Table 4.3

TC-OCKHI Average Track Forecast Errors in km by different models

(Source: IMD report)

Lead time	12 hrs	24 hrs	36 hrs	48 hrs	60 hrs	72 hrs
IMD-GFS	51(11)	68(10)	98(9)	117(8)	123(7)	145(6)
IMD-WRF	59(11)	115(10)	166(9)	226(8)	271(7)	278(6)
JMA	70(11)	70(10)	85(9)	103(8)	148(7)	215(6)
NCEP-GFS	60(11)	65(10)	75(9)	110(8)	91(7)	104(6)
UKMO	42(11)	63(10)	76(9)	122(8)	146(7)	173(6)
ECMWF	58(11)	69(10)	64(9)	62(8)	86(7)	100(6)
IMD-HWRF	58(21)	99(20)	130(18)	180(16)	234(14)	251(12)
IMD/MME	29(11)	44(10)	58(9)	86(8)	100(7)	112(6)
NCUM	82(13)	122(12)	129(11)	121(10)	144(9)	180(8)
NEPS	90(7)	134(6)	178(6)	217(5)	211(5)	208(4)

4.7. **Easterly Waves/Troughs in Easterlies**

From the Table 4.1, it is observed that easterly waves/trough in easterlies form a substantial portion of synoptic systems affecting south peninsula during the NE monsoon season. However, there are not adequate studies on easterly waves forming over the Indian Ocean.

Easterly wave is a wave within the broad easterly current and moves from east to west, generally more slowly than the current in which it is embedded. Although best described in terms of its wave like characteristics in the wind field, it also consists of a weak trough of low pressure. Easterly waves do not extend across the equatorial trough. To the west of the trough line in an easterly wave, there is generally found divergence, a shallow moist layer, and exceptionally fine weather. The moist layer rises rapidly near the trough line; in and to the east of the trough line intense convergence, cloudiness and heavy rain showers prevail. Easterly waves occasionally intensify into tropical cyclones over the Bay of Bengal.

These waves are first identified in the Carribean (Dunn, 1940) and subsequently studied in detail over the African region using synoptic / satellite observations and numerical models. Considerable work on the passage of easterly waves over the African region, their structure, movement and roles in genesis of Atlantic hurricanes have been carried out and reports available in the literature (Burpee (1974), Jury et al., (1991), Berry and Thorncroft (2005) and Ross and Krishnamurti (2007)). Similar studies have also been undertaken for other oceanic regions such as Eastern and Western Pacific (Tai and Ogura, 1987). For the Indian region, Saha et al., (1981) have analysed 24 hour sea level pressure change charts of July-August of three stations for the 10 year period of 1969-1978 and have identified passage of westward propagating disturbances as predecessors to formation of monsoon lows and depressions. Using cross-correlation and power spectral analysis, they have determined the period of the wave as about 5 days, speed of about 6 ms^{-1} and wavelength of 2300 km. There are not adequate studies on Easterly waves forming over the Indian Ocean. 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.

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 upgradient 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 downgradient motion as a result of which the wind speeds increase leading to velocity divergence. Thus, the winds approaching the wave trough are sub-geostrophic and the winds approaching the wave ridge are super-geostrophic (Hess, 1959). The pictorial representation of an easterly wave, taken from Riehl (1968, Tropical Meteorology) is given in Fig. 4.22.

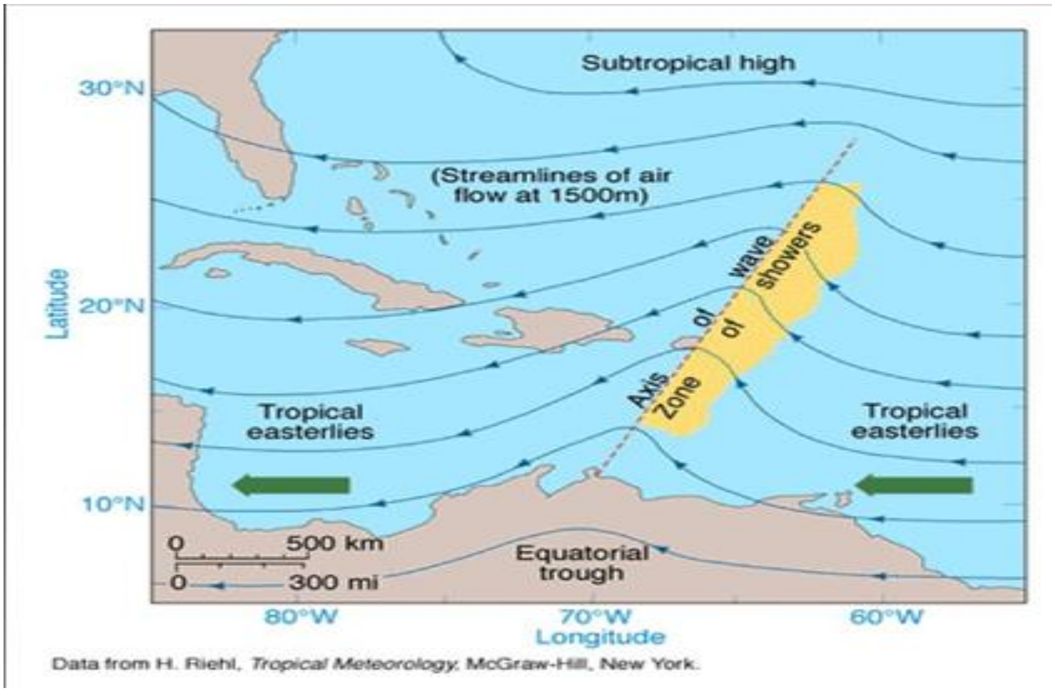


Fig. 4.22. Pictorial Representation of an Easterly Wave observed over the north Atlantic. After Riehl (Tropical Meteorology).

There are a few studies on examining the role of Easterly Waves for enhancing rainfall over south Peninsula during the NE Monsoon season. Reba et al. (2022) examined the years 2015, 2016 and 2017 to understand the variability of synoptic conditions including the propagation of easterly waves (EWs). Further, it is also seen that many active rainfall spells during 2015 and 2017 over Tamil Nadu met-subdivision were associated with passage of EWs over the southern peninsula along east of 85^0E, whereas, the large deficient NE monsoon of 2016 witnessed no such active spell of monsoon and the passage of EW was confined to the eastern part of Bay of Bengal and never entered into the Indian peninsula. Geetha and Balachandran (2014) studied the easterly wave characteristics during 2010 NE monsoon season by means of synergetic analysis using synoptic, statistical and numerical methods. The easterly waves during 2010 had time periods of about 4.5 days. The speed of movement, wavelength and amplitude of EWs were 7.28 ms^{-1}, 2800 m, and 6.7 ms^{-1} respectively. Sanap et al. (2018) examined the 2015 NE Monsoon season in respect of easterly wave activities. Their results indicated that EW activity over the Indian Ocean plays a seminal role in occurrence of heavy rainfall events during the positive phase of the ENSO (El-Niño), while it is found to be weak during negative (La-Niña) and neutral phase.

Here, we now discuss on a case study of formation of an easterly wave and its westward movement across south peninsula during 13-18 November, 2010. As shown in Fig. 4.23, there was widespread rainfall activity over south peninsula and adjoining Bay of Bengal associated with the Easterly wave. It is interesting to note that a wave type structure is observed in precipitation pattern during this period. Fig. 4.24 shows the vector winds at 700 hPa during the period 13-18 November, 2010 and vorticity at 700 hPa. Positive vorticity suggesting large scale ascending motion can be noticed on the eastern side of the trough line of the easterly wave. The easterly wave which formed over southeast Bay of Bengal moved westwards and crossed south peninsula by 17 November and emerged into the Arabian sea on 18th November. This weather system caused widespread rainfall activity over the region. The relevant satellite pictures of this easterly wave are shown in Fig. 4.25.

Fig. 4.26 shows the Longitude-Time cross section of a) Meridional wind at 700 hPa b) Outgoing Longwave radiation c) Precipitable water content and d) Precipitation rate at 10^0N during the period 13-18 November 2010, showing different aspects of an easterly wave, which travelled from east to west during 10-20 November, 2010 and contributed to large scale rainfall activity over south peninsula. These plots very clearly show the westward movement of easterly wave representing meridional winds at 700 hPa, OLR, precipitation rate and vertical velocity, omega. The zero-line separating southerlies and northerlies is shown in Fig. 4.26. It is interesting to note that lower values of OLR, large precipitation rate and large ascending motion (negative omega) are observed east of the zero line. This suggests that in and to the east of the trough line intense convergence, cloudiness and heavy rain showers prevail.

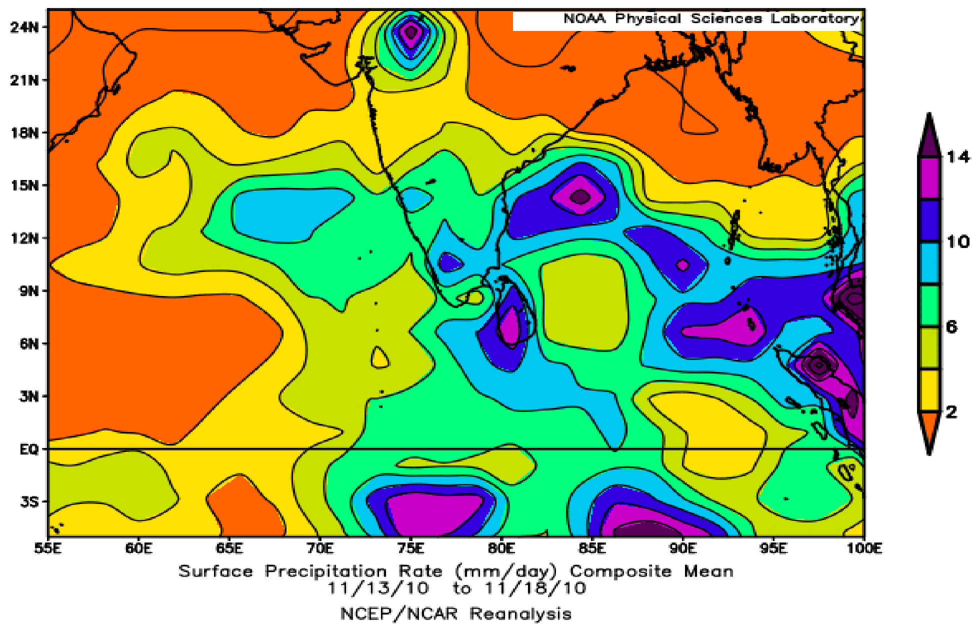
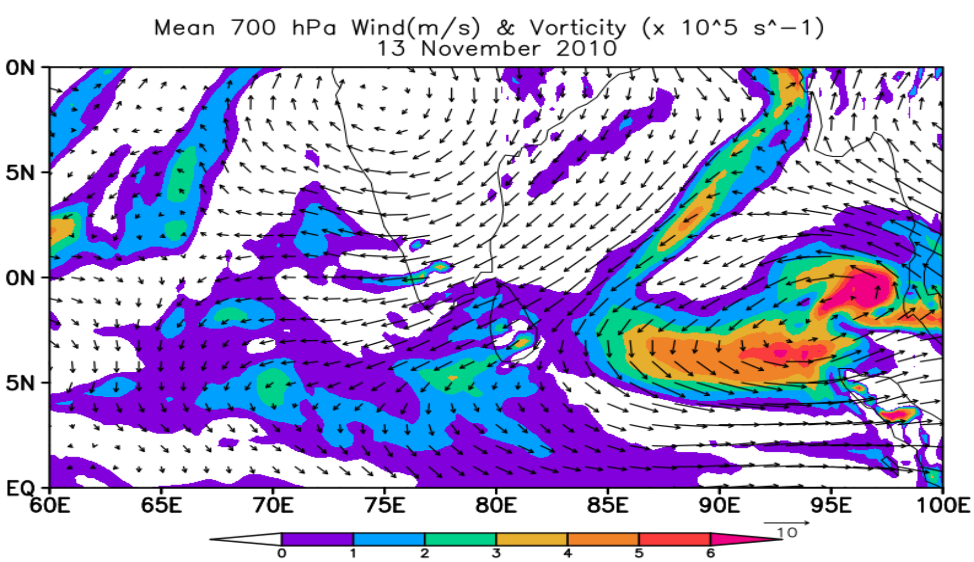
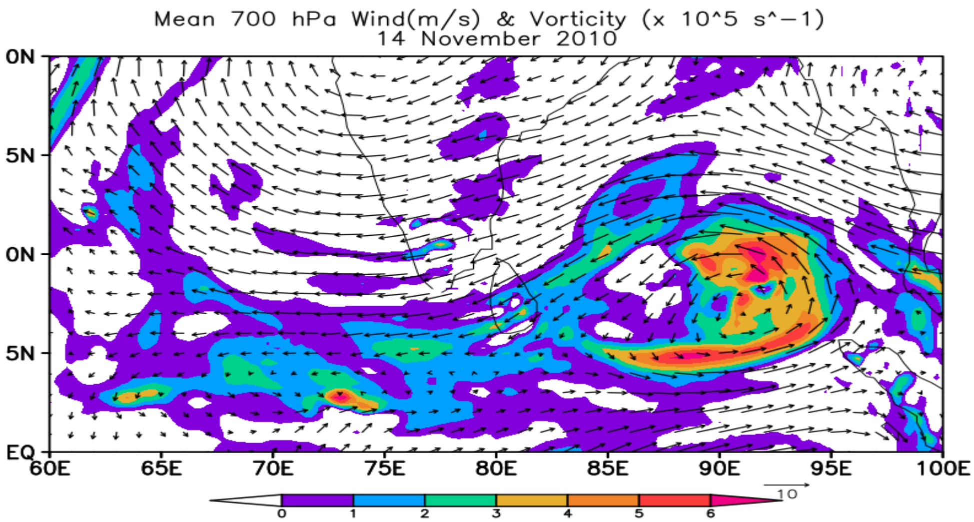
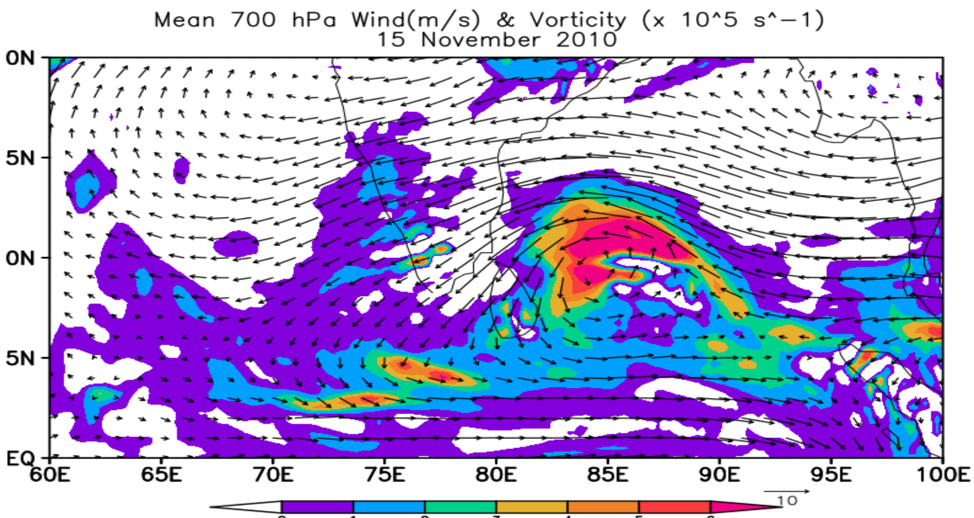
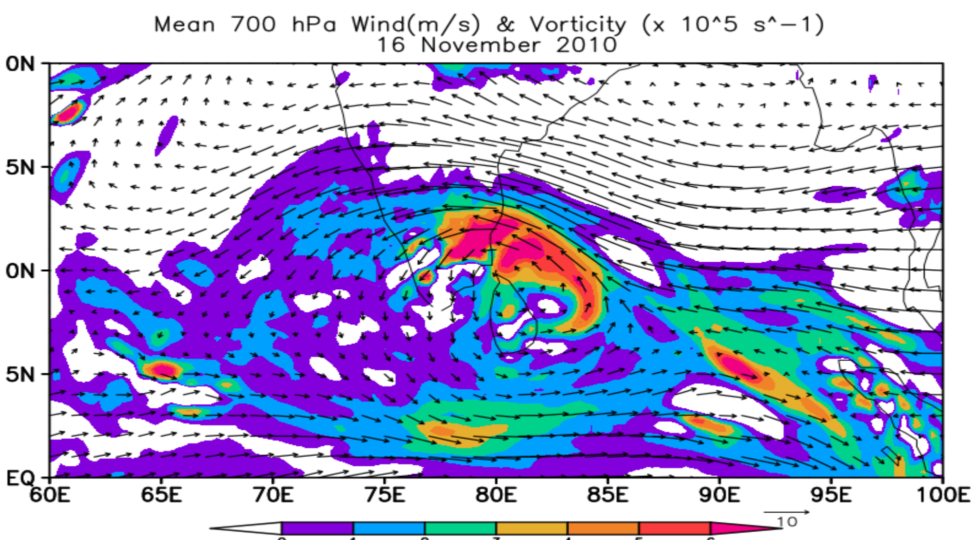


Fig. 4.23. Precipitation rate (mm/day) averaged during 13-18 November 2010 associated with the Easterly Wave. Source: NCEP/NCAR reanalysis.




Mean 700 hPa Wind(m/s) & Vorticity (x 10^5 s^-1)
14 November 2010
0N
5N
0N
5N
EQ
60E
65E
70E
75E
80E
85E
90E
95E
100E
10
0
1
2
3
4
5
6


Mean 700 hPa Wind(m/s) & Vorticity (x 10^5 s^-1)
15 November 2010
0N
5N
0N
5N
EQ
60E
65E
70E
75E
80E
85E
90E
95E
100E
10
0
1
2
3
4
5
6


Mean 700 hPa Wind(m/s) & Vorticity (x 10^5 s^-1)
16 November 2010
0N
5N
0N
5N
EQ
60E
65E
70E
75E
80E
85E
90E
95E
100E
10
0
1
2
3
4
5
6

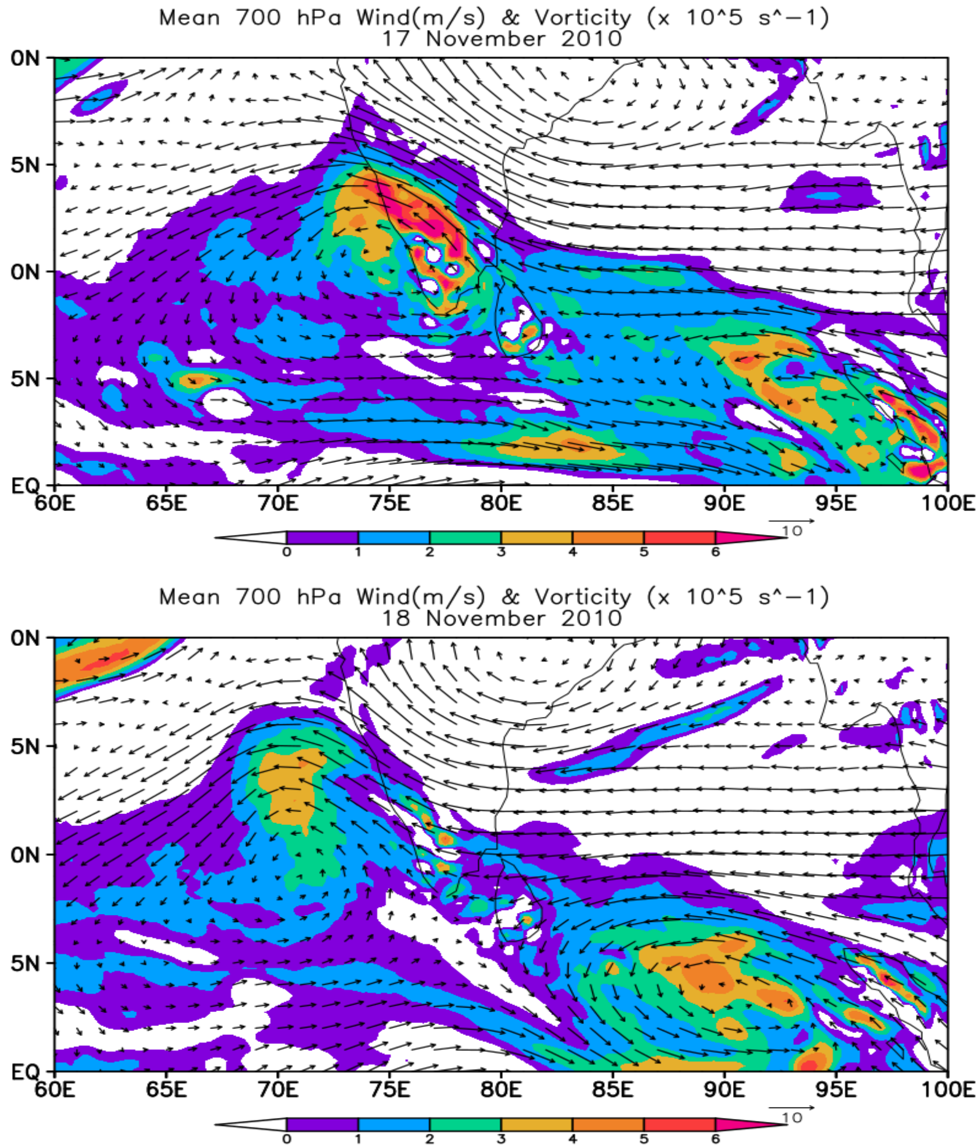
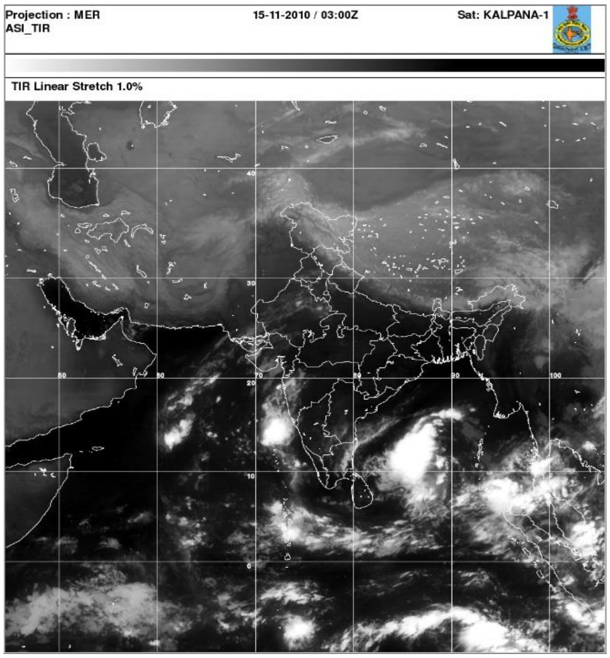
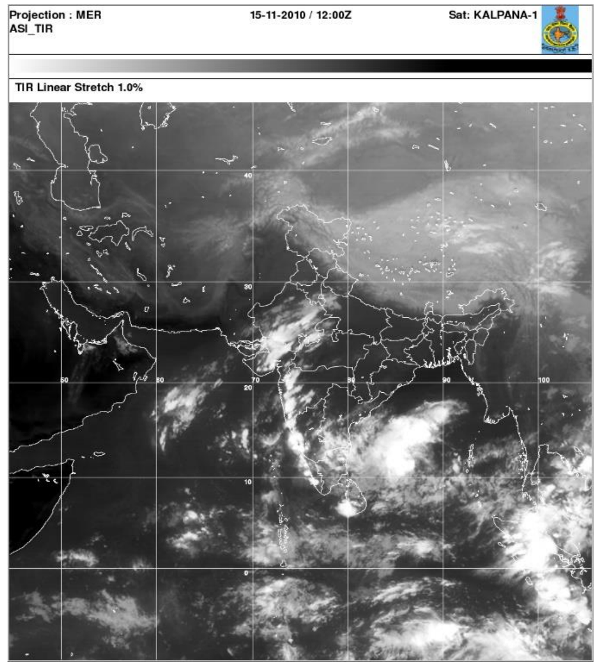


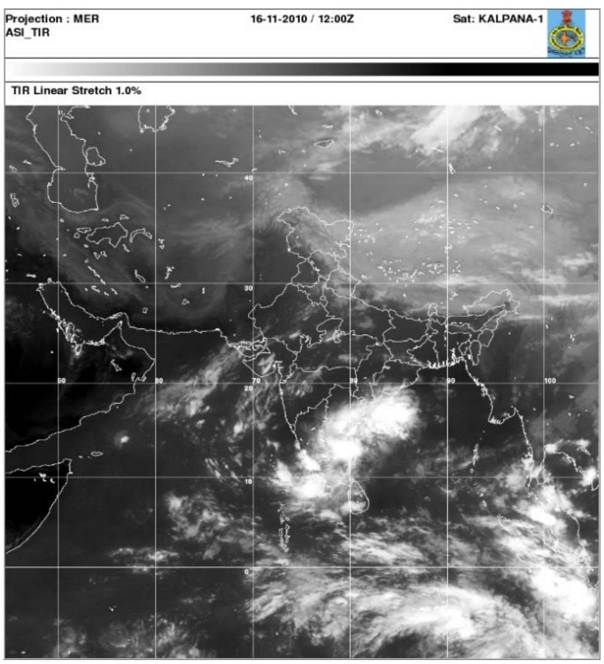
Fig. 4.24. Spatial distribution of 700 hPa winds and vorticity from 13 -18 November, 2010, showing westward movement of an easterly wave, which caused widespread rainfall activity over south Peninsula.



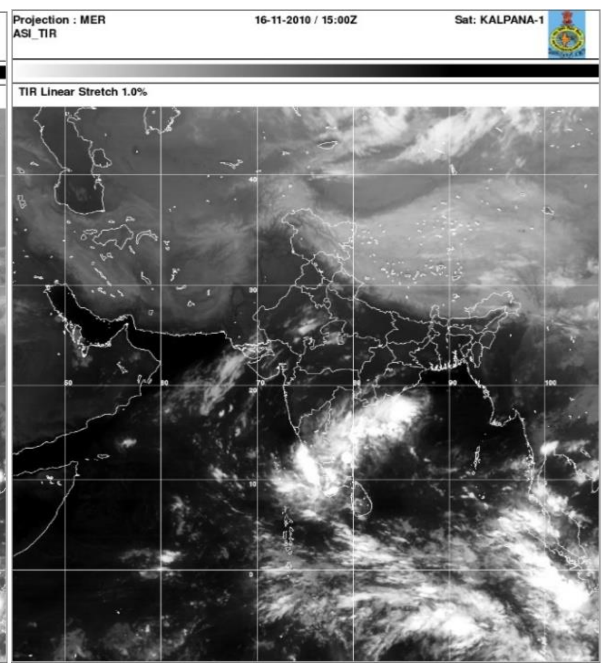
(a)



(b)



(c)



(d)

Fig. 4.25. Kalpana IR Satellite Pictures showing the presence of easterly wave over the Bay of Bengal. a) 0300 UTC 15 November b) 1200 UTC 15 November, C) 1200 UTC 16 November and d) 1500 UTC 16 November. Source: IMD Satellite Directorate.

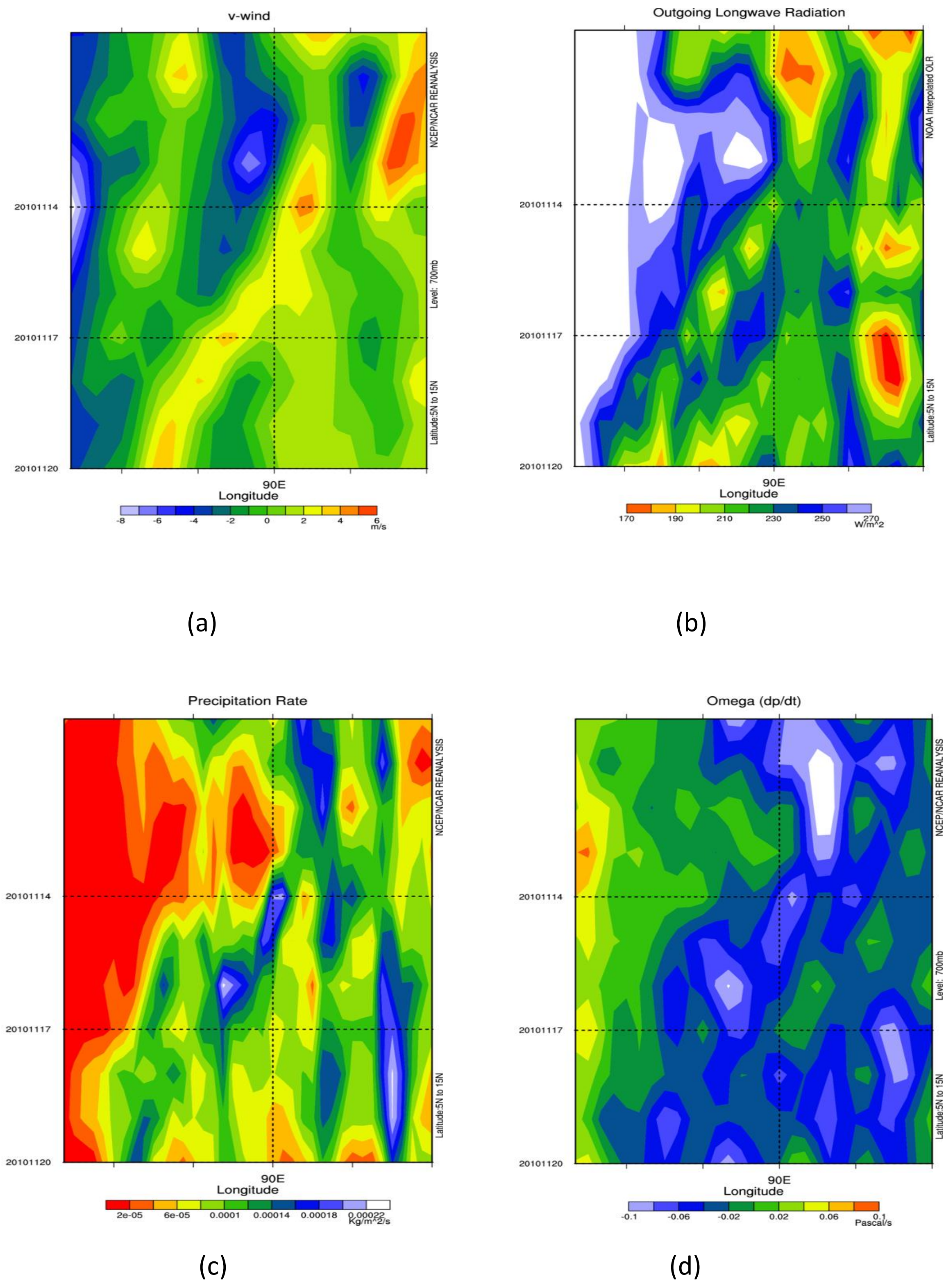


Fig. 4.26. Longitude-Time cross section of a) Meridional wind at 700 hPa b) Outgoing Longwave Radiation (OLR) c) precipitation rate and d) vertical velocity, Omega averaged between 5-15^{0}N during the period 10-20 November 2010