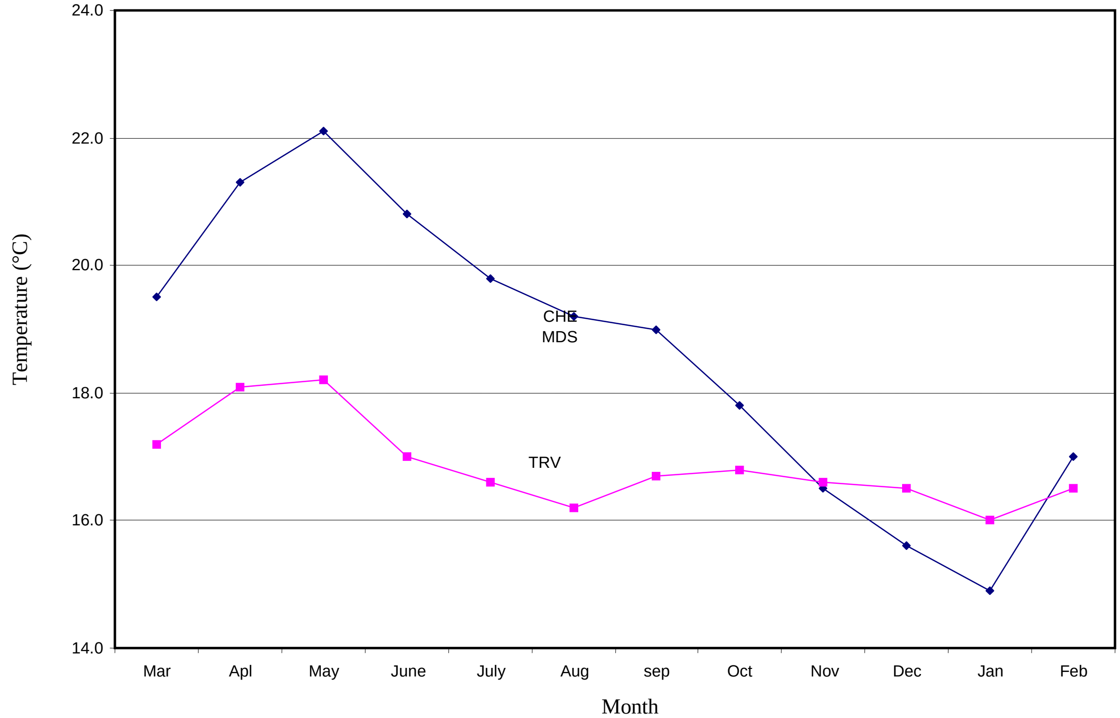


Fig. 8. Normal monthly 850 hPa temperature at 0000 UTC at Chennai and Thiruvananthapuram

approximate, the over all shift/spread of the cloud mass from south to north and east to west could be deduced for all the years.

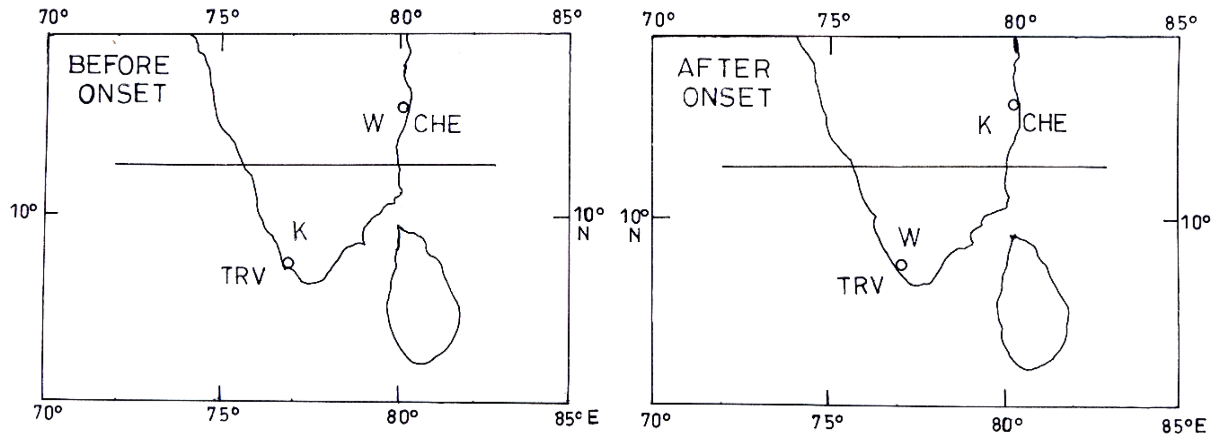
6. Possible causes of the northward movement of ECZ at the time of northeast monsoon onset

The occurrence of north to south movement of the wind based equatorial trough at the time of northeast monsoon onset and the concurrent but contrasting feature of south to north movement of ECZ have been established in the previous section. The movement of clouds from east to west over the Bay of Bengal was also generally observed from the scrutiny of daily satellite imageries. The following mechanisms could be ascribed as the plausible causes:

(*i*) As presented in Figs. 2(a&b) the zonal easterly winds over Chennai and Karaikal with speeds of 1-1.5 m/s at 900 hPa level before onset increase to nearly 5 m/s at Chennai and to 4 m/s at Karaikal at onset. At Thiruvananthapuram the winds are weak easterlies at the time of onset with the wind based equatorial trough shifting close to Comorin. However the nearly three fold increase in zonal wind speed at the low level at the time of onset and the generation of positive vorticity due to zonal easterly speed decreasing from north to south, the transportation of large amount of moisture flux towards the coast, which increases from south to north are all favourable features for the rapid northward spread of clouding .

(*ii*) Fig. 8 presents the normal 0000 UTC 850 hPa monthly mean temperature of Chennai and Thiruvananthapuram for all the months of the year, based on data from India Meteorological Department (1988). It is seen that during June-September Chennai is warmer by 2-3° C than Thiruvananthapuram. In October the gradient reduces to 1° C but in November, Thiruvananthapuram is warmer by 0.1° C, which increases to 0.9° C in December. Thus there is a reversal of temperature gradient taking place during October - December, between the two stations.

To investigate this feature further, a superposed epoch analysis with reference to the northeast monsoon onset dates was performed on the 0000 UTC 850 hPa daily temperature data of 1 October - 31 December, 1981-95 for both Chennai and Thiruvananthapuram. The mean temperatures for one pentad, before and after onset were computed and are presented in Table 4. In the pre-onset pentad Chennai is warmer by 1.0° C than Thiruvananthapuram but in the post onset pentad the former is cooler by 0.6° C than the latter. From the pre to post onset pentads, Chennai cools by 0.9° C where as Thiruvananthapuram warms by 0.7° C . The feature of



W – Warm, K - Cold

Fig.9. Reversal of temperature gradient at 850 hPa over the southern peninsula at the time of northeast monsoon onset

TABLE 4

Mean temperature at 850 hPa level over Chennai and Thiruvananthapuram one pentad before and after onset of northeast monsoon

	Before onset	After onset	Difference
CHE	18.6	17.7	0.9
TRV	17.6	18.3	-0.7
Difference	1.0	-0.6	1.6

Temperature in °C, data based on 15 years *i.e.*, 1981-95

reversal of temperature gradient at the low level is illustrated in Fig. 9.

The reversal of temperature also can be corroborated from the normal upper air data of Chennai and Thiruvananthapuram by invoking the thermal wind concept. For the month of November, when easterlies have firmly set in, the gradient of contour height between Thiruvananthapuram and Chennai is largest close to the surface level and decreases at higher levels. Thus strongest zonal (geostrophic) winds should prevail close to the surface with speed decreasing aloft leading to a westerly thermal wind associated with warmer south and colder north.

A major implication of this feature is that any low pressure system/trough during northeast monsoon would tilt northwards with height , which would generate more clouding northwards than southwards with reference to the low pressure system, which in the present case is the equatorial trough.

TABLE 5

Latitudinal position of surface equatorial trough over Bay of Bengal on or before northeast monsoon onset

Year	L	Latitudinal position (°N)	Year	L	Latitudinal position (°N)
1981	-2	8	1991	-3	10
1982	-1	10	1992	-6	9
1983	-1	9	1993	-1	10
1984	-3	5	1994	0	10
1985	-3	7	1995	-1	7
1986	-6	9	1996	-1	9
1987	-1	9	1997	-2	5
1988	-2	6	1998	-1	9
1989	0	7	1999	-2	8
1990	0	10	2000	-2	7

L : No. of days with reference to the onset date.

(*iii*) That south to north movement of ECZ takes place during Indian summer monsoon with periodicity of nearly 40 days has been well documented (Sikka and Gadgil 1980 and Keshavamurthy *et al*., 1990). Asnani (1993) has provided a brief summary of the phenomenon of 40 day oscillation of rainfall as presented in several other studies. In Raj (2003) it has been shown, based on 100 year rainfall data that the daily rainfall of coastal Tamil Nadu during September-February also under goes a 40-day oscillation with a discernable south to north movement of rainfall anomalies which takes 1-2 days to travel from Pamban (8° N) to Chennai (13º N) (Fig. 1). It has further

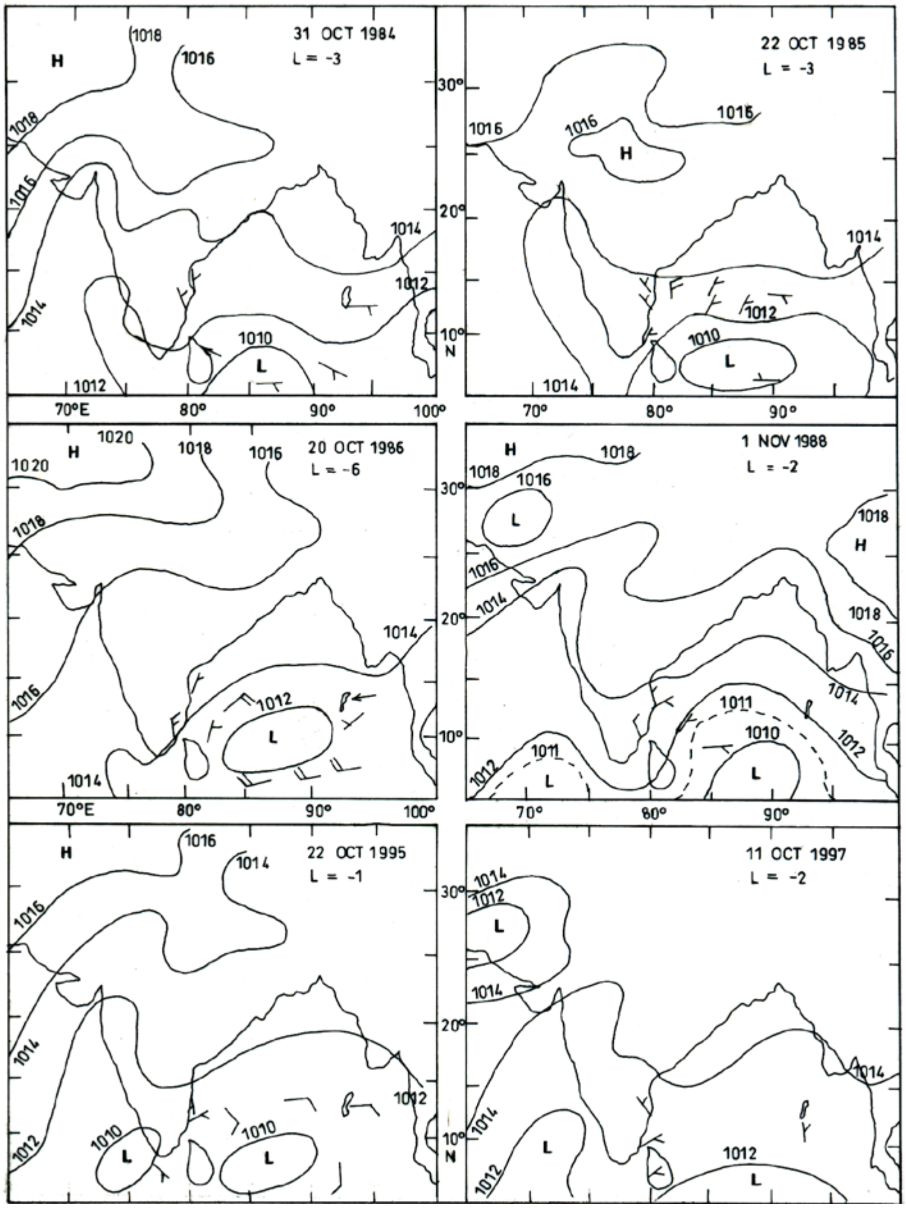


Fig. 10. Surface pressure charts on a pre northeast monsoon date for a few years (L is the no. of days from the onset date)

been shown in the above study that in 70 % of years the 40-day oscillation excites the northeast monsoon onset as well albeit with some upfront lag. The feature of south to north movement of ECZ at the time of northeast monsoon onset based on satellite data thus ties in well with the above postulate based on rainfall data.

(*iv*) The normal low level winds over coastal stations of southeast coast of India are northeasterlies and so are the surface winds over the adjacent southeast Bay of Bengal. However as one moves towards east, the surface winds veer to become easterlies near Port Blair. For *e.g.*, the normal surface wind direction over Bay of Bengal just east of Chennai is 20° but is 90° at about (94° E, 11° N) (India Meteorological Department, 2003). The normal low level upper air winds over Port Blair during November and December are southeasterlies (India Met. Dept., 1988). Thus it is evident that the northern component in the low level surface winds predominate only over the east coast of peninsular India and its closer neighbourhood whereas the eastern parts of Bay of Bengal are dominated by easterly winds. This explains the movement of clouds from east to west over Bay of Bengal.

The above synoptic and dynamical features provide plausible physical reasoning in comprehending the south to north and east to west movement of the ECZ at the time of northeast monsoon onset. It must be pointed out that the south to north shift of ECZ does not in itself imply individual cloud clusters also moving from south to north. It is likely that the cloud clusters by and large are steered by the low level wind flow only while the envelope of cloud belt shifts and spreads northwards. Perhaps a separate study based on cloud motion vectors derived from INSAT products over the same region for the same period will throw more light on this specific aspect. It appears logical and reasonable to conclude that the northeast monsoon cloud bands approach the south coastal peninsula from the southeast only and not from the northeast.

As for the southward movement of wind based equatorial trough at the time of onset, this is a time sequence of the annual movement of equatorial trough from its near equatorial position in January-April to the well known Ganga Nagar–Head Bay axis in July–August and back to the near equatorial position in December. This feature is regional and is considered as thermally driven. However a much more authentic but localised event appears to contribute to the swift southward shift of the equatorial trough during northeast monsoon onset. This is the rapid strengthening of low level easterlies over Bay of Bengal and east coast of Tamil Nadu which virtually annihilates the weak westerlies prevailing in the extreme southern peninsula (Thiruvananthapuram) thus driving the trough southwards of Comorin.

7. Position of surface equatorial trough over southern Bay of Bengal on the eve of northeast monsoon onset

The approximate mean position of wind based equatorial trough at the surface level over Bay of Bengal is about 10-11° N by 15 October and 8-9° N by 15 November as derived from the charts presented in India Meteorological Department (2003). However study of daily pressure charts of October for the 20 year period 1981-2000 revealed that in almost all the years the equatorial trough over south Bay of Bengal was found located south of 9° N prior to or on the date of onset. In Fig. 10 we present the surface pressure charts of India and adjoining seas, for one pre- northeast monsoon onset date for the following six years *viz*., 1984, 1985, 1986, 1988, 1995 and 1997. The date of the chart and the lag L of the latter with reference to the former are given, the dates of onset can be referred from Table 1. It is clearly seen that the equatorial trough between longitudes 80 and 90° E is roughly located along or south of Comorin during the pre-onset phase. Similar southern location of equatorial trough was observed in other years also. Table 5 presents in a nutshell the latitudinal position of equatorial trough over Bay of Bengal in a pre-onset or onset day for each year of 1981 -2000. At 1000 hPa which is almost the surface level, the wind based equatorial trough was found to be located north of 13° N roughly 2 days before onset and at 10° N on the date of onset. It is evident from this exposition, from Table 5 and Fig. 10 that the surface equatorial trough is located over a southerly latitude over the south Bay of Bengal when compared to its position over the peninsular coast.

8. A thematic model of northeast monsoon onset based on sequential events

In the preceding sections some features on northeast monsoon onset were deduced, based on low level winds, surface pressure pattern, OLR data, and the rainfall of coastal Tamil Nadu. From the above results and the other well known characteristics of northeast monsoon the following thematic model of monsoon to northeast onset based on synoptic events leading to onset, can be pieced together. The events taking place in chronological order are described below.

During one pentad before onset of the northeast monsoon, the equatorial trough is weak and diffuse over Bay of Bengal with clouding confined to south of 9° N. Over the peninsula it lies between Chennai and Thiruvananthapuram. Just at the time of northeast monsoon onset, strong easterlies over ride the weak westerlies of the lower latitudes pushing the equatorial trough further south. The temperature gradient over the peninsula at the lower levels hitherto positive changes sign to become negative. The cloud belt over Bay of Bengal which was earlier confined to south of 9° N increases in its intensity and spreads rapidly north and west wards into coastal Tamil Nadu, heralding the onset of northeast monsoon rains. Thus takes place the contrasting and apparently contradicting feature of wind based equatorial trough moving southwards while the equatorial cloud zone moves northwards at the time of onset. After the onset of northeast monsoon, clouding is heavier over northern parts of coastal Tamil Nadu and the adjoining sea areas than over the southern parts. Also clouding and rainfall are heavier over the land region and the adjacent sea areas than over the eastern parts of Bay of Bengal (Suresh and Raj, 2001). The availability of positive relative vorticity, generation of frictional convergence over the coastal region, convergence associated with the equatorial trough, existence of thermodynamic instability in the atmosphere and formation & movement of weak north to south troughs in the low level easterlies - appear to be the important dynamical factors behind the generation of vertical velocity needed for the development of clouding at the time of northeast monsoon onset.

9. Summary

The results of the study are summarised below:

(*i*) The equatorial trough at the lower levels over the southeastern coast of Indian peninsula, and the adjoining Bay of Bengal which lies between Chennai and Thiruvananthapuram before the northeast monsoon onset shifts south of Comorin at the time of onset. The 900 hPa zonal easterly wind speed over Chennai increases from 1-2 m/s to 5-6 m/s at onset.

(*ii*) The ECZ over the same region shifts from south to north at the time of northeast monsoon onset as deduced from a rigorous analysis of INSAT OLR data. The NLECZ which is located at 8–9° N before onset shifts to 15-18° N after onset.

(*iii*) The contrasting feature of wind based equatorial trough moving south and ECZ moving north at the time of northeast monsoon onset has been studied and plausible reasons ascribed. It has been shown that the stronger easterlies present in the northern parts of southwest Bay of Bengal, the reversal of temperature gradient between Chennai and Thiruvananthapuram at the time of onset resulting in tilting of low pressure/trough northwards and also the dynamics of the south to north movement of the well known 40-day oscillation are some of the likely causes.

(*iv*) The northeast monsoon activity over coastal Tamilnadu is shown to be negatively correlated with the low level zonal winds over the coast (*i.e.*, positively correlated with the low level zonal easterlies) with the degree of relation decreasing from north to south. The correlation is high in October, reduces in November and further reduces in December. Over coastal Tamil Nadu the intensity of this relation is high in the northern region and decreases over lower latitudes.

(*v*) The negative relationship between northeast monsoon activity and the zonal winds may not be clearly observed during the movement of an intense low pressure system across the peninsular coast.

(*vi*) Prior to northeast monsoon onset the equatorial trough is generally diffuse and its latitudinal position is in a much southerly position over Central Bay of Bengal than its position over coastal Tamil Nadu.

(*vii*) Positive relative vorticity, frictional convergence resulting from land-sea contrast, thermo dynamic instability and large amount of moisture flux transported towards coast besides convergence associated with equatorial trough -appear to be the major mechanisms behind cloud formation and rainfall, at the time of northeast monsoon onset.

(*viii*) A thematic model of northeast monsoon onset has been postulated.

Acknowledgements

The authors thank the Deputy Director General of Meteorology, Regional Meteorological Centre, Chennai for having provided the facilities for the study. Thanks are also due to S/Shri S. Venkata Krishna Murthi, M. Bharathiar and Selvam for their help.

References

Asnani, G. C., 1993, “Tropical Meteorology”, Noble Printers Pvt. Ltd., Pune, 489-494.

India Meteorological Department, 1973, “Northeast monsoon”, FMU Report No. IV – 18.4.

India Meteorological Department, 1988, “Mean monthly averages (1971-80) of radisonde/rawin data”.

India Meteorological Department, 2003, “Marine Climatological Atlas”, 1961-90.

Kelkar R. R., Rao, A. V. R. K. and Prasad, Sant, 1993, “Diurnal variation of outgoing long wave radiation derived from INSAT – 1B data”, *Mausam*, **44**, 45-52.

Kelkar, R. R., Tiwari V. S. and Prasad, Sant, 1989, “Retrieval of sea surface temperature from INSAT – 1B radiometer measurements using a multi-channel simulation approach”. *Mausam*, **40**, 13-18.

Keshavmurthy, R. N., Kasture, S. V. and Krishna Kumar, V., 1990, “1130 – 50 day oscillations of monsoon Some simple mechanisms”, *Mausam*, **41**, 189-192.

Panofsky, H. A. and Brier, G. W., 1968, “Some applications of Statistics to Meteorology”, University Park, Pennsylvania, 80-104.

Raj, Y. E. A., 1992, “Objective determination of northeast monsoon onset dates over coastal Tamil Nadu for the period 1901-90”, *Mausam*, **43**, 273-282.

Raj, Y. E. A., 1998, “A statistical technique for determination of withdrawal of northeast monsoon over coastal Tamil Nadu”, *Mausam*, **49**, 309-320.

Raj, Y. E. A., 2003, “Onset, Withdrawal and intra-seasonal variation of northeast monsoon over coastal Tamil Nadu, 1901 - 2000”, *Mausam*, **54**, 605-614.

Rao, Y. P., 1976, “Southwest monsoon”, India Meteorological Department, Met. Monograph.

Rao, A. V. R. K. and Phillip, A. Arkin, NOAA, 1987, "Estimation of precipitation and outgoing longwave radiation from INSAT – 1B radiance data", *Mausam*, **40**, 123-130.

Sikka, D. R. and Gadgil, S., 1980, "On the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon", *Mon. Wea. Rev*., **108**, 1840-1853.

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

Wilks, S. D., 1996, "Statistical methods in the Atmospheric Sciences", Academic Press, London.