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An Easterly Wave Generated Heavy Rainfall Event over South India—A Case Study

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Abstract

Easterly waves are one of the rain-bearing systems of northeast monsoon and produce massive rainfall events over south India. In the present case study, an attempt is made to identify extreme heavy rainfall event over south India on 26th October, 2006 due to the passage of the easterly wave. Satellite images provide an inverted v-shape easterly wave. Next, circulation features at different levels clearly indicate the location, movement and speed of the easterly wave. Strong north-easterlies with a magnitude of 9.9 m/s are maintained at the surface. The convergence is mainly occupied between 12˚N - 16˚N, while the divergence is 5˚N - 12˚N on 26th October, 2006 at the surface level. On 25th, easterly wave is advected north of trough with a magnitude of 0.2 m/s and increased during the remaining days. There are two divergence cells along 5˚N and 16˚N before and after the event at 700 hPa level. Thus this study helps to bring out the essential characteristics of the easterly wave during northeast monsoon. The highlight of this study is that the easterly wave creates floods in the absence of tropical cyclones over south India.

Keywords

Easterly Wave, Northeast Monsoon, Heavy Rainfall Event, Potential Vorticity, Divergence

1. Introduction

Northeast monsoon (NEM) is known to be more variable both in space and time caused by retreating monsoon winds and attain moisture from the Bay of Bengal on their way back to south from northeast India. This moisture provides rains in coastal and southern Andhra Pradesh, Tamil Nadu and parts of Karnataka between October through December [1] [2] [3]. Northeast monsoon winds and the sea breeze interact to produce strong offshore low-level convergence that favors organized mesoscale convection. [4] suggested that when upper-air divergence ahead of an approaching easterly wave trough superimposed upon the convergent area of low level monsoon trough, the trough would develop into a depression. The most important drivers of monsoon seasons are low pressures particularly those which form in the Bay of Bengal and move towards various parts of India [5] [6]. There is an increasing trend in the amount of NEM rainfall in the recent years and this rainfall possesses a lot of variability on the interannual scale [7]. The transient synoptic scale systems affect south peninsular India during NEM season [8].

An easterly wave is a trough with westward moving maximum speed 7 - 8 m/s between 600 and 700 hPa; it has the wavelength of 2000 to 4000 km with a period of 3 - 5 days about 6˚ - 7˚ degrees longitude per day. The latitudinal extent is of 10˚ to 15˚ and the maximum amplitude in the lower to mid-troposphere. These waves occur mostly at 15˚N and it is a prominent feature of the atmospheric circulation over the Indian Ocean region. In the Indian Ocean region, inclined monsoon troughs may be found on both sides of the equator. An inclined quasi-stationary monsoon trough appears to offer the most favorable orientation for the development of depression. In the Arabian Sea, development is favored when the trough inclined in Northeast-Southwest (NE-SW) direction, while an inclination in an Northwest-Southeast (NW-SE) direction favors development in the Bay of Bengal. It is hypothesized that with enhanced condensation heating mainly on one side of the trough axis and without any change of structure.

Easterly waves have been explored by several studies [9]-[19]. Over Indian longitudes, easterly waves were investigated especially over peninsular India [20] [21] [22]. With the above-said information, the author made an attempt to understand the impact of easterly waves on NEM rainfall activity over south India. Few dates of easterly waves are collected and they are 7th July, 1999, 28th May, 2001, 26th October, 2006; 14th November, 2010 and 31st October, 2015. These waves moving westward in the tropical easterlies and majority of tropical cyclones is formed from easterly waves.

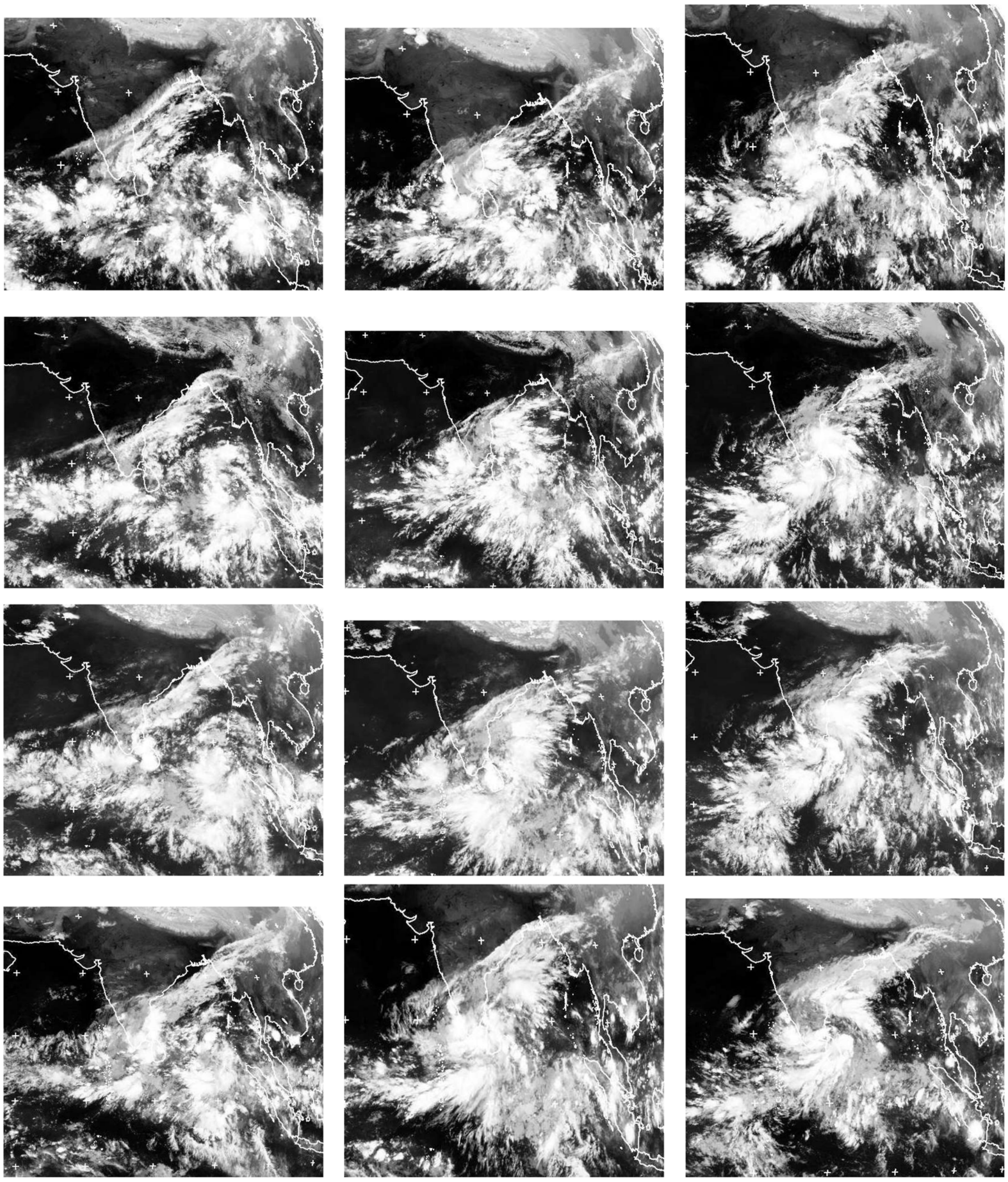
2. Data and Methodology

European meteorological satellite images are considered for the identification of convection and movement of an easterly wave. India Meteorological Department (IMD) high resolution daily gridded rainfall is obtained for the study period [23]. The NCEP/NCAR reanalysis zonal and meridional wind components are also retrieved from the website to observe the circulation features at 1000, 850, 500 and 200 hPa levels [24]. Later potential vorticity and stream functions, divergence are also calculated from the above datasets.

3. Results and Discussions

3.1. Circulation Features at Different Levels

High-resolution images provide convection movement before, during and after the easterly wave at every six-hour interval (**Figure 1**). Meteosat images are clearly depicting the organized pattern of convection with an inverted "V" shape around 26th October 2006. It is necessary to understand the evaluation of easterlies with circulation preceding, during and succeeding the wave at different levels. The streamlines analysis shows closed circulations at 850 and 700 hPa (**Figure 2**). It has a northeast-southwest oriented axis near the coast. **Figure 2** shows the cyclonic circulation is mainly observed at 85˚E with a magnitude of 2 m/s on 25th October 2006. The magnitude of northeasterlies is increased to 9.9 m/s at 850 hPa level. The elongated trough over central India shows that wind is shifting from northerlies to southerlies over the Arabian Sea at 700 hPa level. In contrast,



(a) (b) (c)

Figure 1. High-resolution satellite imageries in every six-hour interval of the easterly wave on 2006 (source: Meteosat website). (a) 25th October; (b) 26th October; (c) 27th October.

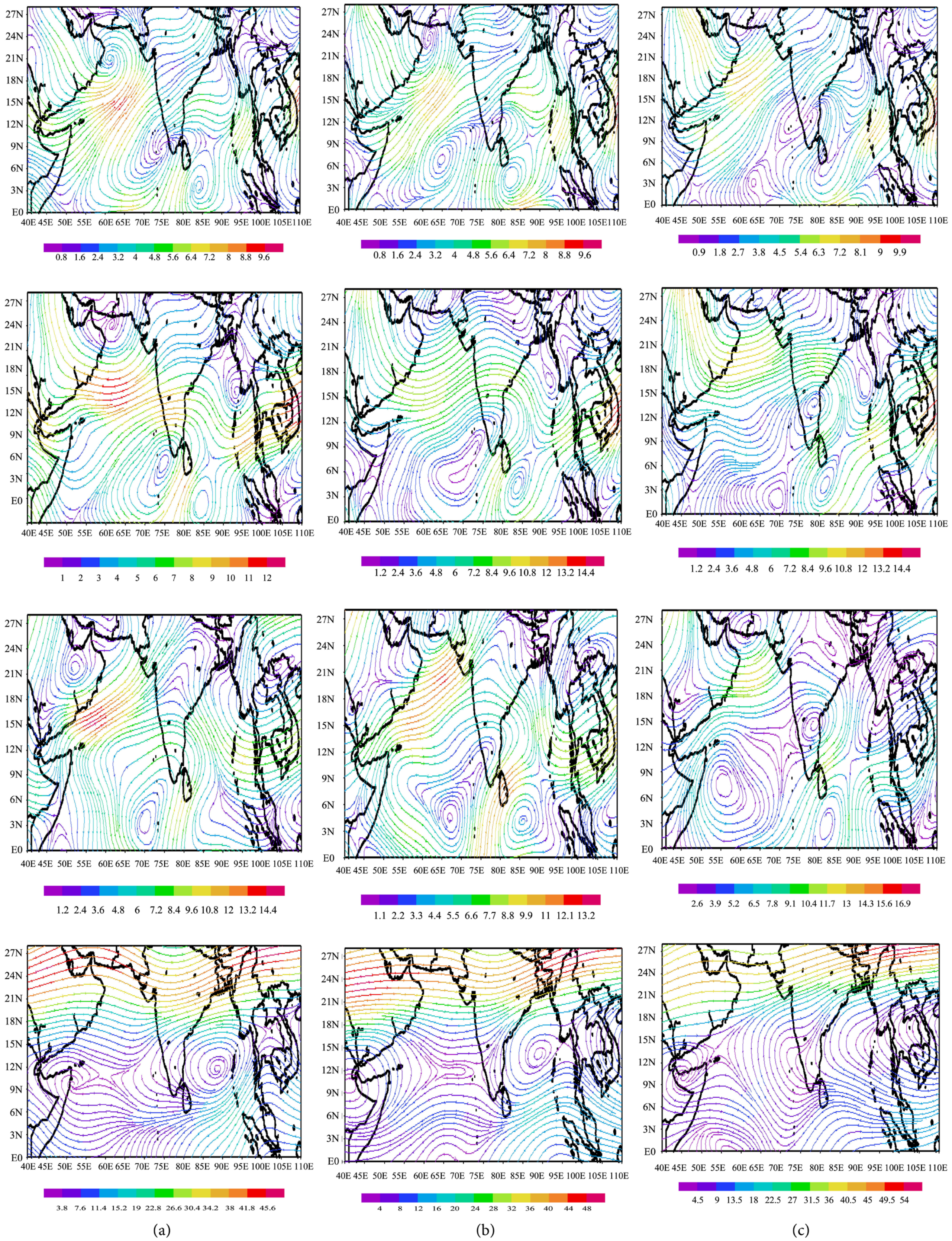


Figure 2. Circulation features along the easterly wave at different levels (a) before the easterly wave day, 25th October, 2006; (b) during the easterly wave, 26th October, 2006; and (c) after the event, 27th October, 2006.

strong anticyclonic circulation prevails over the Bay of Bengal with a maximum wind speed of 12 m/s at 15˚N. At the same time diffluence is noted near and ahead of the trough at 200 hPa. On the next day, the strength of the northeasterlies is further increased at the surface. A closed cyclonic circulation is further established at 850 hPa level.

3.2. Dynamic and Thermodynamic Features

Hovmoller diagrams of wind indicate the vertical structure and its magnitude with latitude and time and are shown in Figure 3. At the surface, easterlies (5.5

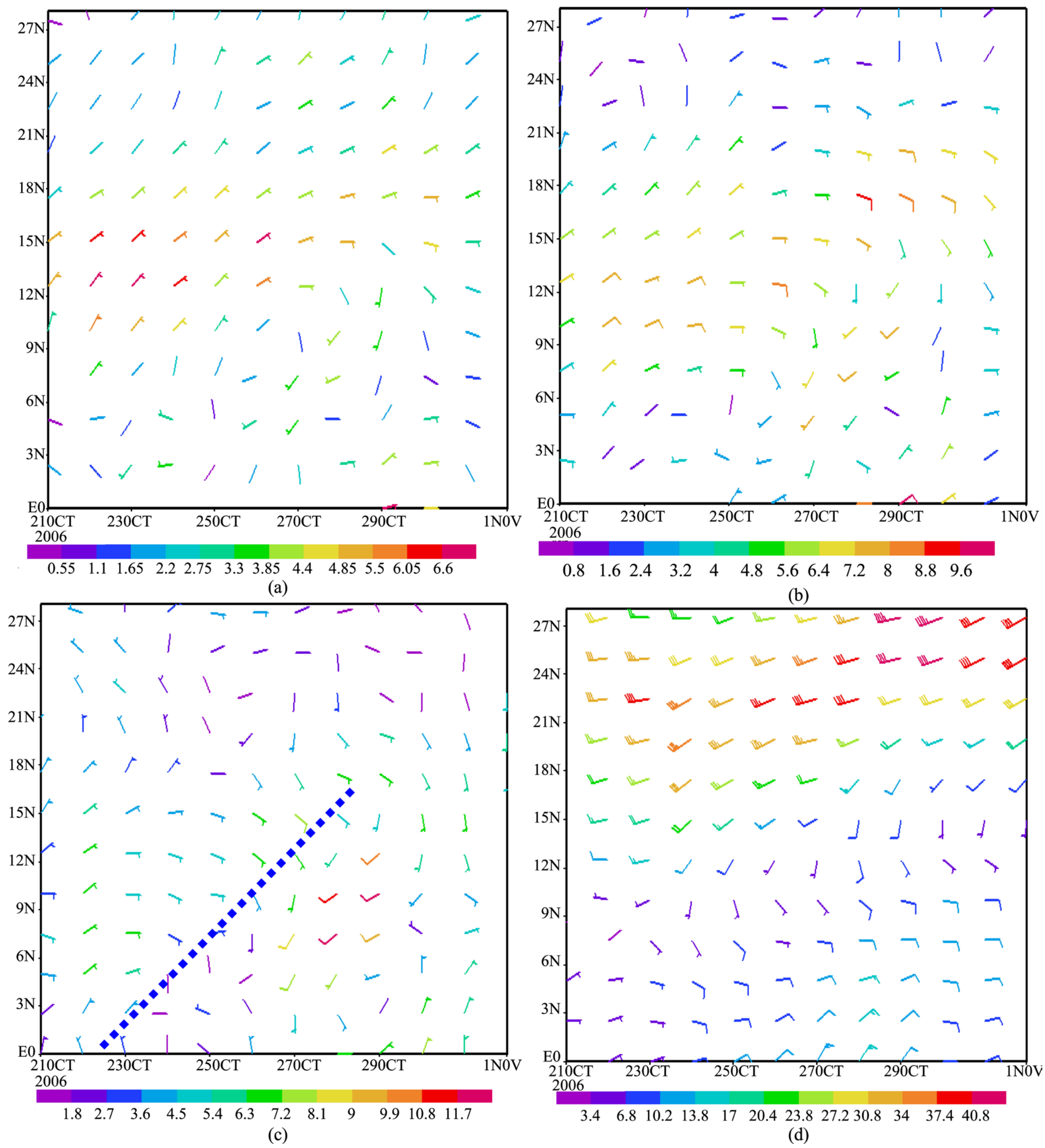


Figure 3. Latitude and time cross-sections of wind circulation at (a) Surface; (b) 850 hPa. (c) 700 hPa; (d) 200 hPa levels on 26th October, 2006.

m/s) with cyclonic circulation are established along 9˚-16˚N. At 850 hPa level, wind circulation is further intensified and at 700 hPa level, where the wind pattern is reversed during 26th October, 2006. Figure 3 represents the subtropical westerly jet stream at 200 hPa level with magnitude of 40.8 m/s at 25˚-28˚N. The vertical structure shows that northeasterlies are intensifying when an easterly wave carry moisture from the Bay of Bengal towards south India. Figure 4 provides the convective available potential energy during the easterly wave from 25th October to 1st November, 2006. The convective available energy is very less on 25th October, later the amount of energy is increased between 11˚N to 16˚N to a tune of 1500 J/Kg on next day. The amount of energy varies in between 1500 to 2500 J/kg on 27th October, 2006. Next, easterly wave influence is still continued up to 30th October, 2006 where the amount of energy varies greater than 2000 J/Kg.

Tracking the development and movement of easterly waves requires identification of a reference point, usually the trough axis, using a variety of methods. The prominent method is low-level convergence ("C" Figure 5) occurs ahead of the trough and divergence (D) behind. This pattern is reversed at 700 and 200 hPa, where areas of divergence and convergence are observed above the regions of low-level convergence and divergence. Corresponding maxima in cloudiness and rainfall are observed ahead of the trough coincident with the low-level convergence.

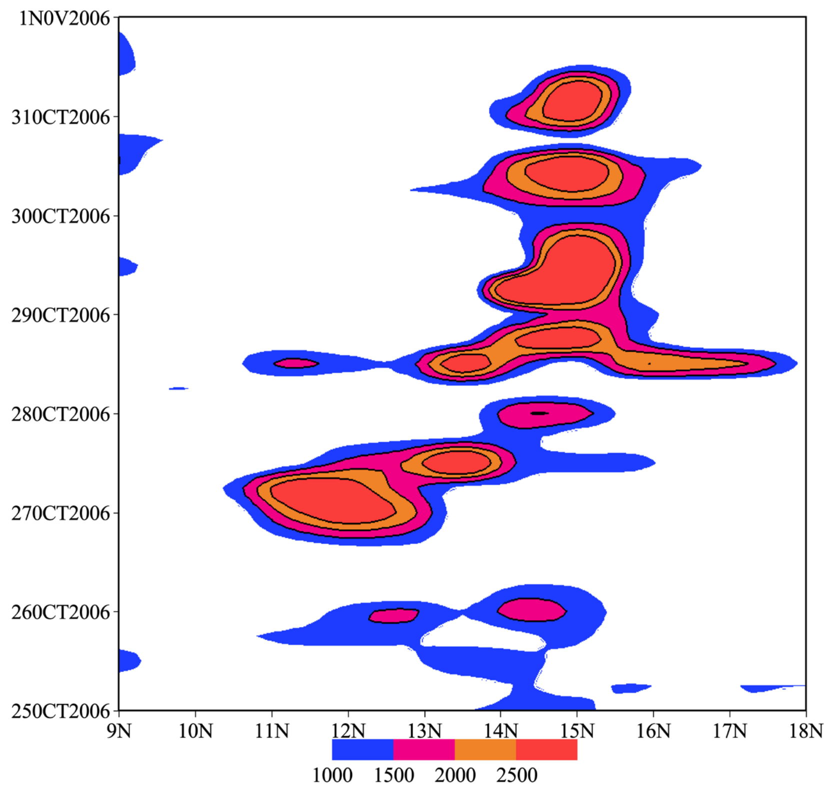


Figure 4. Daily variation of Convective Available Potential energy (J/Kg) for easterly wave, 2006 (ERA-Interim).

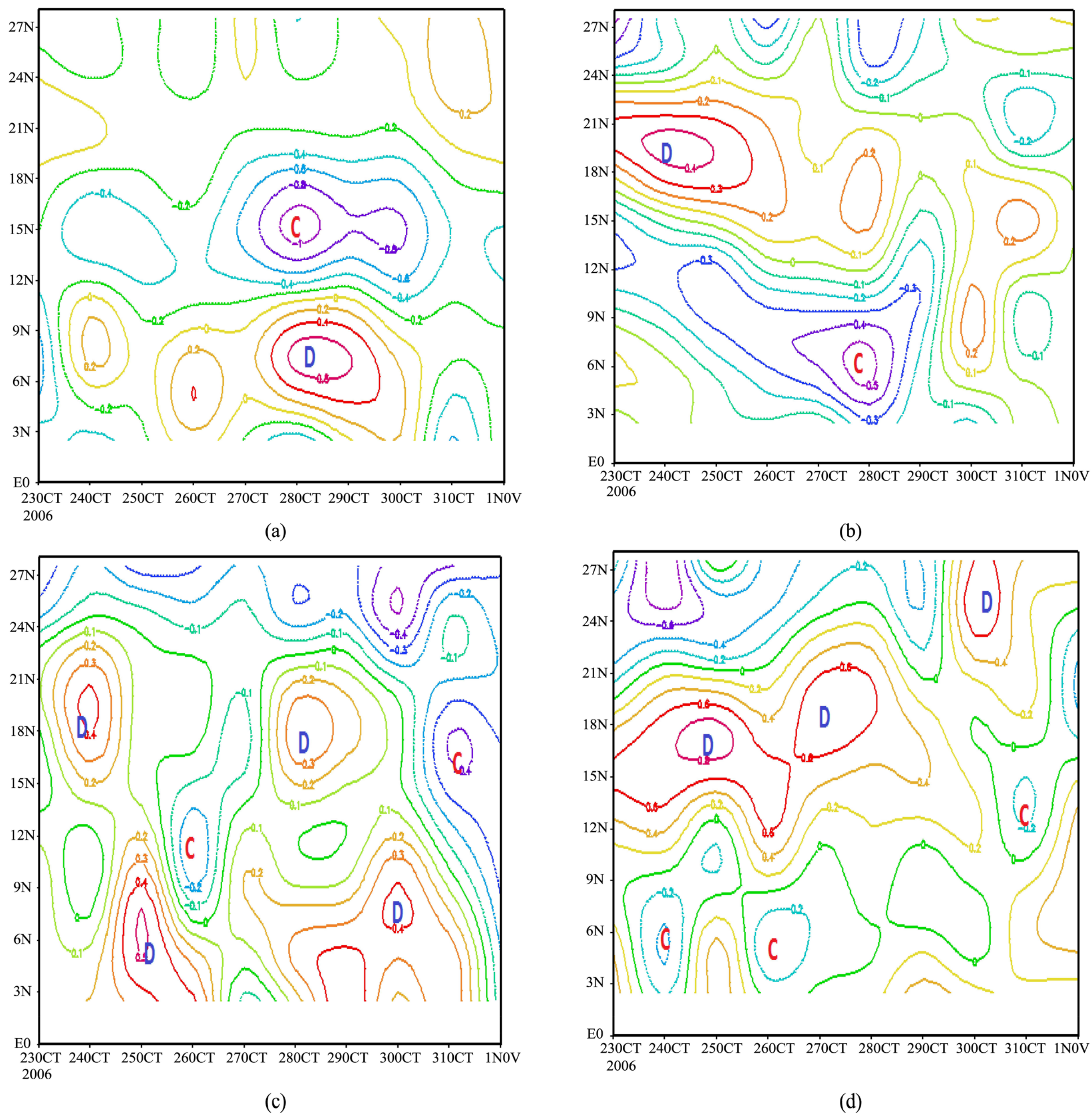


Figure 5. Latitude-time cross section anomalies at different levels on 26th October, 2006. (a) 1000 hPa; (b) 850 hPa; (c) 700 hPa; (d) 200 hPa.

The convergence is mainly occupied between 12˚ - 16˚N, while the divergence is 5˚ - 12˚N on 26th October, 2006 at the surface (**Figure 5(a)**). But at 850 hPa level the reverse pattern is observed when compared to the surface. The divergence area is shifted further northward and the convergence is intensified with a magnitude of -0.5×10^{-5}/s (**Figure 5(b)**). There are two divergence cells along 5˚N and 16˚N before and after the event at 700 hPa level (**Figure 5(c)**). At upper level (200 hPa), convergence is mainly occupied at latitude belt 5˚ - 15˚N (**Figure 5(d)**). Thus the divergence area also reveals the propagation and intensity of the easterly wave. Next, the dynamic characteristics of the easterly wave at upper level using potential vorticity and stream function are also studied and the results revealed a very good information.

Isentropic PV is conserved for adiabatic and frictionless flow is a useful tracer of synoptic-scale disturbances. Especially maximum PV on the 315˚K potential temperature is one of the best tools to identify the waves. The PV of the low-level vortex has been identified as part of the synoptic scale structure and it had a polar vortex that moved by the trough. These waves cause severe weather via heavy rainfall and deadly floods over south India. The climatology of sign reversals of mid-level meridional PV gradients over south India showed heating from deep convection associated with the active monsoon. Coincident with the negative mid-troposphere PV gradient is a strong gradient of potential temperature in the lower-troposphere. Figure 6 provides PV variation during the easterly

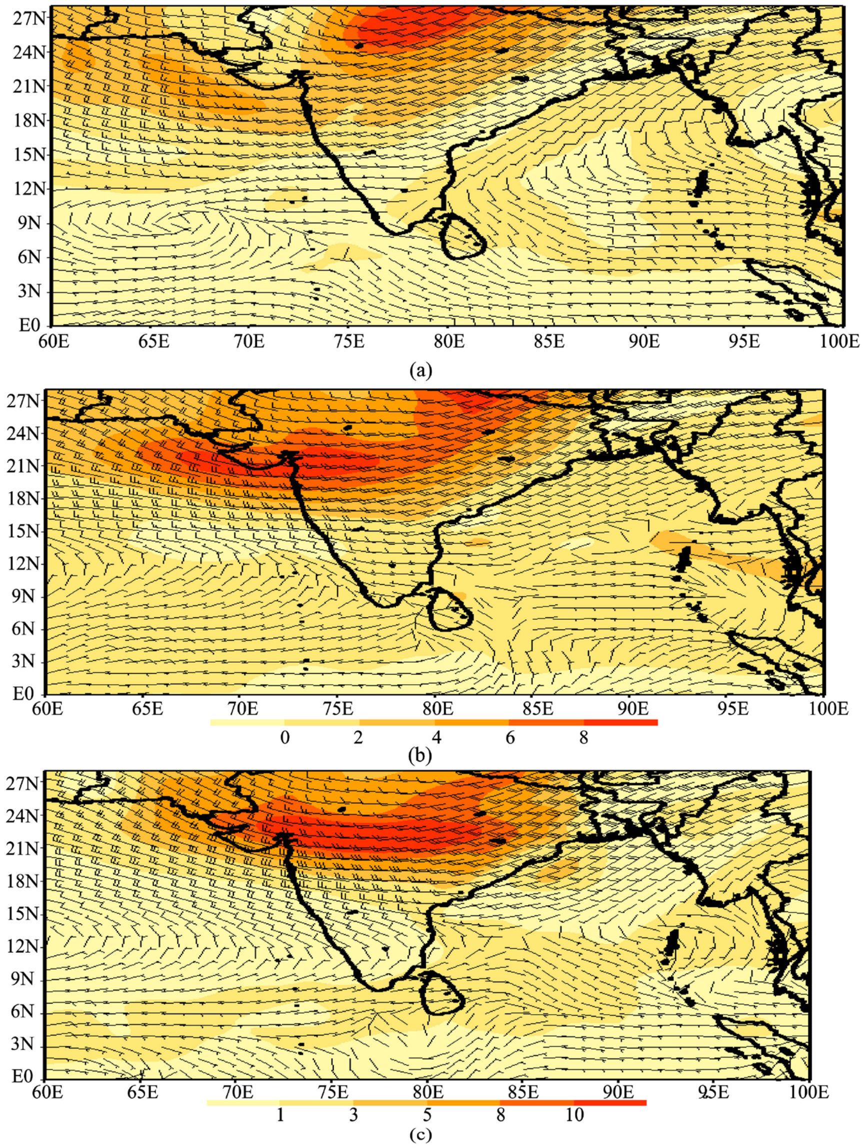


Figure 6. Potential temperature at 300 hPa level (shaded) and associated wind variation on (a) 25th October, 2006; (b) 26th October, 2006; (c) 27th October, 2006;

wave from 25th to 27th October, 2006. Potential vorticity maxima shifted towards south where the value is 2 units (10^{-6} m^{-2} s^{-1} K kg^{-1}) on 26th October, 2006. In general, the greater the number of PV units is, the deeper dry, stratospheric air is expected to penetrate into the atmosphere.

The stream function at the 700 hPa is another method for finding the easterly wave generated troughs and ridges. The stream function is analogous to geo-potential height, which is used to find troughs and ridges in the mid-latitudes. The troughs, the stream function minima, have an inverted "V" shape. In the objective method, developed by Berry *et al.* (2007), defines easterly wave troughs and ridges where the advection of the stream function-vorticity by wind is equal to zero. The trough has positive vorticity advection ahead and negative vorticity advection behind. The trough position is distinguished from the ridge by finding the zero contour of the advection in regions where stream function curvature vorticity exceeds 0.25×10^{-5} s^{-1} and flow is easterly. On 25th October 2006, the easterly wave advected north of trough with a magnitude of 0.2 m/s and increased in their magnitude in remaining days (**Figure 7**).

3.3. Characteristics of Daily Rainfall

Easterly wave provides significant rainfall amount over southern peninsula during northeast monsoon season. The present case study shows that 110 mm rainfall is recorded along the Tamil Nadu and Coastal Andhra Pradesh by using IMD high resolution gridded rainfall data (**Figure 8**). The easterly wave persists on 26th October produced a good amount of rainfall over Tamil Nadu (90 mm). Positive temperature advection and moisture incursion from anticyclonic flow close to the east coast of the south peninsular India provided the highest amount of rainfall. Hence, observing the waves with the internal mechanism makes the study used for operational forecasting and provides a better understanding of easterly waves.

4. Summary and Conclusions

Present attempt is based on the structure and properties of easterly waves and their impact on NEM rainfall activity. Circulation features of the easterly wave are analyzed the day before, on the day and after the day at different levels. On 25th October 2006, the establishment of cyclonic circulation is mainly observed at 85˚E and its strength increased to 9.9 m/s at 850 hPa level. At 700 hPa level, an elongated trough appears over central India with an inverted "V" shape with diffluence near and ahead of the trough at 200 hPa. On the next day, the winds are further increasing its strength at the surface and a closed cyclonic circulation is further established at 850 hPa level.

Next, vertical structure indicates surface easterlies (5.5 m/s) with cyclonic circulation are established along 9˚-16˚N. At 850 hPa level, wind circulation is further intensified and at 700 hPa level, the wind pattern is reversed during 26th October, 2006. The subtropical westerly jet stream is located at 25˚ - 28˚N with magnitude of 40.8 m/s (200 hPa level). The convective Available energy is very less on 25th October, later the amount of energy increased in between 11˚ to 16˚N to a tune of 1500 J/Kg on 26th October, 2006. The amount of energy varies in between 1500 to 2500 J/kg on 27th October, 2006. Next, easterly wave influence is still continued up to 30th October, 2006 where the amount of energy varies more than 2000 J/Kg. From this case study, convergence is mainly occupied between 12˚ - 16˚N, while the divergence is 5˚ - 12˚N on 26th October, 2006 and reverse pattern is observed at 850 hPa level. The divergence area is shifted northward and the convergence is intensified with a magnitude of -0.5×10^{-5}/s. There are two divergence cells along 5˚N and 16˚N before and after the event at

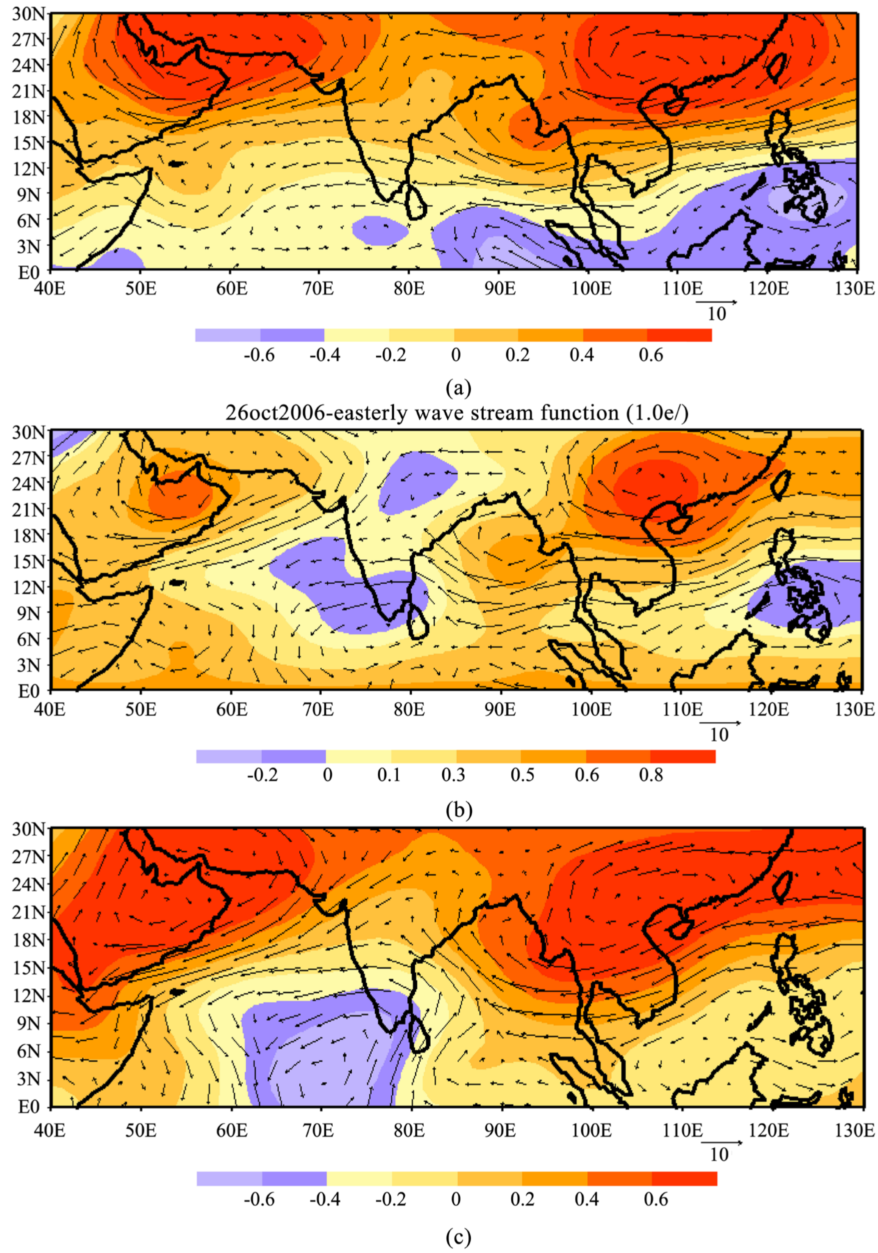


Figure 7. Variation of stream function during the study period. (a) 25th October, 2006; (b) 26th October, 2006; (c) 27th October, 2006;

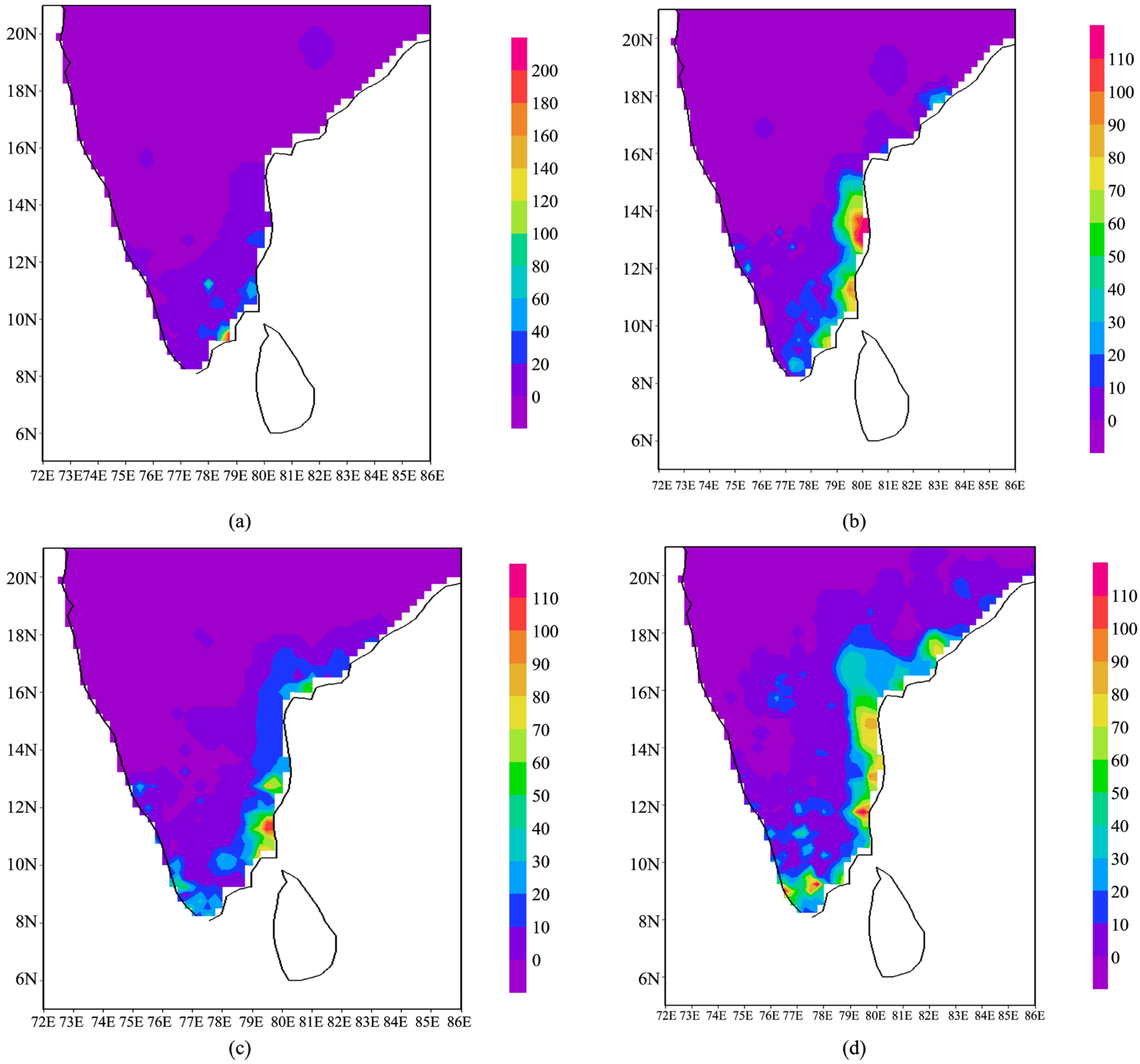


Figure 8. IMD daily gridded rainfall (mm/day) during the easterly wave on (a) 25th October, 2006; (b) 26th October, 2006; (c) 27th October, 2006; (d) 28th October, 2006.

700 hPa level. At the upper level (200 hPa), convergence is mainly occupied at latitude 5˚ - 15˚N. During this case study, Potential vorticity maxima shifted towards south on 26th October where the value is 2 units (10^{-6} m^{-2} s^{-1} K kg^{-1}). In theory, the greater the number of PV units is, the deeper dry, stratospheric air is expected to penetrate into the atmosphere. On 25th of the easterly wave advected north of trough with a magnitude of 0.2 m/s and increased in their magnitude in next days. The easterly wave persists on 26th October produced a good amount of rainfall (90 mm) over Tamil Nadu region. Observing the waves with the internal mechanism makes the study used for operational forecasting and provides a better understanding of easterly waves.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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