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An analytical study of easterly waves over southern peninsular India during the northeast monsoon 2010

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सार – इस शोध पत्र में सिनॉप्टिक, साँख्यिकीय और संख्यात्मक पद्धतियों युक्त सिनर्जेट्रिक विश्लेषण के माध्यम से उत्तर पूर्व मॉनसून ऋतु 2010 के दौरान दक्षिणी प्रायद्वीपीय भारत में पछुआ पवनों के लक्षणों की जाँच की गई है। 20 अक्तूबर से 31 दिसम्बर 2010 की अवधि में 2.5° X 2.5° ग्रिड विभेदन पर क्षेत्रीय और रेखांशिक पवनों, उर्ध्वाधर गति, तापमान और कुल दीर्घ तरंग विकिरण के NCEP 6- घंटेवार पुन: विश्लेषण आँकड़ा सेट इस विश्लेषण का मुख्य आँकड़ा आधार हैं। इस अवधि के दौरान, इस क्षेत्र से पछुआ पवनों के तीन बार गुजरने का पता चल सका है तथा सांख्यिकीय पद्धतियों (सिनॉप्टिक पद्धतियों) द्वारा इन पछुआ पवनों की समय अवधि 4.2 दिन (4.5 दिन) निर्धारित की गई है। तरंगों की गति, तरंगदैर्ध्य और आयाम क्रमश: 7.28 ms^{-1}, 2800 कि.मी. तथा 6.7 ms^{-1} निर्धारित की गई। यद्यपि द्रोणी के ऊपर और पीछे अधिकांश क्षोभमंडलीय स्तरों में गति में वृद्धि देखी गई, तथापि द्रोणी के आगे अवतलन रहा। ऊपरी क्षोभमंडल में द्रोणी के ऊपर और पीछे अपसरण देखा गया जबकि निम्न से मध्य क्षोभमंडल में सहगामी अभिसरण देखा गया। द्रोणी से आगे सहगामी ऊष्णन देखा गया जबकि द्रोणी के ऊपर और पीछे निम्न स्तरों में शीत विसंगतियाँ देखी गई।

ABSTRACT. Easterly wave characteristics over southern peninsular India during the northeast monsoon season of 2010 are examined by means of synergetic analysis involving synoptic, statistical and numerical methods. NCEP 6-hourly reanalysis datasets of zonal and meridional winds, vertical velocity, temperature and net long wave radiation at 2.5° × 2.5° grid resolution for the period 20th October to 31st December, 2010 form the main database for the analysis. During this period, 3 easterly waves could be identified to have passed over this region and the time period of these waves are determined to be 4.2 days (4.5 days) by statistical methods (synoptic methods). The speed of movement, wavelength and amplitude of the waves are determined to be 7.28 ms^{-1}, 2800 km and 6.7 ms^{-1} respectively. While rising motion is observed at most of the tropospheric levels over and behind the trough, subsidence occurs ahead of the trough. Divergence is noted over and behind the trough at upper troposphere while convergence occurs in the lower to mid-troposphere. Concomitantly warming is noted ahead of the trough while colder anomalies are noted in the lower levels over and behind the trough.

Key words – Easterly wave, Northeast monsoon, Statistical, Synoptic, NWP, Power spectrum, Cross-lag correlation.

1. Introduction

The westward propagating wavelike disturbances which originate and traverse as perturbations in the mean easterly flow in the lower and middle troposphere of the tropical easterly trade wind belts are generally referred to as Easterly Waves (EWs) (Riehl, 1954). These transient synoptic scale systems affect southern peninsular India during the northeast monsoon (NEM) season of Oct. to Dec. (OND) (IMD, 1973). Whereas there have been a number of studies on tropical cyclones and depressions of NEM season of the North Indian Ocean (NIO), the role of the transient easterly waves in enhancing NEM activity has not been documented in detail.

The EWs were first identified in the Carribean (Dunn, 1940) and subsequently studied in detail over the African region using synoptic / satellite observations and numerical models. Several works on the passage of easterly waves over the African region, their structure, movement and role in genesis of Atlantic hurricanes have been carried out and reports are available in the literature [Burpee (1975), Jury *et al*. (1991), Berry and Thorncroft (2005); Ross and Krishnamurthy (2007)]. Similar studies have also been undertaken for other oceanic regions such as Eastern and Western Pacific (Tai and Ogura, 1987). For the North Indian Ocean (NIO) region, Saha *et al*. (1981) have analysed 24 hour sea level pressure change charts of July-August of three stations for

TABLE 1(a)

Monthly and seasonal rainfall during the year 2010 over the five meteorological sub-divisions benefitted by northeast monsoon

Met Sub Div.	October			November			December			Season (OND)		
	Act (mm)	Nor (mm)	PDN (%)	Act (mm)	Nor (mm)	PDN (%)	Act (mm)	Nor (mm)	PDN (%)	Act (mm)	Nor (mm)	PDN (%)
CAP	206	197	4	241	104	132	128	26	393	574	327	76
RYS	83	121	-32	163	67	146	29	25	16	275	212	30
TN	154	181	-15	327	165	98	127	84	51	607	430	41
SIK	134	139	-4	194	49	300	4	13	-69	332	201	66
KER	443	291	52	339	164	107	48	43	11	829	498	67

Act : Actual rainfall realised; Nor : Normal rainfall; PDN : Percentage Departure from Normal;
OND : October to December; CAP : Coastal Andhra Pradesh; RYS : Rayalaseema;
TN : Tamil Nadu; SIK: South Interior Karnataka; KER : Kerala

TABLE 1(b)

Weekly rainfall over the five sub-divisions during the weeks of easterly wave activity

Period of easterly wave	Sub-divisional rainfall (mm)				
	TN & PDC	CAP	RYS	SIK	KER
	Week ending 3 November 2010				
26-31 Oct 2010	97	192	67	60	71
	Week ending 17 November 2010				
13-17 Nov 2010	49	46	42	45	98
	Week ending 24 November 2010				
22-26 Nov 2010	87	17	12	22	132
	Total sub-divisional rainfall during the weeks of easterly wave activity				
	233	255	121	127	301
% of seasonal total	38.4%	44.4%	44.0%	38.3%	36.3%

the 10 year period of 1969-1978 and have identified passage of westward propagating disturbances as predecessors to formation of monsoon lows and depressions. They have determined the period of the wave as about 5 days; speed, about 6 ms^{-1}; amplitude, 5 ms^{-1} at 700 hPa level and wavelength, 2300 km. Balachandran *et al*. (1998) have reported some features of an inverted V-type easterly wave over the Indian seas during December 1995 and have determined the speed of the wave as 8.2 knots using satellite imageries. However, systematic analysis of EW activity during the NEM season has not been undertaken so far, apparently due to the difficulty in tracking these waves during their movement over data sparse oceanic regions. Now, with the availability of satellite based data, dynamical models and reanalysis datasets, there is considerable scope to study these waves in detail.

Table 1(a) presents the monthly and seasonal rainfall over the five meteorological sub-divisions benefitted by this monsoon-Coastal Andhra Pradesh : 76%, Rayalaseema : 30%, South Interior Karnataka : 66%, Tamil Nadu: 41% and Kerala : 65% (*Source* : Weekly weather reports of IMD)- during the NEM 2010. It may be noted that the NEM seasonal rainfall was in excess over all the five sub-divisions. However, the contribution from the chief synoptic scale systems, *viz*., cyclones and depressions for the seasonal total was modest with only one cyclone (severe cyclonic storm '*Jal*', 4-8 November, 2010) and another short-lived depression (less than one day, 7th December, 2010) affecting the NEM area. While coastal districts recorded normal rainfall, most interior districts of Tamil Nadu recorded excess rainfall [≥ 20%], during the season (IMD, 2011). Table 1(b) presents the weekly rainfall over the above sub-divisions during the

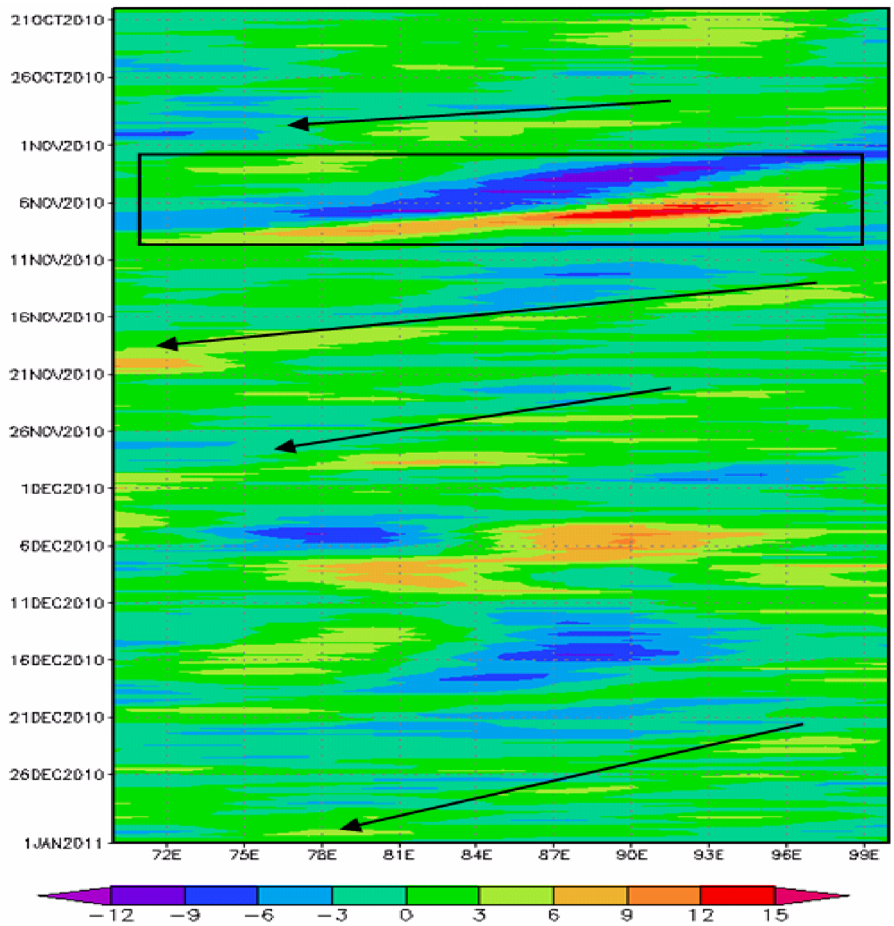


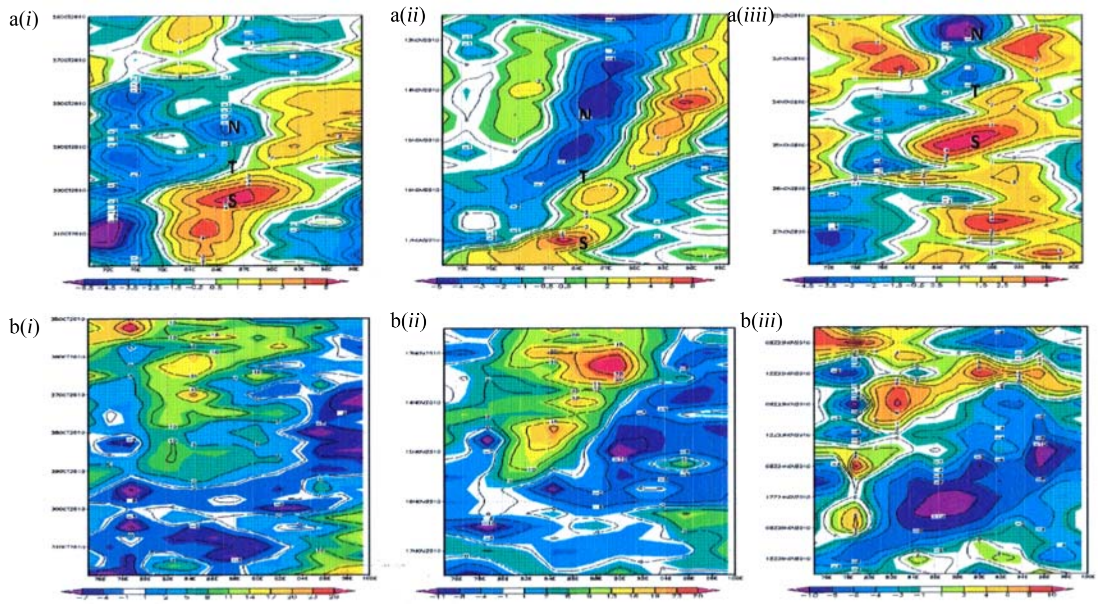
Fig. 1. Time-longitudinal Hovmoller plot of 6 hr'ly meridional wind (m/s) over 10º N and 850 hPa level during the period 21 October-31 December, 2010. The four arrows indicate westward propagating easterly waves with northerly followed by southerly meridional wind anomalies (arrows are drawn along the zero line). The westward moving northerly and southerly anomalies shown inside a box are in association with passage of severe cyclonic storm 'Jal' during 4-8 November, 2010

weeks of easterly wave activity. It may be noted that 36-44% of the total seasonal rainfall over these sub-divisions was realised during the weeks of easterly wave activity indicating that significant contribution to the total rainfall came from easterly waves during NEM 2010. An account on the characteristics of these waves is presented in this paper by a synergetic approach based on statistical, synoptic and numerical techniques.

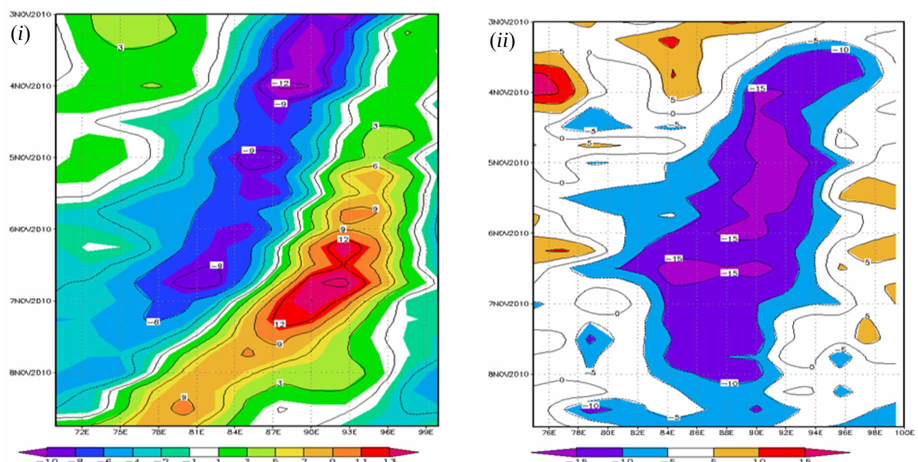
2. Data and methodology

In the present study, the methodology adopted by the earlier workers to study African / Pacific easterly waves mentioned in the introduction section are followed to characterise the passage of easterly waves over southern peninsular India during OND 2010. The propagation of EWs are identified from satellite imageries, Daily / Weekly Weather Reports of India Meteorological Department and WRF model products of Regional Meteorological Centre, Chennai. NCEP 6-hourly reanalysis datasets of zonal and meridional winds, vertical velocity, temperature and net long wave radiation at 2.5º × 2.5º grid resolution for the period 20th October to 31st December, 2010 form the main database for analysis.

The characteristics of the waves are determined using statistical and synoptic methods. Statistically, time period of the waves is determined by power spectral analysis conducted on 6-hourly meridional winds at 850 hPa level over 85° E/10° N during the period 20 October to 31 December, 2010. Here, the latitude 10° N is chosen based on the climatology of the location of equatorial trough over the Indian region during the NEM season. Lag correlation analysis of meridional winds at two



Figs. 2(a&b). (*i-iii*) Time-longitudinal Hovmoller plot of a(*i*)-(*iii*) 6 hrly meridional wind (in m/s) over 10º N and 850 hPa level during (*i*) 26-31 Oct, (*ii*) 13-17 Nov and (*iii*) 22-26 Nov, 2010 & b(*i*)-(*iii*) net longwave radiation anomalies (in W/m^2) over 10º N around the same periods as a(*i*)-(*iii*) respectively. N, T & S indicate the passage of northerly maxima, the wave trough and the southerly maxima over a particular longitude [(*i*)-(*ii*) 85º E, (*iii*) 88º E)]



Figs. 2 (c). (*i-ii*). Time-longitudinal Hovmoller plot of (*i*) 6 hrly meridional wind (m s^{-1}) over 10º N and 850 hPa level during 3-8 November, 2010 (*ii*) net longwave radiation anomalies (W/m^2) over 10º N during the same period

locations identified along the same latitude (85° E/10° N & 75° E/10° N) is conducted to substantiate the movement of the waves and determine the speed of movement of the wave. Synoptically, the time taken between passages of two successive northerly maxima over a particular location is taken to determine the time period and the amplitude is obtained from the velocity maxima. The vertical cross-sections of zonal and meridional winds and other dynamical parameters such as vertical velocity, temperature, horizontal divergence and relative vorticity over a specific location (85° E / 10° N) during the passage of a wave are analysed to examine the structure of the atmosphere during the passage of various parts of an EW. In addition, movement of the EW during 13-17th November, 2010 is studied through numerical simulation using WRF model.

3. Results and discussion

Conceptually, northerly meridional winds, subsidence, divergence and fair weather are the general atmospheric characteristics ahead of an approaching easterly wave trough and southerly meridional winds, rising motion, convergence and active weather are the characteristics behind the wave trough. The southerly meridional winds approaching the wave trough encounter an uphill motion (moving from a low in the south towards a high in the north) and hence slow down leading to velocity convergence. The northerly winds approaching the wave ridge face a downhill motion as a result of which the wind speeds increase leading to velocity divergence. Thus, the winds approaching the wave trough are subgeostrophic and the winds approaching the wave ridge are supergeostrophic (Hess, 1959).

Fig. 1 presents time-longitudinal Hovmoller diagram of 6-hourly meridional wind anomalies at 850 hPa level over 70° E - 100° E longitudes along 10° N during the period 21st October - 31st December, 2010. The meridional wind anomalies were computed at each grid point over the domain so as to remove the mean and seasonal signals for the entire period of study. Tracking the westward propagating northerly (negative) anomalies followed by southerly (positive) anomalies in the Fig. 1, three waves could be identified:-

(*i*) During the onset phase of NEM, 27-31 October (Wave 1),

(*ii*) 13-18 November (Wave 2) and

(*iii*) 22-26 November (Wave 3).

Figs. 2(a&b) (*i-iii*) present the 6-hourly 850 hPa meridional wind anomalies and net longwave radiation (NLR) anomalies over 10° N and 70 - 100° E in respect of the three waves. It can be seen that in each case, the northerly (negative) anomalies of meridional winds Figs. 2a(*i-iii*) are associated with positive NLR anomalies ahead of the trough (zero line in the meridional wind anomaly) indicating subsidence and fair weather. Southerly (positive) anomalies behind the trough are associated with negative NLR anomalies indicating convection and bad weather. The fourth wave is somewhat ill-defined in unfiltered data and hence is not considered for further analysis.

It may be noted that the most prominently propagating northerly and southerly anomalies during 4-8 November, 2010 are in association with passage of severe cyclonic storm '*Jal*'. Figs. 2c(*i-ii*) depict positive anomalies of NLR in association with northerly meridional winds during the initial formative stages of '*Jal*' suggesting the genesis of this cyclone from an easterly wave.

3.1. *Determination of wave characteristics*

Statistically, the time periods of the waves are determined from power spectral analysis of auto correlations of meridional wind and the speeds of the waves are determined from cross lag correlations in the meridional wind between two locations separated by a known distance (Wilks, 1995).

3.1.1. *Power spectral analysis*

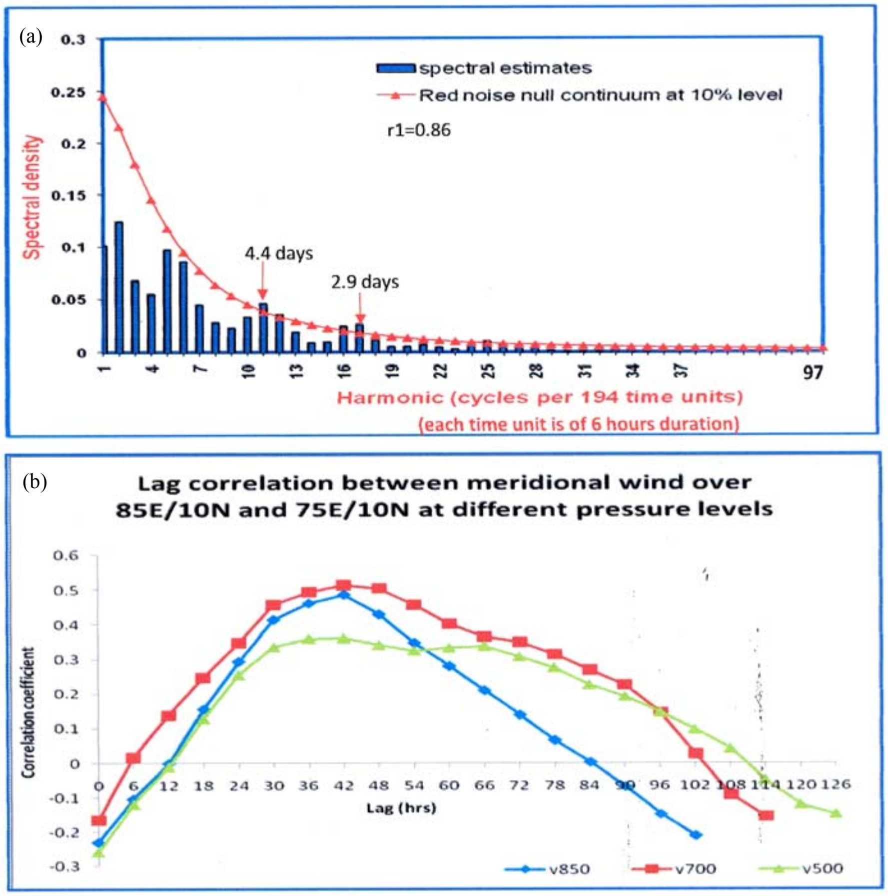
The periodicity in the 6-hourly meridional wind over the selected location 85º E/10º N at 850 hPa level is first determined by subjecting the autocorrelations of the standardised anomalies of the 6-hourly meridional wind data to power spectral analysis up to lag 97 (1/3rd of the sample size (292). The power spectrum is presented in Fig. 3(a) reveals two significant peaks at 10% level. The first significant band explaining about 10% of variance in the data exhibits a cyclic periodicity of 4.4 days which is identified as the spectral band associated with the passage of easterly waves. Another band explaining about 7% variance in the data exhibits a periodicity of 2.9 days which may be due to other type of higher frequency oscillations.

3.1.2. *Cross lag correlation analysis*

In Fig. 3(b), plots of lag correlation coefficients between 6-hourly meridional winds over 85° E/10° N and that over 75° E/10° N at 850, 700 and 500 hPa levels for the period 20 October - 31 December, 2010 are presented. It can be seen that highly significant and largest CCs of 0.48 to 0.51 are obtained for the 850 and 700 hPa series for lag 42 (sample size = 286). Thus, the waves take 42 hours to traverse a distance of 10º longitude from which the speed of movement of the waves is determined as 7.28 ms^{-1} or 26.2 kmh^{-1}. The wavelength of the wave is determined as 2800 km from the speed and time period. The cross lag correlation is more sharply defined in the case of 850 hPa than the 700 hPa level.

3.1.3. *Synoptic methods*

Synoptically, the wave characteristics are determined from time-longitudinal [Hovmoller diagrams plotted for 10° N and 850 hPa levels Fig. 2a (*i-iii*)]. The time period is determined as twice the time taken from the instance of passage of northerly maxima to the instance of passage of



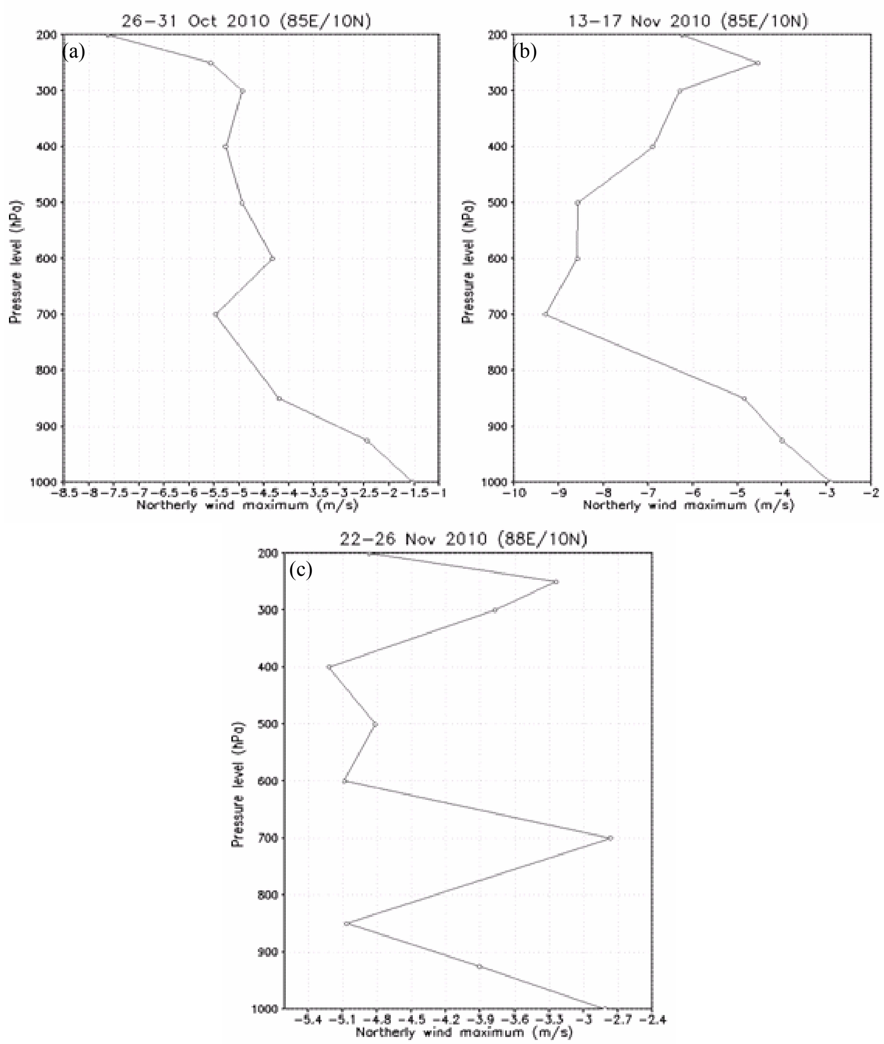
Figs. 3 (a&b). (a) Power spectrum of 6 hourly meridional winds at 850 hPa at 85° E / 10° N and 10% limit of red noise null continuum and (b) Lag correlation between 6 hourly meridional winds over 85° E / 10° N and 75° E / 10° N at 850, 700 & 500 hPa for the period 20 Oct - 31 Dec, 2010

TABLE 2

Determination of time period of easterly waves at 850 hPa level

S. No.	Wave	Long. °E/ Lat. °N	Time of passage of			Time taken from N to S (hours)	Time period (days)
			Northerly maxima (N)	Wave trough (T)	Southerly maxima (S)		
(i)	26-31 Oct 2010	85 / 10	28th/1200 UTC	29th/1200 UTC	30th/0600 UTC	42	3.5
(ii)	13-17 Nov 2010	85 / 10	14th/1200 UTC	15th/1800 UTC	17th/0000 UTC	60	5.0
(iii)	22-26 Nov 2010	88 / 10	22nd/1200 UTC	23rd/1800 UTC	25th/0000 UTC	60	5.0
			Mean time period				4.5

southerly maxima over a particular longitude. In the Fig. 2a(*i*-*iii*) the instances of occurrences of northerly and southerly maxima over 85° E / 10° N, 85° E / 10° N and 88° E / 10° N respectively (where the waves are best defined) are marked as N and S respectively. The instant of passage of the wave trough over the specific longitude is marked as T. Table 2 presents the time periods of each of the three waves determined as 3.5, 5.0 and 5.0 days



Figs. 4 (a-c). Vertical distribution of northerly maxima in respect of the three waves determined at (a) 85° E / 10° N (b) 85° E / 10° N and (c) 88° E / 10° N respectively

respectively and the mean time period, 4.5 days. The amplitudes are determined from the supergeostrophic northerly maxima ahead of the wave trough. Fig. 4(a-c) present the vertical distribution of velocity maxima of the northerly meridional wind anomalies for the three waves over 85° E/10° N, 85° E/10° N and 88° E/10° N respectively. It can be seen that the maxima are located in the 700 - 500 hPa levels and the amplitudes are 5.5, 9.5 and 5 ms^{-1} at 700 hPa, 700 hPa and 600 hPa levels respectively. The mean amplitude of the wave is determined to be 6.7 ms^{-1}.

3.2. *Vertical structure of atmosphere during the passage of the EW (Wave 2)*

Next we discuss the vertical structure of the atmosphere during the passage of an EW (Wave 2) during 13-17 November, 2010. Fig. 5 presents the Infra red (IR) imageries corresponding to 0000 UTC of 14^{th}, 15^{th}, 16^{th} and 17^{th}. The westward movement of the convective clouds associated with the passage of the wave is clearly seen and is indicated by an arrow. Fig. 6(a) presents the TRMM based rainfall over the Indian region during 13^{th} to 17^{th} November, 2010 and Fig. 6(b) presents the metgrams of rainfall over Trincomallee (81.2° E/8.5° N), Chennai (80.1° E/13° N) and Bangalore (77° E/12.5° N) during the period 17-21 November, 2010 which indicate westward propagation of rainfall regime in association with the passage of the wave.

Figs. 7(a-f) present the vertical cross-section of meridional wind anomalies, zonal wind anomalies, vertical velocity, temperature anomalies, horizontal divergence and relative vorticity during the passage of the wave over 85° E / 10° N. The markings N, T and S correspond to locations of northerly maxima, trough axis

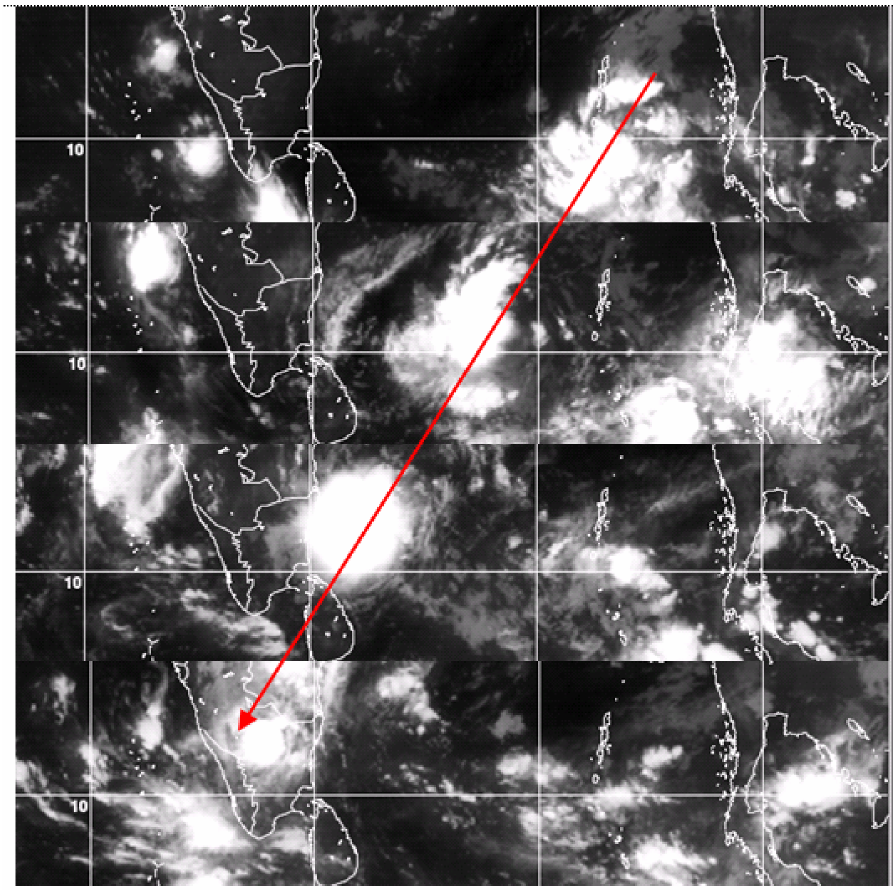


Fig. 5. Satellite IR imageries corresponding to 0000 UTC of 14, 15, 16 & 17 November, 2010. Westward propagation of the convective clouds associated with the wave is indicated by the arrow

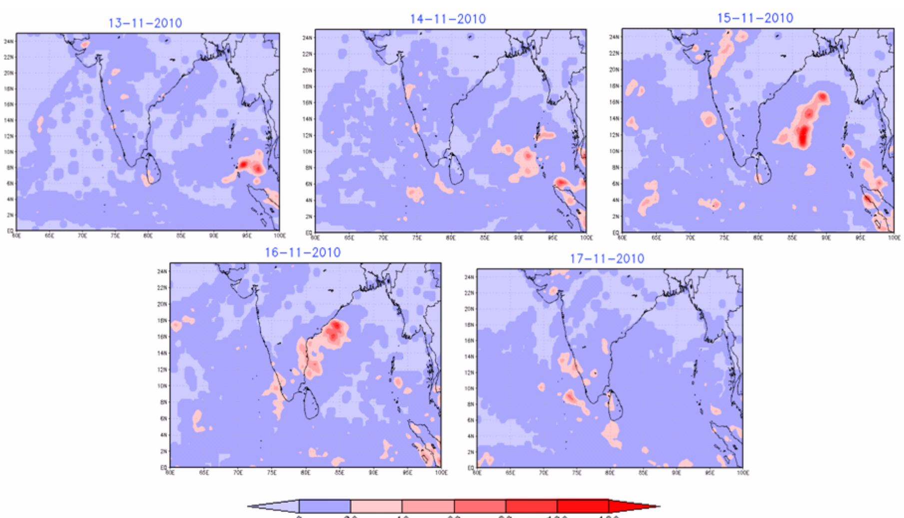


Fig. 6 (a). TRMM based daily accumulated rainfall (in mm) during the period 13-17 November, 2010

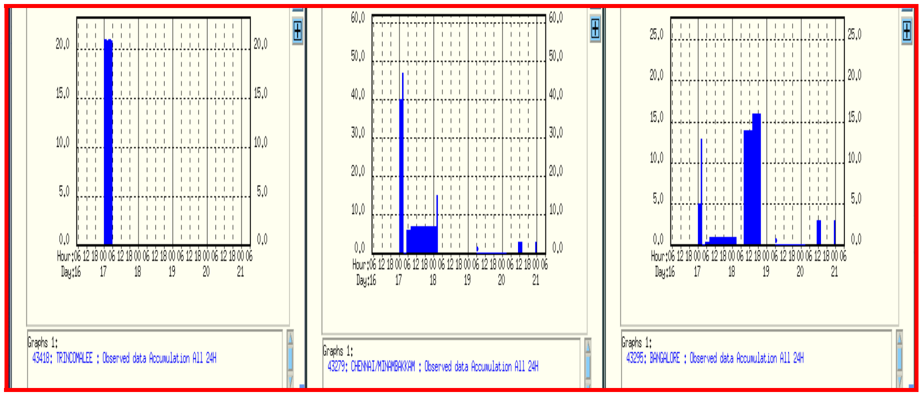
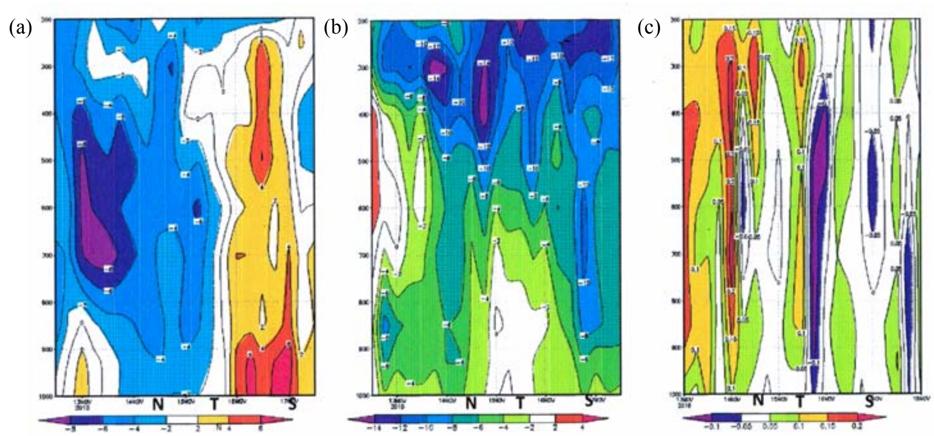
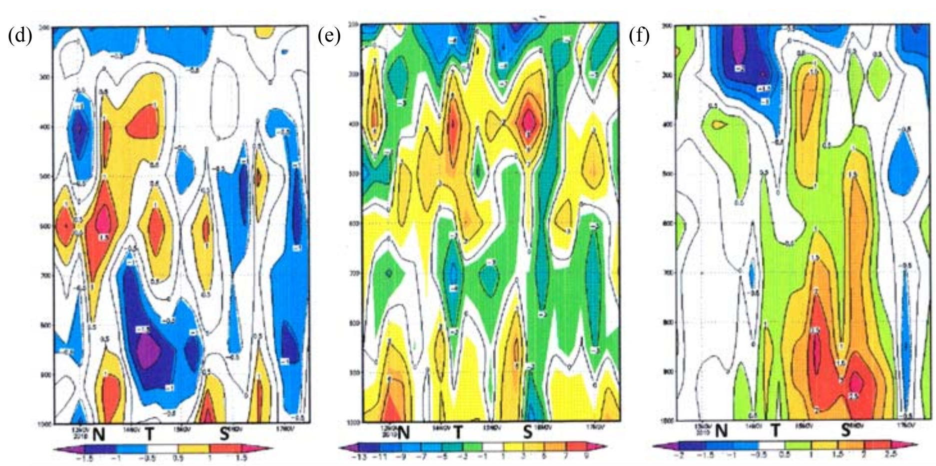


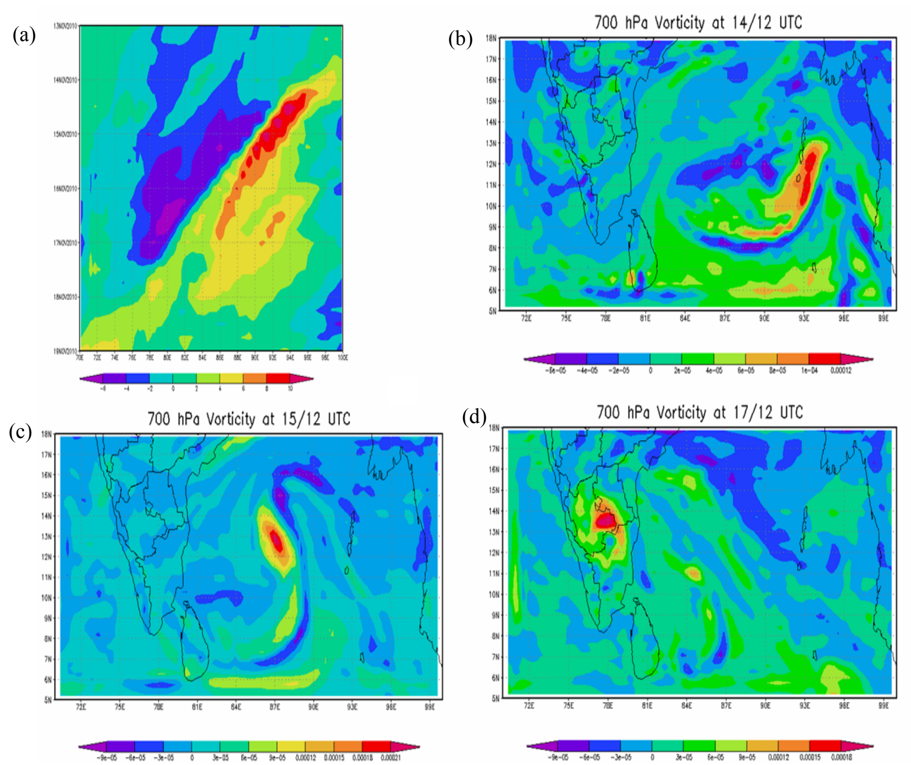
Fig. 6(b). Metgrams (plots of amount of rainfall against time) of Trincomallee (81.2° E / 8.5° N), Chennai (80.1° E / 13° N) and Bangalore (77° E / 12.5° N) for the period 17-21 November, 2010. (*Source* : Synergie forecasting tool, Regional Meteorological Centre, Chennai)



Figs. 7(a-c). Vertical cross section of wave related (a) meridional wind anomalies in ms^{-1} (b) zonal wind (ms^{-1}) and (c) vertical velocity (Omega) anomalies (in Pa s^{-1}) over 85° E / 10° N during 13-17 November, 2010



Figs. 7(d-f). Vertical cross section of (d) temperature anomalies (°C) (e) horizontal divergence ($\times 10^{-6}$ s^{-1}) and (f) relative vorticity ($\times 10^{-5}$ s^{-1}) over 85° E / 10° N during 13-17 November, 2010

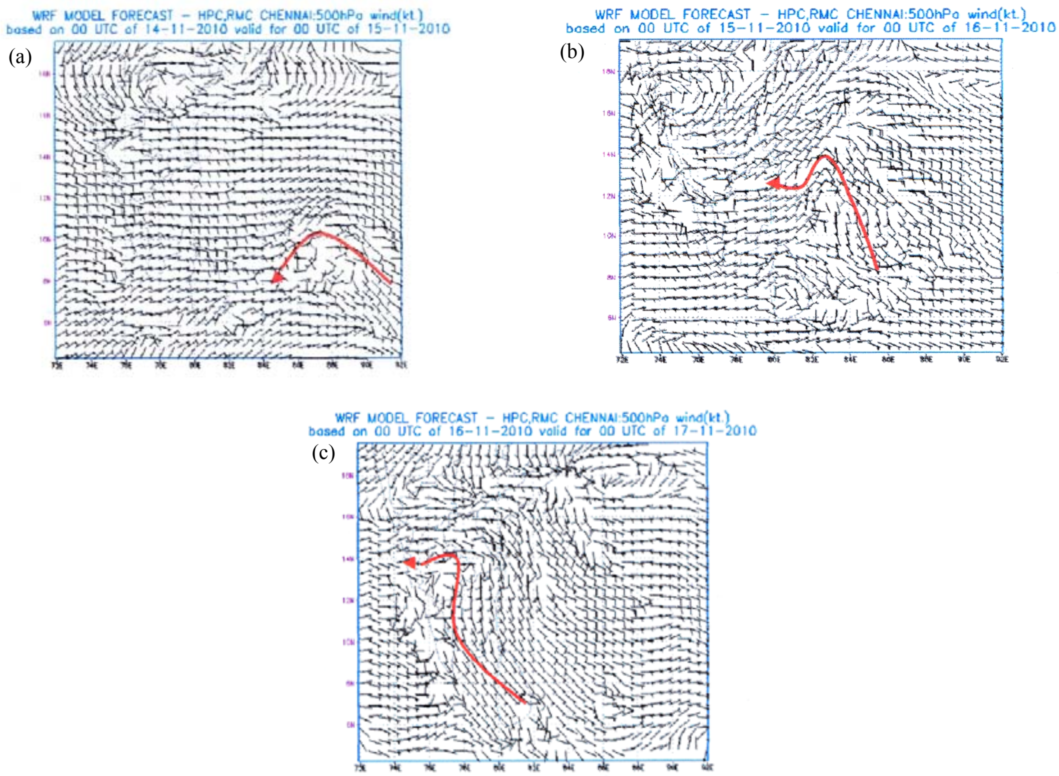


Figs. 8 (a-d). WRF simulated (a) Time-longitudinal Hovmoller plot of meridional wind (m/s) over 10° N and 850 hPa level during 13-18 November, 2010 and (b-d) relative vorticity fields (s^{-1}) at 700 hPa level during different instances of wave motion

and southerly maxima respectively at 850 hPa levels only. It can be seen that ahead of the wave trough meridional anomalies are northerly and behind the trough the anomalies are southerly throughout the troposphere. The 700 hPa northerly maxima ahead of the trough, are seen ahead of the location of 850 hPa maxima (N) indicating a tilt in the location of the velocity maxima. The zonal anomalies are easterly throughout and the wind speeds are min. near the trough. The easterly strength increases with height and highest zonal maxima are found in the upper troposphere ahead of the trough. Vertical velocity profile indicates upward motion over and behind the trough and subsidence ahead of the trough at all levels. The temp. anomalies indicate that atmosphere is cooler in the low levels above the trough. In the mid-troposphere, mainly warming is seen excepting behind the trough were colder anomalies are found. In the upper troposphere, up to 300 hPa level, warmer anomalies are seen ahead of the trough and elsewhere, the anomalies are near zero. Convergence is observed between 800-600 hPa levels over and behind the trough with divergence aloft upto 300 hPa level. Relative vorticity fields indicate cyclonic vorticity around the trough in the low levels. In the upper levels, ahead of the trough, anti cyclonic vorticity is seen.

3.3. *Numerical simulation*

Next, the possibility of tracking such waves in forecast fields using numerical simulation is shown using the WRF model (version 3.2) for the Wave-2. The model is run for the domain 70-100° E and 5-18° N at 30 km resolution for 5 days with 13^{th}/0000 UTC as initial conditions from NCEP FNL (final) analysis data (at 1.0° × 1.0° resolution). WSM 3-class simple ice scheme and Kain-Fritsch scheme are used for micro and cumulus physics respectively. Fig. 8(a) presents time-longitudinal hovmoller diagram of meridional wind field forecasts for the period 13-18 November, 2010 and Figs. 8(b-d) present the relative vorticity field forecasts at 1200 UTC of 14^{th}, 15^{th} and 17^{th} November, 2010. It is noted that the movement of the wave could be tracked from the meridional wind fields as well as from the westward propagating positive vorticity centres. The model is able to predict the movement of the easterly wave fairly well based on 13^{th}/0000 UTC conditions. In Figs. 9(a-c), real-time WRF model 24 hour forecasts of winds at 500 hPa based on 0000 UTC of 14^{th}, 15^{th} and 16^{th} November, 2010 are presented wherein southeasterly winds becoming northeasterly and moving westwards are clearly seen.



Figs. 9 (a-c). Real-time 24 hour wind forecasts of WRF model runs at RMC Chennai based on 0000 UTC of 14th/ 15th and 16th November, 2010

Though the present study is based on an analysis of one NEM season only (2010), similar study with more seasons would help in bringing out characteristics of easterly waves and their forecasting aspects over southern peninsular India during the NEM season.

4. Conclusion

Based on the present study on characteristics of easterly waves over southern peninsular India during the northeast monsoon 2010 the following results could be summarised:

(*i*) During the NEM 2010, 3 easterly waves could be identified from the time-longitudinal Hovmoller diagram of 6-hourly meridional winds over 10° N.

(*ii*) Based on power spectral analysis of 6-hourly meridional winds, the time period of the waves is determined to be 4.2 days. Synoptically the time period of waves are determined to be 4.5 days.

(*iii*) Based on cross lag correlation method, the speed of Easterly waves is determined to be 7.28 ms^{-1} (26.2 kmh^{-1}). The wavelength of the waves is determined to be 2800 km and the amplitude is determined from the velocity maxima as 6.7 ms^{-1}.

(*iv*) While rising motion is observed at most of the tropospheric levels over and behind the trough, subsidence occur ahead of the trough. Divergence is noted over and behind the trough at upper troposphere while convergence occurs in the lower to mid-troposphere. Concomitantly warming is noted ahead of the trough while colder anomalies are noted in the lower levels over and behind the trough.

(*v*) Passage of the easterly waves over the southern peninsular India could be identified in numerical forecast fields of meridional wind and vorticity.

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References

Balachandran, S., Pai, D. S. and Prasad, S. K., 1998, "Some features of an inverted V-type easterly wave over Indian seas", *Mausam*, **49**, 2, 266-268.

Berry, G. J. and Thorncroft, C., 2005, "Case study of an intense African easterly wave", *Mon. Wea. Rev*., **133**, 752-766.

Burpee, R. W., 1975, "Some features of synoptic-scale waves based on a compositing analysis of GATE data", *Mon. Wea. Rev*., **103**, 921-925.

Dunn, G. F., 1940, "Cyclogenesis in the tropical Atlantic", *Bull. Amer. Meteor. Soc.,* **21,** 215-229.

Hess, S. L., 1959, "Introduction to Theoretical Meteorology", Holt, Rinehart & Winston, New York.

India Meteorological Department, 1973, "Northeast monsoon", FMU Report No. IV-18.4.

India Meteorological Department, 2011, 'Weather in India', "Post Monsoon Season (October-December, 2010)", *Mausam*, **62**, 4, 673-706.

Jury, M. R., Pathack, B., Campbell, G., Wang, B. and Landman, W., 1991, "Transient convective waves in the Tropical SW Indian Ocean", *Meteorol. Atmos. Phys.,* **47**, 27-36.

Riehl, H., 1954, "Tropical Meteorology", McGraw Hill Book Co., Inc, New York.

Ross, R. S. and Krishnamurthy, T. N., 2007, "Low level African easterly wave activity and its relation to Atlantic Tropical cyclogenesis in 2001", *Mon. Wea. Rev*., **135**, 3050-3964.

Saha, K., Sanders, F. and Shukla, J., 1981, "Westward propagating predecessors of monsoon depressions", *Mon. Wea. Rev*., **109,** 330-343.

Tai, K. S. and Ogura, Y., 1987, "An observational study of easterly waves over the eastern pacific in the northern summer using FGGE data", *Jl. Atm. Sc.,* **44**, 2, 339-360.

Wilks, 1995, "Statistical methods in the Atmospheric Sciences", Academic Press, London.