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The deluge of peninsular India during Northeast Monsoon 2015 : observational aspects of thermodynamical, dynamical and microphysical features

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सार – 1 नवंबर 2015 से 4 दिसंबर 2015 की अवधि के दौरान, दक्षिणी भारत विशेष रूप से चेन्नै शहर 8-11 नवंबर 2015 के दौरान गहन अवदाब और 13-18 नवंबर 2015, 19-24 नवंबर 2015 और 29 नवंबर 2015 - 4 दिसंबर 2015 के दौरान कम दाब वाले क्षेत्रों के कारण भारी वर्षा से प्रभावित रहा। इन प्रणालियों से जुड़ी भारी वर्षा के कारण आई बाढ़ के कारण जान-माल की भारी क्षति हुई। नवंबर 2015 में गहरे क्षेत्रीय प्रवाह में एक क्षोभ लहर पूर्व से पश्चिम में चली गई। स्व-स्थाने सतह प्रेक्षणा, उपग्रह प्रेक्षणा और पुनः विश्लेषित डेटासेट का प्रयोग करके इन प्रणालियों के प्रेक्षणात्मक, सिनॉप्टिक, गतिशील और सूक्ष्म भौतिकीय पहलुओं का विश्लेषण किया गया।

प्राप्त परिणाम 850 हेक्टा पास्कल पर प्रायद्वीपीय भारत के दक्षिण-पूर्वी तट पर पूर्वी हवाओं में एक प्रबल द्रोणी के मौजूदगी को दर्शाते हैं और देश के मध्य भागों में 500 हेक्टा पास्कल पर विषम प्रतिचक्रवाती परिसंचरण ऊपरी क्षोभमंडल तक फैले इन निम्नदाब प्रणाली के उत्तर की ओर गतिशील होने और एनएमआर पर प्रचुर वर्षा के लिए अनुकूल थे। स्वचालित मौसम स्टेशनों (AWS), हाई विंड स्पीड रिकॉर्डिंग (HWSR) सिस्टम, ट्रॉपिकल रेनफॉल मेजरमेंट मिशन (TRMM) और ग्लोबल रेन मेजरमेंट (GPM) उपग्रहों का उपयोग करके अतिवृष्टि के समय सतह प्रेक्षण संबंधी विशेषताओं का पता लगाया गया। TRMM और ERA-अंतरिम डेटासेट का उपयोग करके इन निम्नदाब प्रणालियों के सूक्ष्म-भौतिक पहलू का भी विश्लेषण किया गया है।

ABSTRACT. During the period 1st November 2015 to 4th December 2015, Southern India especially the city of Chennai was battered by heavy rainfall owing to the passage of a Deep Depression during 8-11 November 2015 and low-pressure areas during 13-18 November 2015, 19-24 November 2015 and 29 November 2015 - 4 December 2015. The deluge due to heavy rainfall associated with these systems resulted in enormous loss of life and property. A wave perturbation in deep zonal flow moved from east to west in November 2015. The observational, synoptic, dynamical and microphysical aspects of these systems have been analysed using *in-situ* surface observations, satellite observations and reanalysed datasets.

The results show the existence of a dominant trough in the easterlies off the southeast coast of peninsular India at 850 hPa and anomalous anticyclonic circulation over central parts of the country at 500 hPa extending up to the upper troposphere were conducive to the northward movement of these low-pressure systems and copious rainfall over NMR. The surface observational features of the deluge were explored using the Automatic Weather Stations (AWS), High Wind Speed Recording (HWSR) systems, Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) satellites. The microphysical aspects of these low-pressure systems are also analysed using TRMM and ERA-Interim datasets.

Key words – Northeast Monsoon, AWS, ARG, HWSR, GPM.

1. Introduction

Many populous Asian cities would be vulnerable to coastal flooding by the 2070. This could lead to flood

management problems within the cities (Hanson *et al.*, 2011). Presently, the city of Chennai in India ranks 14th among the top 20 cities of the world with the greatest rate of increase in a population exposed to extreme sea levels

and it is projected to see more than 300% increase in exposure by 2070. According to IPCC Fifth Assessment Report (IPCC, 2013), future increases in precipitation extremes related to the monsoon are very likely in East, South, and Southeast Asia. More than 85% of CMIP5 models show an increase in mean precipitation in the East Asian summer monsoons, while more than 95% of models project an increase in heavy precipitation events. All models and all scenarios project an increase in both the mean and extreme precipitation in the Indian summer monsoon.

The Indian summer monsoon regime dominates precipitation over South Asia from June to September. The northeast winter monsoon which sets in over peninsular India from October to December contributes substantially to annual rainfall over southeastern India and Sri Lanka. The state of Tamil Nadu, Kerala, Coastal Andhra Pradesh and the Rayalaseema region receives extensive rainfall during this period. The coastal Tamil Nadu receives 75-100 cm of rainfall during the season which is about 60% of its annual total. Ample studies on features of the northeast monsoon are available in the literature. The relationship of northeast monsoon with Southern Oscillation Index (Raj and Geetha, 2008), ENSO (De and Mukhopadhyay, 1999; Zubair and Ropelewski, 2006), easterly waves (Geetha and Balachandran, 2014), Spatial rainfall patterns and movement of low-level clouds (Amudha *et al.*, 2016 a,b) have also been studied in detail. Kriplani and Kumar (2004) have shown that the positive phase of Indian Ocean Dipole (IOD) augments northeast monsoon activity over south peninsular India owing to moisture convergence supported by wind flow pattern over southeast Indian Ocean and Bay of Bengal.

Raj (2003) has shown using harmonic analysis and cross lag correlation over 100-year rainfall data that daily rainfall of coastal Tamil Nadu from September to February exhibits a periodicity of 40 days and this periodicity has bearing on the onset and withdrawal of northeast monsoon.

Lately, it has been established that extreme rainfall events show an increase at the expense of weaker rainfall events (Goswami *et al.*, 2006) over the central Indian region and in many other areas (Krishnamurthy *et al.*, 2009). With a declining number of monsoon depressions (Krishnamurthy and Ajayamohan, 2010), the increasing trend in extreme rainfall events may be due to enhanced moisture content (Goswami *et al.*, 2006) or warmer SSTs in the tropical Indian Ocean (Rajeevan *et al.*, 2008) and interaction of mid-latitude westerlies and monsoon current (Ranalkar *et al.*, 2016). Such extreme and heavy rainfall events often lead to floods. The risk of flood and associated human and material losses are heavily



Fig. 1. An aerial photo of flood relief operation by Indian Coast Guard at flood-affected areas of Kanchipuram District on the outskirts of Chennai on 24th Nov, 2015. (Courtesy : Press Trust of India)

concentrated in India, Bangladesh, and China. Therefore, there is urgent need of dense observational network that can help to improve the weather forecasting due to the assimilation of more localized data in high resolution regional numerical weather prediction models. This will further improve understanding of the local environment and observation climatology around the area. This information will help to address the risk of data gap issues of Global Basic Observation Area Network (GBON) and dealing with the reliable high quality weather forecasts and climate analyses as per World Meteorological Organisation (WMO) guidelines.

During November 2015 and early December 2015, the city of Chennai was battered by incessant heavy rainfall owing to the passage of a Deep Depression during 8-11 November, 2015 and low-pressure areas during 13-18 November, 2015, 19-24 November, 2015 and 29 November, 2015 - 4 December, 2015. The deluge due to heavy rainfall associated with these systems resulted in enormous loss of life and property as shown in Fig. 1. November 2015 was the rainiest month for Northeast Monsoon Region (NMR) since 1901. Incidentally, it was also the warmest November for the Indian Region since 1901. For November 2015, rainfall (251.5 mm) over the south peninsula (northeast monsoon region) was 227 % of its Long Period Average (LPA) value, which is the fifth-highest since 1901 (IMD, 2015). From 1 November, 2015 to 4 December, 2015 many peninsular stations received heavy (≥ 6.5 cm), very heavy (≥ 12.5 cm) or extremely heavy (≥ 24.5 cm) rainfall in 24 hours and some stations received record-high 24-hour rainfall for the month.

Synoptic conditions associated with these incessant heavy rainfall events over peninsular India have been reported in IMD (2015) and Chakraborty (2016). The analyses of events based on Doppler radar data are presented by Ray *et al.* (2016). Energy drawn by the synoptic-scale system from organized convection within the disturbances, the role of Sea Surface Temperature of the Bay of Bengal and Gill's antisymmetric heat source of El Nino has been analysed by Krishnamurty *et al.* (2017) in the context of scale interaction during this extreme rain event over southeast India. They have brought out that ISO and quasi-biweekly components contribute to the augmentation of moisture supply from the Bay of Bengal. In this paper, we present the analyses based on modern ground and satellite-based observational systems in conjunction with a reanalyses dataset. The thermodynamical, dynamical and microphysical perspective of these events resulted in inundation owing to the interaction between wave-like tropical disturbances in moist zonal flow which moved from east to west and dry mid-tropospheric sub-tropical westerly trough with anomalous southward penetration. The interaction between two wind regimes culminated in increased lapse rate, sustained rising motion, high cloud top and deep localized convective systems.

2. Data and Methodology

Subtle intensification in the ENSO-Northeast monsoon rainfall has been reported by Zubair and Ropelewski (2006). In this context, the monthly mean ERA-interim Sea Surface Temperature (SST) data (Dee *et al.*, 2011) and merged precipitation product (Huffman *et al.*, 2014) from the Global Precipitation Measurement (GPM) mission constellation of satellites created using Integrated Multi-satellite Retrievals for GPM (IMERG) have been used to explore copious rainfall recorded at different stations owing to Depressions and Deep Depressions developed in the Bay of Bengal during November, 2015. However, the data set used in this study optimally reproduces the spatial patterns of precipitation and exhibit a slight different behaviour on mountainous and coastal regions both in the magnitude and the variability of precipitation estimates (Sun *et al.*, 2018). The Outgoing Longwave Radiation (OLR) is an indicator of cloudiness and serves as a proxy for convection in the tropical and subtropical region. These aspects were analysed in this study using the monthly averaged Outgoing Longwave Radiation (OLR) data set prepared by Mahakur *et al.* (2013).

Since the year 2006, India Meteorological Department (IMD) has established a network of 675 Automatic Weather Stations (AWS) across the country (Ranalkar *et al.*, 2014). The network has been further

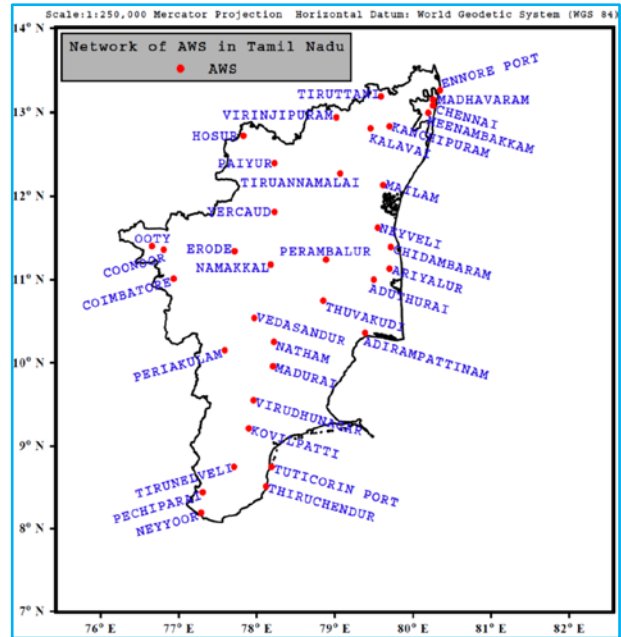
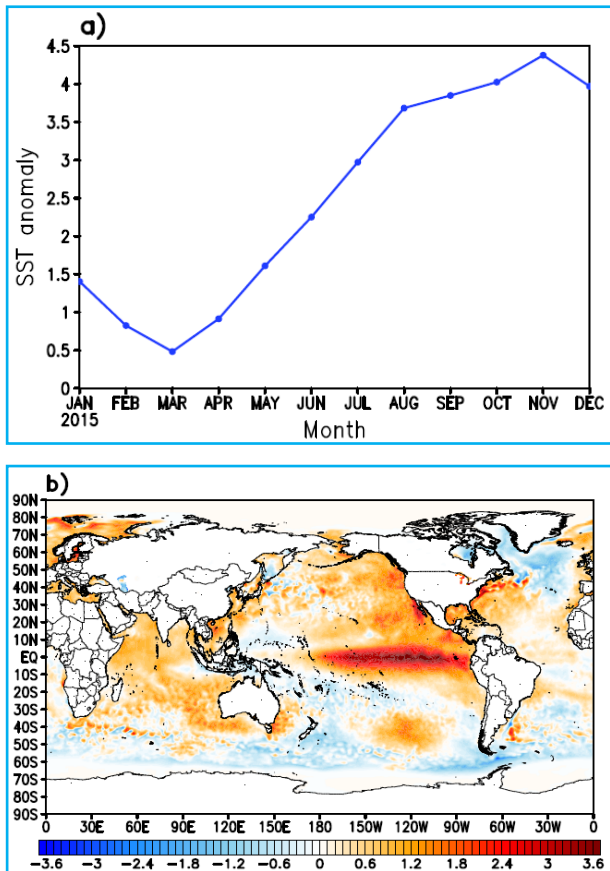


Fig. 2. Network of Automatic Weather Stations in the state of Tamil Nadu

expanded by 200 Agro-AWS installed in different agro-climatic zones of India and additional stations have been installed in the Pune and Mumbai for urban climate studies. Presently, a network of 918 AWS is available in India for various operational requirements. A fairly dense network of AWS as shown in Fig. 2 is now available in the state of Tamil Nadu, India for operational utilization. The near-real-time data of AWS can be accessed online at <http://aws.imd.gov.in:8091>. The hourly and daily rainfall data recorded by these networks during November 2015 and December 2015 have been retrieved from satellite data receiving Earth Station for analyses of depression and deep depression events.

Real-time monitoring of wind speed and direction is of paramount importance especially during the passage of tropical disturbance to determine the direction of movement, intensity and damage potential. A network of robust, reliable and cost-effective High Wind Speed Recording systems (HWSR) has been established by IMD along the east and west coast of India (Vashishta *et al.*, 2010) for monitoring tropical disturbances developed over the North Indian Ocean (NIO) basin. Presently, the network comprises 34 stations configured to measure data at a high temporal resolution of 1 minute/ 30 minutes. The wind data recorded at Chennai (1-minute resolution) and Karaikal (30-minute resolution) HWSR systems (<http://air.imdpune.gov.in>) have been used to understand the evolution of wind regimes during depressions and deep depressions in November 2015.



Figs. 3(a&b). (a) Monthly SST anomaly averaged over Nino 3.4 region for the year 2015 and (b) SST anomaly for Nov, 2015

The westward propagating tropical waves near 10°N to 13°N over the Bay of Bengal are the primary source of moisture for rainfall over the eastern coast of India during the post-monsoon season. ERA-interim data set (Dee *et al.*, 2011) has been used to describe the prevalent synoptic conditions conducive to copious rainfall in peninsular India during November and December 2015. The vertically Integrated Moisture Flux Convergence (VIMFC) analysis is also presented using ERA-interim data set following van Zomeren and van Delden (2007) to unravel dynamical features associated with Depressions, Deep Depressions and associated easterly wave troughs. The vertically integrated moisture transport is defined as:

$$\text{VIMFC} = -\frac{1}{g} \int_{700\text{hPa}}^{1000\text{hPa}} \left(\frac{\partial uq}{\partial x} + \frac{\partial vq}{\partial y} \right) dp$$

Where g is the acceleration due to gravity, q is specific humidity, p is atmospheric pressure, u and v are zonal and meridional components of wind.

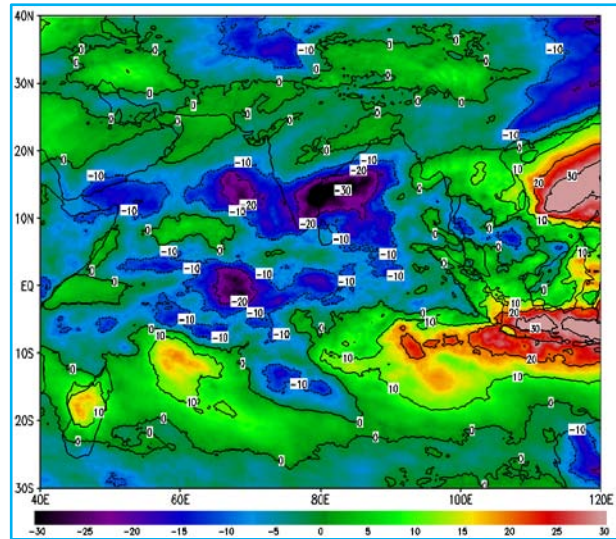


Fig. 4. OLR anomaly of Nov, 2015 indicating significant clouding over peninsular India near Chennai

The thermodynamical and microphysical features of rainfall activity is analysed using high-resolution Level 1 and Level 2 Tropical Rainfall Measuring Mission (TRMM) Version 7 datasets (ftp://disc2.nascom.nasa.gov/ftp/data/s4pa/TRMM_L2). The TRMM 2A23 dataset is used to study the height of the storm/cloud system.

To explore the thermodynamics of convective rainfall activity embedded within the monsoon flow radiosonde data of Chennai obtained from the Wyoming University website (<http://weather.uwyo.edu/upperair/sounding.html>) has been used.

3. Results and discussion

3.1. Synoptic features

The gradual increase in monthly SST anomaly during 2015 averaged over Nino 3.4 region as shown in Fig. 3(a) indicates the prevalence of El Nino conditions. It can be seen from Fig. 3(b) that a Positive SST anomaly exceeding 2 to 3 $^{\circ}\text{C}$ was observed over the North and South Pacific Ocean in November 2015. The SST over the Bay of Bengal was near normal and that over the eastern Arabian Sea was warmer by about 1 to 2 $^{\circ}\text{C}$. SST anomaly over all Nino regions was above normal by about 2 to 3 $^{\circ}\text{C}$. In contrast to the weakening relationship between ENSO and summer monsoon rainfall over India (Kumar *et al.*, 1999) modest strengthening of ENSO - Northeast Monsoon Rainfall relationship is reported by Zubair and Ropelewski, 2006. The rainfall activity over the core region of the southern peninsula was indeed substantially above normal (132% of Long Period Average) during Northeast Monsoon 2015 (IMD, 2015).

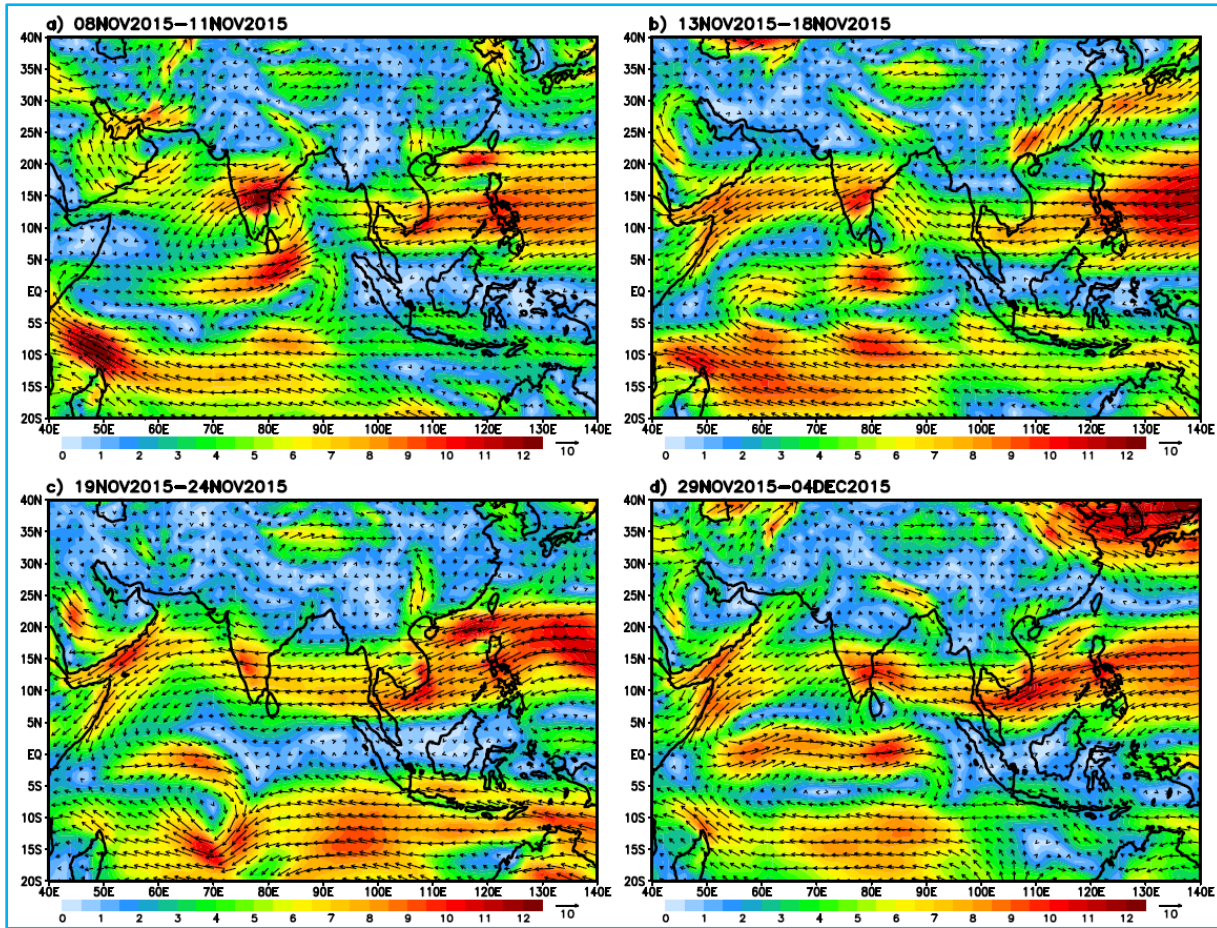


Fig. 5. ERA-Interim based wind direction (vector; unit : Degree) and wind speed (shaded; unit : m/s) at 850 hPa during the passage of synoptic systems averaged over (a) 08 Nov, 2015 - 11 Nov, 2015 (b) 13 Nov, 2015 - 18 Nov, 2015 (c) 19 Nov, 2015 - 24 Nov, 2015 (d) 29 Nov, 2015 - 04 Dec, 2015

The anomaly of Outgoing Longwave Radiation (OLR) for November, 2015 for the Indian region and neighbourhood is shown in Fig. 4. The positive OLR anomaly is seen over parts of central India, North Bay of Bengal and the adjoining east coast of India. The positive OLR anomaly exceeding 20 W m^{-2} is seen over the South China Sea, Jakarta and the adjoining Java Sea. The negative OLR anomaly exceeding 20 W m^{-2} is seen over the eastern peninsular coast of India and adjoining Bay of Bengal, parts of the Southwest Arabian sea and the Equatorial Indian Ocean indicating strong convection and cloudiness over the eastern peninsula of India.

The role of a large-amplitude extended westerly trough in trapping and transporting moisture from the ITCZ region of the Southern Hemisphere to the south-east coast of India has been brought out by Krishnamurty *et al.* (2002). They have further linked the formation of the westerly trough to persistent intense anticyclone over north Africa.

The wind speed and wind direction averaged over 8 - 11 Nov, 2015, 13 - 18 Nov, 2015, 19 - 24 Nov, 2015 and 29 Nov - 4 Dec, 2015 at 850 hPa level is shown in Fig. 5. It is seen from Fig. 5 that an anomalous cyclonic circulation prevailed over the south Arabian Sea and strong easterlies prevailed over peninsular India at 850 hPa with an anomalously strong trough in easterlies off the southeast coast of peninsular India. At 700 hPa level, anomalous anticyclonic circulation was observed over central India as shown in Fig. 6. The anticyclonic circulation became more prominent and widespread at the 500 hPa level as shown in Fig. 7 during the life cycle of all four low-pressure systems. From the wind circulation described above, it can be seen that the warm moist easterly winds at lower tropospheric levels over peninsular India (see Fig. 5) interacted with cold dry winds of mid-latitude westerly origin in the form of an outflow from an anticyclone over central India. Such interaction is highly conducive higher lapse rate and hence convective instability. The persistence of the trough in the easterly

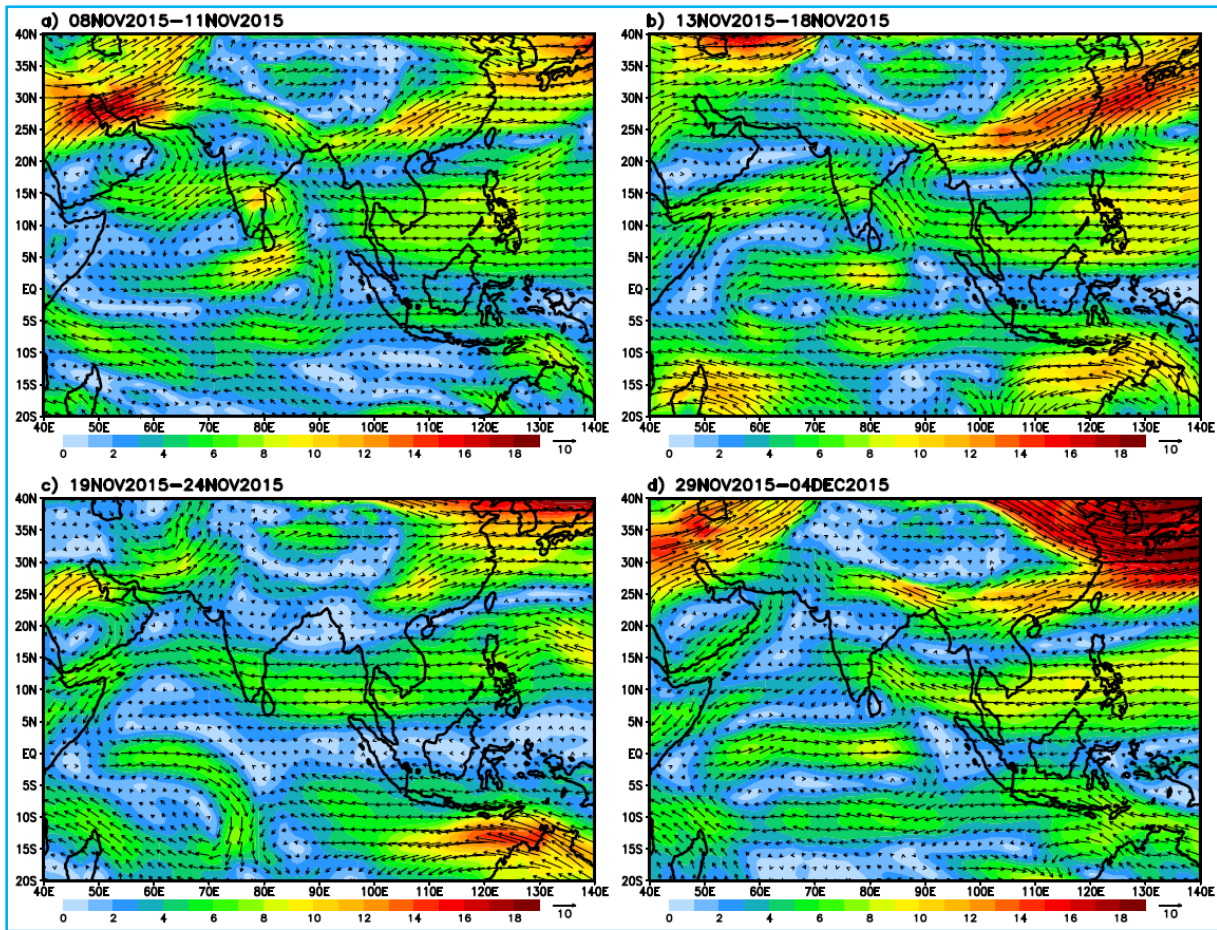


Fig. 6. ERA-Interim based wind direction (vector; unit : Degree) and wind speed (shaded; unit : m/s) at 700 hPa during the passage of synoptic systems averaged over (a) 08 Nov, 2015 - 11 Nov, 2015 (b) 13 Nov, 2015 - 18 Nov, 2015 (c) 19 Nov, 2015 - 24 Nov, 2015 (d) 29 Nov, 2015 - 04 Dec, 2015

wind regime in the lower troposphere along the southeastern peninsular coast of India during November 2015 (See Fig. 5) was also favourable for the convective activity ahead of the trough. These synoptic settings culminated in relentless rainfall activity over peninsular India in Nov. 2015.

3.2. Observational aspects

Of late, the modern automatic surface observational systems have become an extremely useful tool for monitoring severe weather phenomena. For the sake of brevity, we present the variation in hourly Station Level Pressure and Wind field recorded by AWS and HWSR systems during the deep depression (08-11 Nov, 2015).

As the system approached the east coast, the wind speed increased from 5 kt at 0000 UTC on 8th Nov, 2015 to 25 kt at 0600 UTC on 9th Nov, 2015 at Neyveli and Chidambaram AWS as shown in Fig. 8(a). The Chennai

and Madhavaram AWS also recorded an increase in wind speed as the system approached the station. The variation in maximum wind speed during the measurement interval recorded by HWSR systems installed at Chennai and Karaikal is shown in Fig. 9. These AWS also recorded the fall in Station Level Pressure of approximately 6 hPa during the passage of the system. From 0000 UTC of 8th Nov, 2015 to 0900 UTC of 9th Nov, 2015 as shown in Fig. 8(b). The wind direction gradually changed from northerly, northwesterly, westerly to southerly at Neyveli and Chidambaram AWS and from northeasterly, easterly, southeasterly, to southerly at Chennai and Madhavaram AWS as shown in Fig. 10. Under the influence of the synoptic conditions described in Section 3.1 above, many stations in the state of Tamil Nadu experience copious rainfall in Nov, 2015. The daily rainfall recorded at selected AWS in Tamil Nadu from 1st Nov, 2015 to 4th Dec, 2015 is shown in Fig. 11. Yercaud, Neyveli and Chidambaram experienced exceptionally heavy rainfall during 9-10 Dec, 2015. The cumulative and hourly rainfall

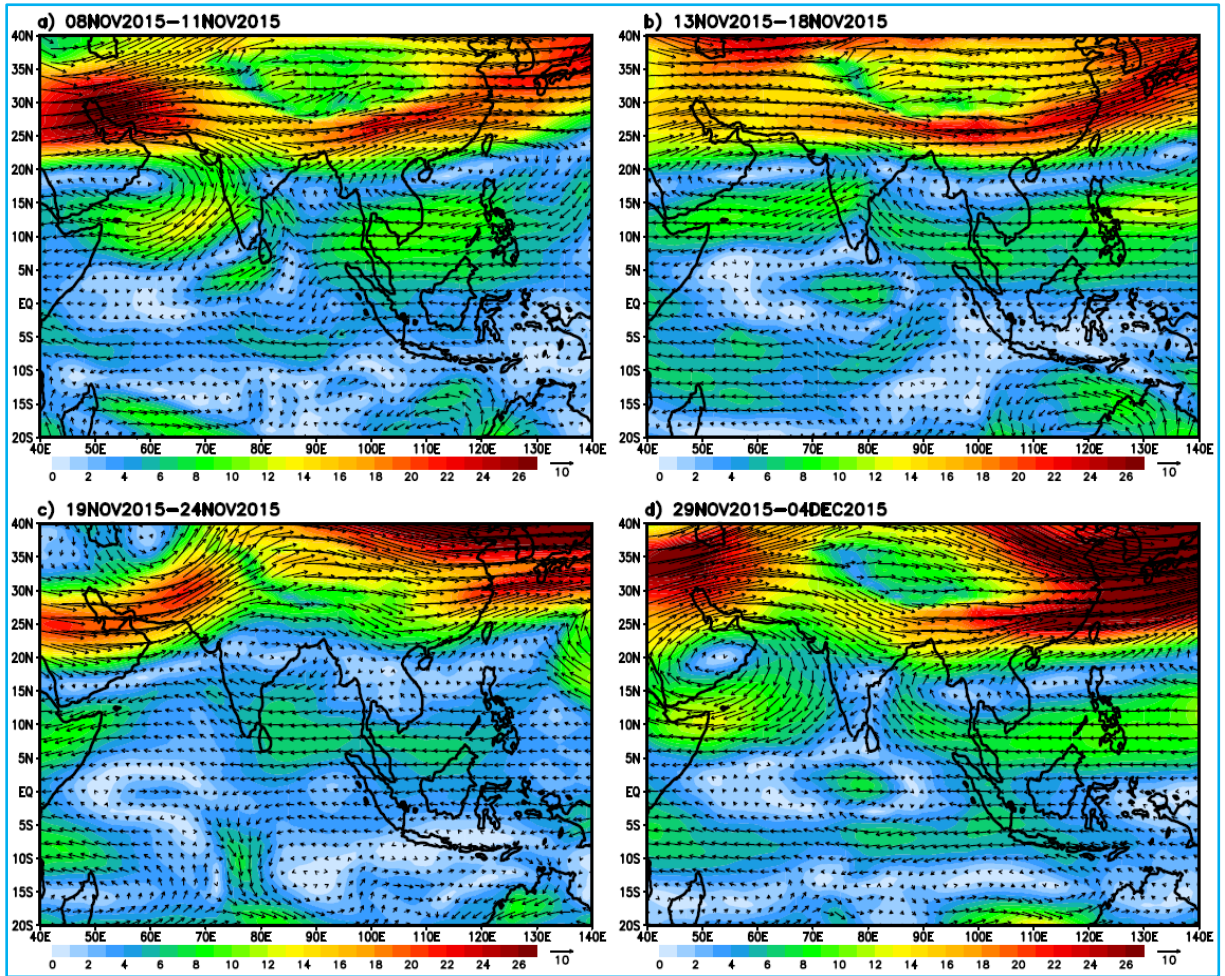
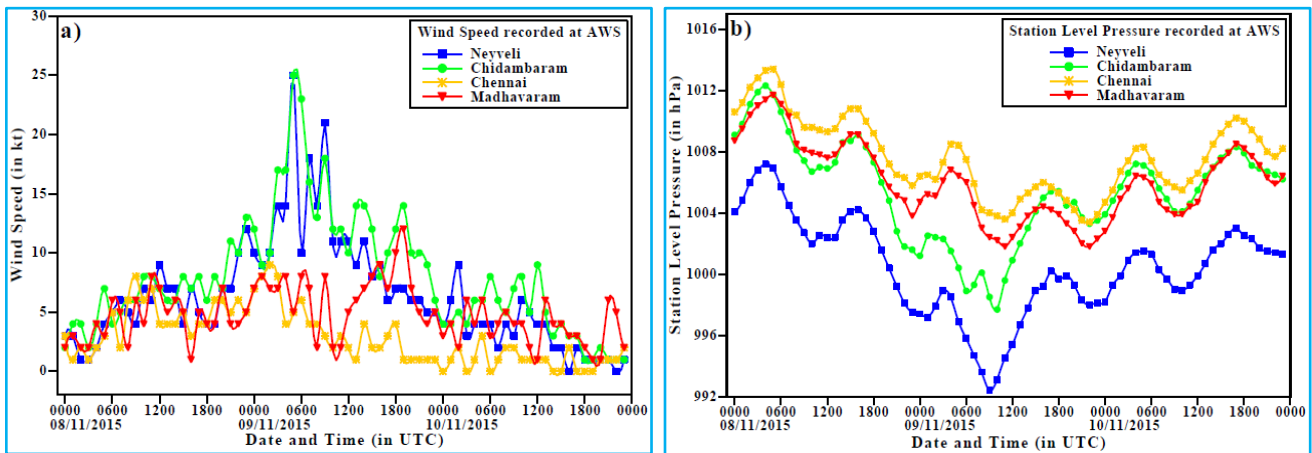


Fig. 7. ERA-Interim based wind direction (vector; unit : Degree) and wind speed (shaded; unit : m/s) at 500 hPa during the passage of synoptic systems averaged over (a) 08 Nov, 2015 - 11 Nov, 2015 (b) 13 Nov, 2015 - 18 Nov, 2015 (c) 19 Nov, 2015 - 24 Nov, 2015 (d) 29 Nov, 2015 - 04 Dec, 2015



Figs. 8(a&b). Wind Speed recorded at selected AWS in the state of Tamil Nadu during the passage of the synoptic system

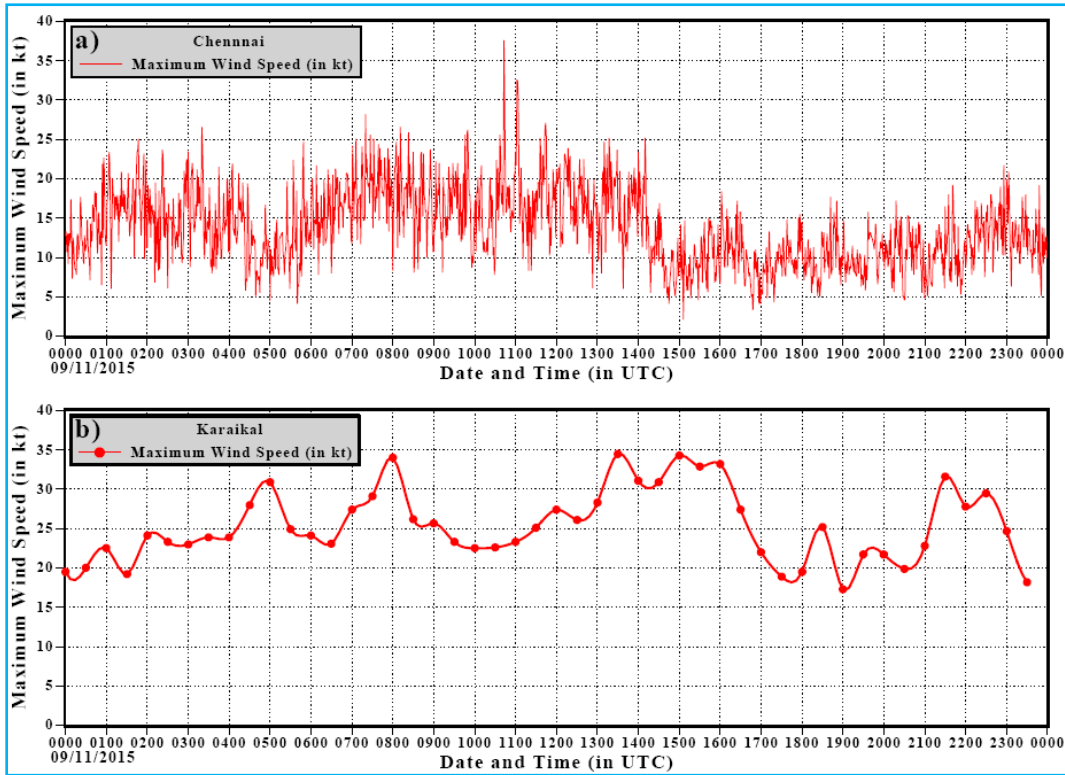


Fig. 9. Variation in maximum wind speed recorded at Chennai and Karikal High Wind Speed Recording system during Deep Depression

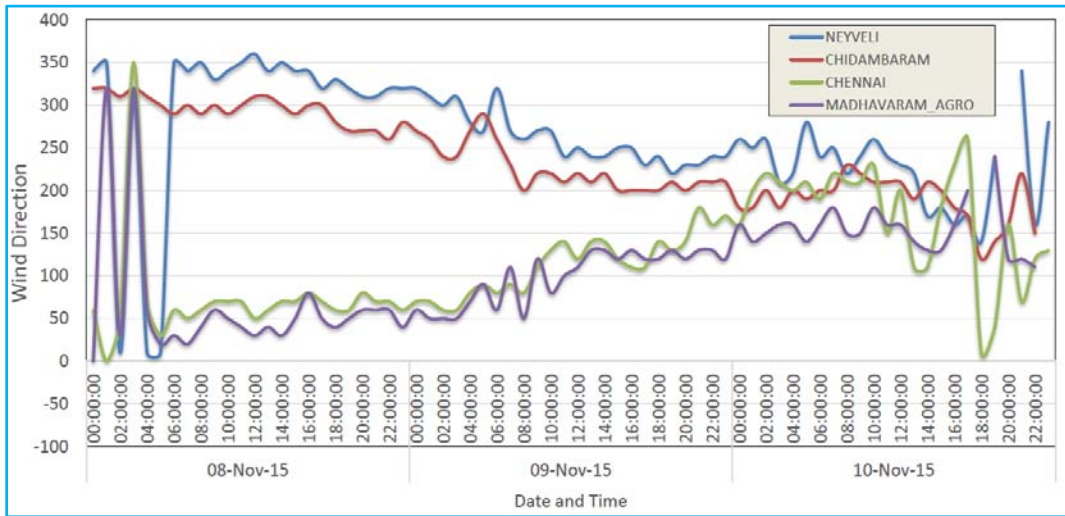


Fig. 10. Wind Direction recorded at selected AWS in the state of Tamil Nadu during the passage of the synoptic system

recorded at Yercaud and Neyveli AWS are depicted in Fig. 12. It can be seen that about 60% of the daily rainfall (637 mm) at Yercaud occurred during 1300 - 2000 UTC on 9th Nov, 2015 and about 88% of daily rainfall (483 mm) at Neyveli occurred during 0300 - 1000 UTC on 9th Nov, 2015. The half-hourly accumulated rainfall

estimate based on Integrated Multi-satellitE Retrievals for GPM (IMERG) algorithm for the deep depression (8-11 Nov, 2015) and low-pressure area during 13-18 Nov, 2015, 19-24 Nov, 2015 and 29 Nov, 2015-4 Dec, 2015 is presented in Fig. 13. It can be construed from Figs. 5-7 and Fig. 13 that the interaction of warm moist air

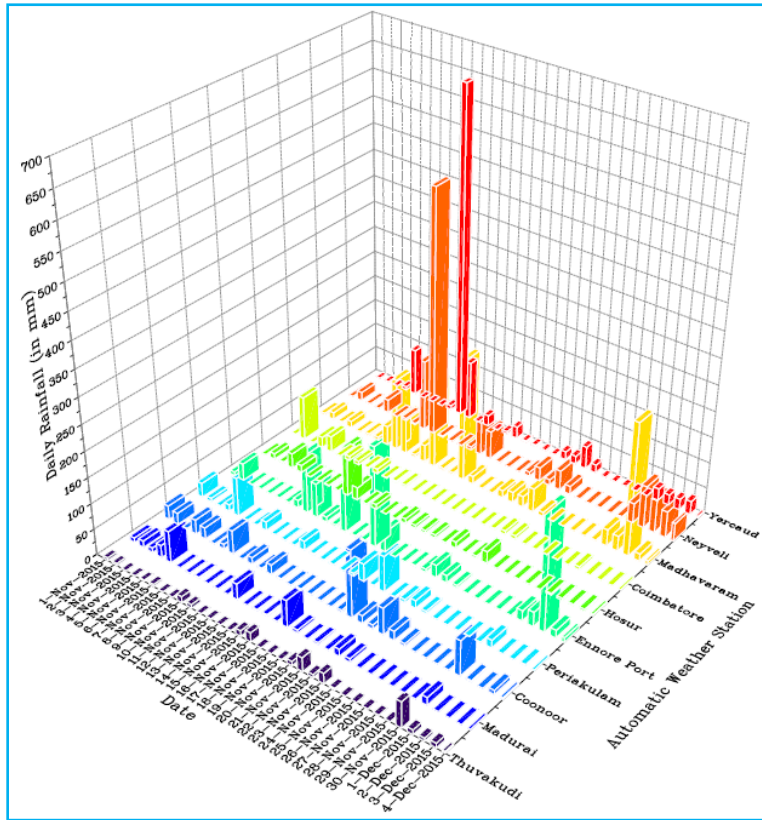


Fig. 11. Daily rainfall (mm) recorded at AWS during the passage of Depression and Deep Depression

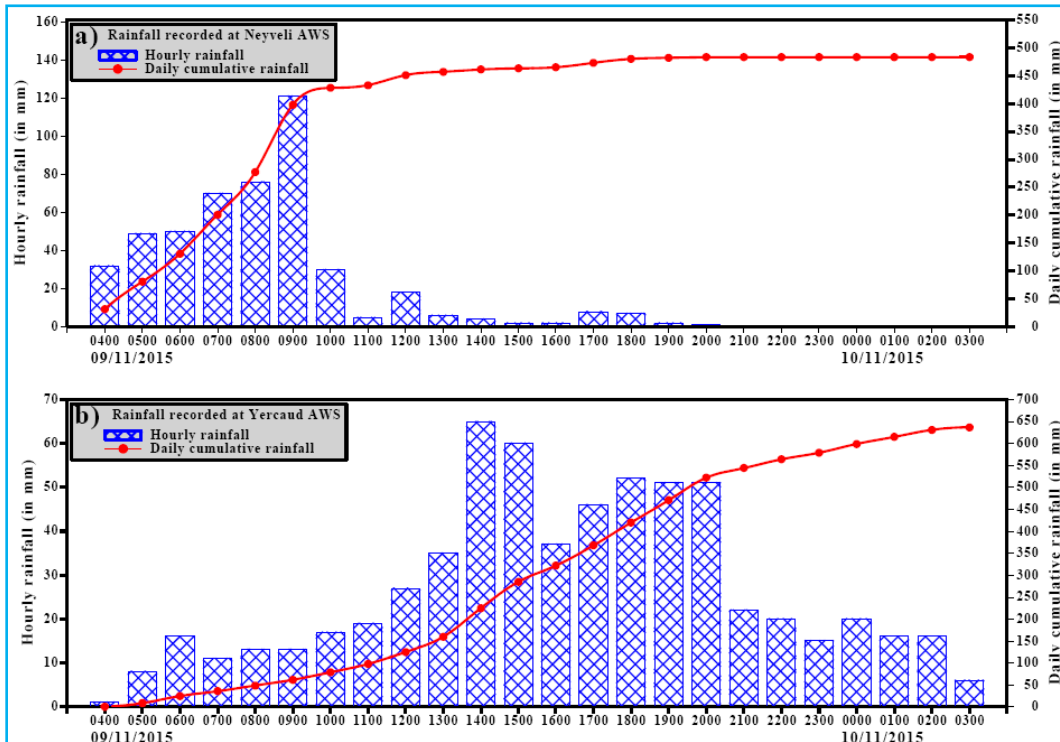


Fig. 12. Cumulative and Hourly rainfall recorded at representative Yercaud and Neyveli AWS

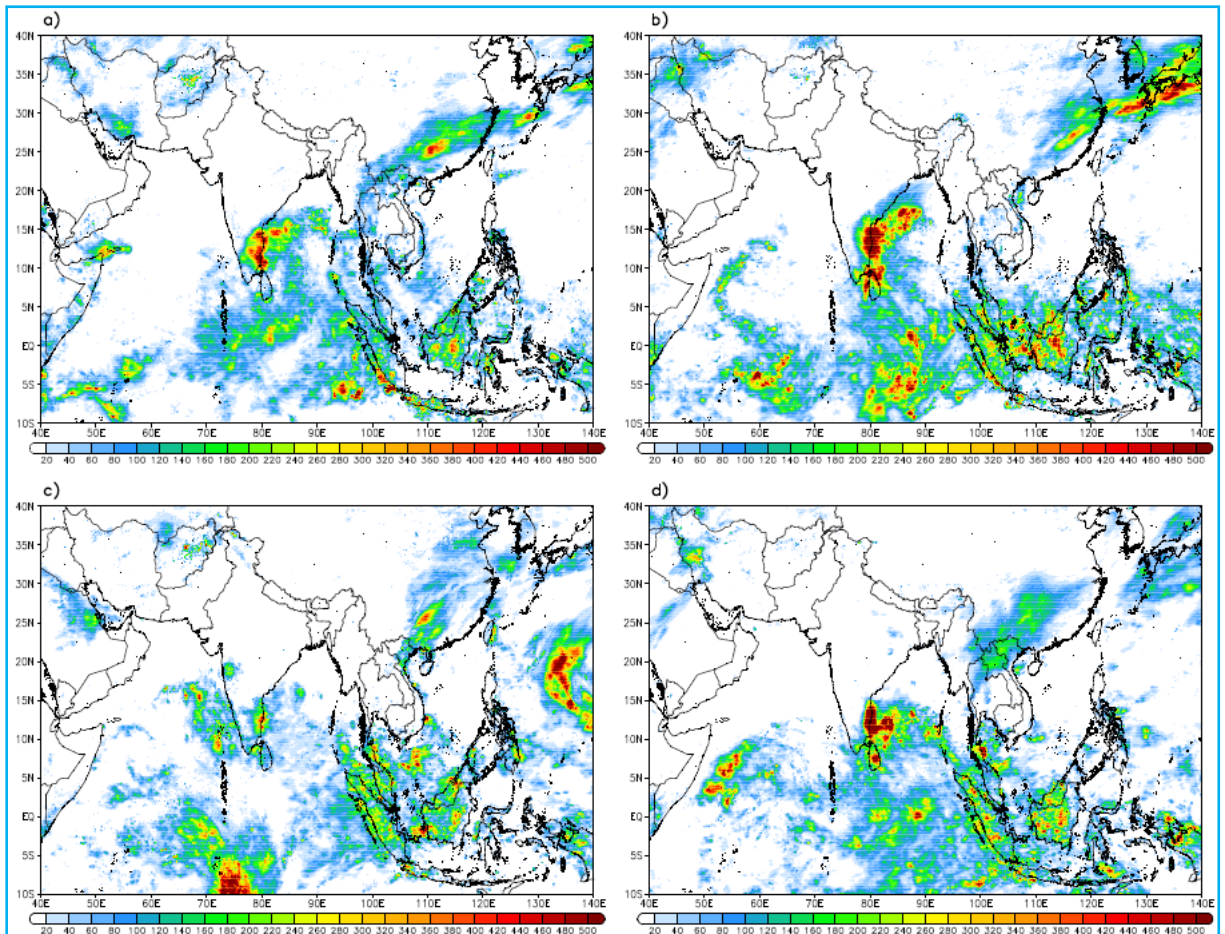
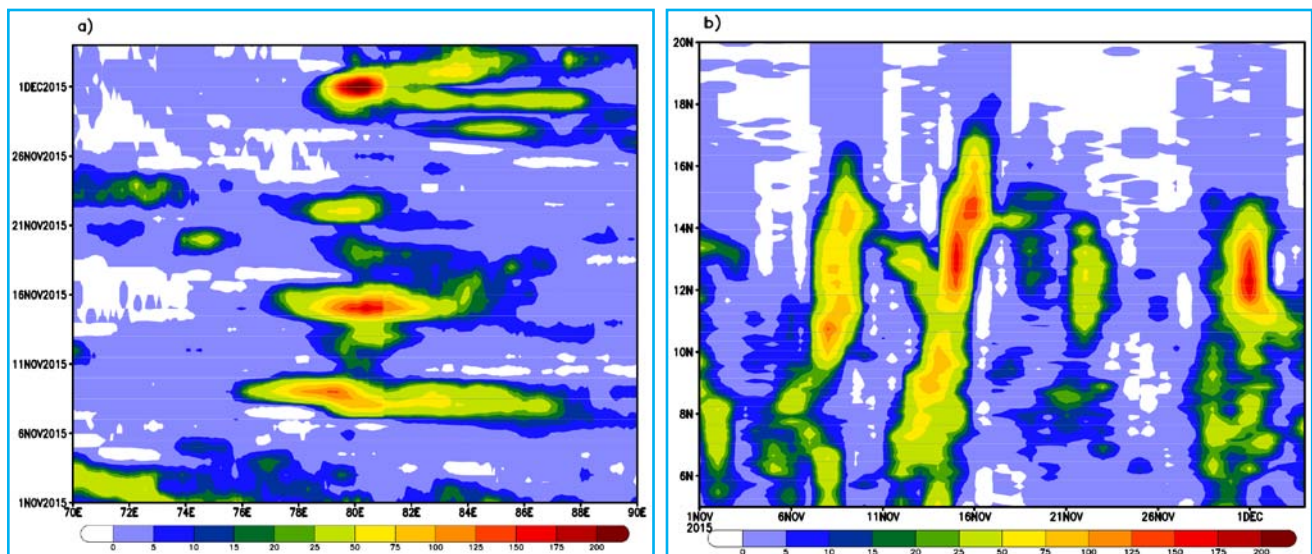


Fig. 13. Accumulated half hourly GPM Rainfall (mm) for (a) 8-11 Nov, 2015, (b) 13-18 Nov, 2015, (c) 19-24 Nov, 2015 and (d) 29 Nov - 4 Dec, 2015



Figs. 14(a&b). Houmoller diagram showing the variation of daily rainfall (mm/day) using (a) averaged over 11°N - 15°N and (b) 78°E - 82°E

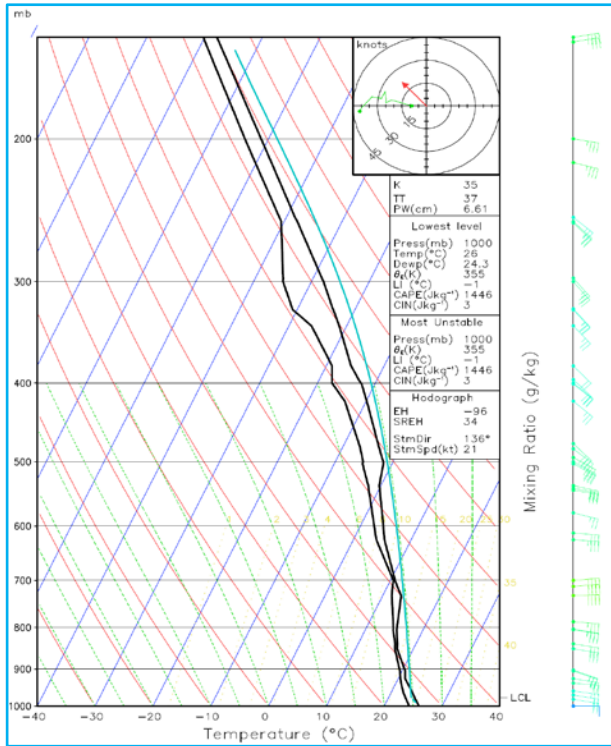


Fig. 15. Skew *T* diagram based on Radiosonde data of Chennai for 1200 UTC of 9th Nov, 2015

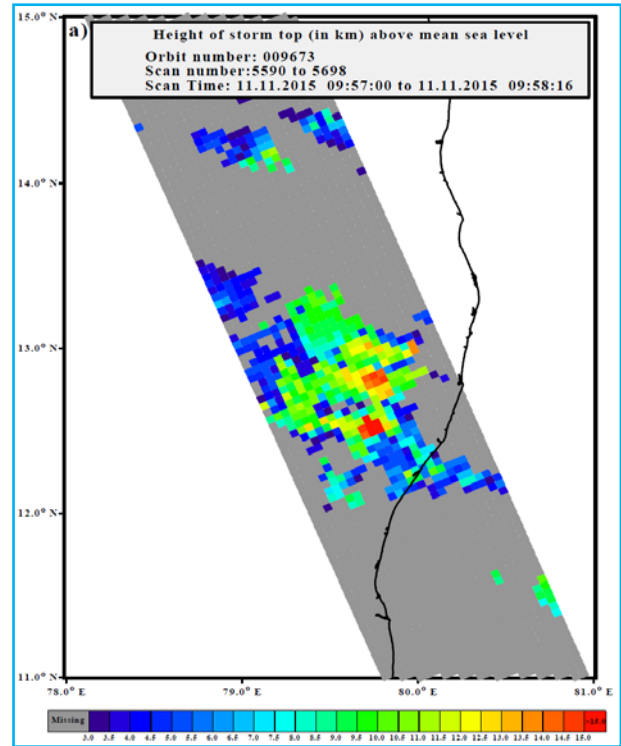


Fig. 16. Storm height (Unit : metre) on 11 Nov, 2015 as seen by TRMM satellite

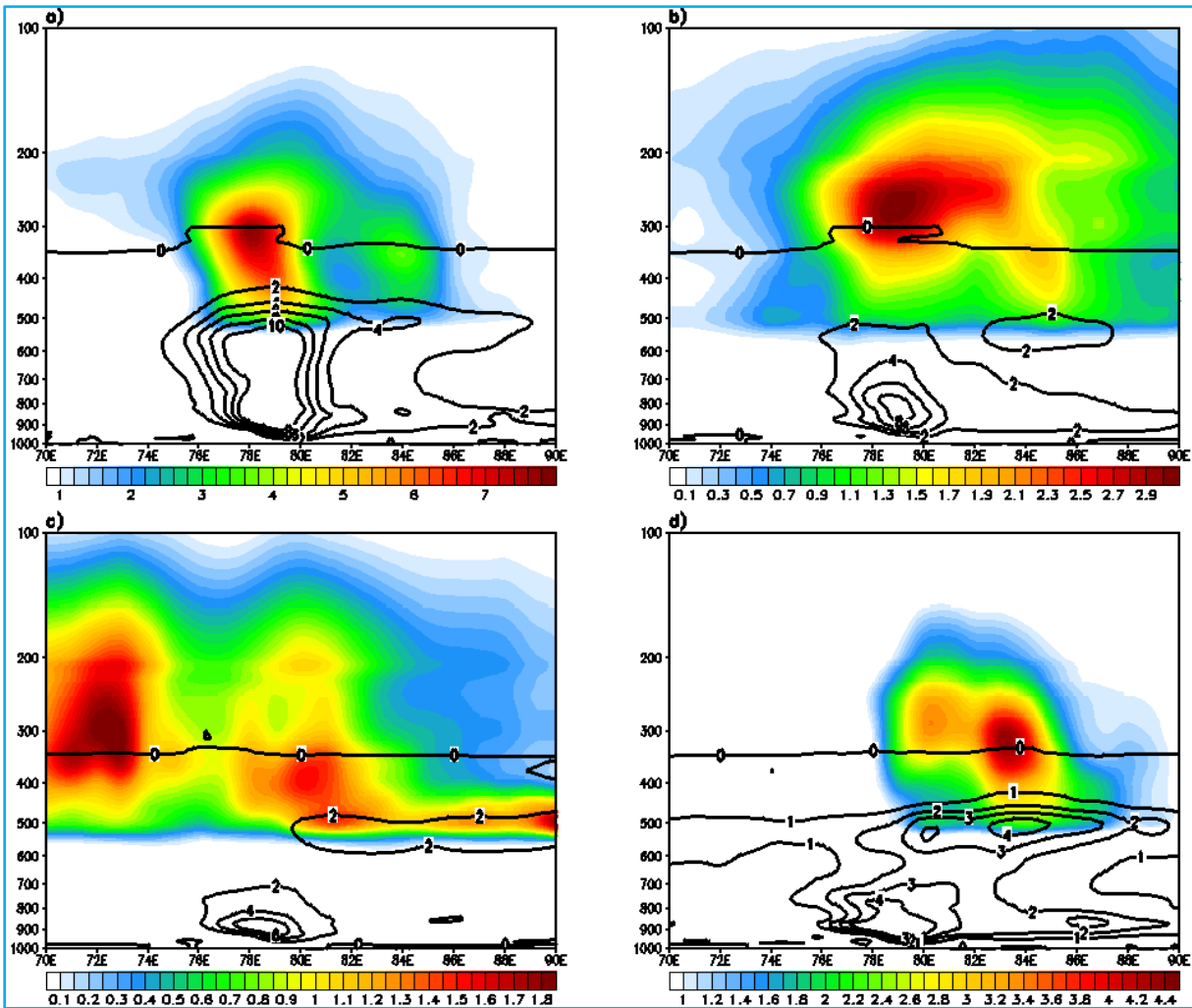
in the lower troposphere owing to the trough of the easterly wave and mid latitudinal cold and dry air aloft due to anticyclone over central India over the eastern coast of peninsular India resulted in copious rainfall during the passage of these four systems. From Fig. 11 and Fig. 13 it can be concluded that GPM (IMERG) estimate is in agreement with the IMD AWS data. The time-longitude and latitude - time cross-section of daily accumulated rainfall averaged over 11°N - 15°N and 78°E - 82°E respectively from 1 Nov, 2015 to 4 Dec, 2015 is shown in Fig. 14(a) and Fig. 14(b). These Houmoller diagrams bring out four prominent rainfall regimes corresponding to deep depression (8-11 Nov, 2015) and low-pressure areas over the eastern peninsular coast from 13-18 Nov, 2015, 19-24 Nov, 2015 and 29 Nov - 4 Dec, 2015.

3.3. Thermodynamical, dynamical and microphysical features

The thermodynamic features prevalent during the passage of deep depression on 9th Nov, 2015 is explored using 1200 UTC radiosonde data of representative station Chennai following pseudo-adiabatic ice process as depicted in Fig. 15. The wind regime is easterly in the lower troposphere and southeasterly in the middle and upper troposphere. It is evident from the hodograph that

the system moved from southeast to northwest. The dew point depression is less over the entire depth of the troposphere. The CAPE value of 1436 J/kg and CIN of 3 J/kg and K-index of 35 indicates that the atmosphere was conducive to scattered convection embedded within the stratiform rainfall regime.

The height of the storm/cloud system as seen by the TRMM satellite (2A23 dataset) on 11 Nov, 2015 is shown in Fig. 16. It can be seen that during the passage of the system the storm height/cloud system associated with deep depression extended up to 10 km in and around Chennai indicating the strong updraft and downdraft. The strong updraft leads to microphysical changes associated with phase changes of cloud hydrometeors. The strong updraft carries the water vapour and cloud liquid water to upper levels where cloud ice grows as shown in Fig. 17. It can be seen from Fig. 17 that in and around Chennai, the cloud liquid water dominated in the lower troposphere and cloud ice content in the upper troposphere. The time-height variation of cloud liquid water content and cloud ice content from 1 Nov, 2015 to 4 Dec, 2015 is shown in Fig. 18. The cloud liquid water content during the deep depression (8-11 Nov, 2015) was confined below 400 hPa and it increased with height. The cloud liquid water content was higher at the lower pressure level during the



Figs. 17. Vertical variation of cloud liquid water content $\times 10^5$ (unit : kg/kg, represented by contours) and cloud ice content $\times 10^5$ (unit: kg/kg, shown as shaded) averaged over 12 °N - 14 °N for (a) 8-11 Nov, 2015, (b) 13-18 Nov, 2015, (c) 19-23 Nov, 2015 and (d) 29 Nov - 04 Dec, 2015

deep depression (8-11 Nov, 2015) indicating the presence of a convective cloud. However, during the passage of the other three low-pressure systems, the cloud liquid water content was very low. From the synoptic features described in Section 3.1 above it is evident that the moisture-laden winds from the Bay of Bengal played a crucial role in the copious rainfall activity over the eastern peninsular coast of India. Ahead of the trough in the easterly wind regime convergence occurs and hence such a synoptic situation leads to convergence of moisture. To explore this feature, we present Vertically Integrated Moisture Flux Convergence (VIMFC) in the lower troposphere (1000 hPa to 700 hPa) for the deep depression (8-11 Nov, 2015) and low-pressure areas (13-18 Nov, 2015, 19-24 Nov, 2015 and 29 Nov, 2015 - 04 Dec, 2015).

The VIMFC is a combination of convergence of horizontal wind vector and moisture advection. Fig. 19 depicts a significant VIMFC around Chennai owing to the easterly wave trough and outflow from an anticyclone over central India. The intensity of the heaviest extreme precipitation events have potentially large societal impacts and intense events almost doubles per degree of warming, increases with the strength and hence, the rareness of the event (G. Myhre *et al.*, 2019).

4. Conclusion

The features of a low-pressure system that crossed the East coast of India were captured very well by the surface observational networks of IMD, *viz.*, AWS and

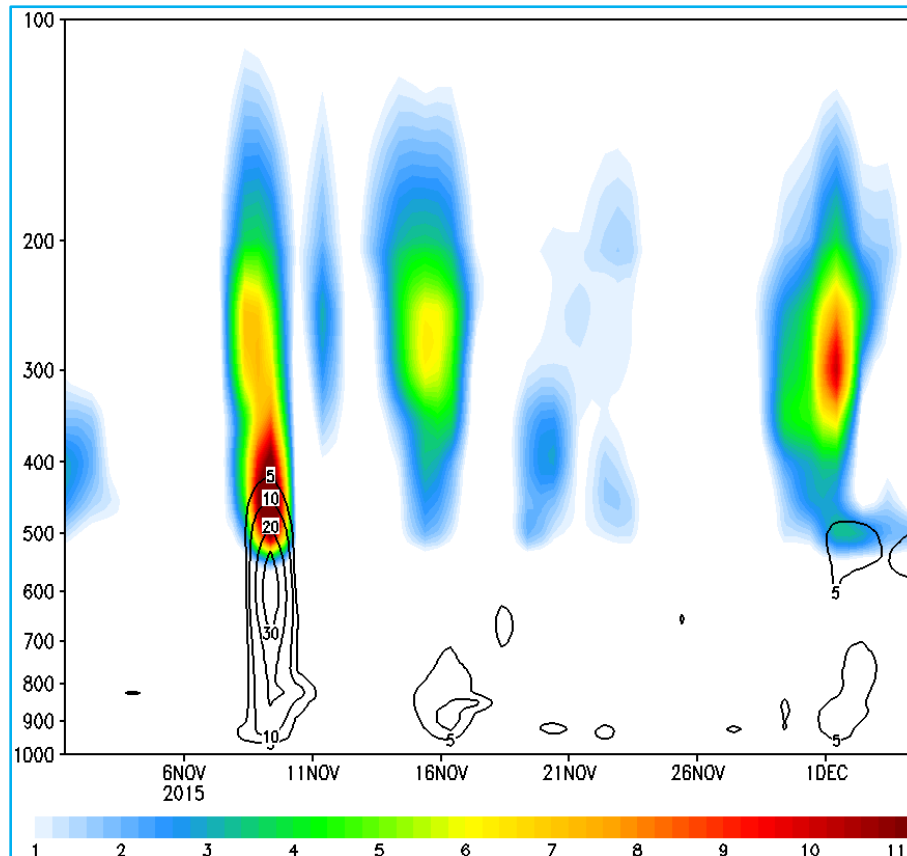


Fig. 18. Time and height variation of cloud liquid water content $\times 10^5$ (unit : kg/kg, represented by contours) and cloud ice content $\times 10^5$ (unit : kg/kg, shown as shaded) averaged over a box bounded by 12 °N - 14 °N and 79 °E - 81 °E

HWSR systems. These systems were maintained routinely by Regional Meteorological Centre (RMC) Chennai. The analysis underpins the importance of automatic and unattended systems in monitoring severe weather events with a high temporal and spatial resolution of data. The hourly and daily rainfall and winds recorded by AWS and HWSR systems have proved their utility in monitoring severe weather events. The large-scale synoptic conditions such as negative OLR anomaly (exceeding 20 Wm^{-2}) over the eastern peninsular coast of India and adjoining Bay of Bengal, parts of the Southwest Arabian sea and positive SST anomaly over Nino regions were favourable for NE monsoon over India. The interaction between the trough of easterlies over the eastern coast of peninsular India and the anchoring of the trough due to anomalous anticyclone over central India favoured rainfall activity ahead of the trough of easterly wind regime. The moisture convergence in the lower troposphere and intrusion of cold dry air in the mid-troposphere invigorated the instability and the cloud system extended up to 10 km establishing thermodynamical conditions favourable for convection.

The increase in cloud liquid water content with height in the lower troposphere and presence of cloud ice content above 400 hPa level around Chennai was favourable for the development of a convective cloud system. All these factors resulted in incessant rainfall activity around the city of Chennai in Nov, 2015. Forecasting and warning services are linked with national as well as state agencies. In the prevailing scenario weather events in recent years World Meteorological Organisation (WMO) suggested a mechanism of common alert protocol (CAP) to warn the affected society in advance. India Meteorological Department (IMD) and National Disaster Management Authority (NDMA) have initiated CAP service for any severe weather events like lightning, thunderstorms or heavy rainfall over a locality. The state level authorities tie up central agencies and issued the warnings and necessary information as per the requirements and consensus with central authorities/agencies. This information also linked with MHEWS domain through WMO alert hub and this will also support to work together globally.

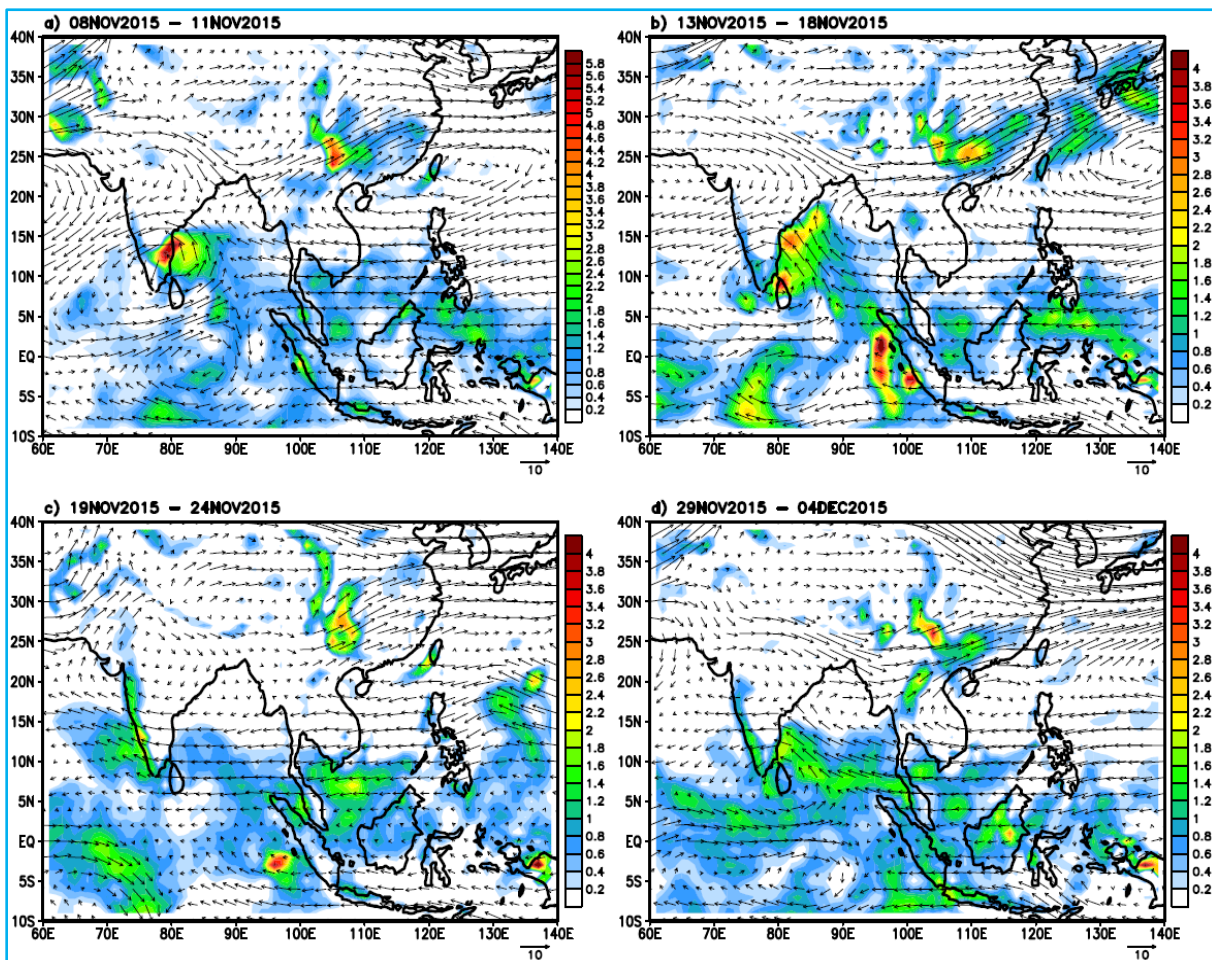


Fig. 19. Vertically Integrated Moisture Flux Convergence (VIMFC) $\times 10^4 \text{ kg m}^{-2} \text{ s}^{-1}$ (shaded) and wind regime at 850 hPa (Vectors)

Therefore, to strengthen cutting edge technology with latest algorithm's (Machine language, Artificial Intelligence, deep learning, geo-spatial domain etc) and quality controlled information in multi-ensemble weather prediction models. Generally, Coarse-resolution regional climate models are likely to provide reliable future projections, provided that large-scale changes from the global climate model are reliable. The improved representation of convective storms also has implications for projections of wind, hail, fog, and lightning (Kendon EJ, *et al.*, 2017). Therefore high resolution with improved convective parameterization schemes can help prediction better accuracy.

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