Heavy Rainfall over Southeast India

During

November & early December, 2015

NWP Division

India Meteorological Department

December, 2015

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1. Introduction

Southeast India, especially Tamil Nadu and Puducherry experienced unprecedented rainfall activity during November and early December 2015 leading to devastating flood over Tamil Nadu. Chennai was worst affected during the end of November and early part of December. The weather systems leading to this flood situation, model guidance and forecast performance of IMD and the monitoring and prediction system of IMD including the observational network are presented in the following sections. IMD has predicted well in advance the severity of weather events to help disaster management functionaries. The short and medium range prediction is solely based on NWP models.

The essence of this report is to evaluate IMD (NWP) models' performance in predicting unprecendented rainfall activity over Tamilnadu during November and early December 2015. The details of the operational NWP models of IMD are presented in Section 2. NWP based objective forecast products are prepared to support weather forecast and warning service by IMD, Indian Air Force, various state disaster management agencies like Northeast Space Application Centre, Flood forecasting centre of Government of Patna etc.

The extremely heavy rainfall over north coastal Tamil Nadu including Chennai occurred in three different spells, viz., 8-9 Nov, 16-17 November and 30 Nov.-1- Dec., 2015. Details of the synoptic situations for these three spells are presented in section 3. It was mainly due to a Deep depression over southwest Bay of bengak, well marked low pressure area over southwest bay of Bengal and a trough of low with embedded cyclonic circulation extending upto middle tropospheric level respectively. The performance of the IMD GFS and WRF model for these three extreme spells are evaluated and presented.

Genesis Potential Parameter (GPP) based on model analysis is utilised to predict cyclogenesis. The performance of this GPP for the cyclogenesis during November has also been examined.

2. IMD's operational models:

IMD operationally runs the following models for short to medium range prediction

(i) IMD Global forecast System (GFS) model

(ii) Weather Research and Forecasting (WRF) regional model

Deils of these models are discussed in the following sections

2.1. IMD Global forecast System (GFS) model

NWP division at Hq. of IMD runs global model GFS T574/L64(horizontal resolution over the tropics ~ 22 km) incorporating Global Statistical Interpolation (GSI) scheme as the global data assimilation for the forecast up to 7 days. Currently, it runs twice in a day (00 UTC and 12 UTC).

2.2. Weather Research and Forecasting (WRF) regional model

The meso-scale forecast system WRF (ARW) with 3DVAR data assimilation is being operated daily twice, at 27 km, 9 km and 3 km horizontal resolutions for the forecast up to 3 days using initial and boundary conditions from the IMD GFS-574/L64. At ten other regional centres, very high resolution mesoscale models (WRF at 3 km resolution).

2. 3. District level NWP guidance

District Level Quantitative five days weather forecasts based on Multi-Model Ensemble (MME) system are being generated to support AgroMeteorological Advisory Service of India, making use of model outputs of state of the art global model GFS, regional model WRF among others from the leading global NWP centres. All these NWP products are routinely made available on the IMD web site www.imd.gov.in. Detailed technical specifications of these two global and regional model are given in Annexure I.

2.4. Genesis Potential Parameter (GPP) for cyclogenesis guidance

Genesis Potential Parameter (GPP) based on model analysis is utilised to predict cyclogenesis: Genesis Potential Parameter (GPP) is defined as: GPP = S 850xMxIξ 850ξif > 0, M > 0 and I > 0 850 ≤ 0, M ≤ 0 or I ≤ 0ξ= 0 if 850 = Low level relative vorticity (at 850 hPa) in 10-5 sξWhere , -1 S = Vertical wind shear between 200 and 850 hPa (knots) = Middle troposphere relative humidity Where, RH is the mean relative humidity between 700 and 500 hPa

I = (T850 – T500) °C = Middle-tropospheric instability (Temperature difference between 850 hPa and 500 hPa). All the variables are estimated by averaging of all grid points over an area of radius 2.5o around the centre of cyclonic systems using model analysis field.

3. Weather systems affecting southeast India during November 2015 and associated rainfall

The northeast monsoon season (NEM) of October to December (OND) is the chief rainy season for the southeastern parts of peninsular India (Tamil Nadu and Puducherry). This season is also the chief cyclone season over the North Indian Ocean and hence, low pressure systems forming over the Bay of Bengal and moving westwards contribute significantly towards the NEM rainfall over meteorological sub-division of Tamil Nadu and Puducherry (TN&PDC). During the year 2015, the onset of NEM took place on 28th October against the normal date of 20th October. Subsequently, during the month of November, the following three synoptic scale weather systems affected Tamil Nadu and Puducherry causing extensive rainfall activity over the region:

- Deep Depression over Bay of Bengal (08-10 November 2015)
- Well marked Low pressure area over SouthWest Bay of Bengal (12-18 November 2015)
- Low (28 November-04 December 2015).

Brief history of these weather systems and associated rainfall are presented below:

3.1 Deep Depression over Bay of Bengal (08-10 November 2015)

On 7th November, a low pressure area formed in the south Bay of Bengal which rapidly concentrated into a deep depression (one stage lower than Tropical Cyclone) on 8th November. The deep depression was associated with strong winds of 55-65 kmph and remained practically stationary very close to the coast of Tamil Nadu for nearly 12 hours during the day time on 9th before crossing north Tamil Nadu coast near Puduchhery in the evening of 9th November. The system retained its intensity nearly for another 15 hours over northern parts of Tamil Nadu. This caused very heavy rainfall (13-24 cm) at a few places with isolated extremely heavy rainfall (>25 cm) over Tamil Nadu and adjoining Districts of Andhra Pradesh.

INSAT-3D satellite imagery of the system as on 09th/1130 UTC, Doppler Weather Radar, Chennai based on 09th/1400 UTC (just prior to landfall around 1400 UTC) and observed and forecast track (based on 09th/1200 UTC) are presented in Fig.1(a-b).

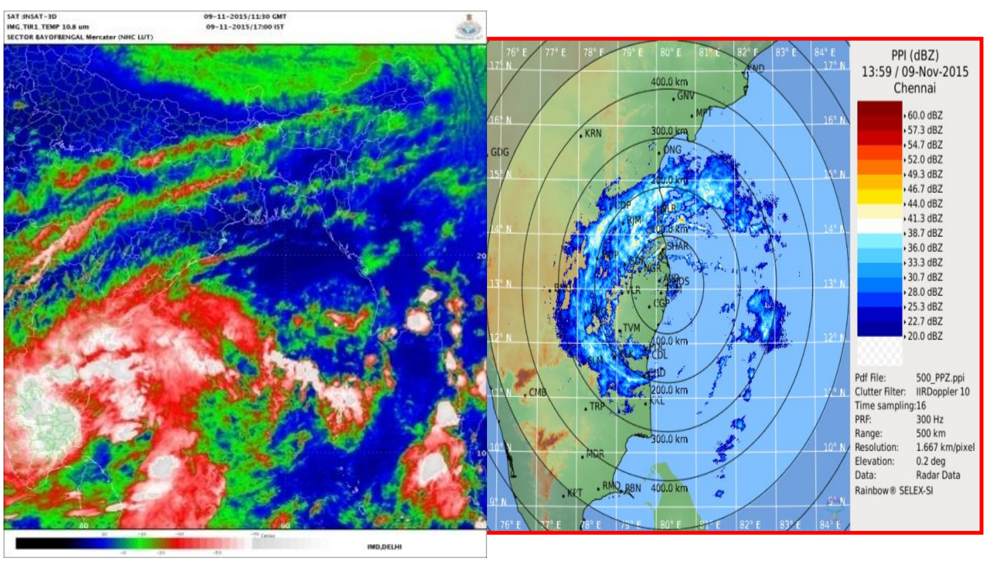


Fig.1a INSAT-3D satellite imagery of DD (08-10 Nov 2015) based on 09th/1130 UTC, Doppler Weather Radar, Chennai imagery based on 09th/1400 UTC

North Tamil Nadu and adjoining Rayalaseema received heavy to extremely heavy rainfall during 24-hr ending 0300 UTC of 09th. Neyveli of Cuddalore district in north coastal Tamil Nadu recorded highest 24 hr rainfall amount of 48 cm ending at 10th/0300 IST. Tirumala in Rayalaseema recorded extremely heavy rainfall of 30 cm during the same period. Spatial distribution of 24-hr heavy rainfall occurences as on 0300 UTC of 08-11 November 2015) is depicted in Fig.1b. (Description of rainfall terminologies: *Rainfall amount*: ***Heavy***: 64.5 to 124.4 mm, ***Very Heavy***: 124.5 to 244.4 mm and ***Extremely Heavy***: ≥244.5 mm; *Spatial distribution*: ***Isolated (ISOL)***: 1-25% of stations reporting rainfall, ***Scattered (SCT / A few places)*** : 26-50% of stations reporting rainfall, ***Fairly WideSpread (FWS/ Many places)***: 51-75% of stations reporting rainfall and ***Widespread (WS/ Most places)***: 76-100% of stations reporting rainfall during the last 24 hours ending at 0300 UTC of every day).

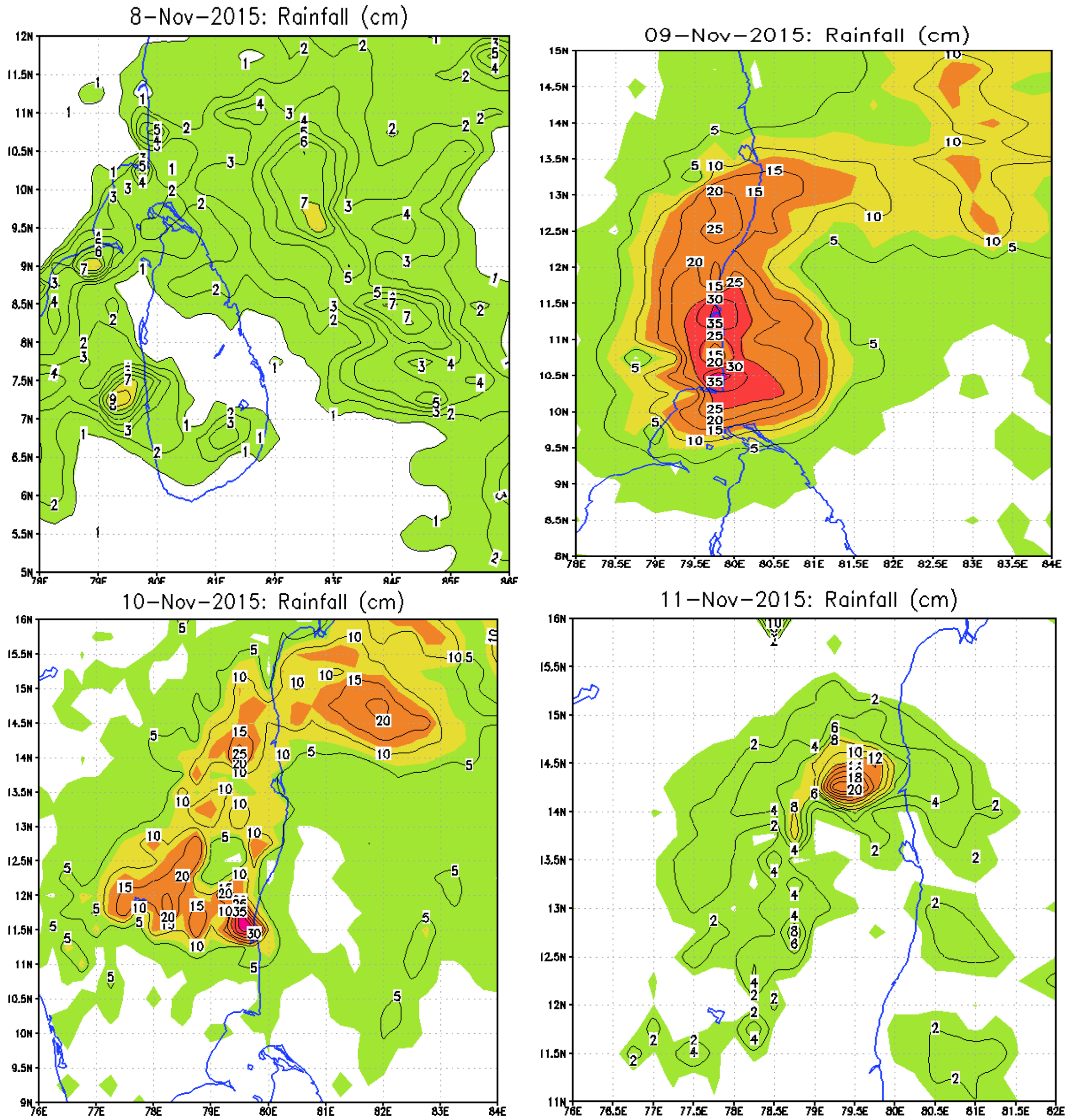


Fig.1c Rainfall realised in association with Deep Depression (08-10 Nov 2015) (based on IMD-NCMRWF GPM gauge merged rainfall data)

3.2 Well marked Low pressure area over SouthWest Bay of Bengal (12-18 November 2015)

In quick succession, a trough of low lay over south Andaman Sea and neighbourhood with associated cyclonic circulation extending upto 3.1 km a.s.l on 12^{th}. On 13^{th} November, it lay over southeast Bay of Bengal and neighbourhood with associated cyclonic circulation extending upto 4.5 km a.s.l. Under its influence, a low pressure area formed over southeast Bay of Bengal on the same day. It became well marked on 14^{th} and lay over to southwest Bay of Bengal off North Tamil Nadu and adjoining Sri Lanka coasts on 15^{th}. It lay over southwest Bay of Bengal of north Tamil Nadu coast with associated upper air cyclonic circulation extending upto mid-tropospheric levels and tilting southwestwards with height on 16^{th}. Moving northwards, it lay over westcentral and adjoining southwest Bay of Bengal off south Andhra Pradesh – north Tamil Nadu coasts on 17^{th}. On 18^{th}, it lay as a low pressure area over westcentral Bay of Bengal off Andhra Pradesh coast with associated upper air cyclonic circulation extending upto 2.1 km a.s.l. It resulted in narrow core of strong winds and very heavy rainfall over north Tamil Nadu and south Coastal Andhra Pradesh and Rayalaseema during 16-18 November. INSAT-3D satellite imagery of the system as on 0000 UTC of 16^{th} November is shown in Fig.2(a)

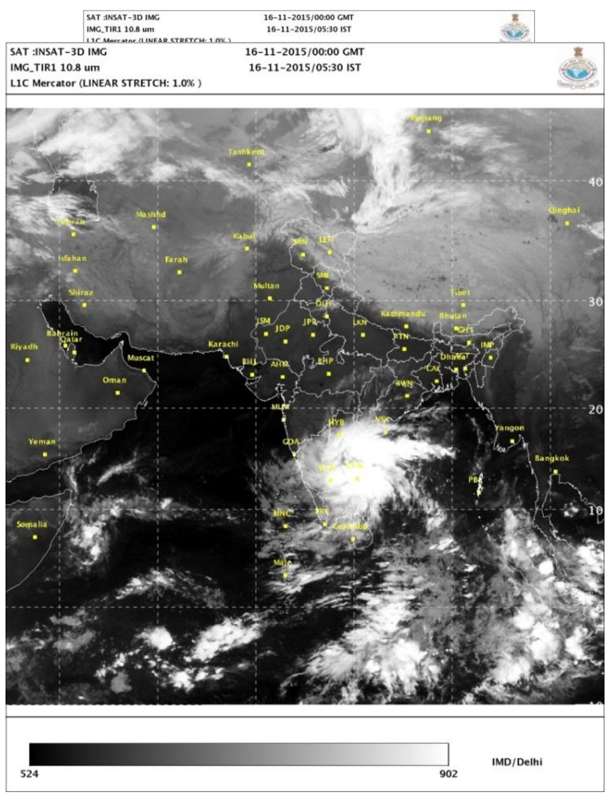


Fig.2a INSAT-3D satellite imagery based on 09^{th}/1130 UTC of the well marked low pressure area during 12-18 November 2015

Associated with this system, rainfall activity occurred over coastal Tamil Nadu during 12-18 November. Heavy to extremely heavy rainfall occured along the entire north Tamil Nadu coastal belt during the 24-hr ending 0300 UTC of 16[th] and isolated heavy to very heavy rainfall on the other days. Spatial distribution of 24-hr heavy rainfall occurences as on 0300 UTC of 13-19 November 2015) is depicted in Fig.2b.

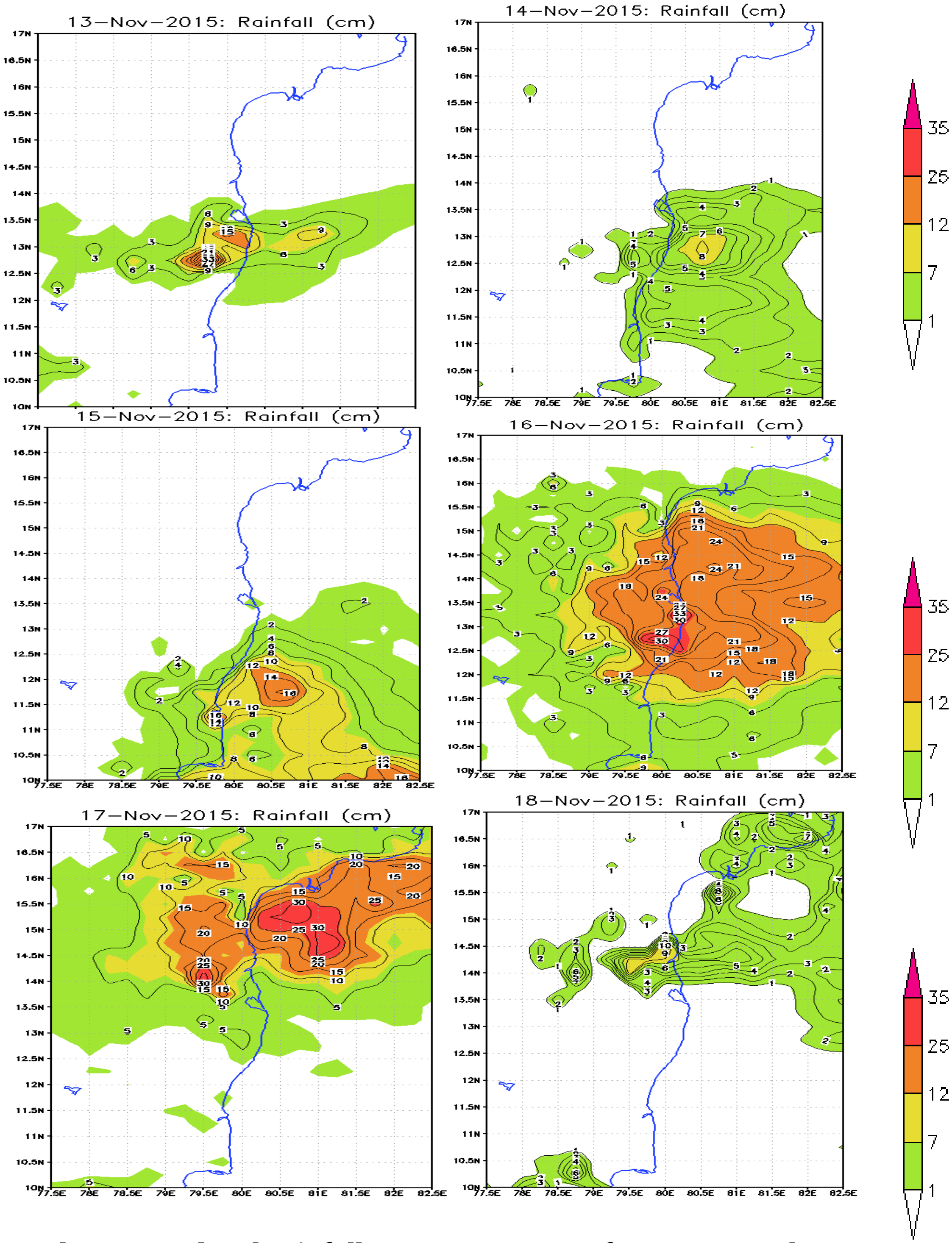


Fig.2b 24-hr accumulated rainfall as on 0300 UTC of 13-18 November 2015 in association with well marked low of 12-18 Nov 2015 (based on IMD-NCMRWF GPM gauge merged rainfall data)

3.3 Low pressure area (28 November - 04 December 2015)

In a quick succession, two troughs of low pressure developed over southeast Bay of Bengal during the last week of November which moved westwards towards Tamil Nadu coast. The first trough of low pressure with an associated upper air cyclonic circulation extending upto 3.6 km above mean sea level lay over southwest Bay of Bengal off Tamil Nadu coast on 28th November. It persisted over the same region on 29th. On 30th, the second trough of low pressure also moved westward and lay over southwest Bay of Bengal with associated cyclonic circulation in lower tropospheric levels and the first trough merged with the second trough of low pressure. It persisted over the same region till 2nd December. Under its influence, a low pressure area formed over southwest Bay of Bengal off Tamil Nadu coast on 3rd December. The low persisted over the same region on 04th December.

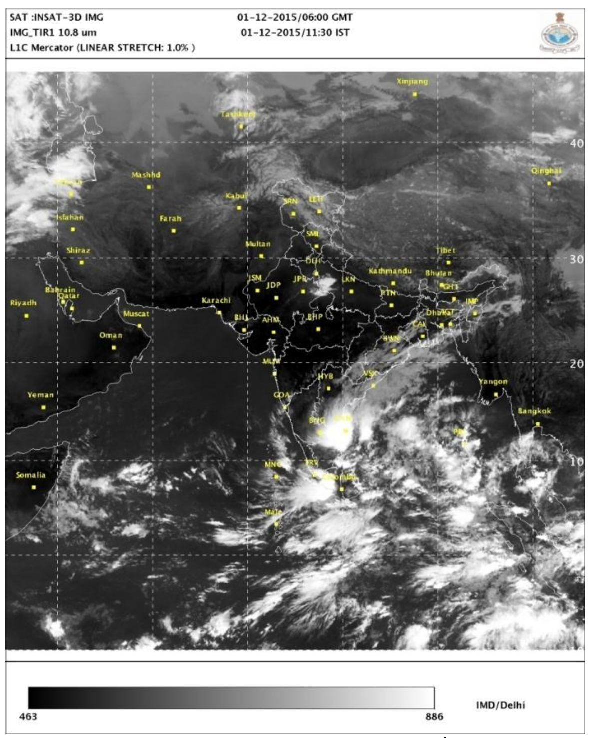


Fig.3a INSAT-3D satellite imagery based on 01st/0600 UTC of the trough of low pressure during 28 November -03 December 2015

Associated with this system, rainfall activity occurred over coastal Tamil Nadu during 29 November-03 December. Over north coastal Tamil Nadu and Puducherry, heavy to extremely heavy rainfall occured along the entire coastal belt during the 24-hr ending 0300 UTC of 02nd December, very heavy rainfall over a few places on 01st December and isolated heavy to very heavy rainfall on the other days. Spatial distribution of 24-hr heavy rainfall occurences as on 0300 UTC of 30 November – 03 December 2015) is depicted in Fig.3b

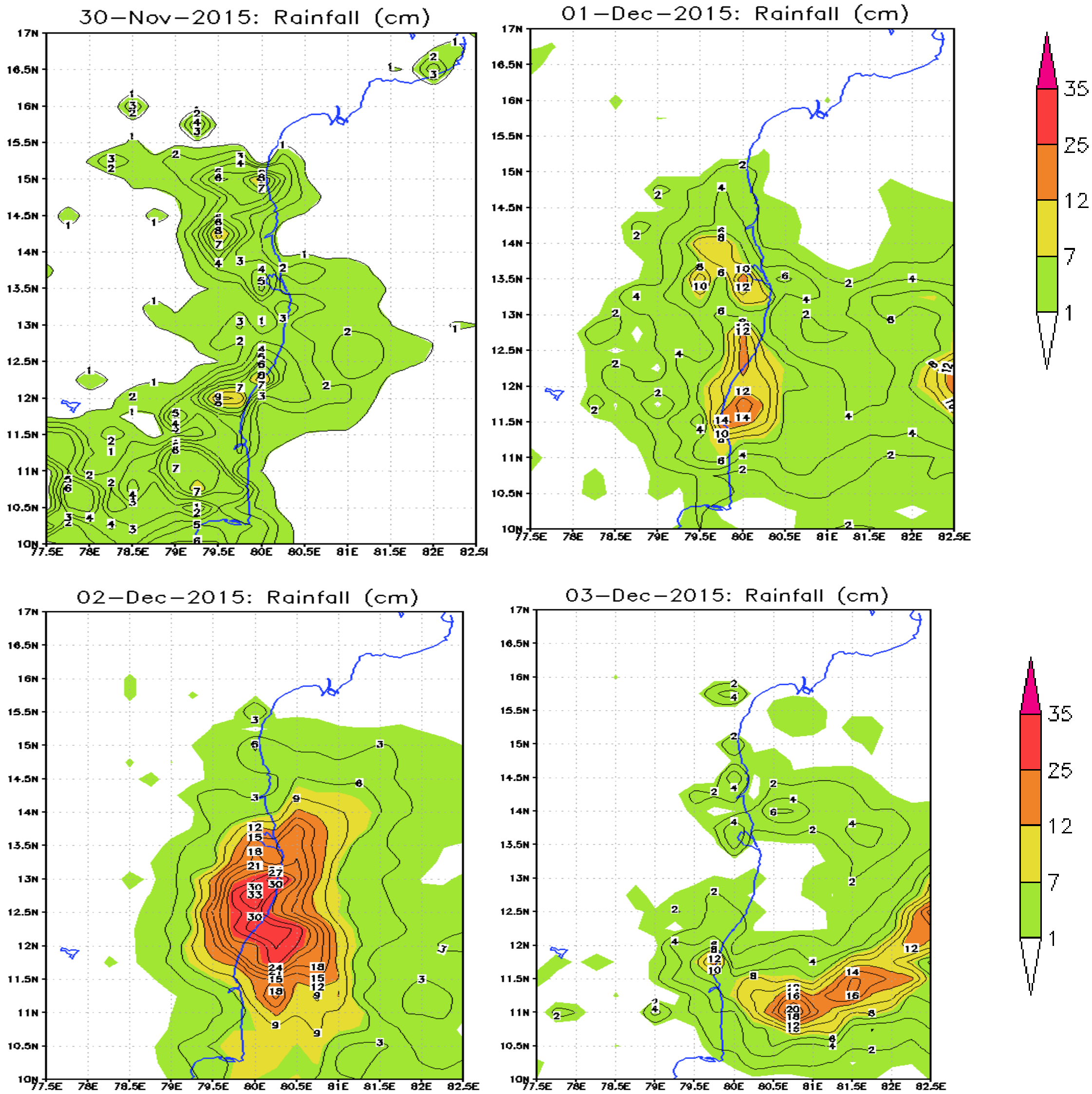


Fig.3b 24-hr accumulated rainfall as on 0300 UTC of 30 Nov – 03 Dec 2015 in association with trough of low off Tamil Nadu coast (28 November – 03 December 2015) (based on IMD-NCMRWF GPM gauge merged rainfall data)

4. Performance of IMD GFS for Chennai Heavy Rainfall

In November, there are three synoptic scale systems affected Tamilnadu and Pondicherry causing heavy rainfall over the region.

- Deep Depression over Bay of Bengal (08-10 November 2015)
- Well marked Low pressure area over Bay of Bengal (15-18 November 2015)
- Low (30 November-04 December 2015).

4.1 Heavy rainfall during 8-11 November 2015

The Heavy rainfall (24 hour accumulative) due to the low pressure system (8-11 November 2015) occurred mainly over coast of Tamilnadu and Pondicherry on 9th and 10th November 2015. In order to assess the ability of the IMD GFS to capture center and structure of the LOW pressure system and rainfall, the wind and vorticity analysis at 850 is shown in Fig 4(a); Wind and Divergence at 500 hPa in Fig 4(b) and 200 hPa in Fig 4(c) ; and observed rainfall in Fig 4(d) for 8-11 November, 2015. From the observation of rainfall (Fig 4d), it was seen that the maximum amount of rainfall more than 35 cm occurred over Tamilnadu coast to the south of Pondicherry. The GFS Analysis of wind and vorticity at 850 hPa (Fig.4a) captured the position and intensity of the system with reasonable accuracy during 8-11 November 2015. The GFS analysis of wind and divergence field at middle (Fig 4b) and upper level (Fig 4c) also supports the circulation during 8-11 November 2015. On 9th November, a cyclonic circulation at 850 hPa over BOB Sea off Tamilnadu coast was seen in the 850 hPa wind analysis. The 850 hPa vorticity maximum of the order of 15 × 10−5/sec on 9 November was situated around 10.7◦N/80.5◦E. The magnitude of 850 hPa vorticity value gradually increases from 9 to 10 November over the areas of low pressure system. ==

The 24 ,48 and 72 hour forecast of IMD GFS 850 hPa wind &vorticity, wind & divergence at 500 hPa and 200 hPa and Rainfall valid on 09th November 2015 is shown in Fig 5(a), 5(b) and 5(c) respectively. With respect to the rainfall event of 9 November 2015, which occurred with respect to a deep depression, the location of the heavy rainfall (along the coast of Tamil Nadu) event was very well predicted with a lead time of 2 days, although its intensity was underestimated. With respect to day 3 forecast although the location was predicted reasonably well, the intensity was not captured in the model (Fig. 5c). With respect to the rainfall of 10 November 2015 the GFS model predicted comparatively better than that of 9th rainfall episode with 3 days lead time. It is found from the Fig 6(a) –6(c) that the heavy rainfall episode on 10th November 2015 was very well captured in the model in terms of circulation and distribution of rainfall amount, although there were some variations in magnitude and spatial locations.

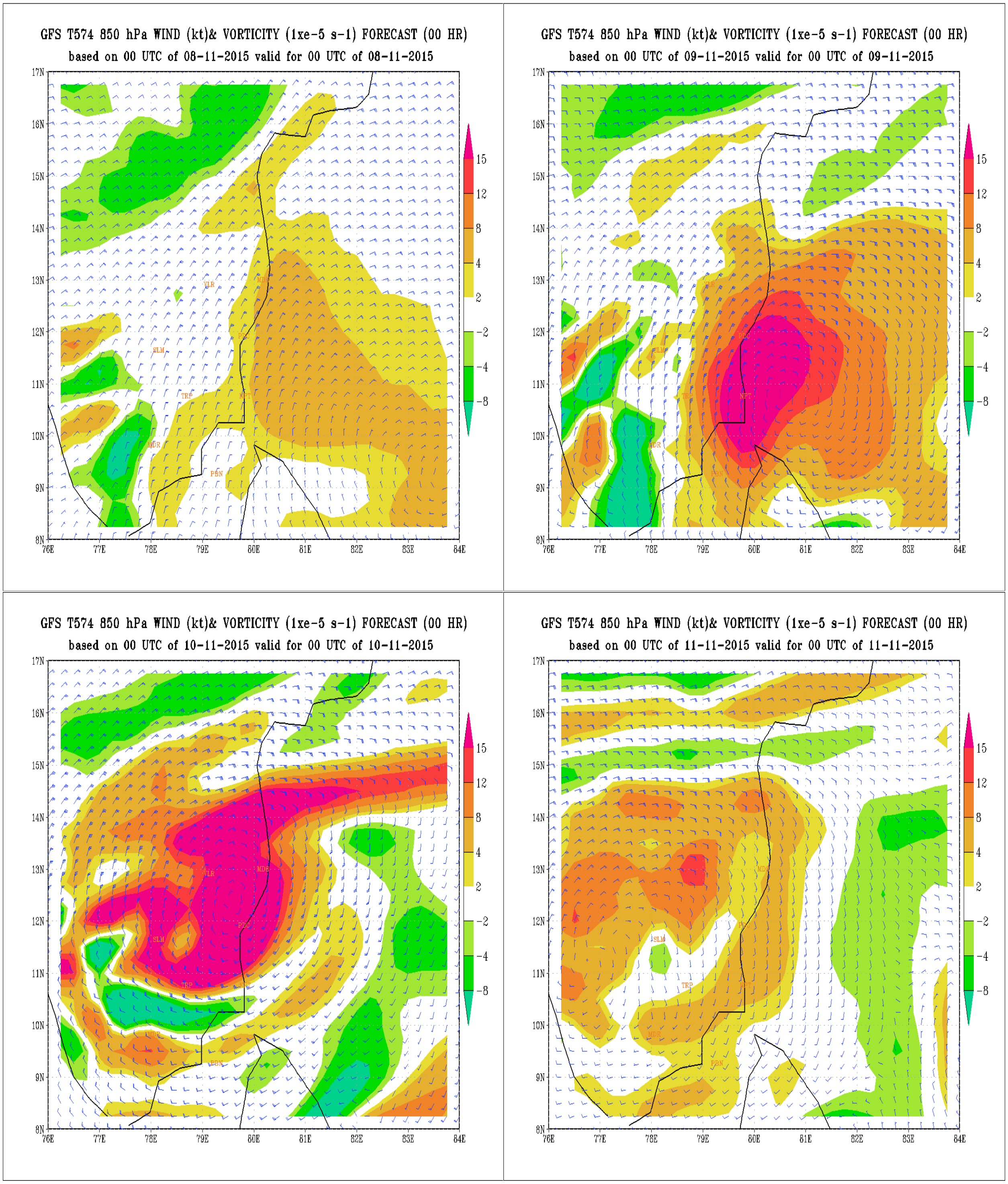


Fig.4 (a) IMD GFS 850 hPa wind & vorticity analysis for **8-11 November 2015**

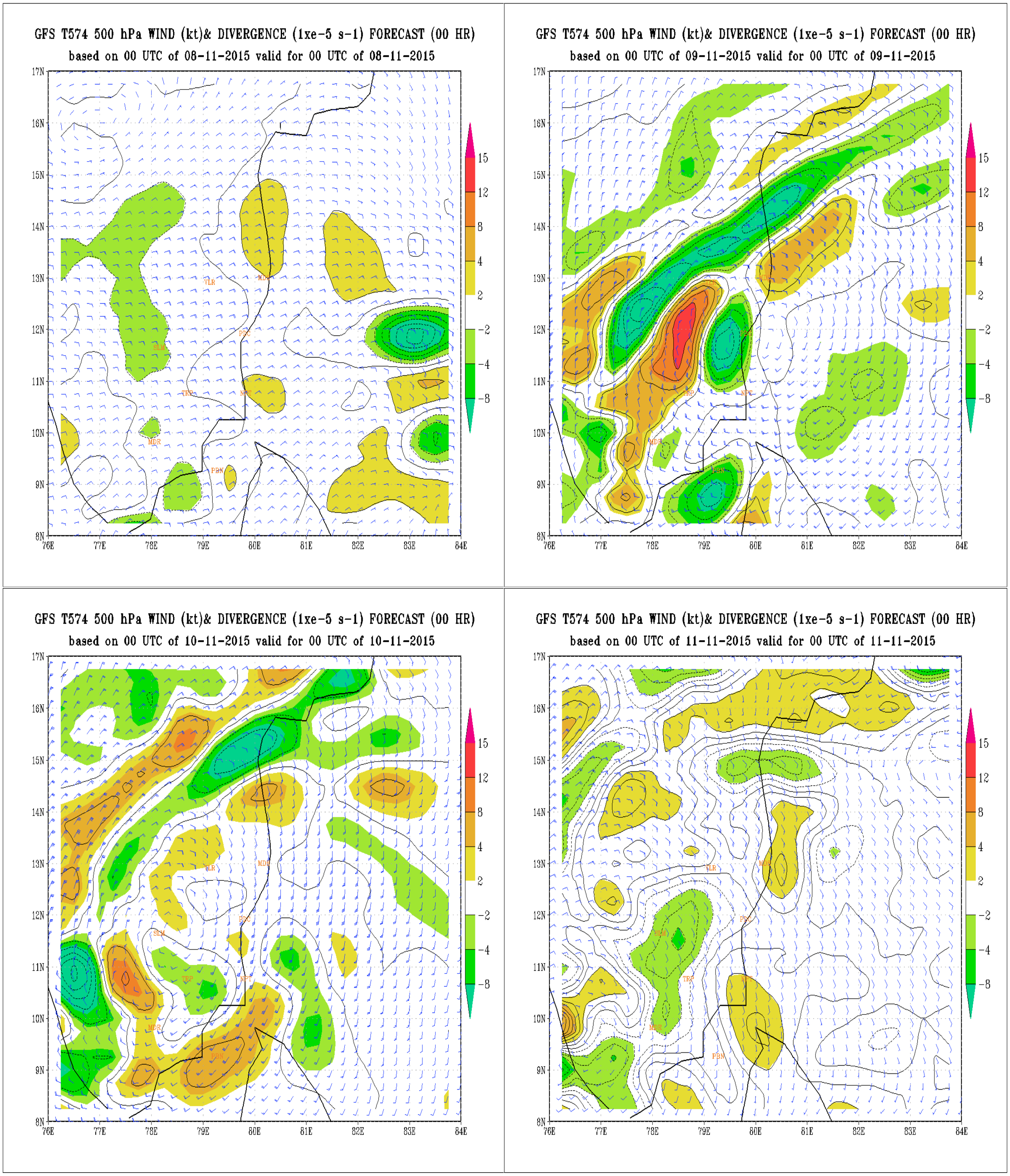


Fig.4 (b) IMD GFS 500 hPa wind and Divergence analysis for **8-11 November 2015**

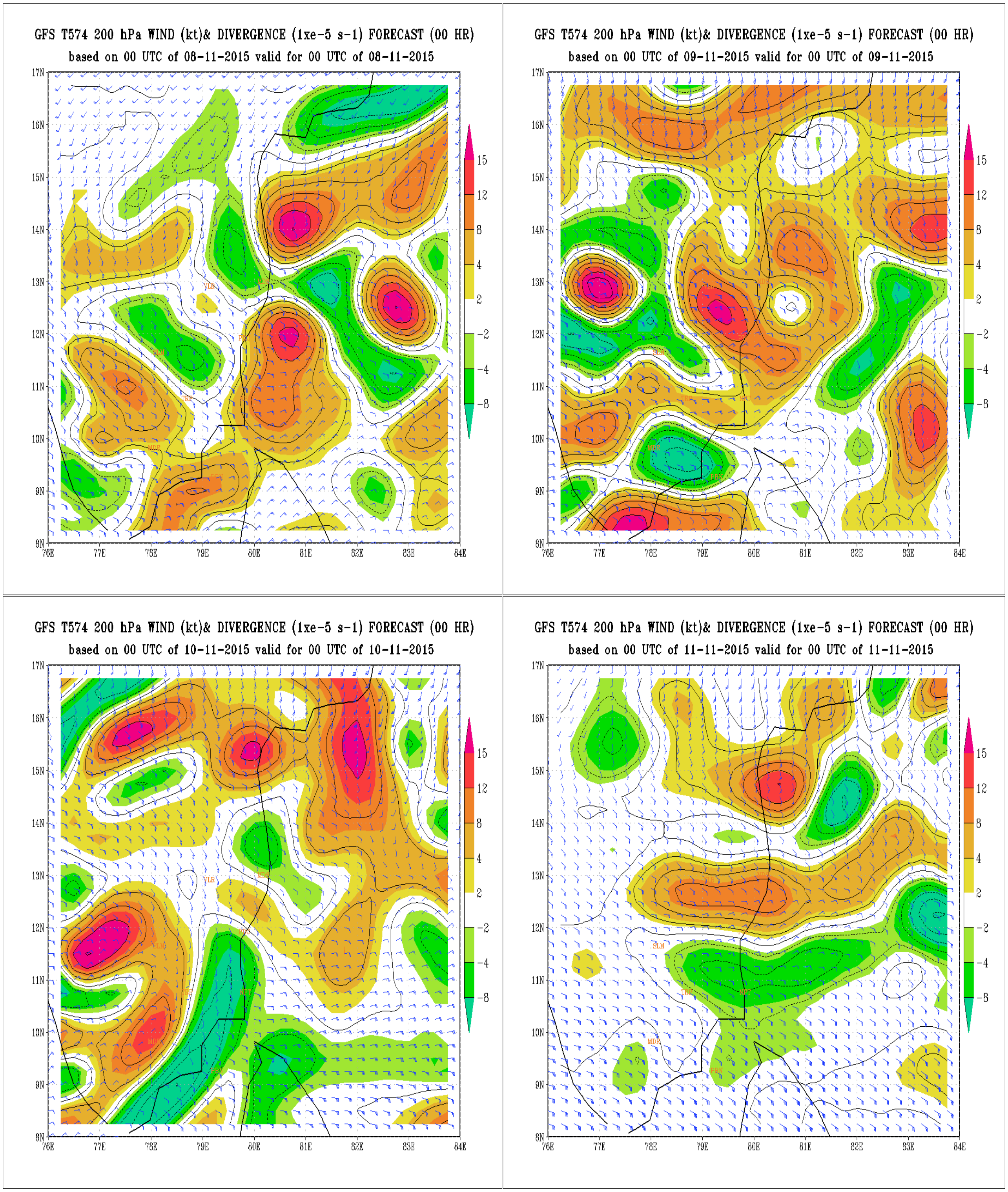


Fig.4 (c) IMD GFS 200 hPa wind and Divergence analysis for **8-11 November 2015**

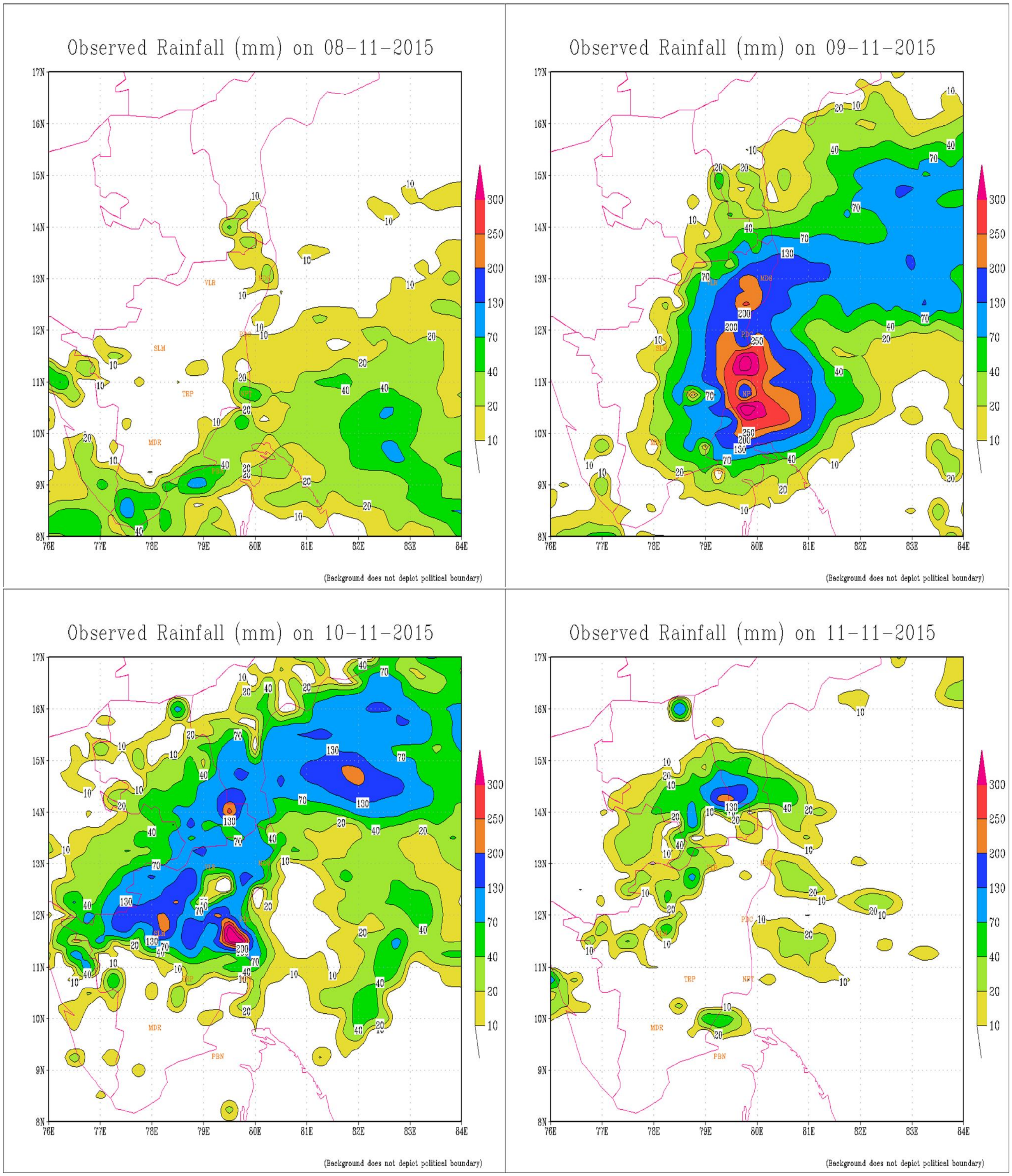


Fig.4 (d) Observed Rainfall for **8-11 November 2015**

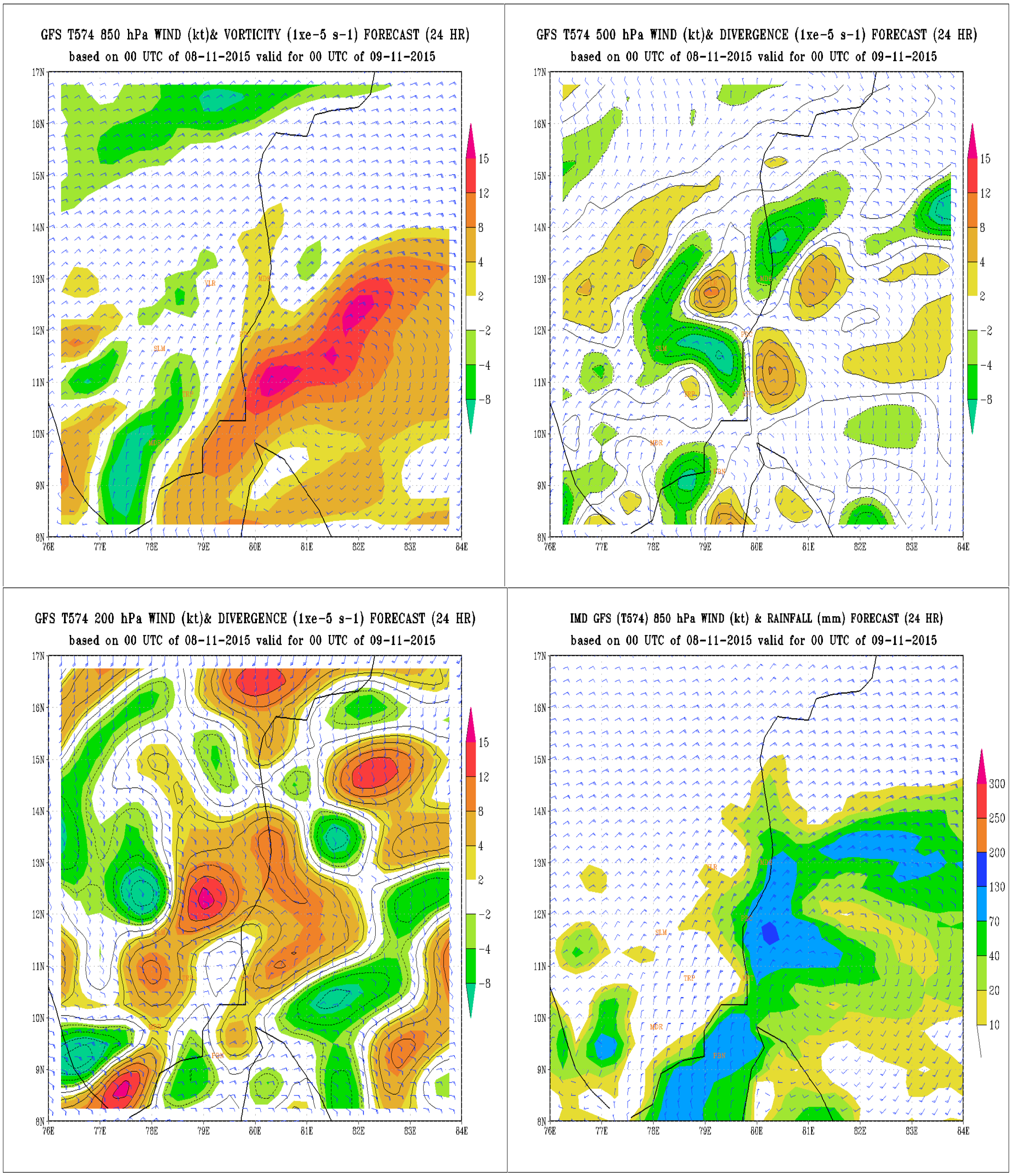


Fig.5(a) 24 hour forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **09th November 2015.**

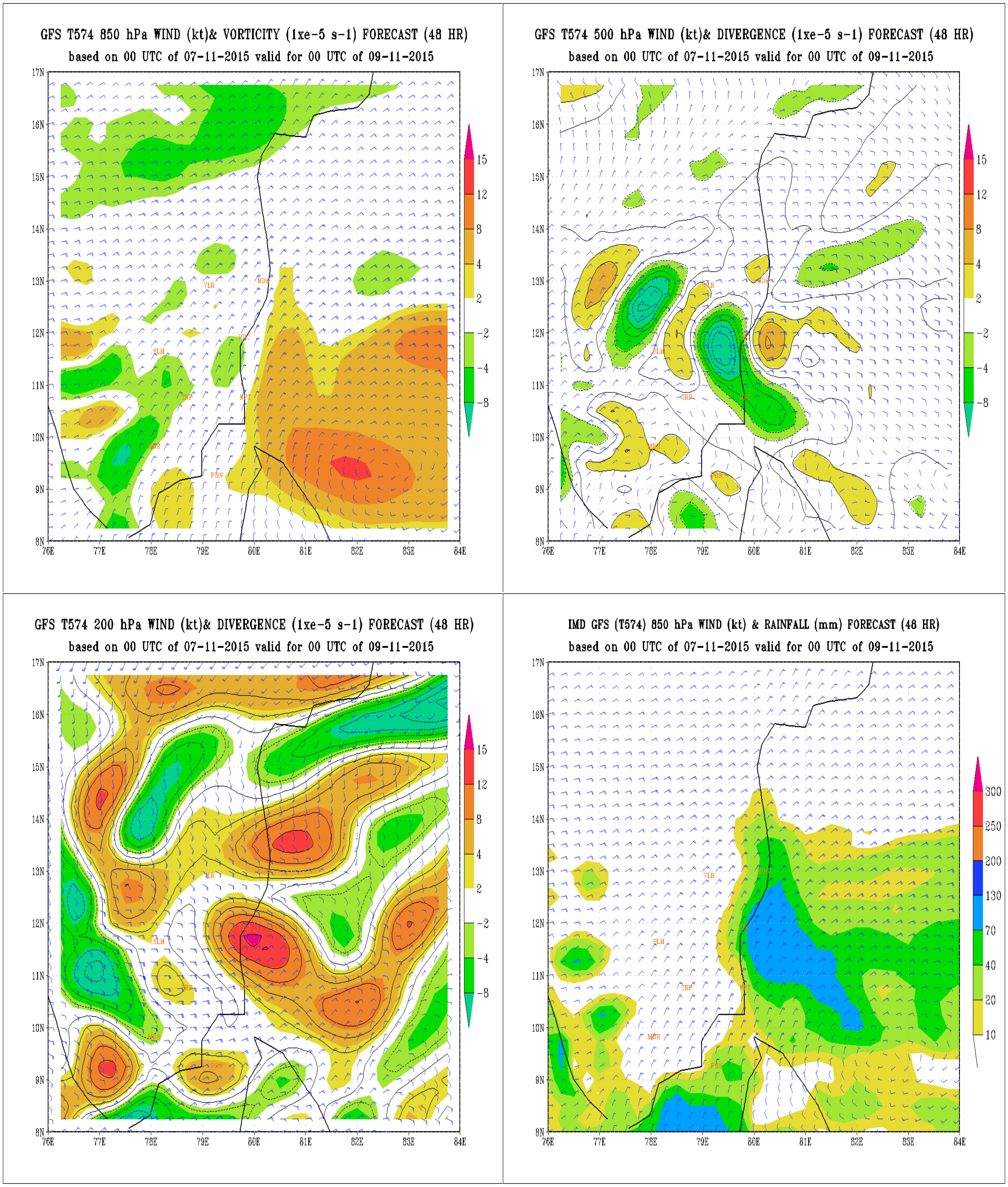


Fig.5(b) 48 hour forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **09th Nov 2015.**

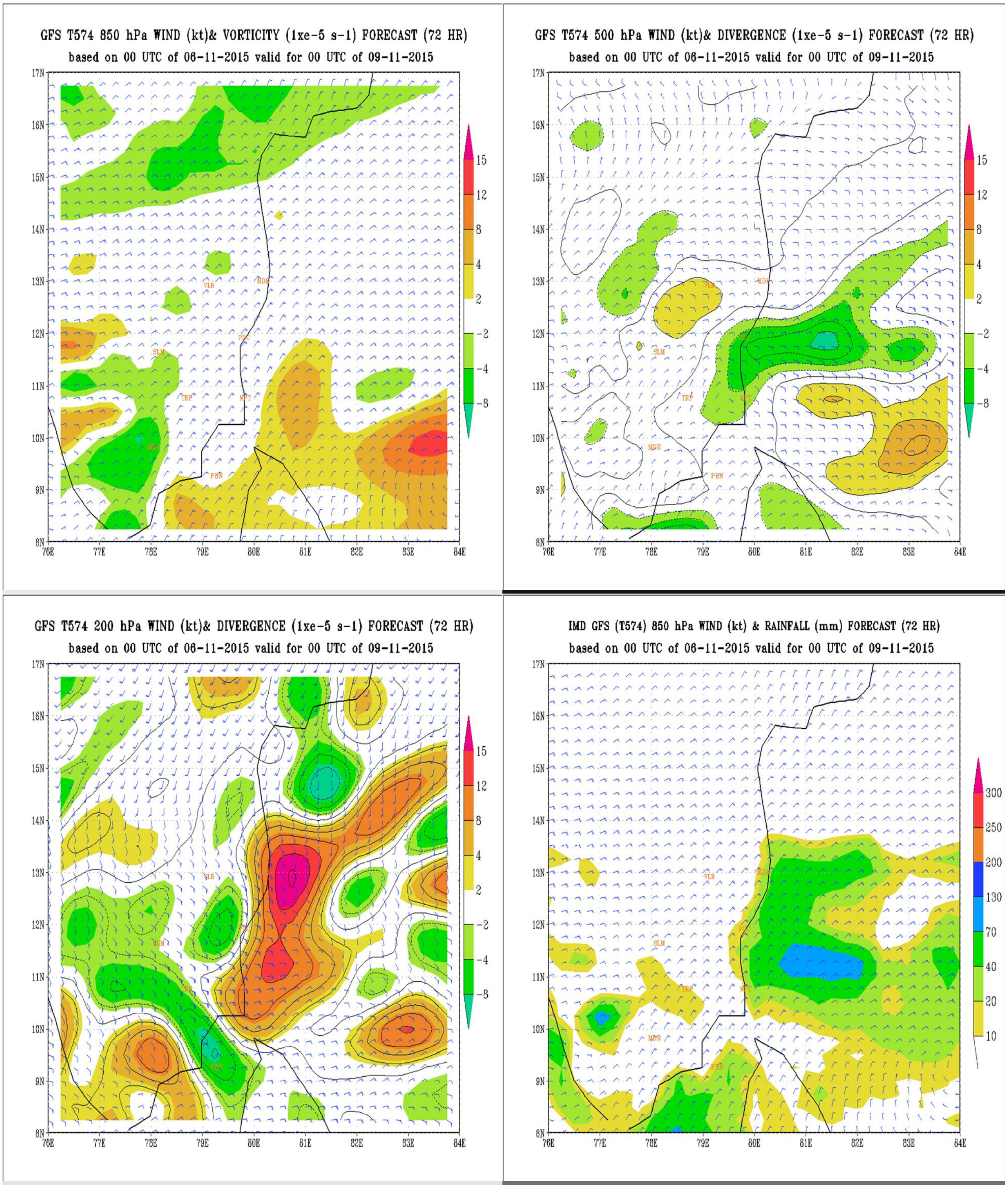


Fig.5(c) 72 hours forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **09th Nov 2015.**

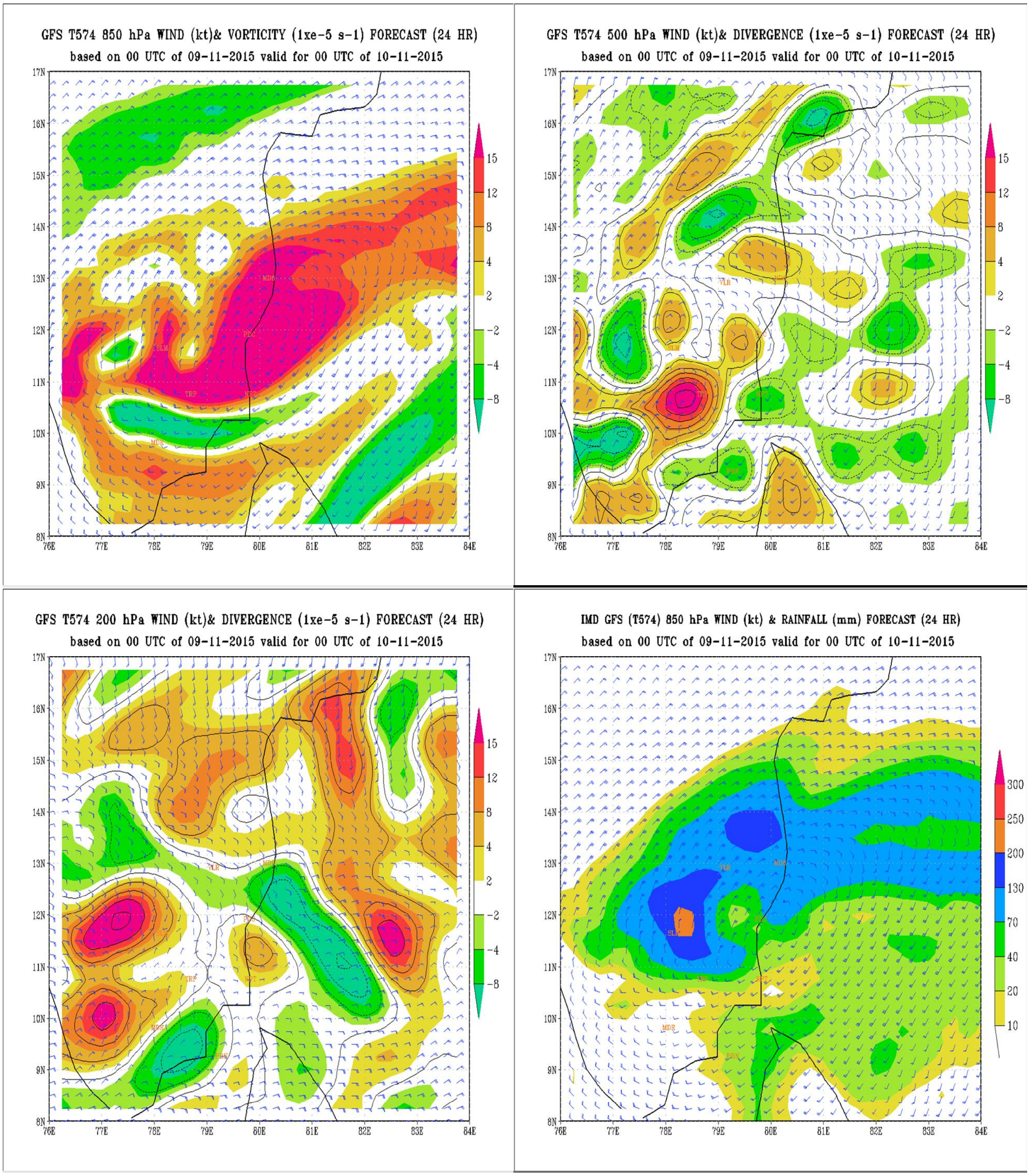


Fig.6(a) 24 hours forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **09th Nov 2015.**

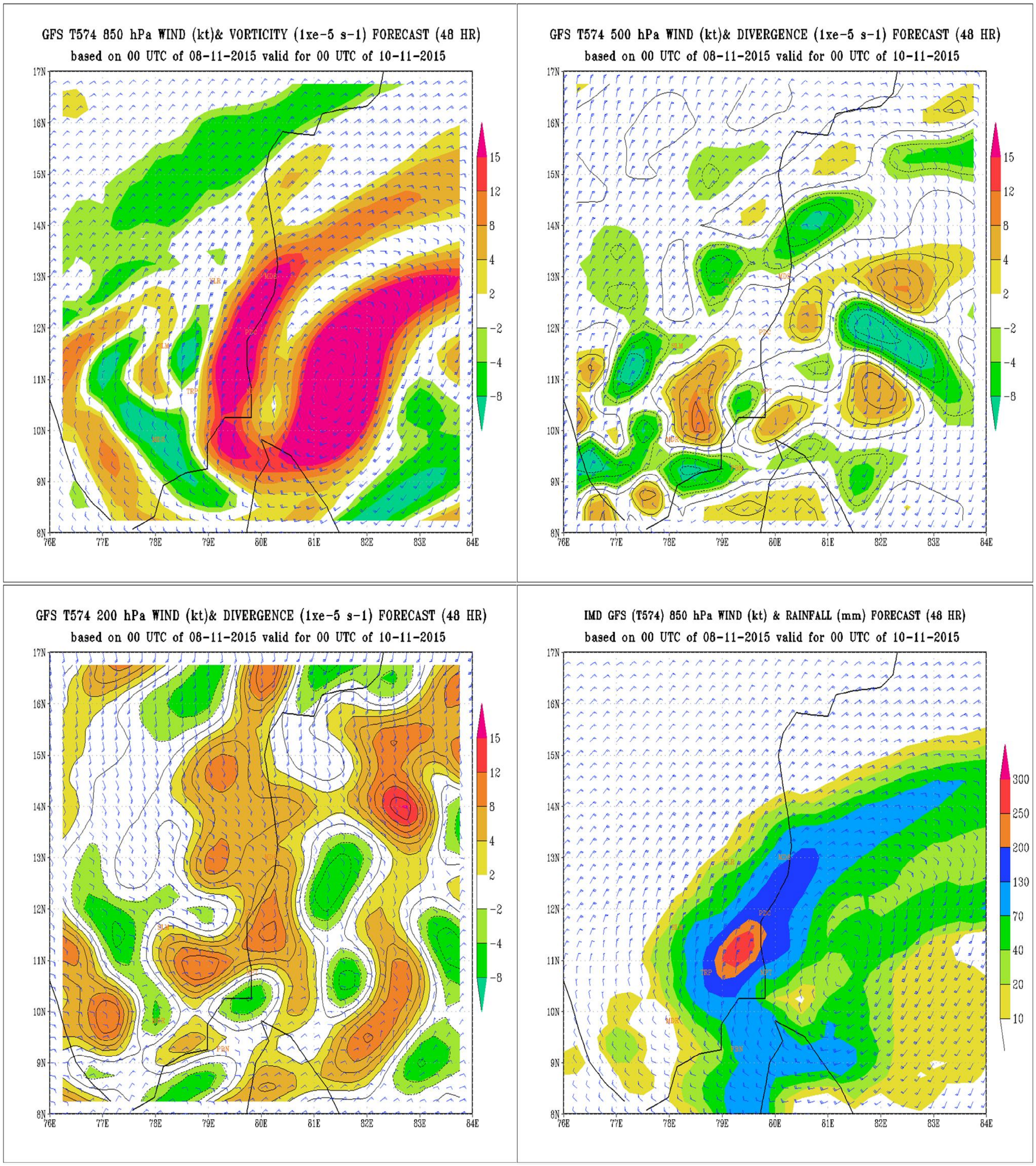


Fig.6(b) 48 hour forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **10th Nov 2015.**

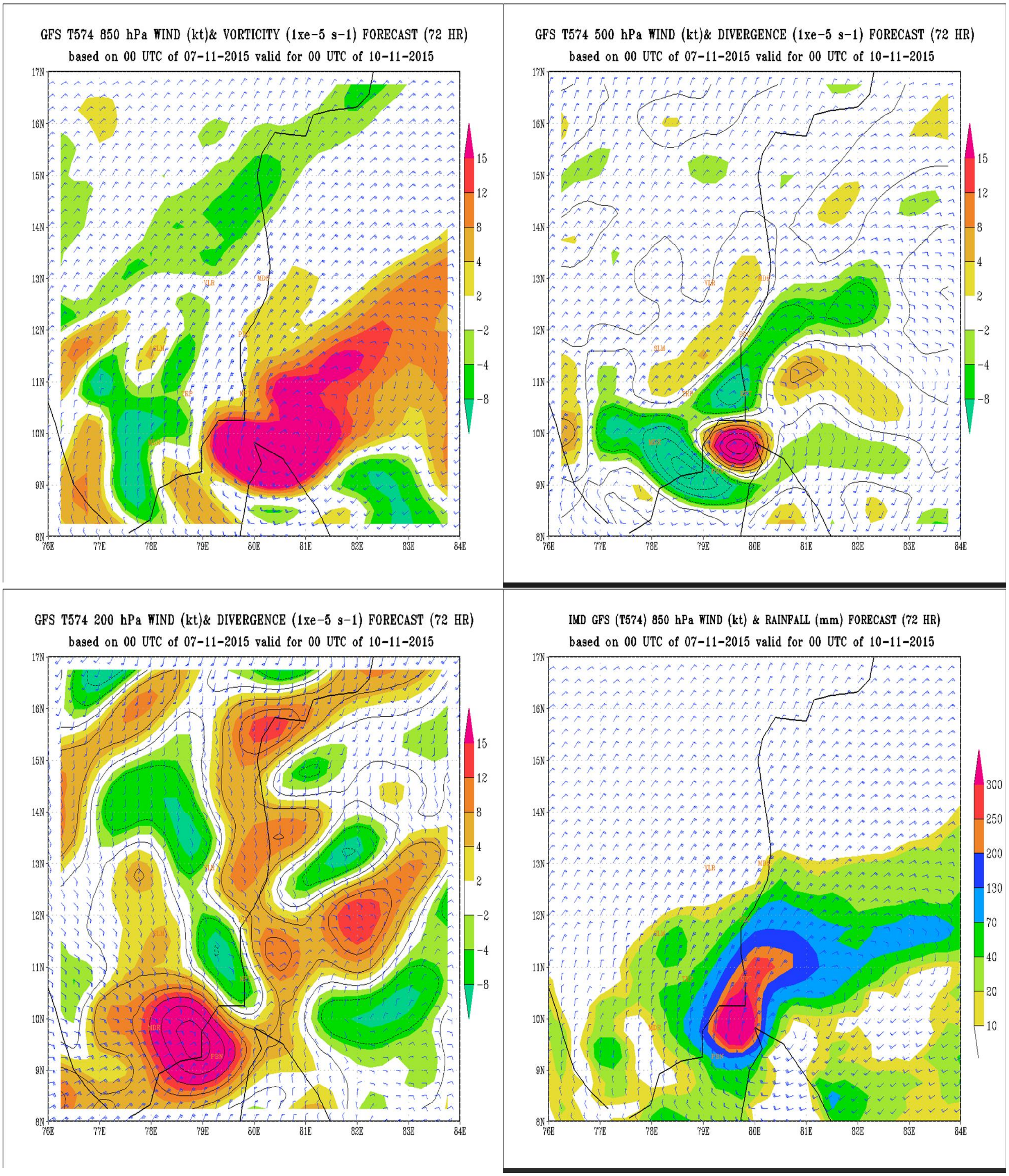


Fig.6(c) 72 hours forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **10th Nov 2015.**

4.2 Well marked low and heavy rainfall during (15-18 November 2015)

The 24 hour accumulative Heavy rainfall due to the low pressure system during 15-18 November 2015 occurred mainly over north Tamilnadu and south Coastal Andhra Pradesh and Rayalaseema regions on 16^{th} and 17^{th} November 2015. In order to assess the ability of the IMD GFS to capture center and structure of the low pressure system and rainfall, the wind and vorticity analysis at 850 is shown in Fig 7(a) ; Wind and Divergence at 500 hPa in Fig 7(b) and 200 hPa in Fig 7(c); and observed rainfall in Fig 7(d) for 15-18 November, 2015. From the observation of rainfall (Fig 7d), it was seen that the maximum amount of rainfall more than 20 cm occurred along the entire north Tamil Nadu coastal belt during the 24-hr ending 0300 UTC of 16^{th} November 2015.The GFS Analysis of wind and vorticity at 850 hPa (Fig.7a) captured the position and intensity of the system with reasonable accuracy during 15-18 November 2015. The GFS analysis of wind and divergence field at middle (Fig 7b) and upper level (Fig 7c) also supports the circulation during 15-18 November 2015. On 16^{th} November, a cyclonic circulation at 850 hPa along the Tamilnadu coast was seen in the 850 hPa wind analysis. The 850 hPa vorticity maximum of the order of 8-12 $\times$ 10−5/sec on 16 November was situated around 10.5◦N/79.5◦E. The magnitude of 850 hPa vorticity value gradually increases and shifted northward along the coast towards south Coastal Andhra Pradesh on 17^{th} November 2015.

The 24 ,48 and 72 hour forecast of IMD GFS 850 hPa wind &vorticity, wind & divergence at 500 hPa and 200 hPa and Rainfall valid on 16^{th} November 2015 is shown in Fig 8(a), 8(b) and 8(c) respectively. GFS 24 & 48 hr forecast of wind and vorticity at 850 hPa (Fig.8a) captured the position and intensity of the system with reasonable accuracy on 16^{th} November 2015 and subsequent heavy rainfall (Fig 8d). The GFS forecast of wind and divergence field at 500 hPa and 200 hPa also supports the circulation during 16 November 2015. The location of the heavy rainfall along the coast of Tamil Nadu was very well predicted with a lead time of 2 days (Fig 8 a&b), although its intensity was underestimated. With respect to day 3 forecast although the location was predicted reasonably well, the intensity was not captured in the model (Fig. 8c). With respect to the Heavy rainfall of 17 November 2015 along the Tamilnadu coast is also well predicted by this model in the 24 -72 hour forecast It is found from the Fig 9(a) –9(c) that the heavy rainfall episode on 17^{th} November 2015 was very well captured in the model interms circulation and distribution of rainfall amount, although there were some variations in magnitude and spatial locations. The location of Heavy rainfall in 17^{th} November was reasonably well predicted; although the intensity was underestimated (Fig.9a-c).The Heavy rainfall on 17 November 2015 was well predicted comparatively that of 16^{th} rainfall episode with 3 days lead time.

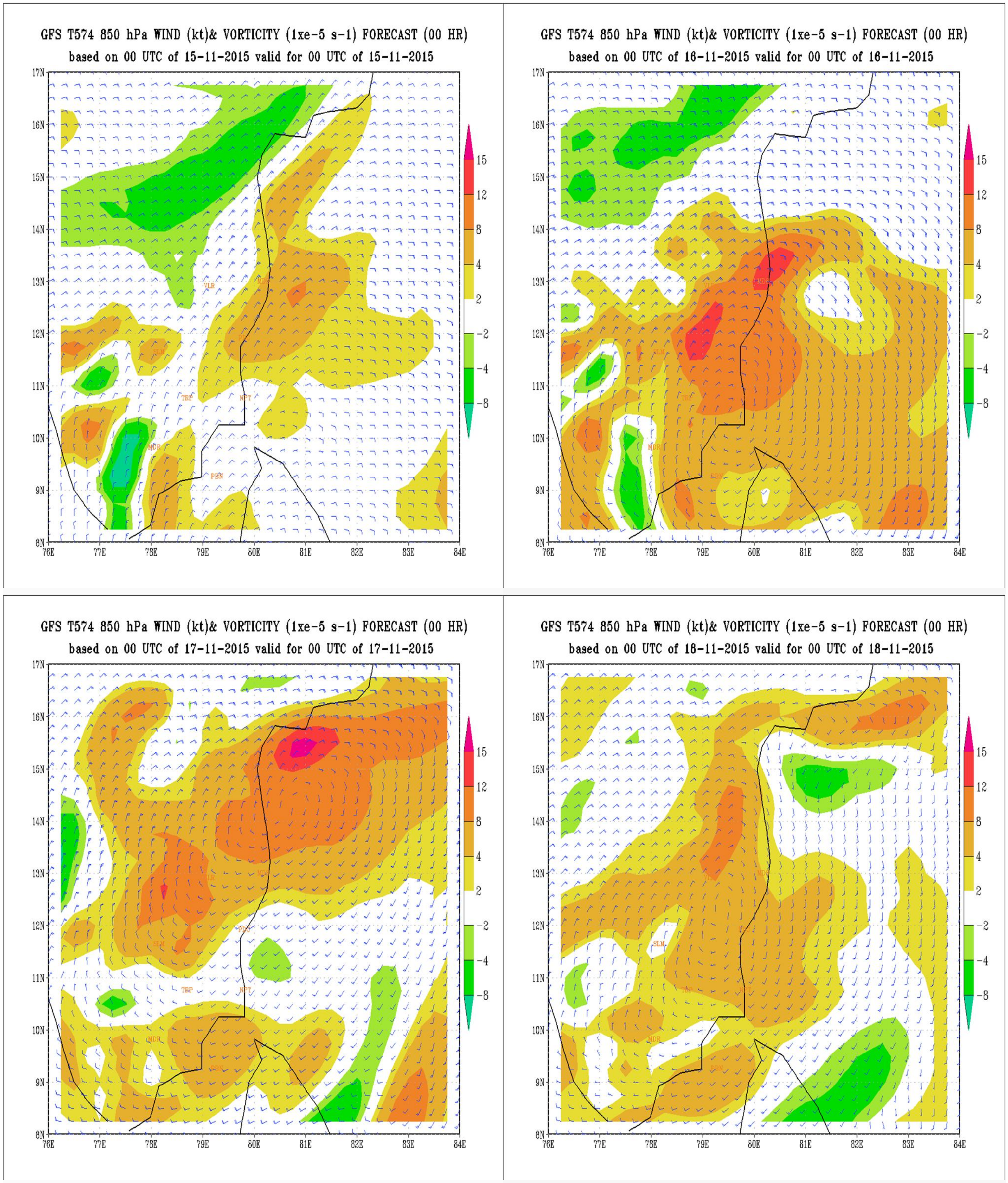


Fig.7(a) IMD GFS 850 hPa wind &vorticity analysis for **15-18 November 2015**

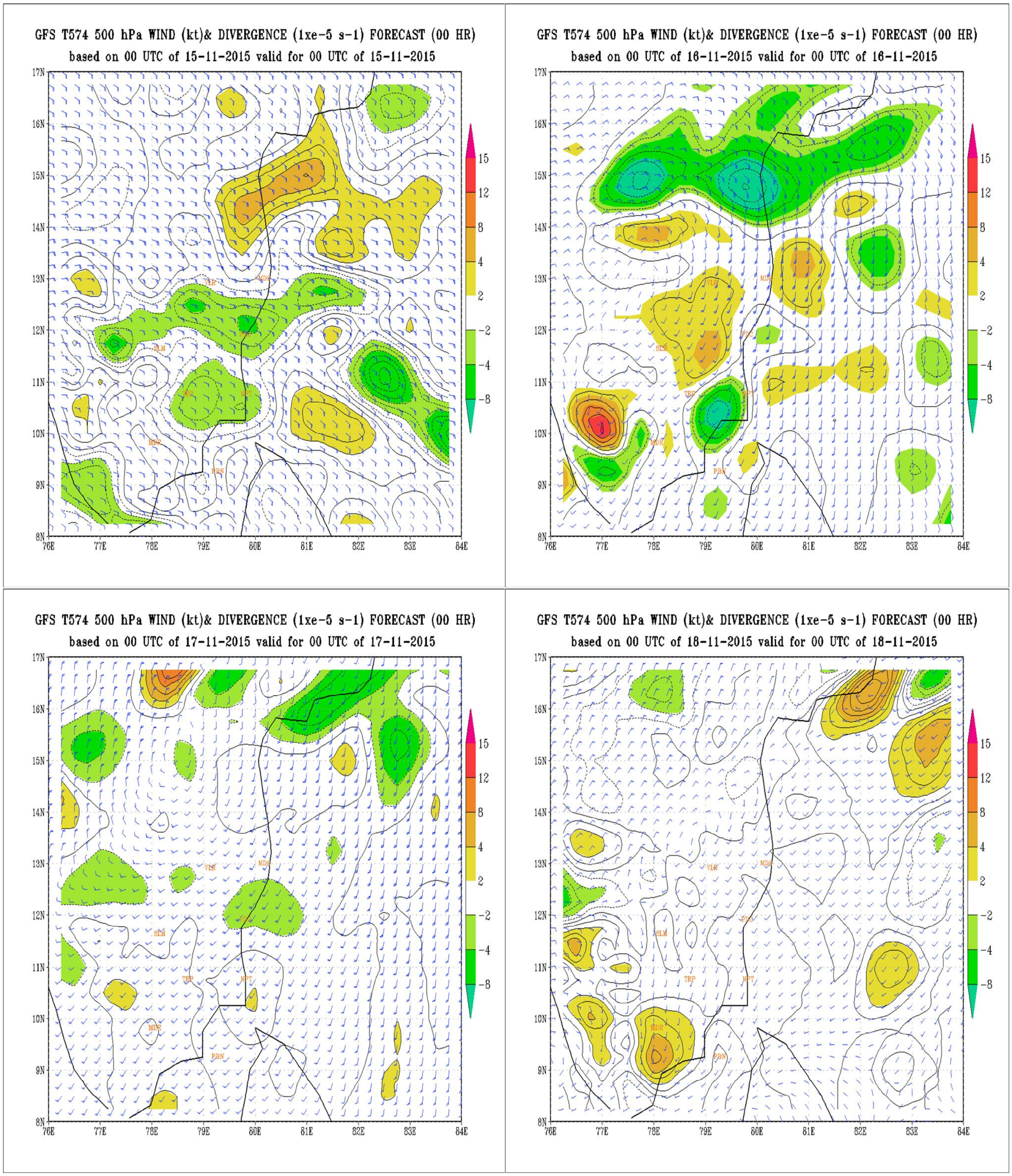


Fig.7(b) IMD GFS 500 hPa wind and Divergence analysis for **15-18 November**

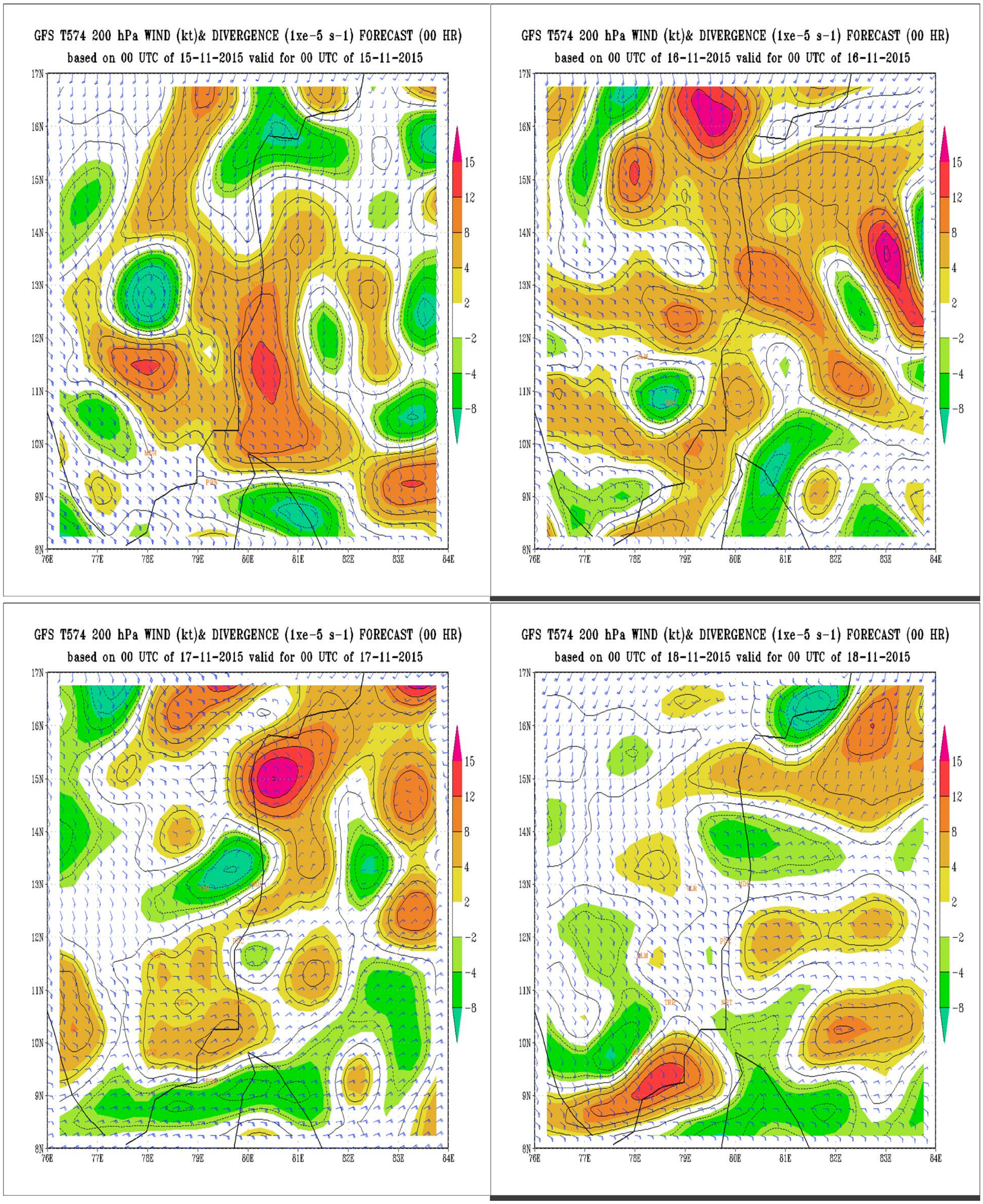


Fig.7(c) IMD GFS 200 hPa wind and Divergence analysis for **15-18 November**

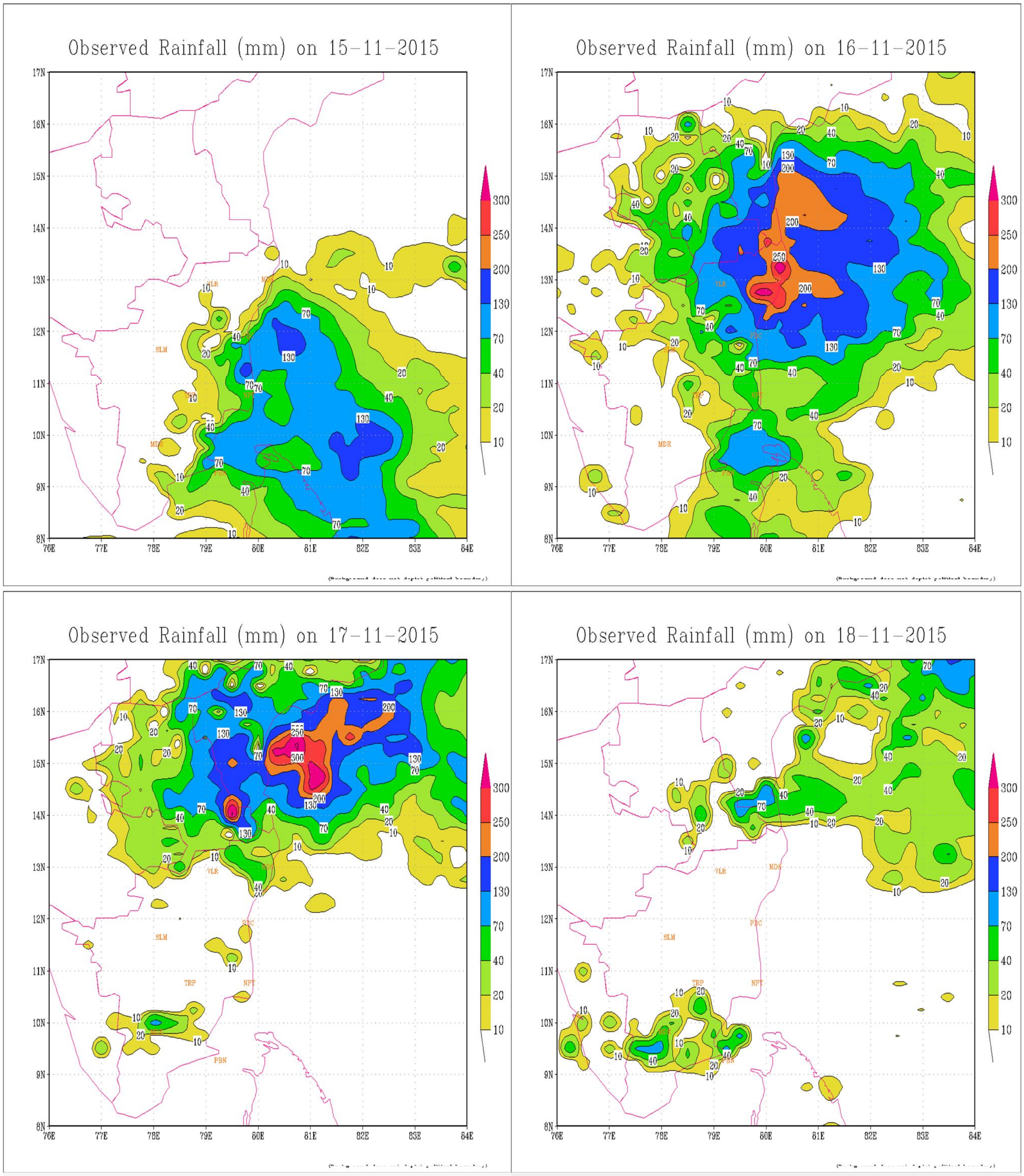


Fig.7(d) Observed Rainfall for **15-18 November 2015**

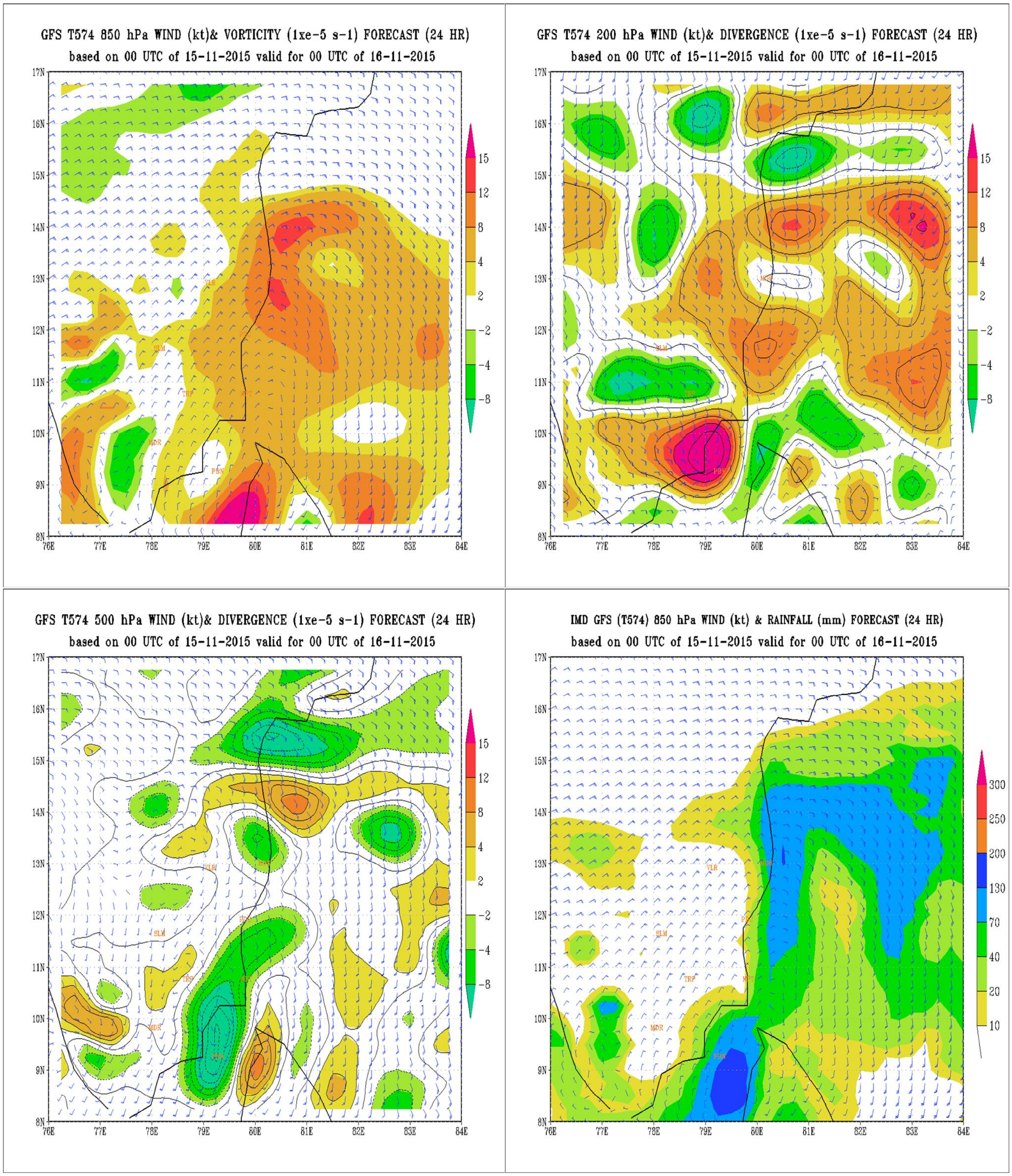


Fig.8(a) 24 hour forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **16th Nov 2015.**

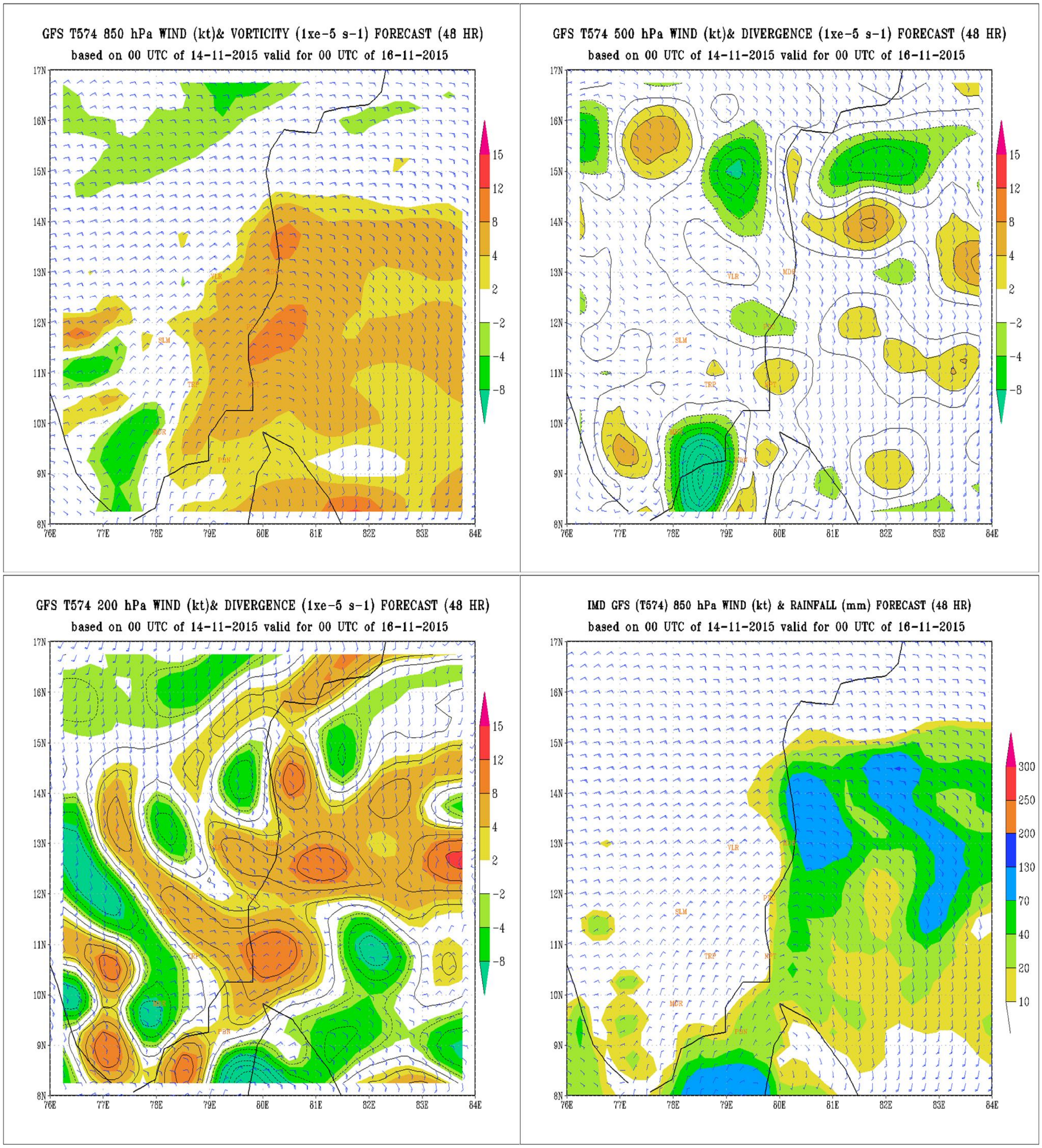


Fig.8(b) 48 hour forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **16th Nov 2015.**

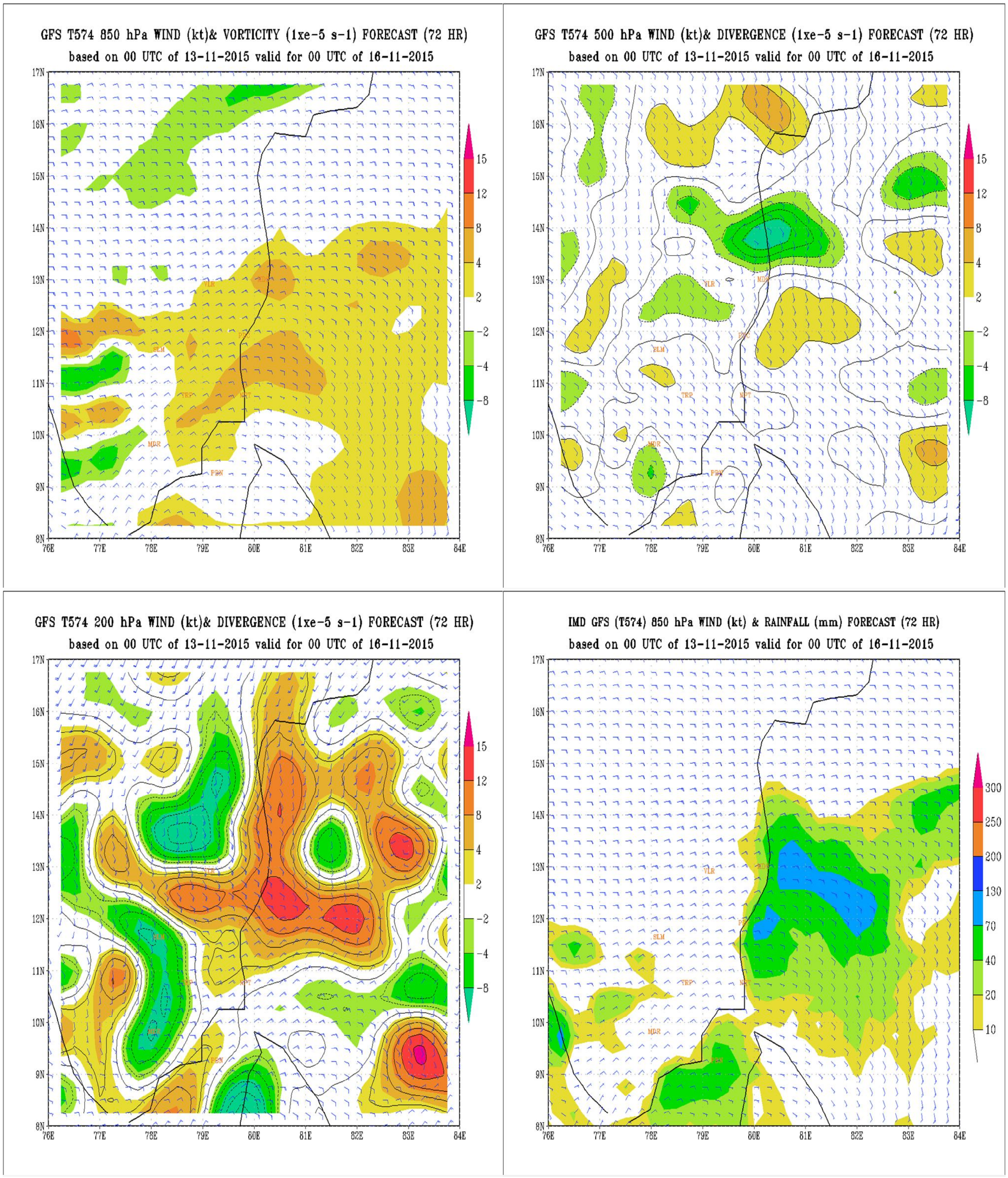


Fig.8(c) 72 hours forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **16th Nov 2015.**

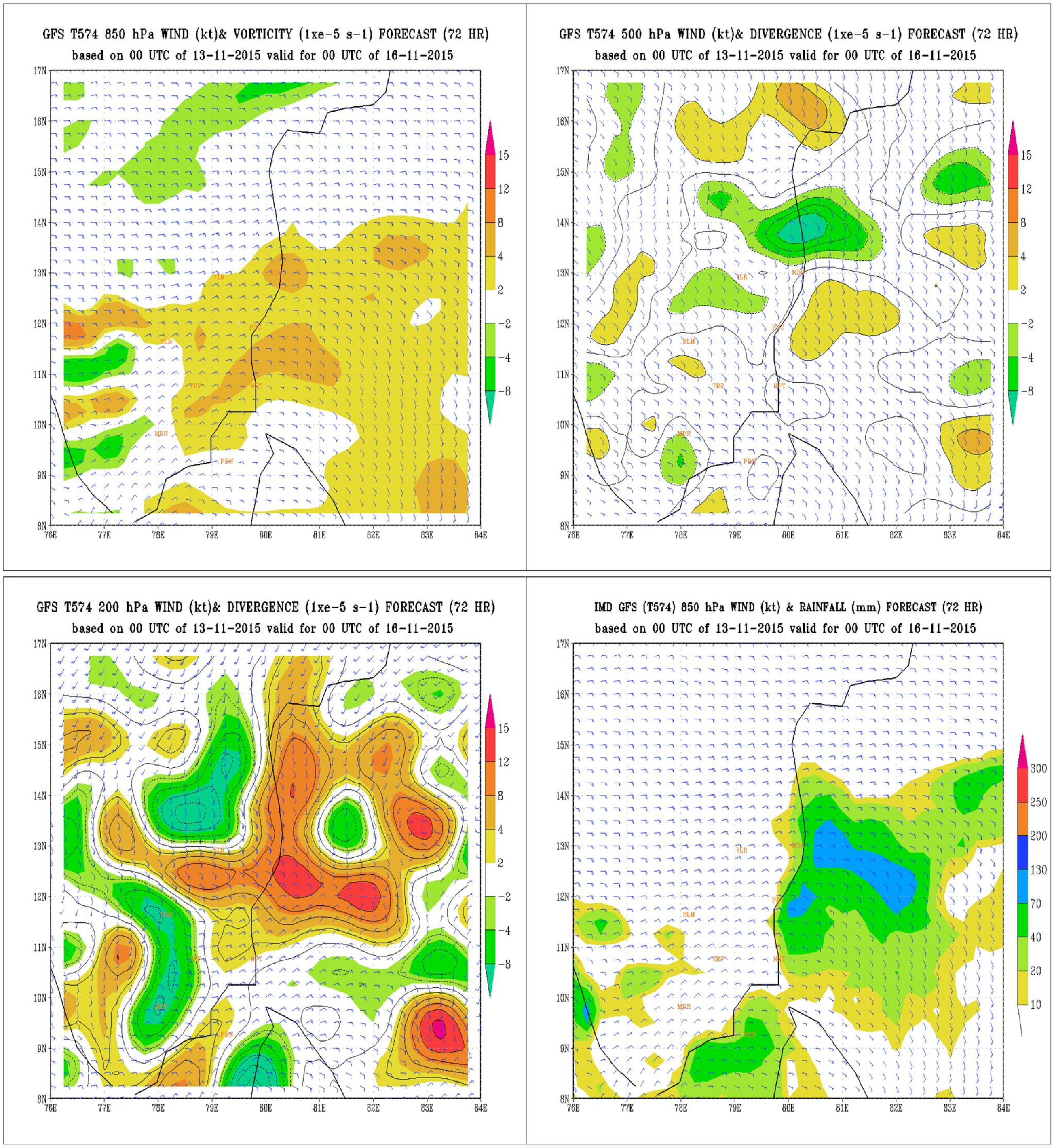


Fig.9(a) 24 hour forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **17th Nov 2015.**

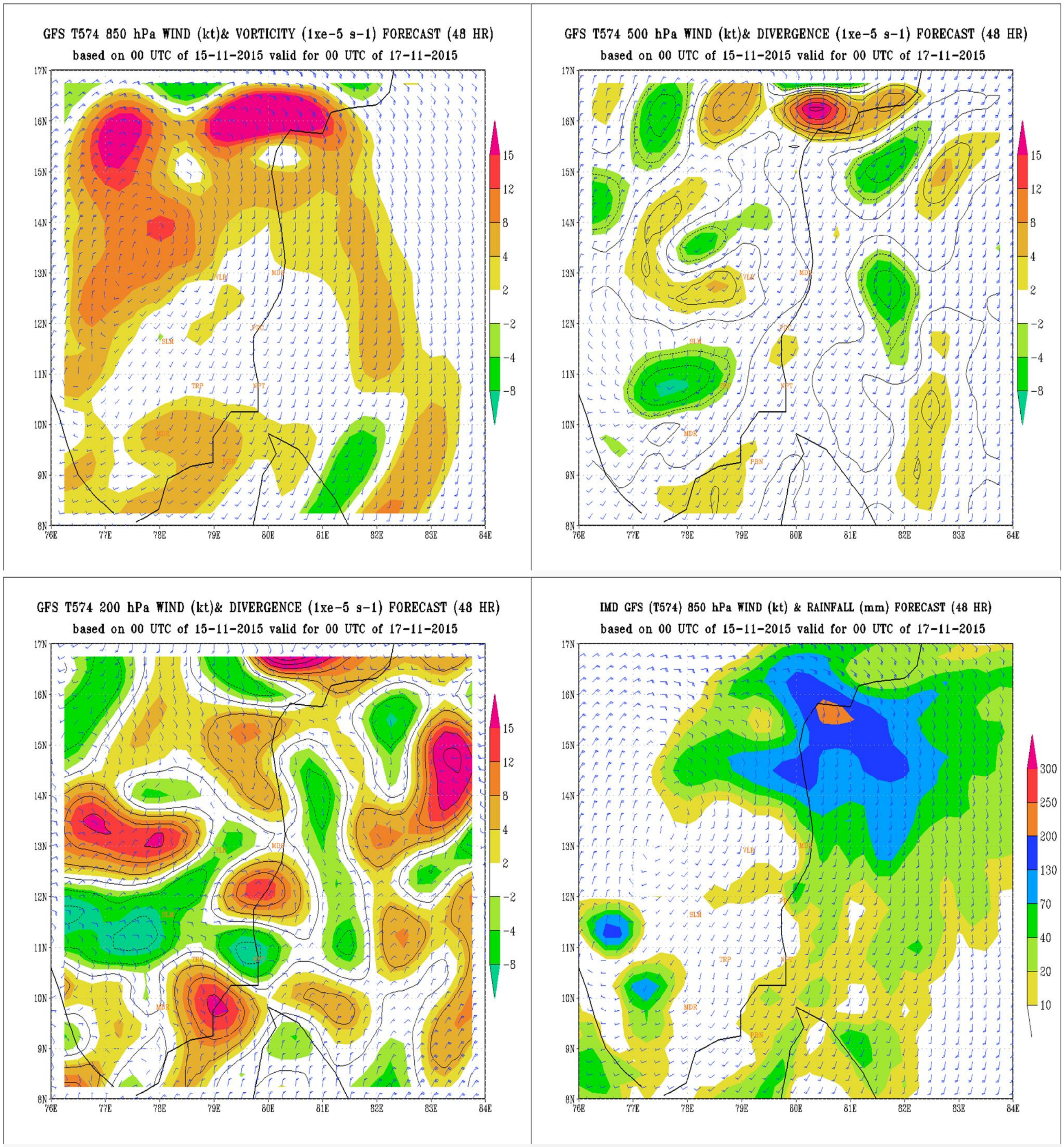


Fig.9(b) 48 hour forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **17th Nov 2015.**

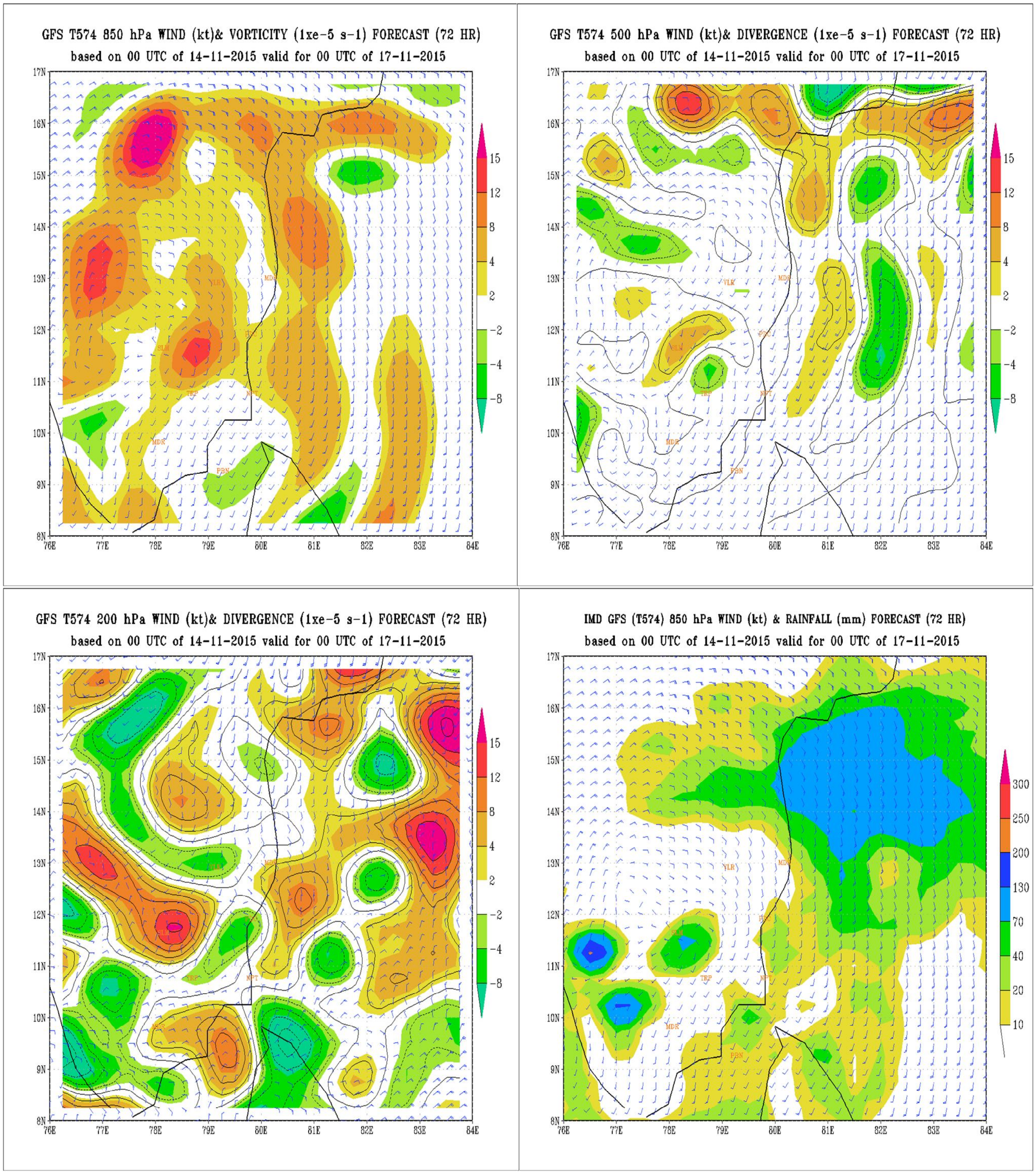


Fig.9(c) 72 hours forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **17th Nov 2015.**

4.3 Trough of low with embedded cyclonic circulation and heavy rainfall during (30 November-03 December 2015)

The Heavy rainfall (24 hour accumulative) due to the low pressure system (30 November -04 December 2015) occurred mainly over north coastal Tamilnadu and Pondicherry and over a few places along the Tamilnadu coast on 01st December,2015, heavy to extremely heavy rainfall occurred along the entire Tamilnadu coastal belt on 2nd December 2015.In order to assess the ability of the IMD GFS to capture center and structure of the LOW pressure system and rainfall, the wind and vorticity analysis at 850 is shown in Fig 10(a) ; Wind and Divergence at 500 hPa in Fig 10(b) and 200 hPa in Fig 10(c); and observed rainfall in Fig 10(d) for 30 November-03 December 2015. From the observation of rainfall (Fig 10d), it was seen that the maximum amount of rainfall more than 13 cm occurred over north coastal Tamilnadu and Pondicherry on 1st December 2015. The GFS Analysis of wind and vorticity at 850 hPa (Fig.10a) captured the position and intensity of the system with reasonable accuracy during 30Nov-3 Dec 2015. The GFS analysis of wind and divergence field at middle (Fig 10b) and upper level (Fig 10c) also supports the circulation during 30 November-03 December 2015. On 1st December 2015, a cyclonic circulation at 850 hPa over north Tamilnadu coast was seen in the 850 hPa wind analysis. The 850 hPa wind analysis shows a north south oriented trough in easterly along the Tamilnadu coast on 1st December 2015. The trough in easterly moved westward towards land areas at 850 hPa.

The 24 ,48 and 72 hour forecast of IMD GFS 850 hPa wind &vorticity, wind & divergence at 500 hPa and 200 hPa and Rainfall valid on 1st December 2015 is shown in Fig 11(a), 11(b) and 11(c) respectively. GFS forecast of wind and vorticity at 850 hPa (Fig.11a) captured the position and intensity of the system with reasonable accuracy on 1st December 2015 and subsequent heavy rainfall (Fig 11d), which occurred due to a trough in easterly wave. The GFS forecast of wind and divergence field at 500 hPa and 200 hPa also supports the circulation due to this low pressure system. With respect to the rainfall event of 1 December, 2015, which occurred with respect to a low pressure system, the location of the heavy rainfall over north coastal Tamilnadu, Pondicherry and along the coast of Tamilnadu was very well predicted with a lead time of 2 days, although its intensity was underestimated. With respect to day 3 forecast although the location was predicted reasonably well, the intensity was not captured in the model (Fig. 11c).With respect to the rainfall of 2nd December 2015, though the model could capture the heavy rainfall on day 1 forecast (Fig 12a) its location was north of the actual location (Chennai). Similar situation was also found on 48 and 72 hour forecast (Fig 12 b&c) with reduction in rainfall amount

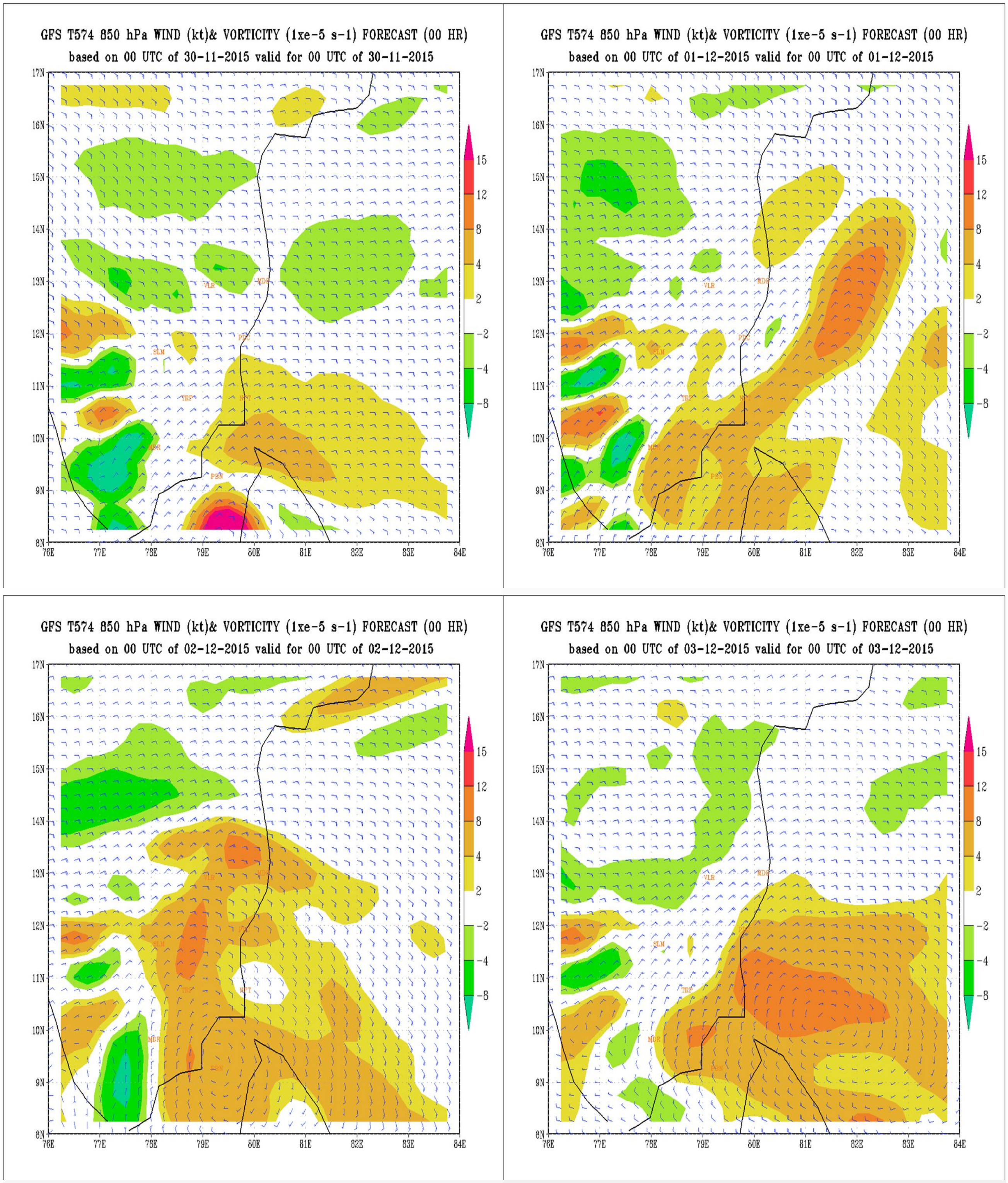


Fig.10(a) IMD GFS 850 hPa wind &vorticity analysis for **30 Nov -03 Dec2015**

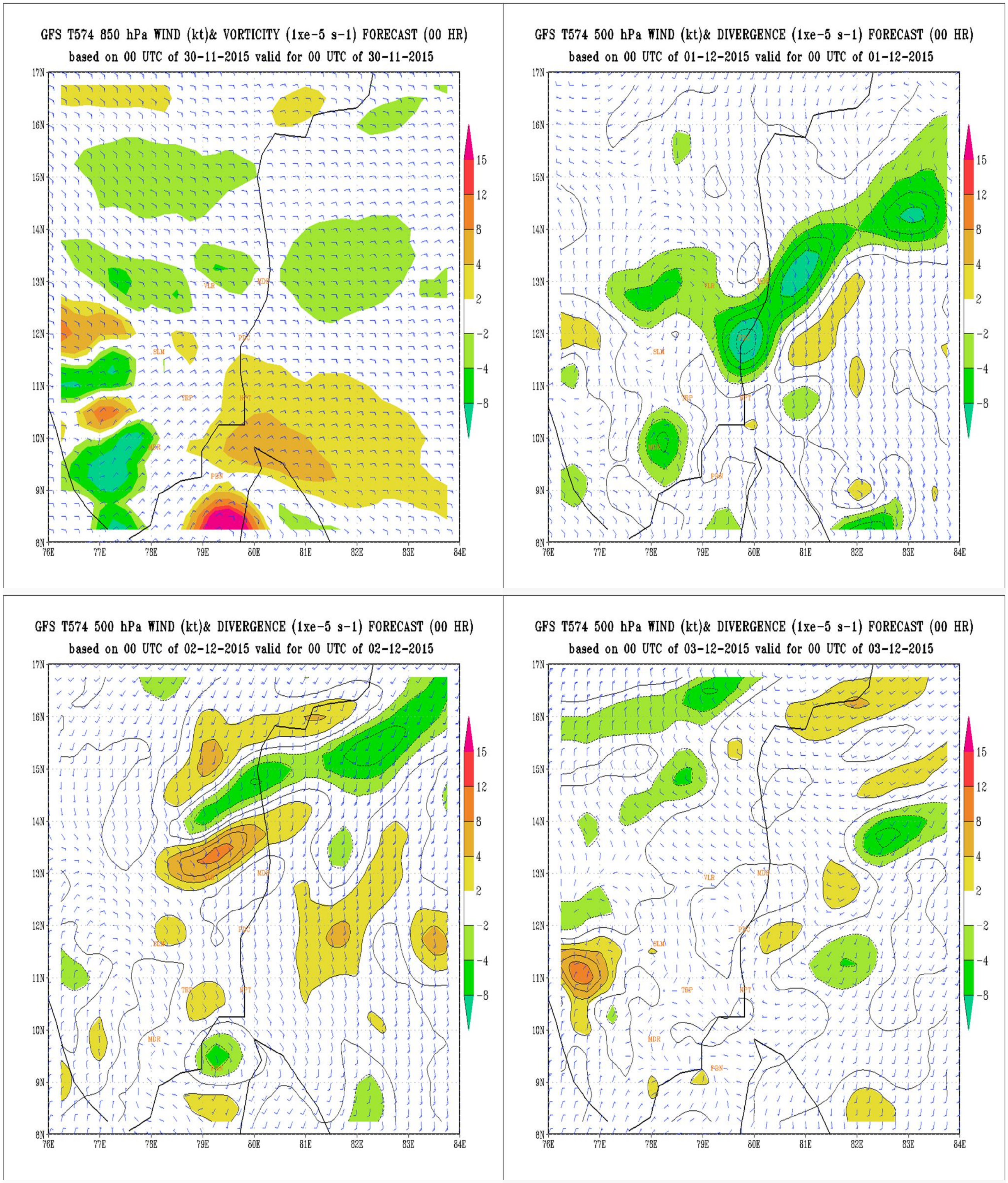


Fig.10(b) IMD GFS 500 hPa wind and Divergence analysis for **<u>30 Nov -03 Dec2015</u>**

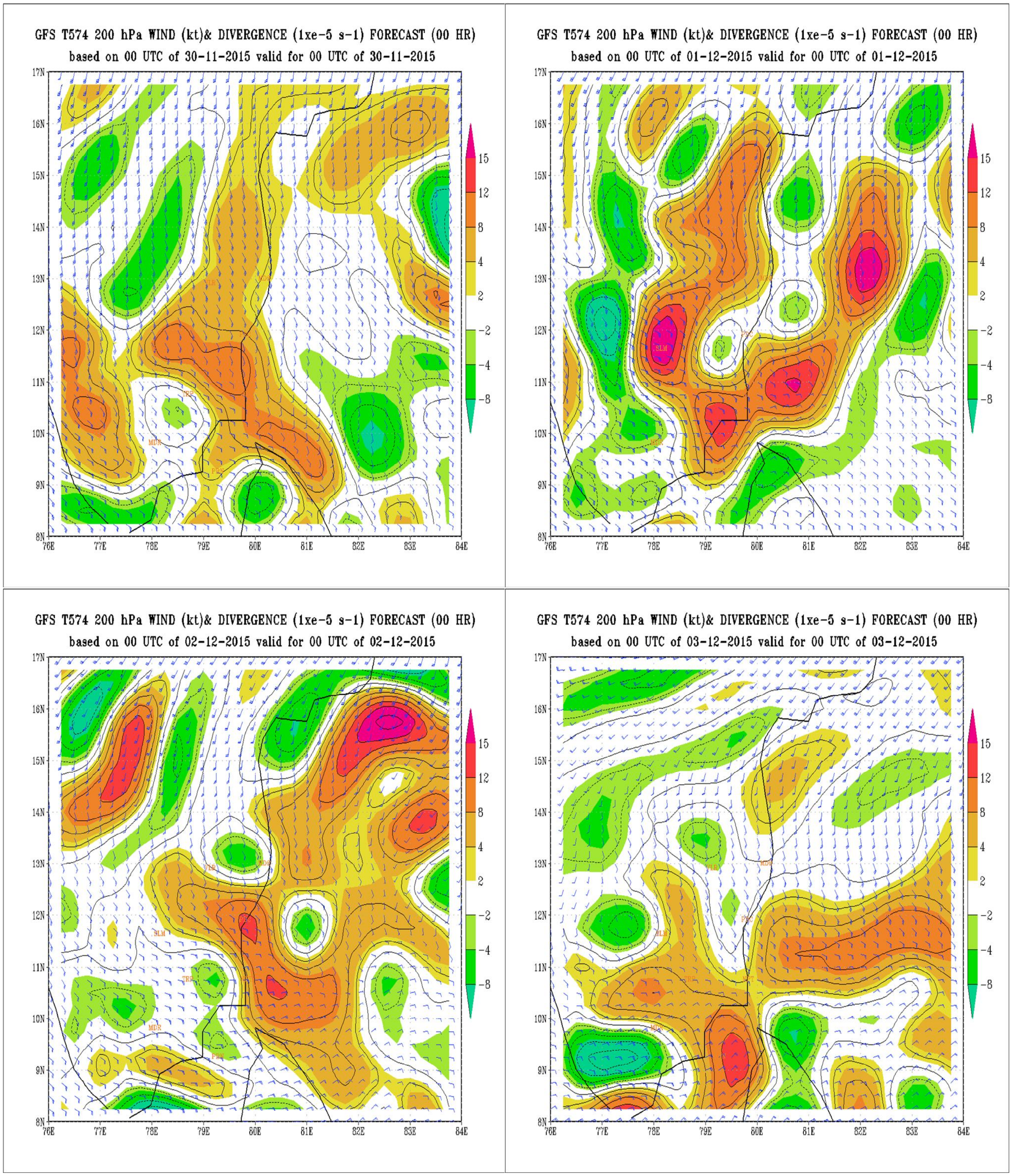


Fig.10(c) IMD GFS 200 hPa wind and Divergence analysis for **30 Nov -03 Dec2015**

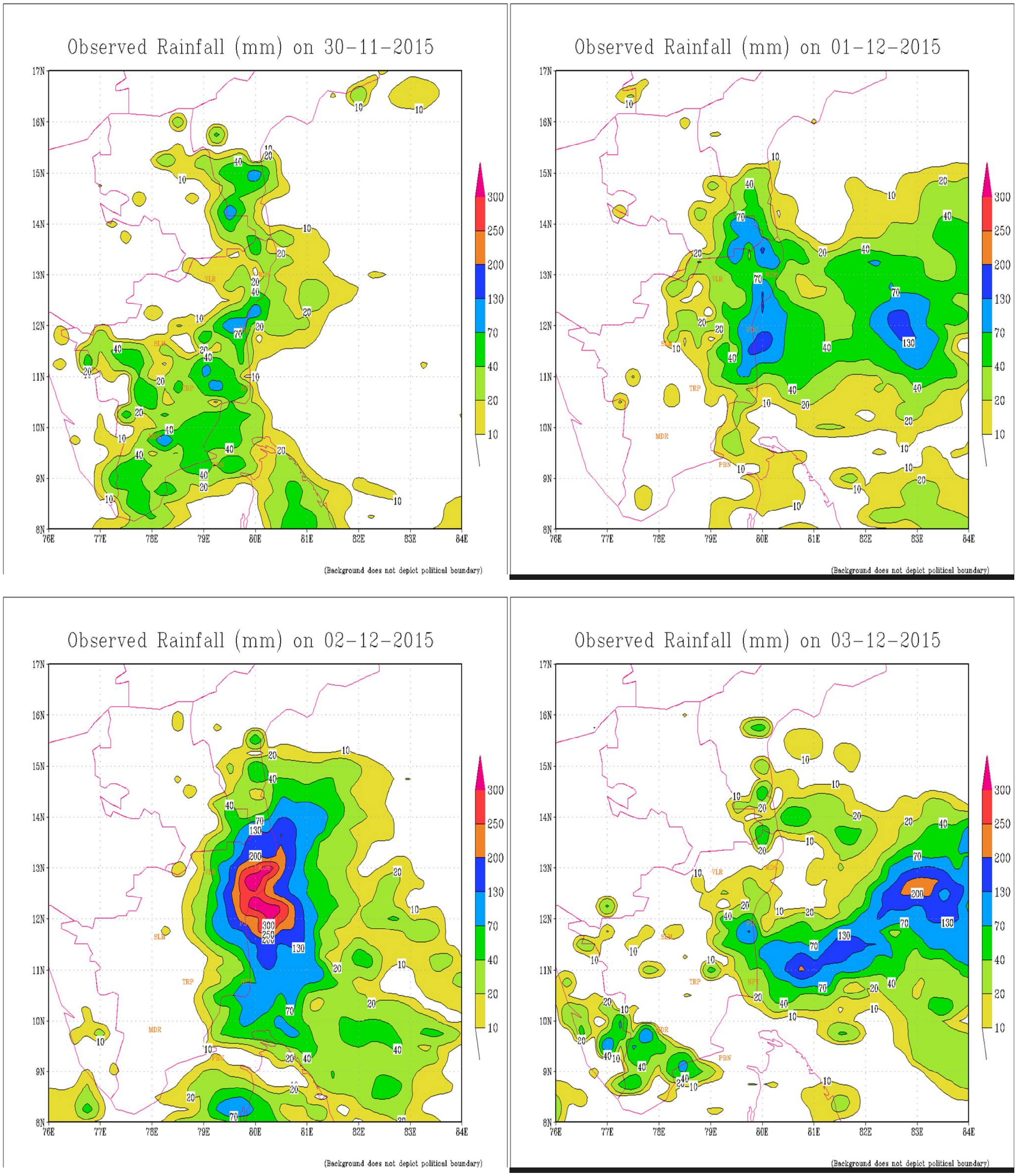


Fig.10(d) Observed Rainfall for **30 Nov -03 Dec2015**

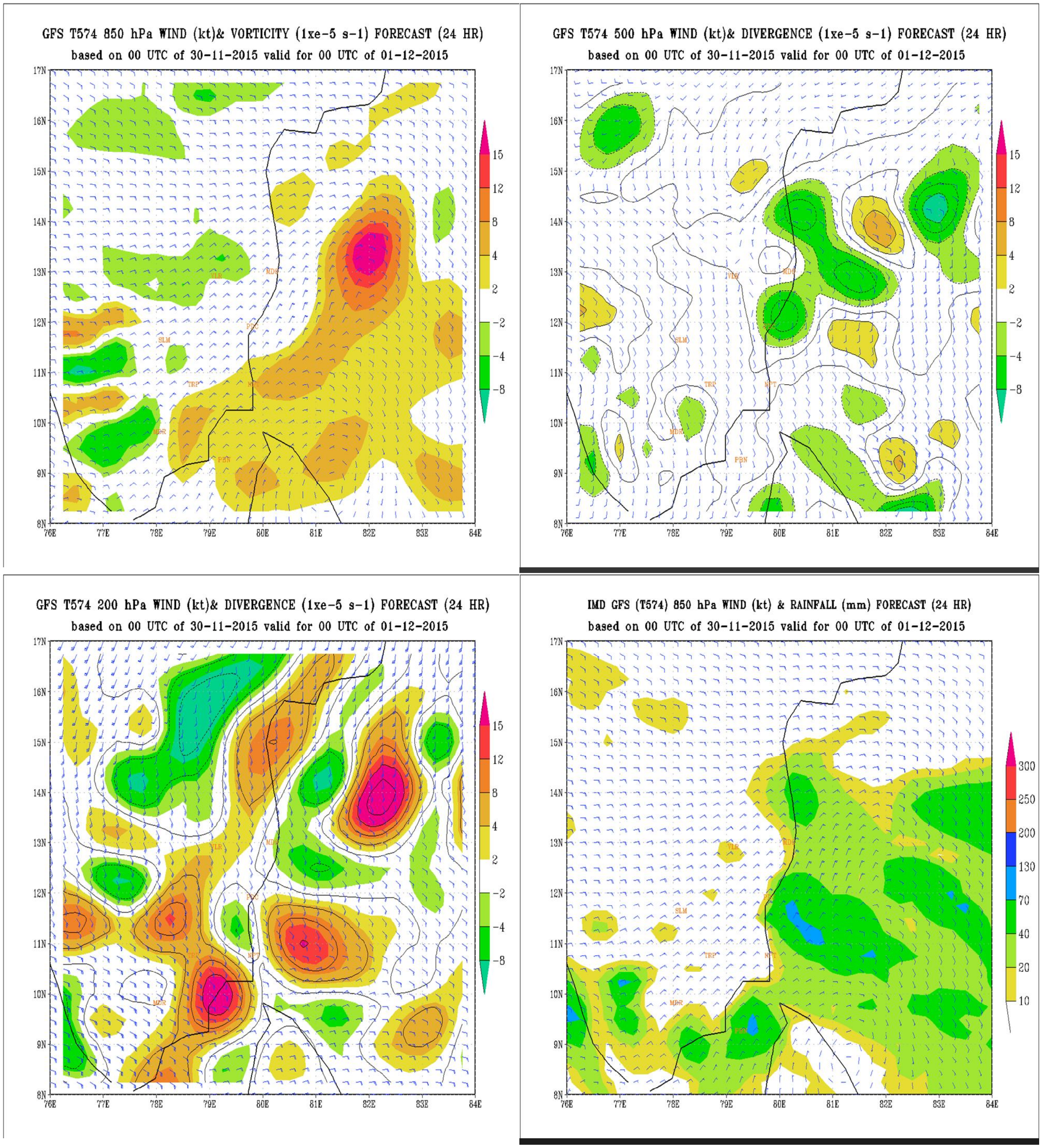


Fig.11(a) 24 hour forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **01 Dec 2015.**

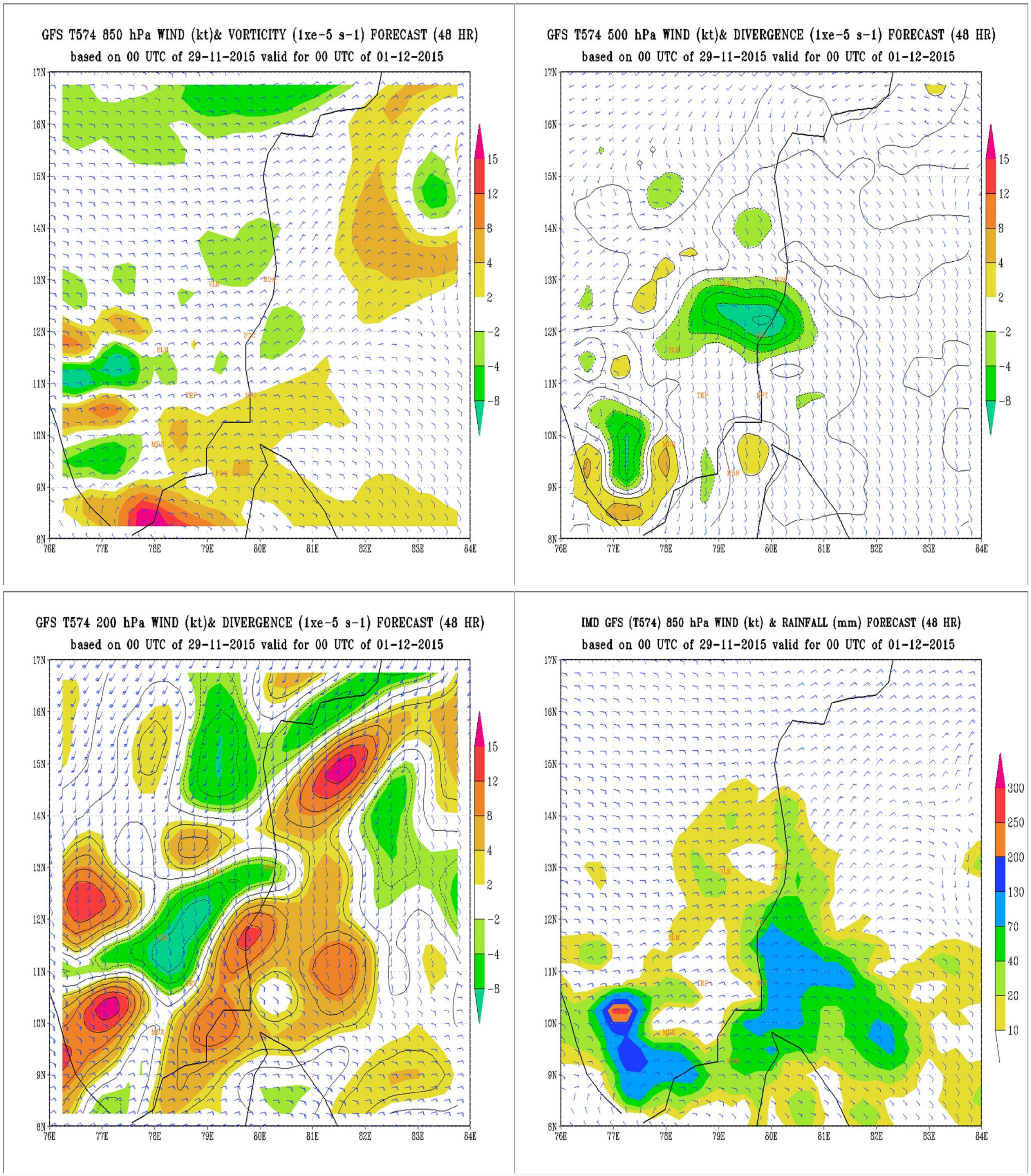


Fig.11(b) 48 hour forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **01 Dec 2015.**

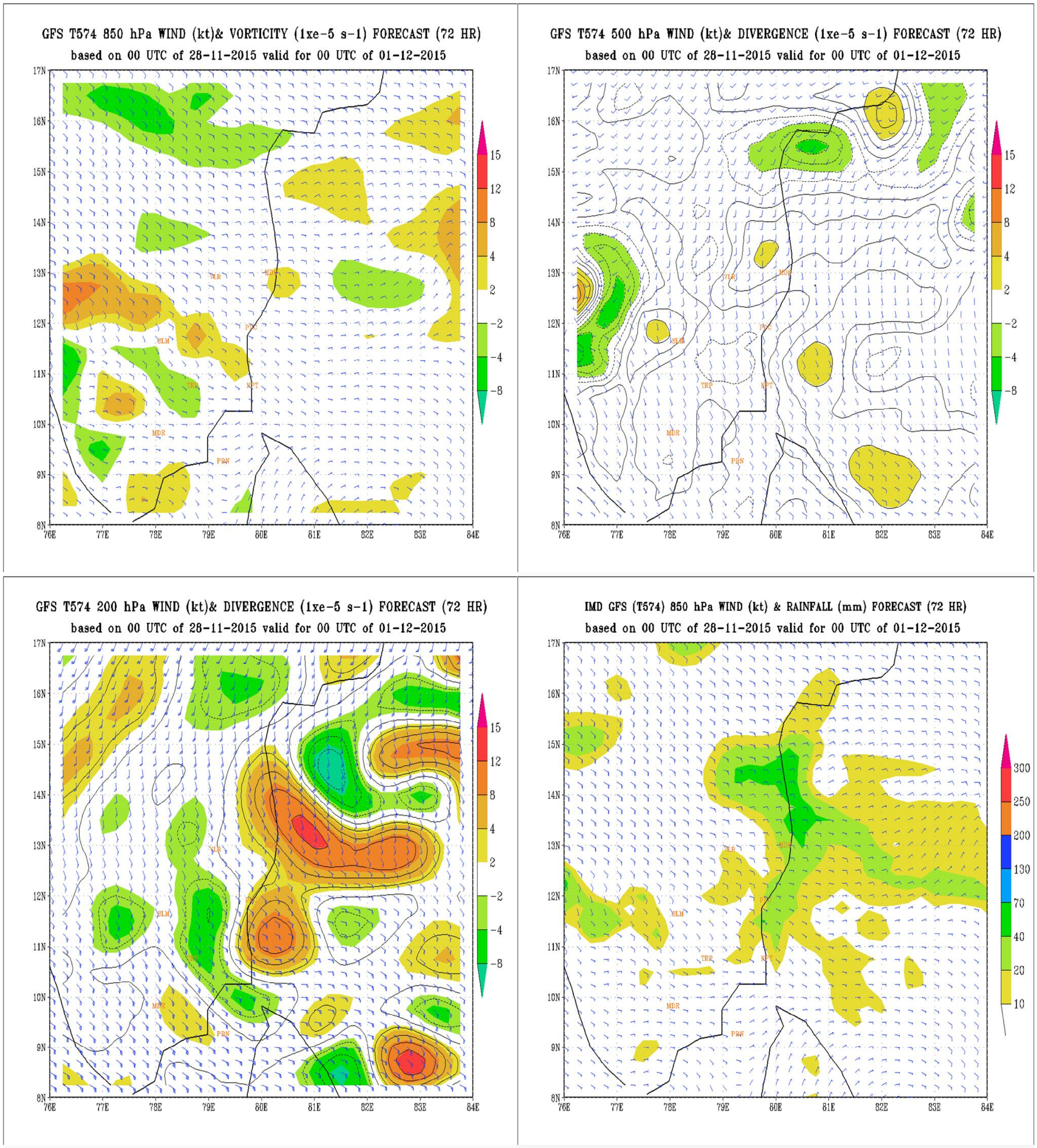


Fig.11(c) 72 hours forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **01 Dec 2015.**

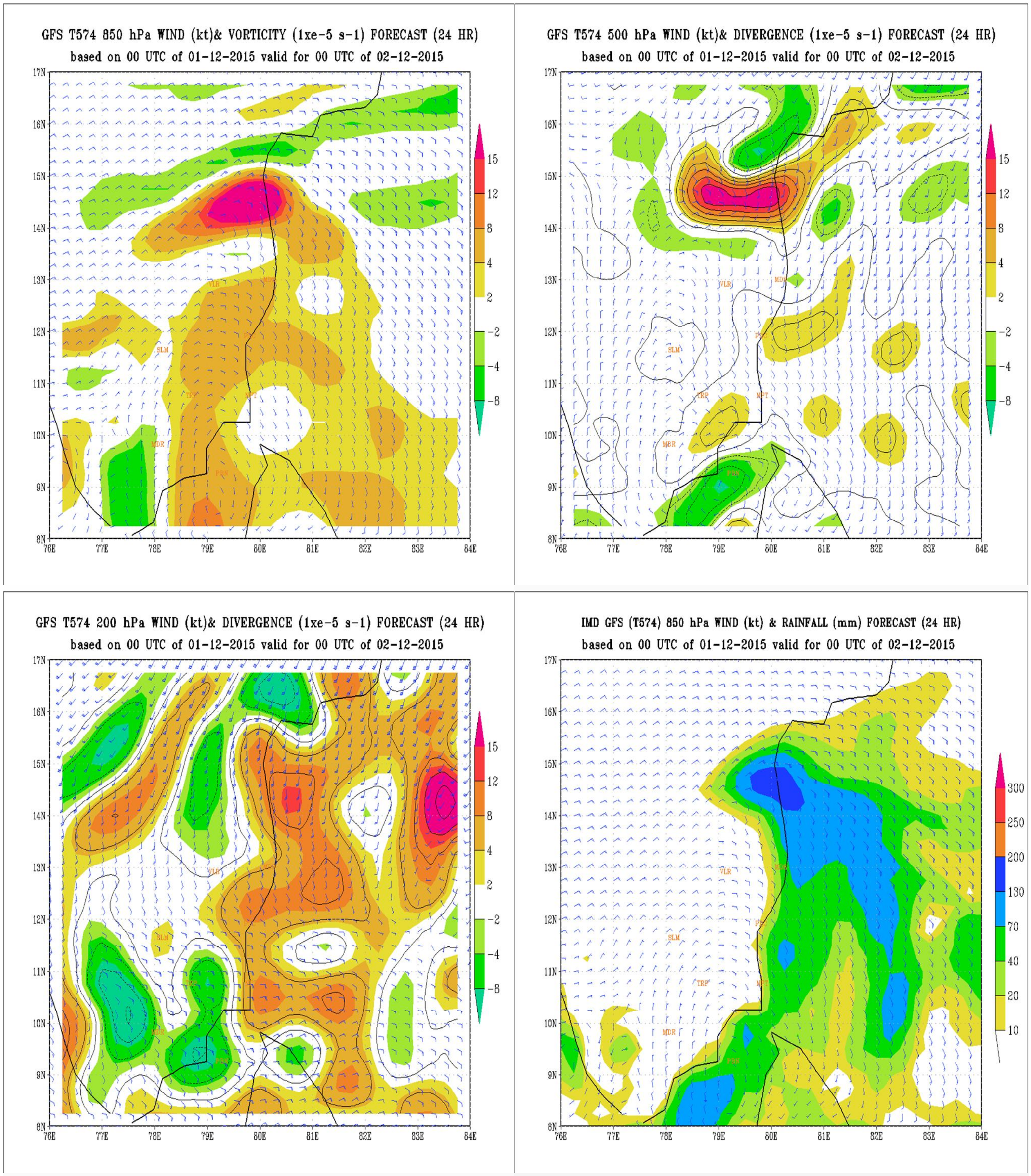


Fig.12(a) 24 hour forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **02Dec 2015.**

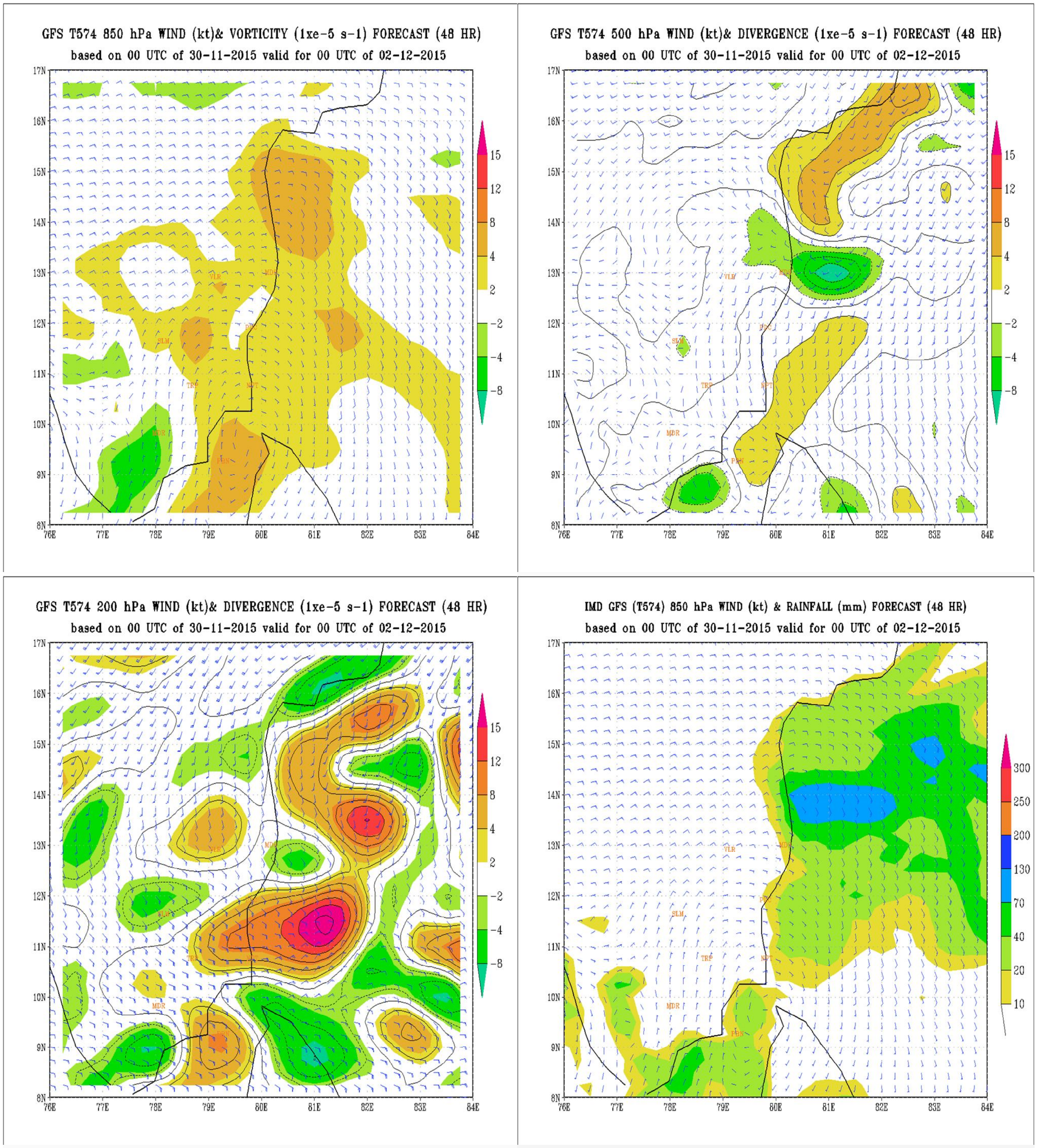


Fig.12(b) 48hour forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **02Dec 2015.**

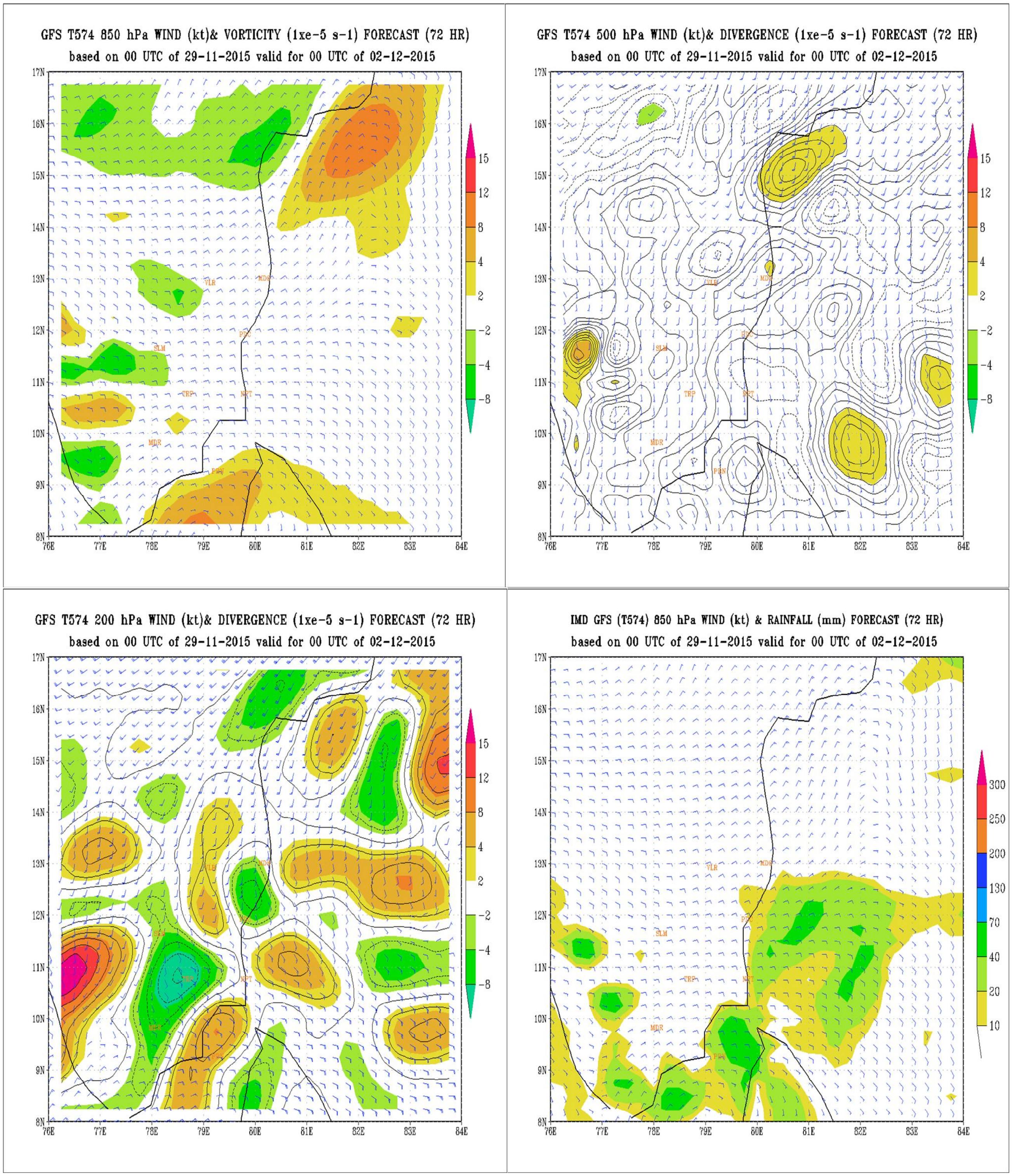


Fig.12(c) 72 hours forecast of IMD GFS 850 hPa wind &Vorticity, 500 hPa Divergence, 200 hPa Divergence and Rainfall on **02Dec 2015.**

5. Performance of WRF model

5.1 Deep depression (08 – 11 November 2015)

The heavy rainfall event during 09-10 November 2015 occurred over Tamil Nadu was caused by a depression formed over southwest Bay of Bengal as a low moving over inland on 9 November and stayed over the region as a depression on 10 November as well. The figure 1 shows the 9 km WRFDA analyses of mean sea level pressure during 8 November to 11 November valid at 00 UTC. It shows the movement of low pressure system from southwest BOB to land in first three days and dissipating thereafter on 11 November 2015 as a trough.

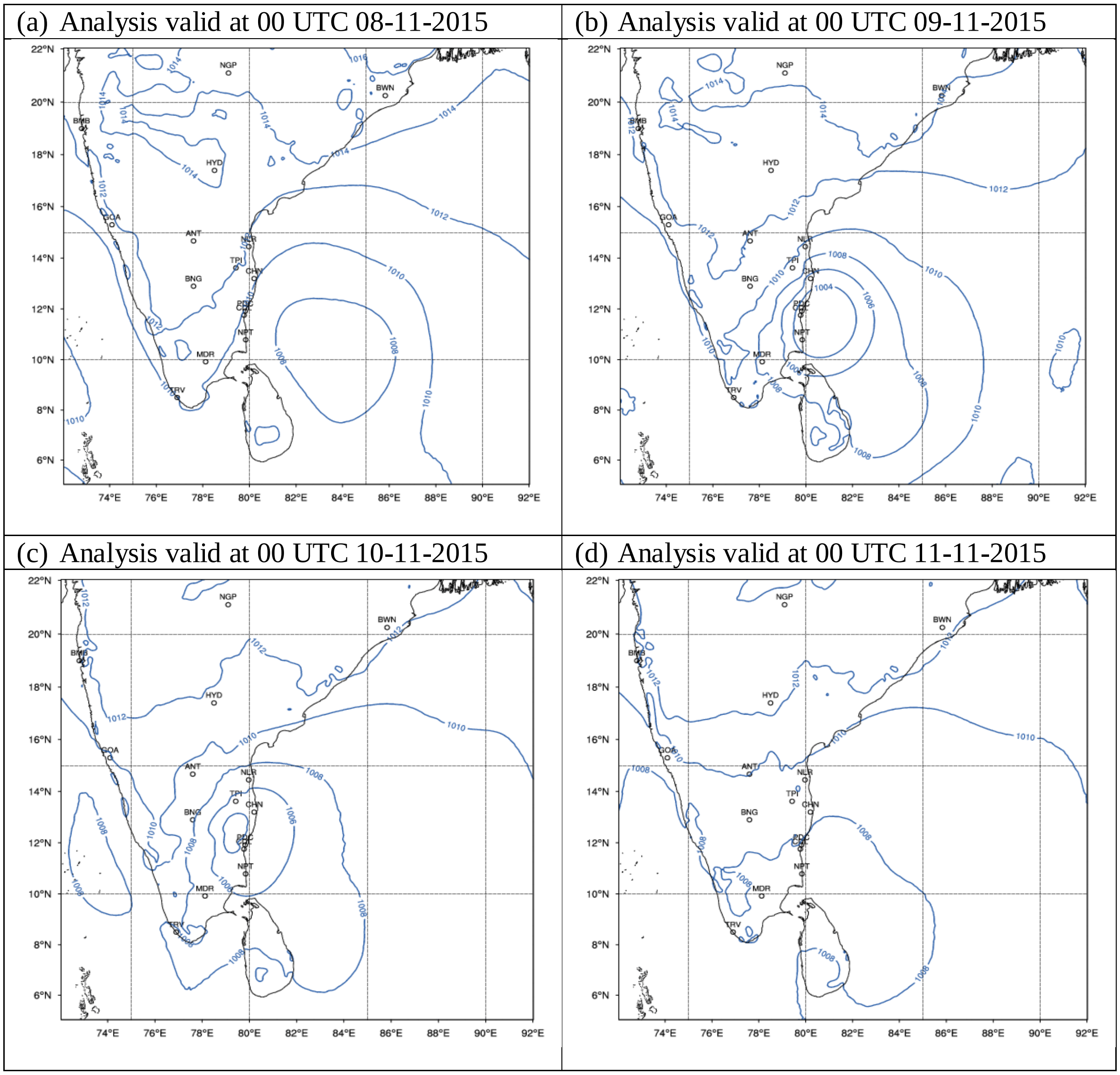


Fig. 13 Mesoscale analyses of mean sea level pressure (hPa) valid at 00 UTC of (a) 8, (b) 9, (c) 10 and (d) 11 November 2015.

The relative vorticity evolution along with wind flow pattern at 850 hPa during the same period has been shown in figure 14. It is clearly shown that the system intensified as it moved towards Tamilnadu coast on 09th November and persists over coastal Tamilnadu region north of Chennai with a little weakening during 10th November 2015.

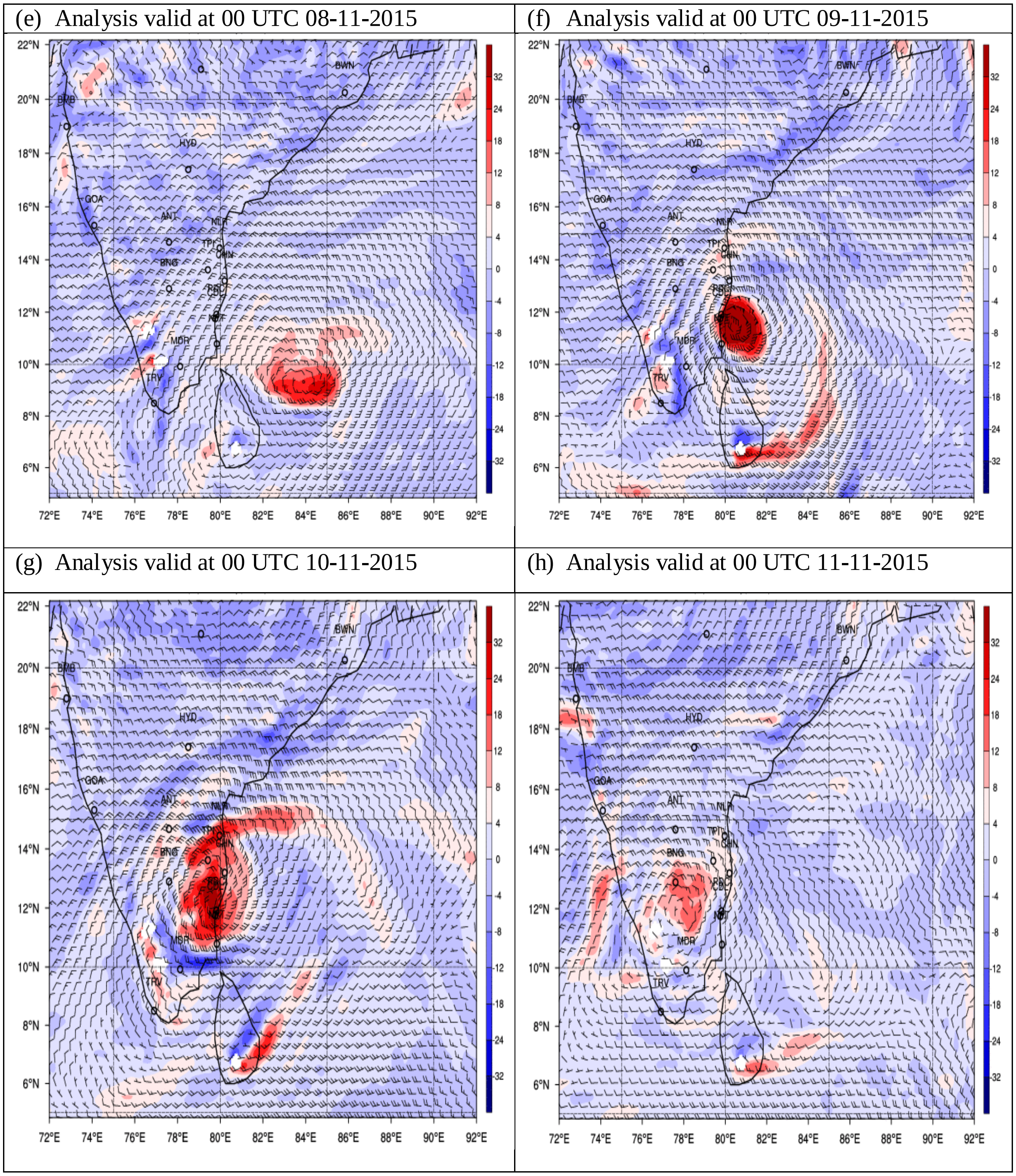


Fig. 14 The mesoscale analyses of wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa level during 00 UTC on (a) 08, (b) 09, (c) 10 and (d) 11 November 2015.

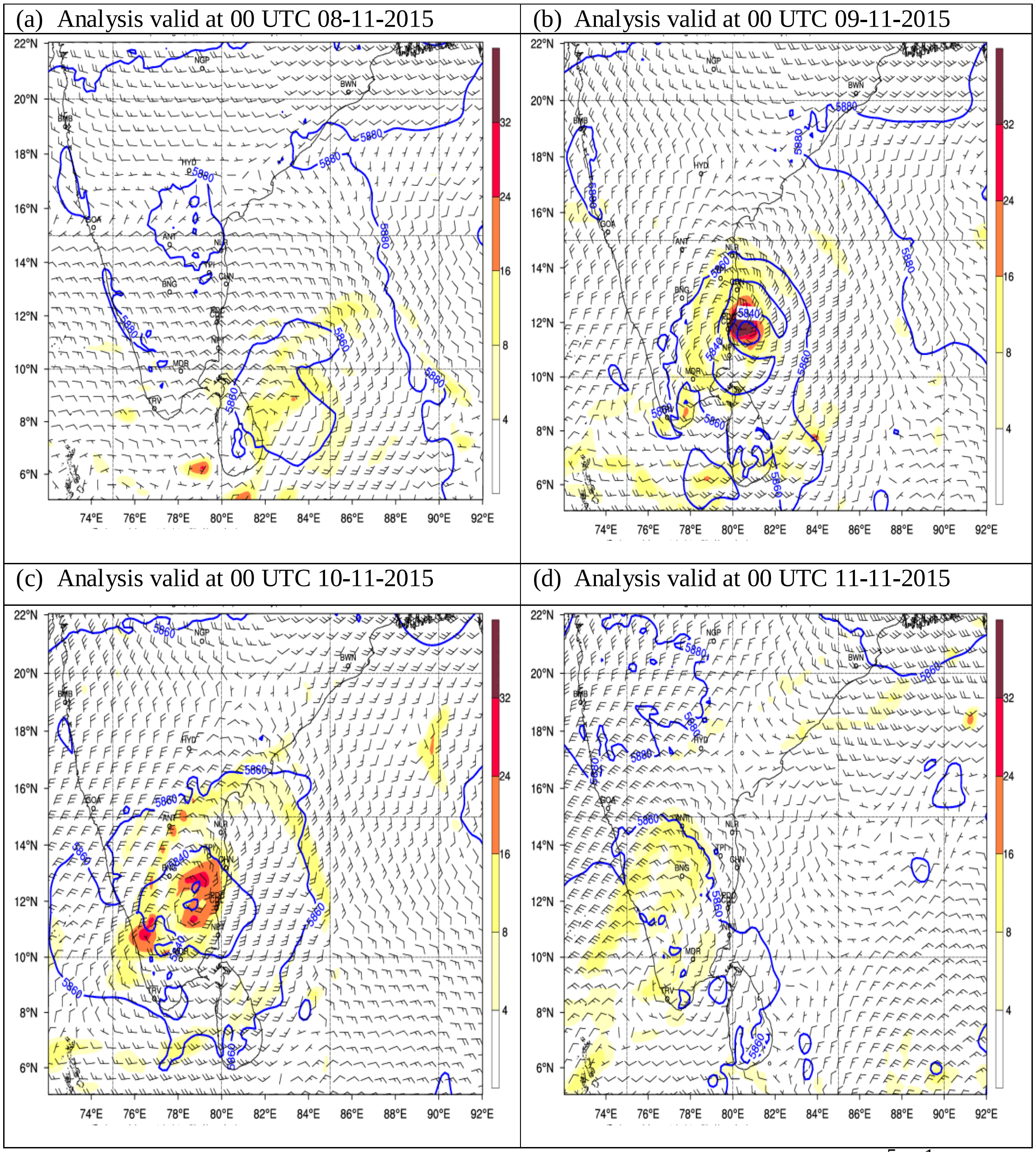


Figure 15 The analyses of wind and positive relative vorticity (x 10^{-5} s^{-1}) at 500 hPa during 00 UTC on (a) 08, (b) 09, (c) 10 and (d) 11 November 2015.

The figure shows that the relative vorticity value diminishes on 11th as system dissipates at the surface.

Figure 15 shows the analyses of wind and positive (cyclonic) relative vorticity maps during 00 UTC of four consecutive days during the event. Similar to the vorticity change at 850 hPa, the systems also shows intensification along with circular structure up to 500 hPa level on 9th November. But, on 10th November, the structure of the system at mid-troposphere being elongated orients itself in northeast-southwest direction. At the same time, it shows likely weakening as well. The maximum value of positive vorticity diminishes and moved westward further as the system weakens on 11th November.

The figure 16 describes the wind and divergence state of the upper troposphere at 200 hPa during 00 UTC of each day of the event discussed above. The panels of the figure show that a zone of divergence lies over Tamilnadu and adjoining BOB region along with the ridge at this level during the event. The maximum divergence occurred on 9th November over Tamilnadu which shifted northward on 10th and further northeastward on 11th November. It is also noted that the location of low pressure system at the surface was south of the ridge line at 200 hPa in all four days.

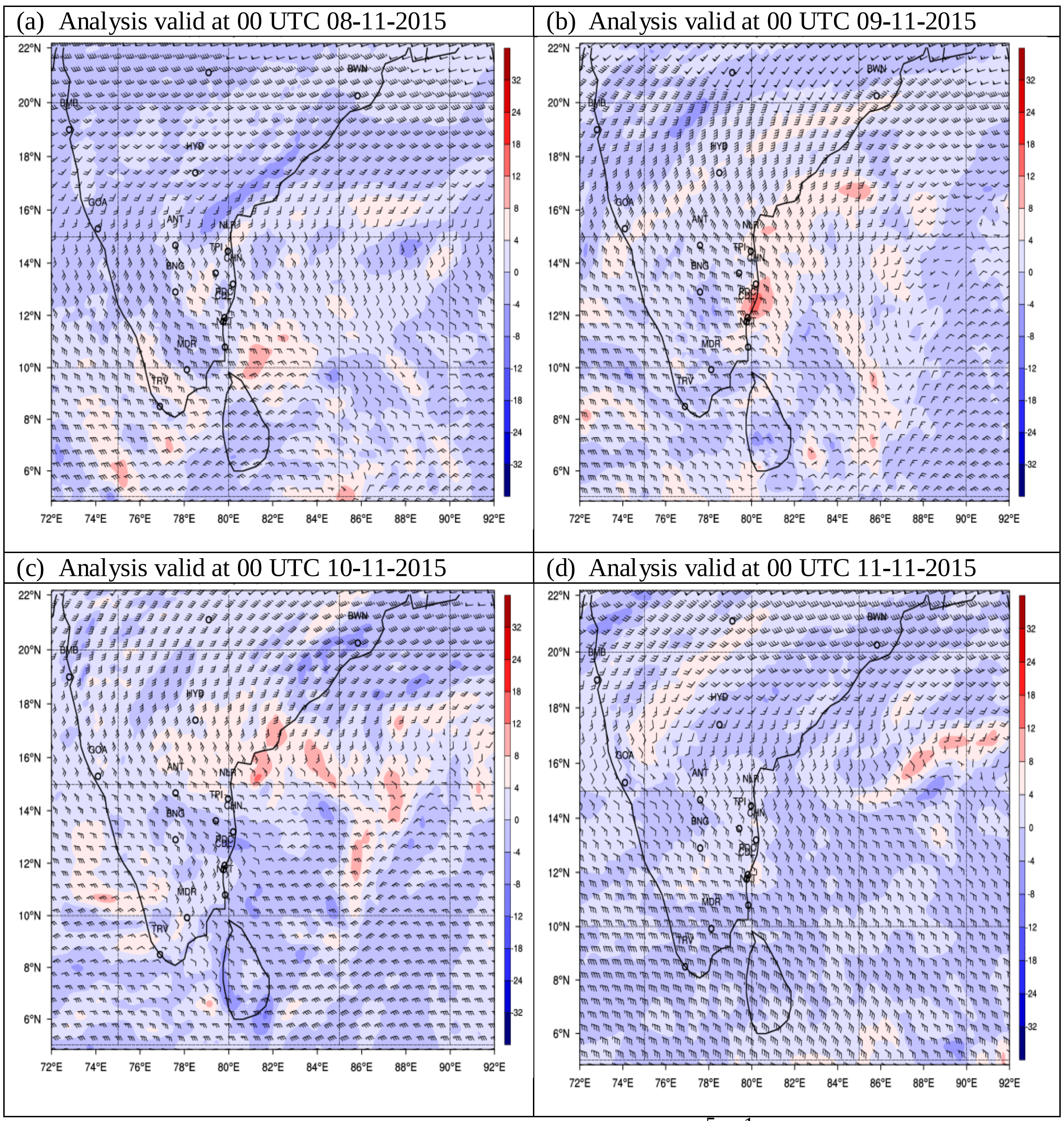


Figure 16 The analyses of wind and divergence (x 10^{-5} s^{-1}) at 200 hPa during 00 UTC on (a) 08, (b) 09, (c) 10 and (d) 11 November 2015.

The circulation features as described in Figures 1-4 are clearly showing the possibility of prominent weather activity over the region during 9 to 11th November 2015. The figure 5 shows the observed rainfall analyses (0.25^{o}x0.25^{o}) over the region. The rainfall activity occurring over southwest BOB shifted over Tamilnadu coast and produced intense rainfall on 9th November with north-south orientation. The rainfall belt shifted inland next day but intensity has been reduced subsequently. On 11th November, the rainfall was confined over north Namilnadu region and reduced rainfall activity occurred over rest of the region.

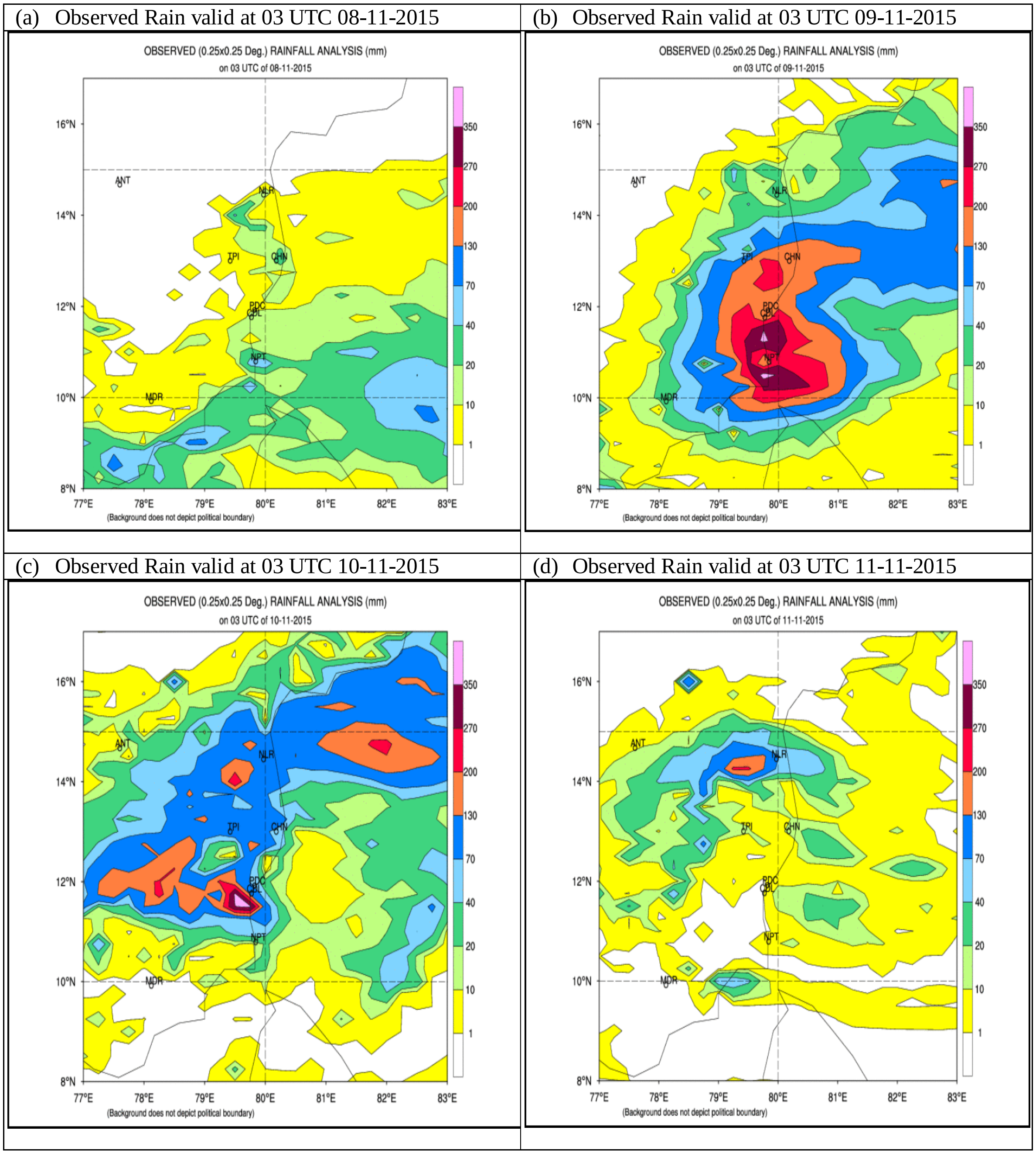


Figure 17 Observed rainfall analyses (0.25^{o}x0.25^{o}) valid at 03 UTC on (a) 08-11-2015, (b) 09-11-2015, (c) 10-11-2015 and (d) 11-11-2015.

The 24 hour forecasts of wind circulation feature in lower troposphere (850 hPa) from WRF model valid at 00 UTC of 09 to 11th November are shown in different panels of figure 6. The overall representation of system movement along with its intensification and dissipation matches well with analyses (figure 14). The locations of maximum cyclonic vorticity near Tamilnadu coast and adjoining area on 9th and 10th November are well predicted by the model. The associated band structure of the system is well brought out in the forecast which may not be present in the mesoscale analysis due to coarse resolution of first guess used in the assimilation system and scarcity of upper-air observations matching with the resolution (9 km) of the analysis. Therefore, the verification of the structure of the system in model forecasts is invariably difficult in this regard.

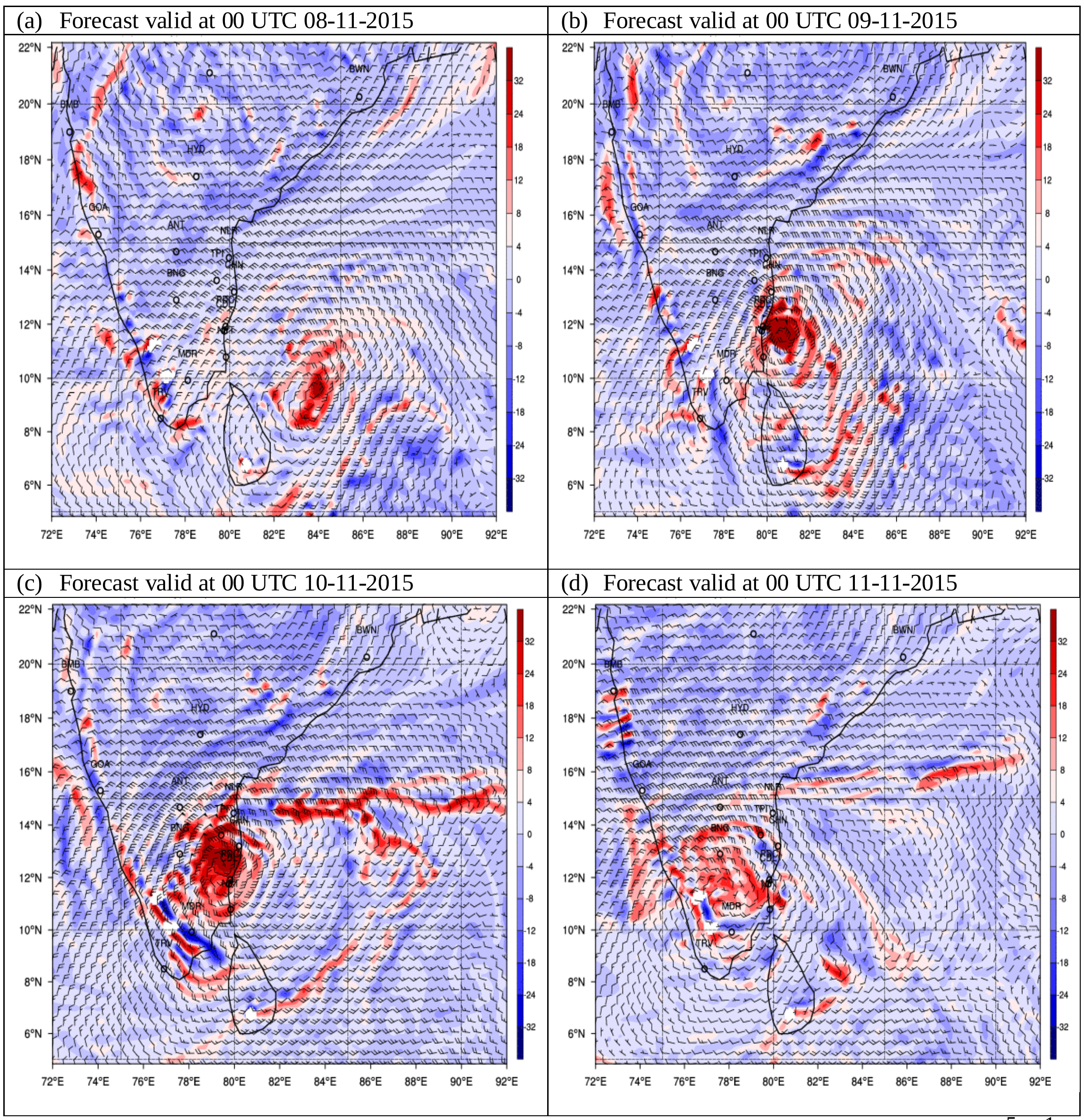


Figure 18 The WRF model 24 forecasts of wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa level valid at 00 UTC on (a) 08, (b) 09, (c) 10 and (d) 11 November 2015.

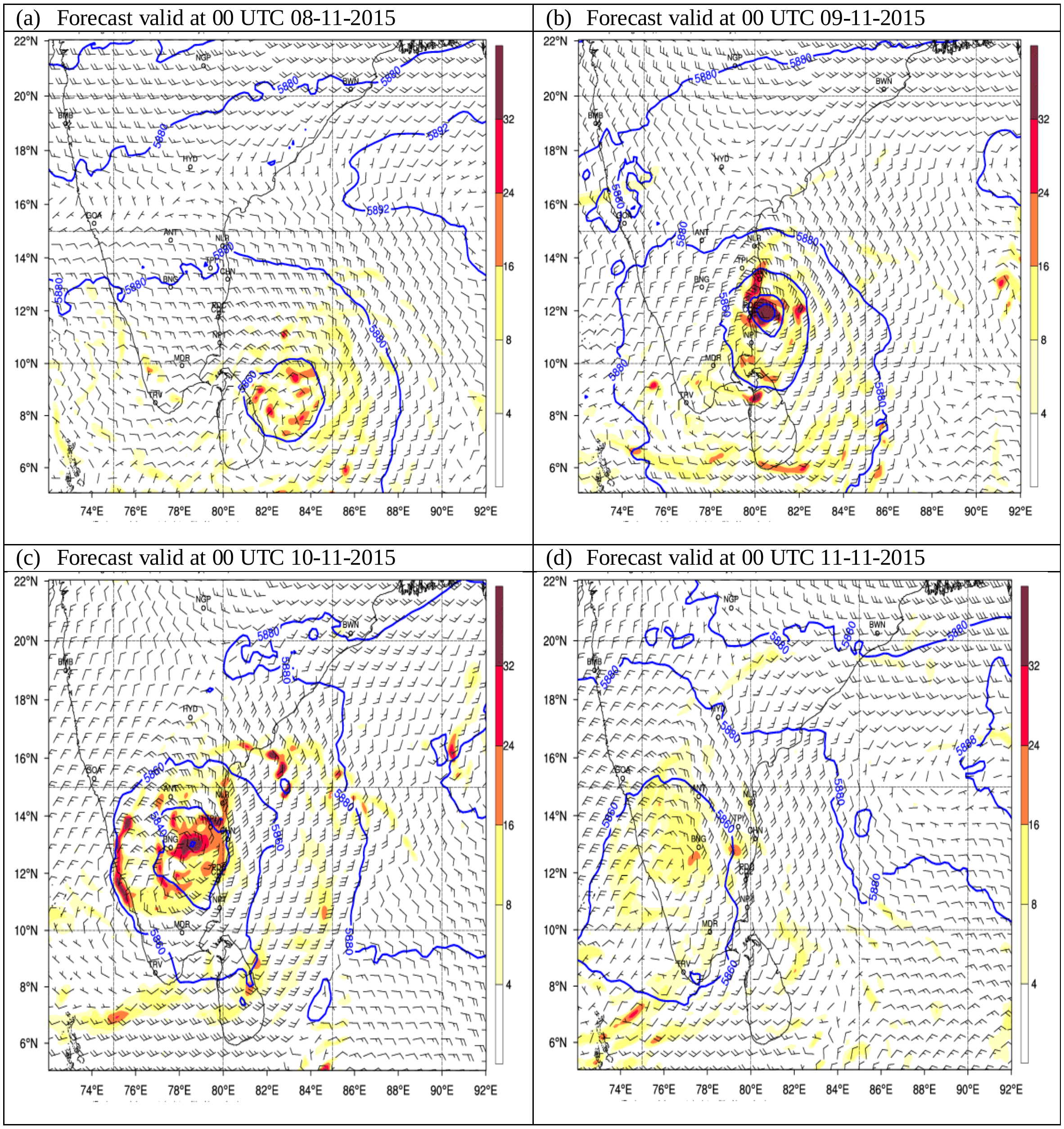


Figure 19. The WRF model 24 hour forecasts of wind and positive relative vorticity (x 10^{-5} s^{-1}) at 500 hPa during 00 UTC on (a) 08, (b) 09, (c) 10 and (d) 11 November 2015.

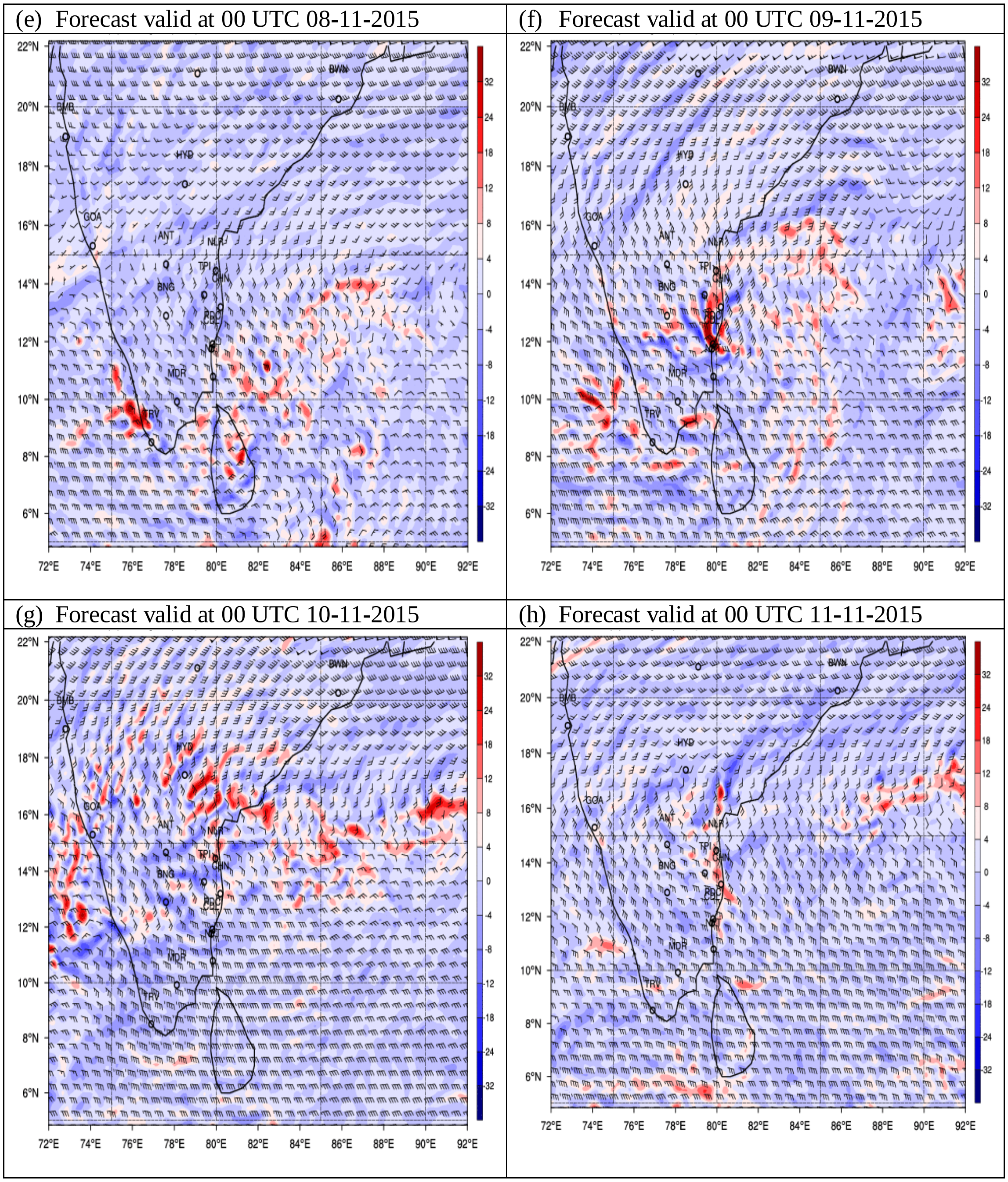


Figure 20 The WRF model 24 hour forecasts of wind and divergence (x 10^{-5} s^{-1}) at 200 hPa during 00 UTC on (a) 08, (b) 09, (c) 10 and (d) 11 November 2015.

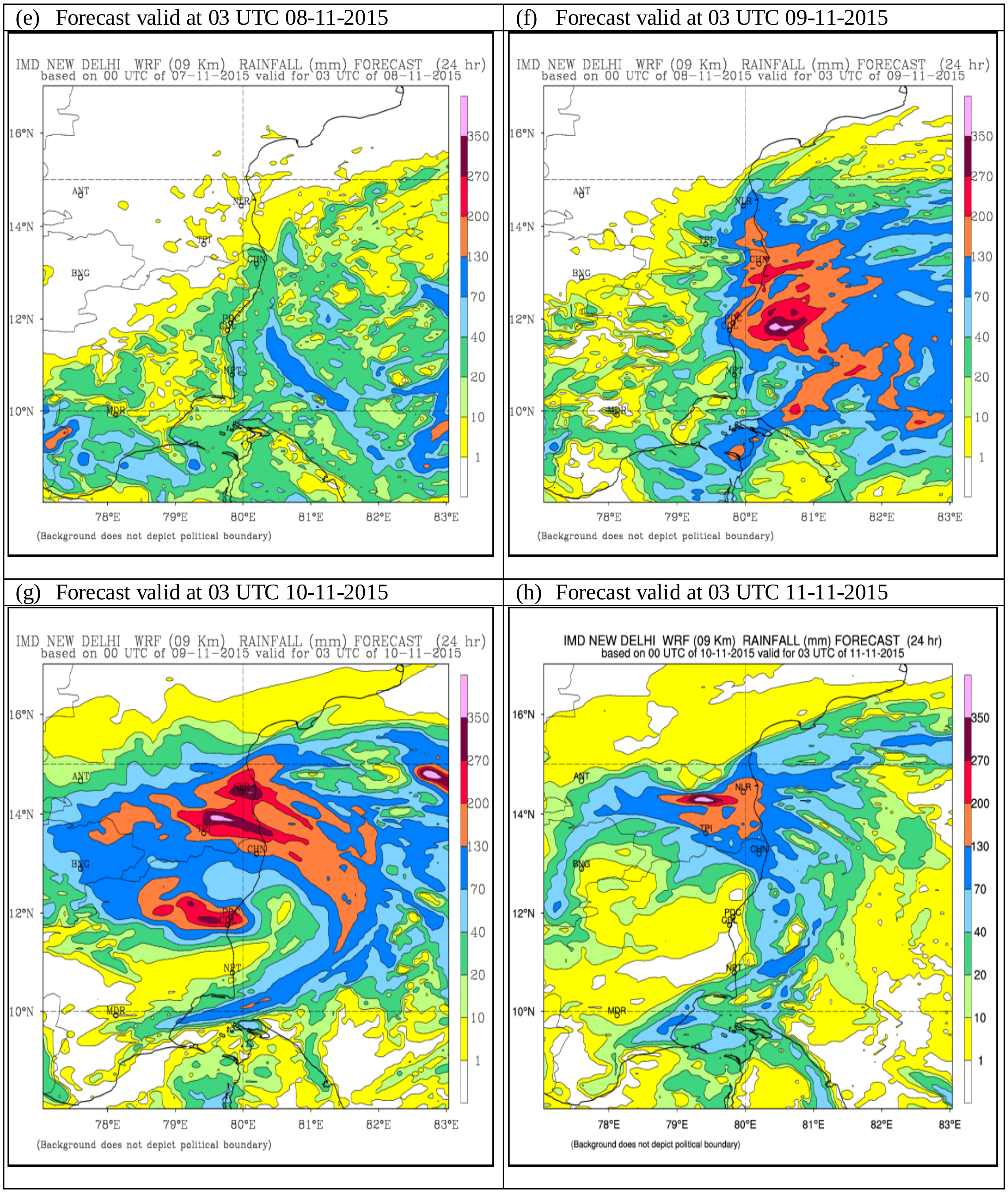


Figure 21. The WRF model 24 hour rainfall forecasts valid at 03 UTC on (a) 08-11-2015, (b) 09-11-2015, (c) 10-11-2015 and (d) 11-11-2015.

The figure 19 shows the 24 hour forecast of wind circulation along with positive relative vorticity over the region on 9th to 11th November 2015. The comparison of the 24 hour forecasts (figure 19) with the analyses (figure 15) depicts that the location of maximum vorticity associated with the low pressure system is well captured by the model. But over prediction of intensity of the system at mid-tropospheric level (500 hPa) as described by the magnitude of wind speed and relative vorticity is clearly noticeable. The figure 19 also shows that the model is capable to bring out the time sequence of intensification and dissipation from 8th to 11th November.

The 24 hour forecasts of upper-air divergence (at 200 hPa) during 8th to 11th November valid at 00 UTC of each day are shown in figure 8. Although, the model forecasts show the patchy zones of divergence and convergence, the maximum divergence is found over Tamilnadu region on 9th November and locates north of Tamilnadu on 10th November. The spatial coverage of upper-air divergence over the region reduces as on 11th November along with the dissipation of the system. The orientation of the ridge line at 200 hPa and the relative positions of the low pressure system from the ridge are also well predicted in the 24 hour forecasts (compared with figure 16). Only the magnitude of divergence is greater than the values observed in the analyses during the event.

The figure 21 shows the 24 hour rainfall forecasts of the model valid at 03 UTC of four different days. The model forecasts show that intensity of rain increases over the region from 8th to 9th November and rain belt moved from BOB to coastal Tamilnadu. The heavy rainfall zone moved inland during 10th November but two maxima have been found with a split. The model forecast show persistent intense rain activity whereas the observed analyses show a reduction from 10th onwards. Besides the overestimation of the rainfall, the spatial coverage of rain in the model forecasts fairly matches with the observation in figure 17.

The circulation characteristics in the lower and mid-troposphere in 48 hour forecasts of the model is shown in figure 22 and 23 respectively. The situation over upper troposphere is plotted in figure 24. Comparing the general features of the cyclonic circulation at 850 hPa and 500 hPa in figure 22 and 23 with that of figure 14 and 15, it has been found that like 24 hour forecast, 48 hour forecasts also portray and over estimation about the intensity of the system. Even in 48 hours forecasts, the locations of strong cyclonic vorticity have been captured by the model. The westward movement of the cyclonic circulation from 10th to 11th November is faster compared to analyzed field. The upper-air divergence field in the forecasts is stronger than the analysis and depicts a band structure on 9th November due to over-prediction of the intensity.

Corresponding 48 hour rainfall forecasts of the model for all four days are shown in figure 25. The penetration of rainfall belt from BOB over coastal region of Tamilnadu can be seen in 48 hour forecast as well. But the spatial orientation of rainfall forecast is more east-west direction compared with observed fact on 9th

November whereas the forecast distribution of rainfall on 10th is fairly similar with 24 hour forecast with a less split between two maxima. The overestimation of rainfall is again seen for the rainfall on 10th November.

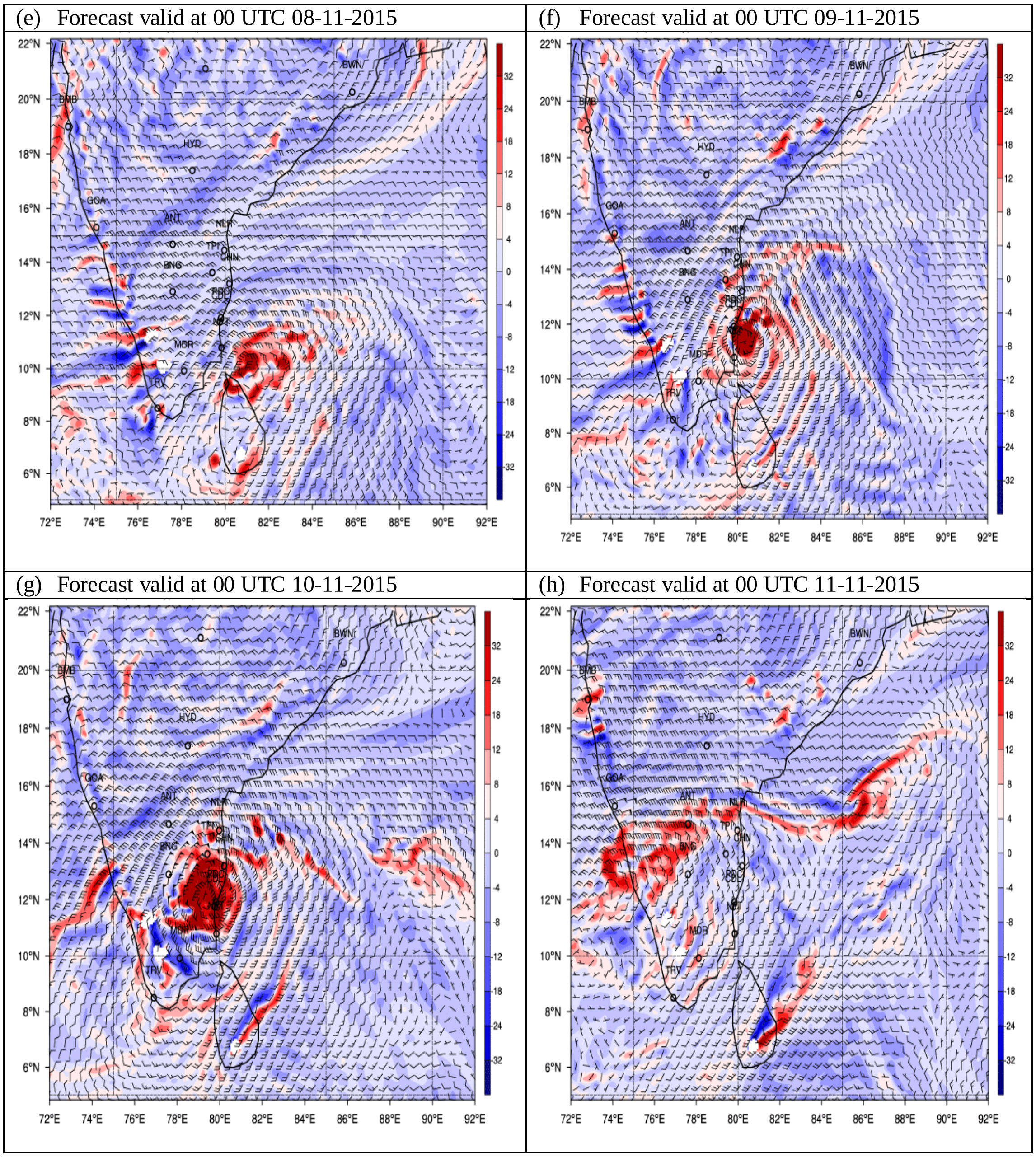


Figure 22. The WRF model 48 forecasts of wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa level valid at 00 UTC on (a) 08, (b) 09, (c) 10 and (d) 11 November 2015.

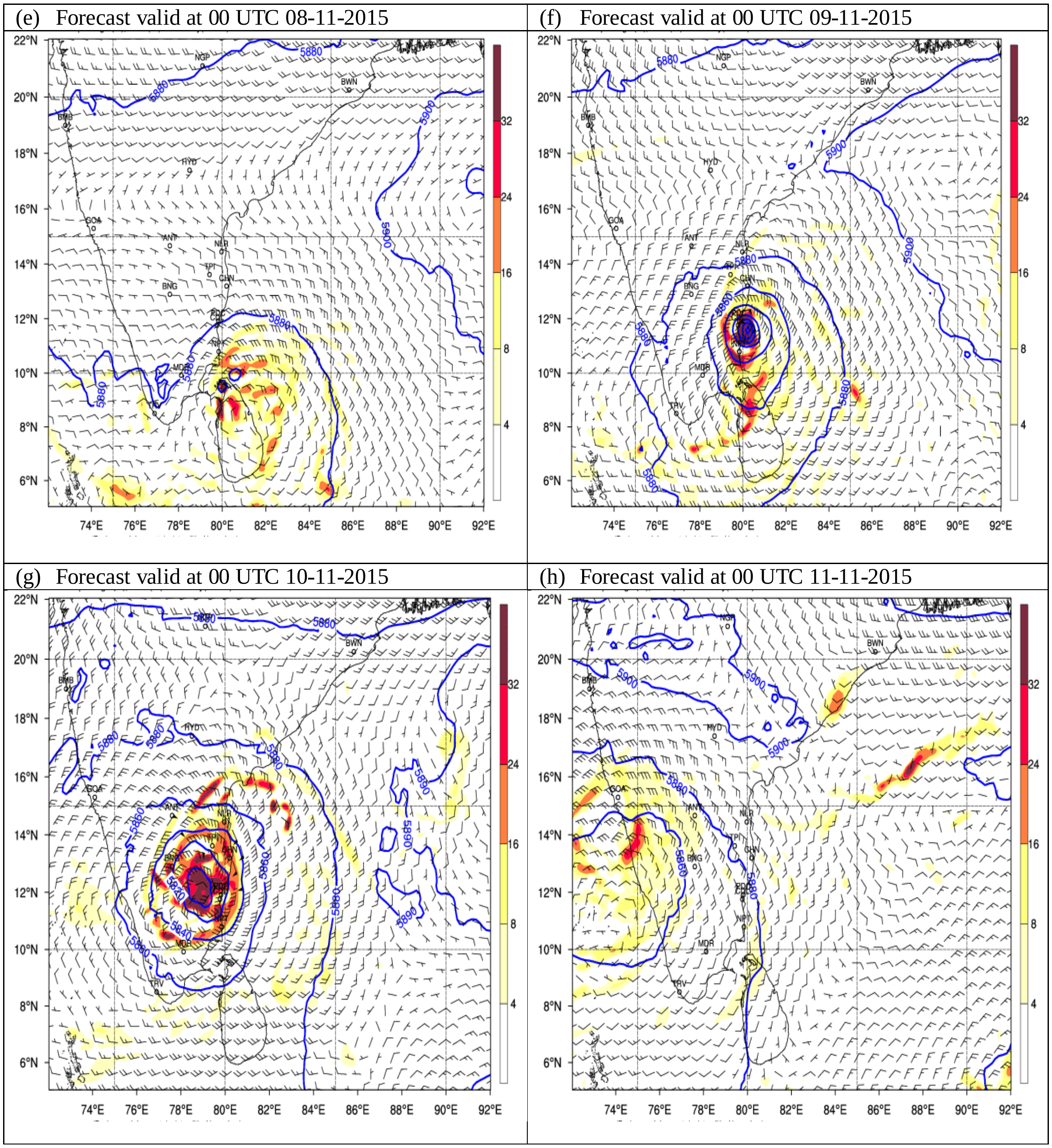


Figure 23. The WRF model 48 hour forecasts of wind and positive relative vorticity (x 10^{-5} s^{-1}) at 500 hPa during 00 UTC on (a) 08, (b) 09, (c) 10 and (d) 11 November 2015.

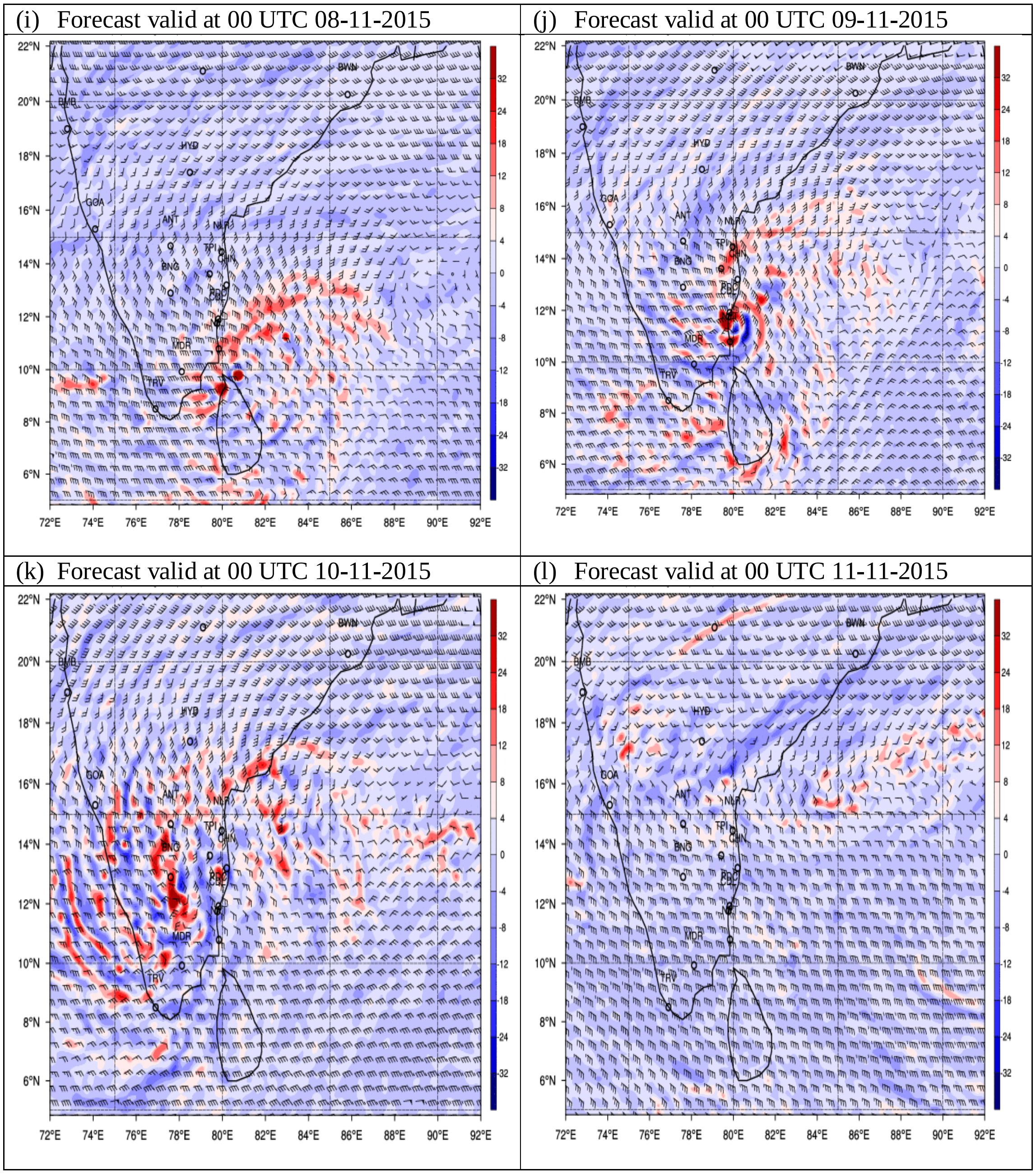


Figure 24. The WRF model 48 hour forecasts of wind and divergence (x 10^{-5} s^{-1}) at 200 hPa during 00 UTC on (a) 08, (b) 09, (c) 10 and (d) 11 November 2015.

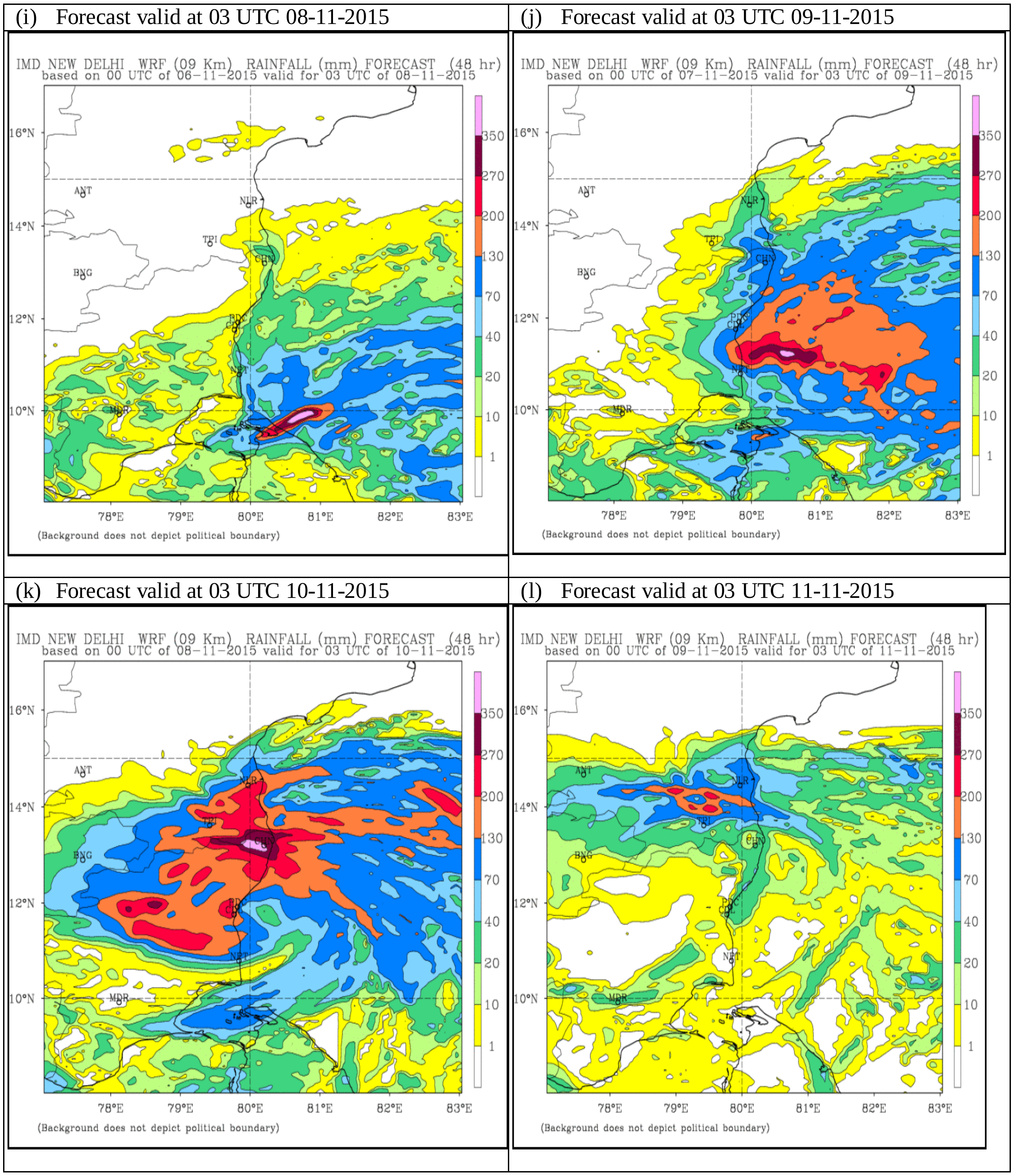


Figure 25. The WRF model 48 hour rainfall forecasts valid at 03 UTC on (a) 08-11-2015, (b) 09-11-2015, (c) 10-11-2015 and (d) 11-11-2015.

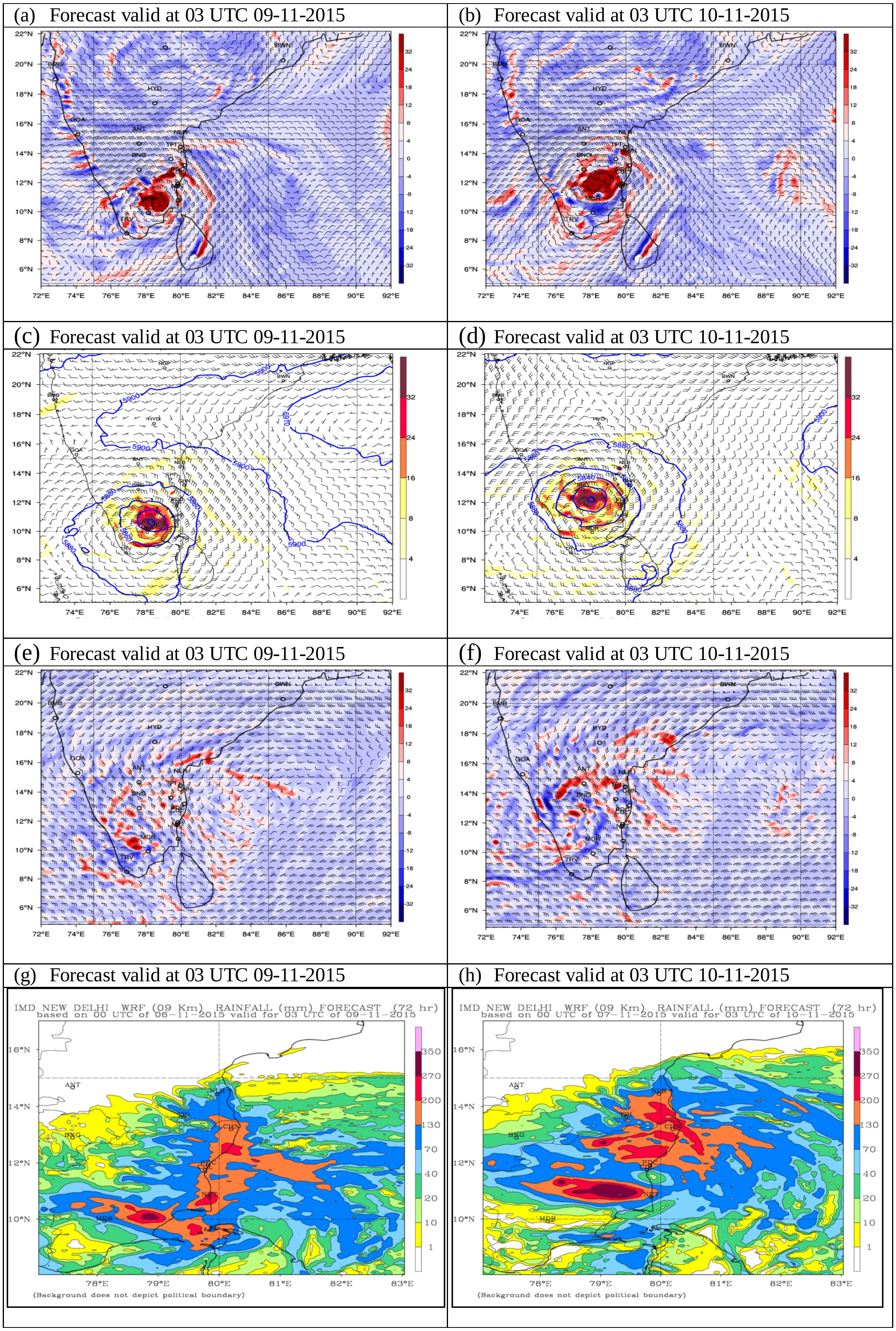


Figure 26. The WRF model 72 hour forecasts. (a) and (b) wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa, (c) and (d) wind and positive vorticity (x 10^{-5} s^{-1}), (e) and (f)

wind and divergence (x 10^{-5} s^{-1}) valid at 00 UTC and (g) and (h) 24 hours accumulated rainfall during 9th and 10th November respectively.

The scenarios after 72 hours forecast of the model on 9th and 10th November during the event have been shown in figure 14. In general, the circulation features in the forecasts are in good agreement with the analyses but a little southward shift has been noticed. The intensity of the system in model forecast in stronger than the analysis. The performance of the model in capturing the intensity and distribution of rainfall has been degraded compared with 48 hour forecasts but still overall representation of heavy rainfall episode is evident in 72 hour forecasts as well.

5.2. Well marked low pressure area (15-17 November 2015)

The weather event during 15-17 November over Tamilnadu region is caused due to a low pressure system migrated from southwest BOB near Sri Lanka coast and moved northward along the east coast of India. The analyses of mean sea level pressure during three days of the event are shown in figure 15.

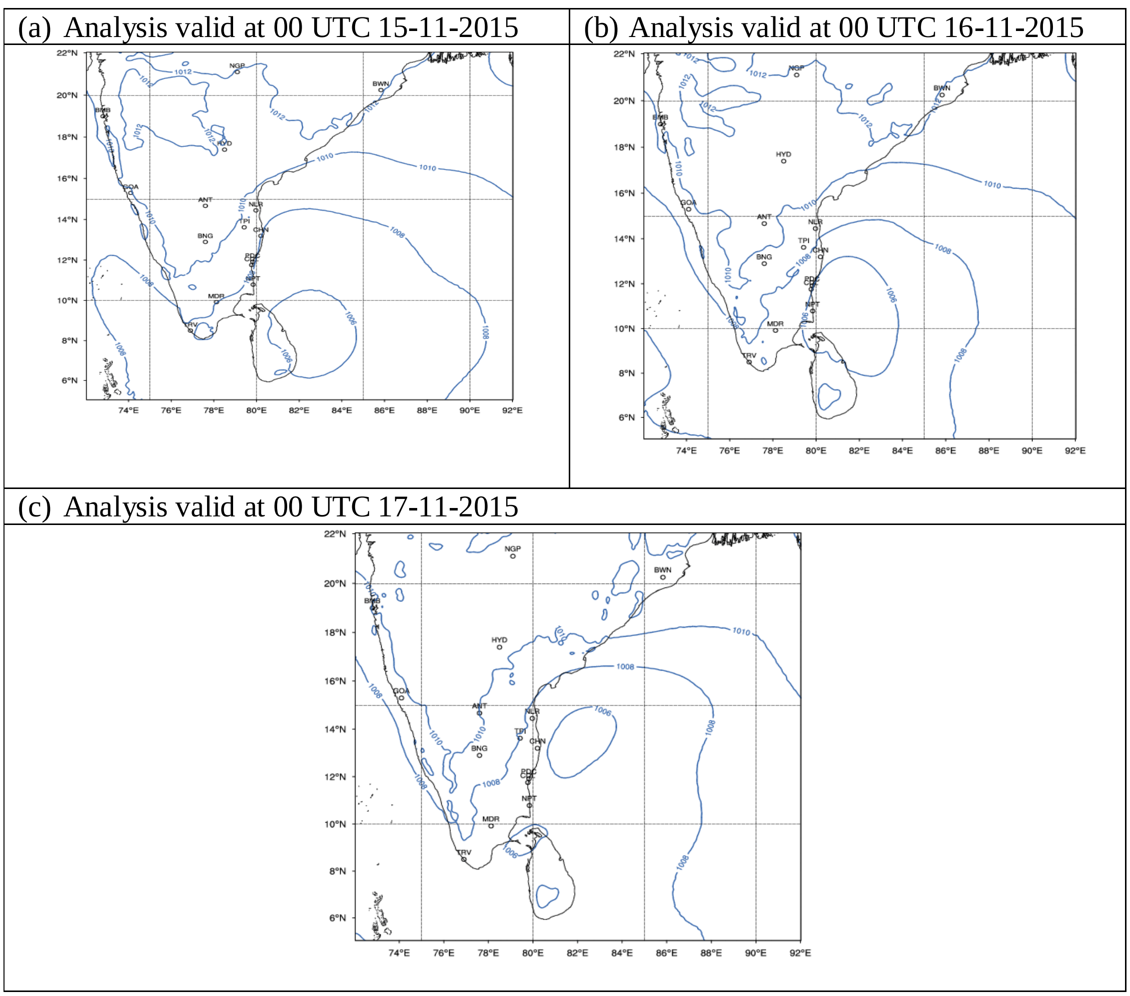


Figure 27. Mesoscale analyses of mean sea level pressure (hPa) valid at 00 UTC of (a) 15, (b) 16, and (c) 17 November 2015.

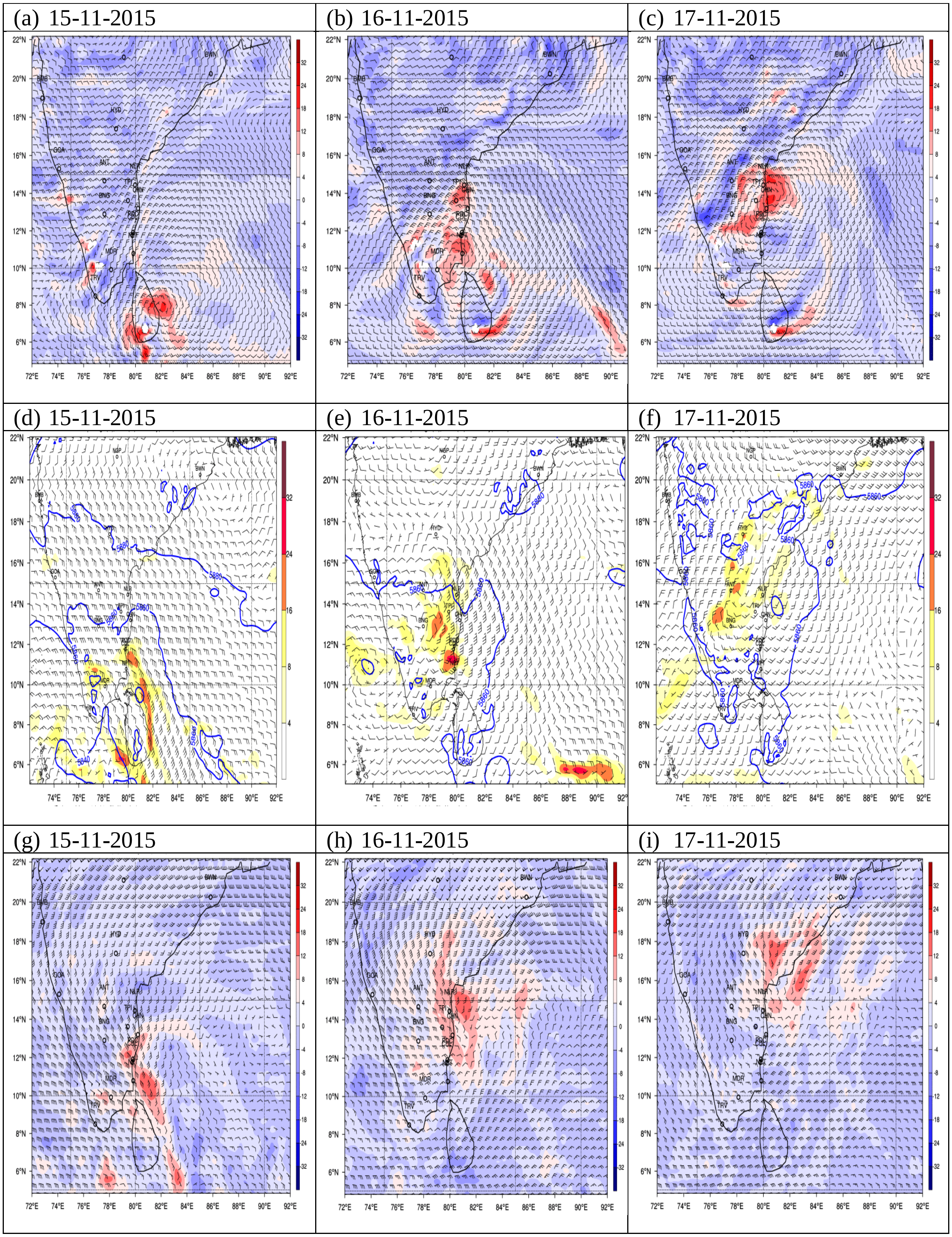


Figure 28. The analyses valid at 00 UTC. (a), (b) and (c) for wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa level, (d), (e) and (f) for wind and relative vorticity at 500 hPa and (g), (h) and (i) for wind and divergence at 200 hPa on 15, 16 and 17 November 2015 respectively.

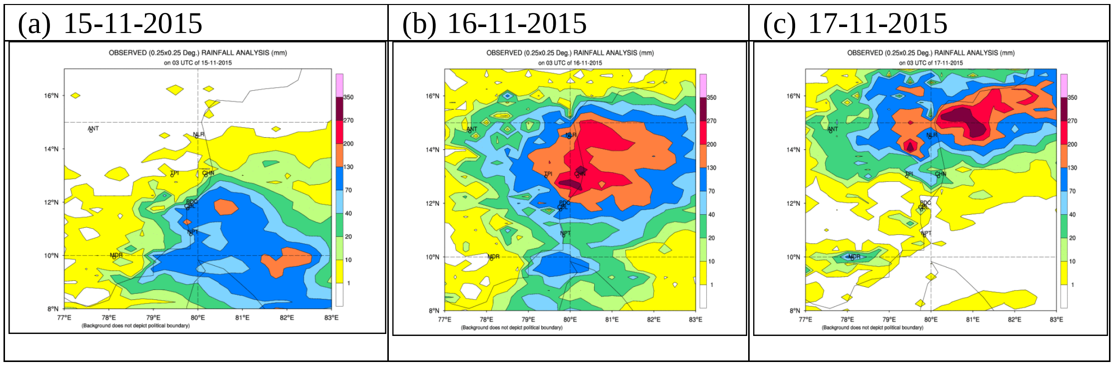


Figure 29. Observed rainfall analyses (0.25^ox0.25^o) valid at 03 UTC on (a) 15-11-2015, (b) 16-11-2015 and (c) 17-11-2015.

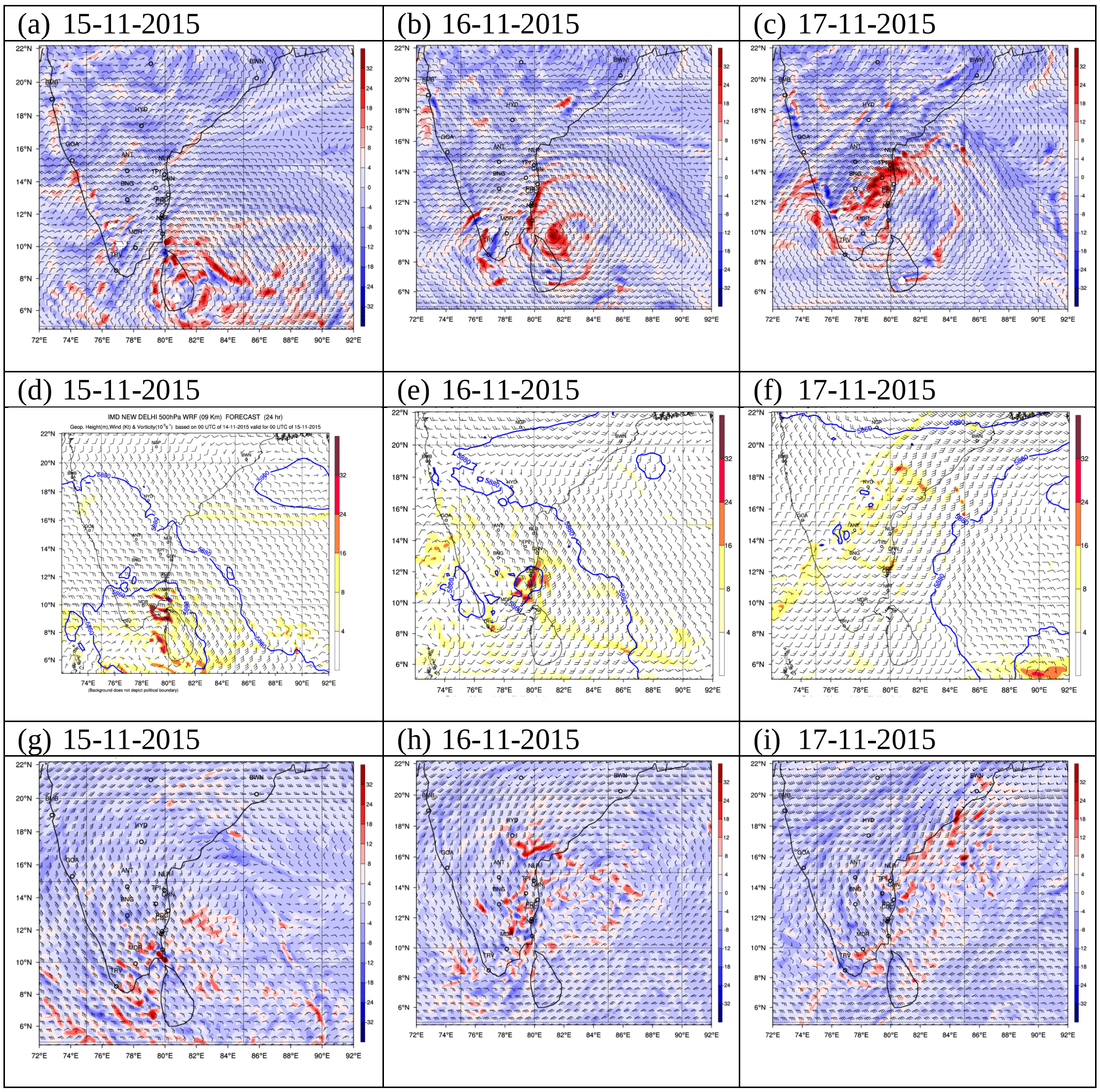


Figure 30. The 24 hour WRF forecasts valid at 00 UTC. (a), (b) and (c) for wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa level, (d), (e) and (f) for wind and relative vorticity at 500 hPa and (g), (h) and (i) for wind and divergence at 200 hPa on 15, 16 and 17 November 2015 respectively.

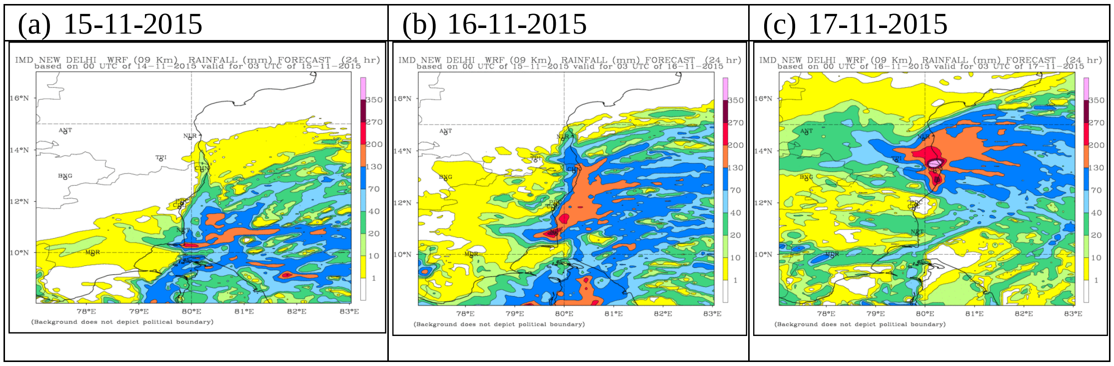


Figure 31. The WRF model 24 hour rainfall forecasts valid at 03 UTC on (a) 15-11-2015, (b) 16-11-2015 and (c) 17-11-2015.

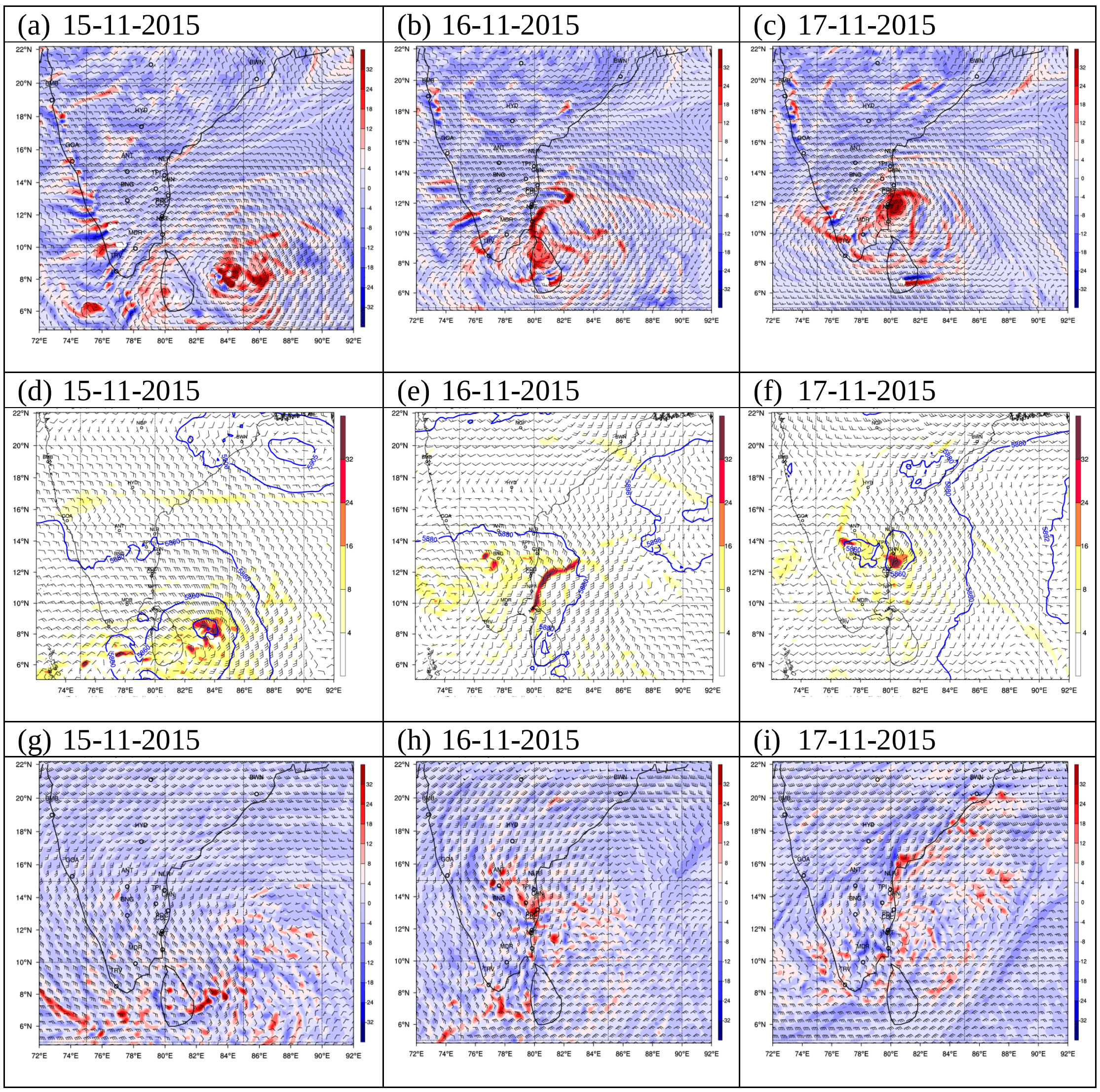


Figure 32. The 48 hour WRF forecasts valid at 00 UTC. (a), (b) and (c) for wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa level, (d), (e) and (f) for wind and relative

vorticity at 500 hPa and (g), (h) and (i) for wind and divergence at 200 hPa on 15, 16 and 17 November 2015 respectively.

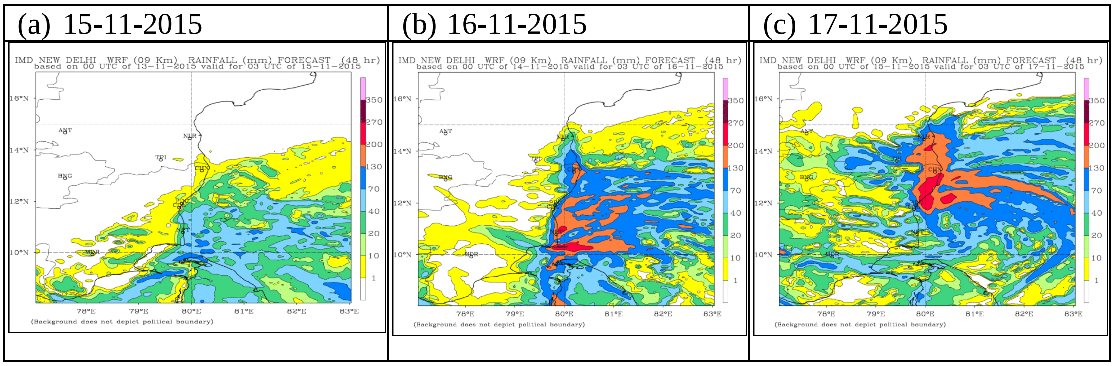


Figure 33 The WRF model 48 hour rainfall forecasts valid at 03 UTC on (a) 15-11-2015, (b) 16-11-2015 and (c) 17-11-2015.

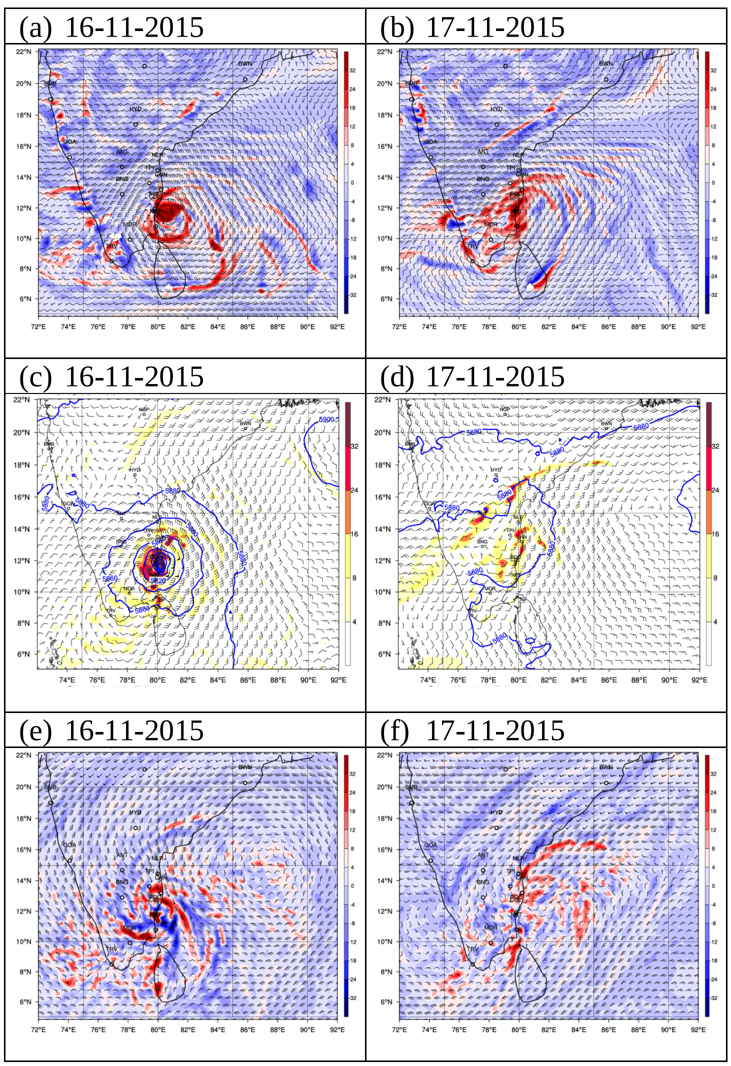
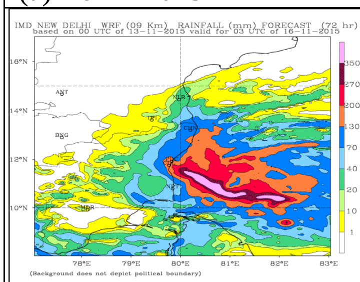


Figure 34. The 72 hour WRF forecasts valid at 00 UTC. (a), (b) and (c) for wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa level, (d), (e) and (f) for wind and relative vorticity at 500 hPa and (g), (h) and (i) for wind and divergence at 200 hPa on 15, 16 and 17 November 2015 respectively.

(a) 16-11-2015



(b) 17-11-2015

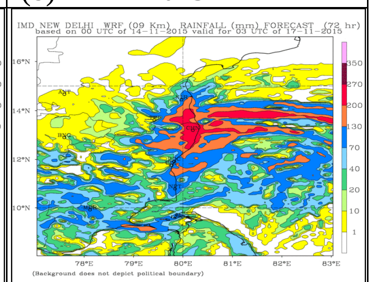
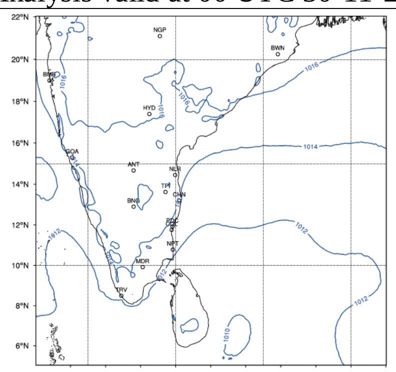


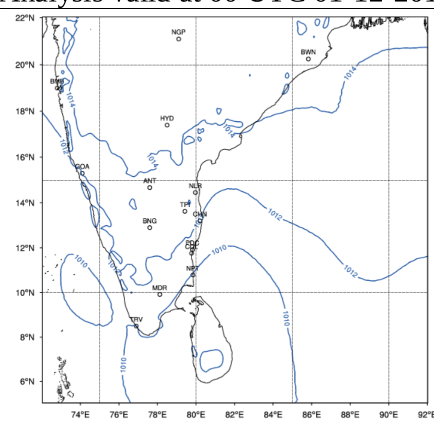
Figure 35. The WRF model 72 hour rainfall forecasts valid at 03 UTC on (a) 15-11-2015, (b) 16-11-2015 and (c) 17-11-2015.

5.3. Low pressure area (30 Nov.- 02 December 2015)

(a) Analysis valid at 00 UTC 30-11-2015



(b) Analysis valid at 00 UTC 01-12-2015



(c) Analysis valid at 00 UTC 02-12-2015

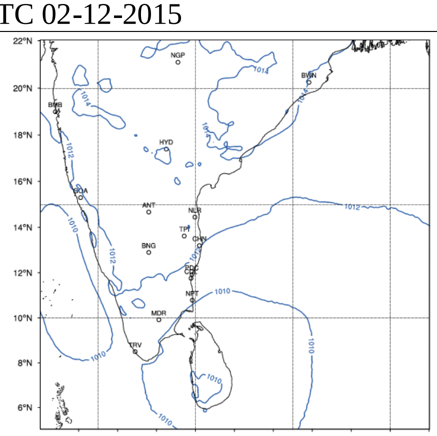


Figure 36. Mesoscale analyses of mean sea level pressure (hPa) valid at 00 UTC of (a) 15, (b) 16, and (c) 17 November 2015.

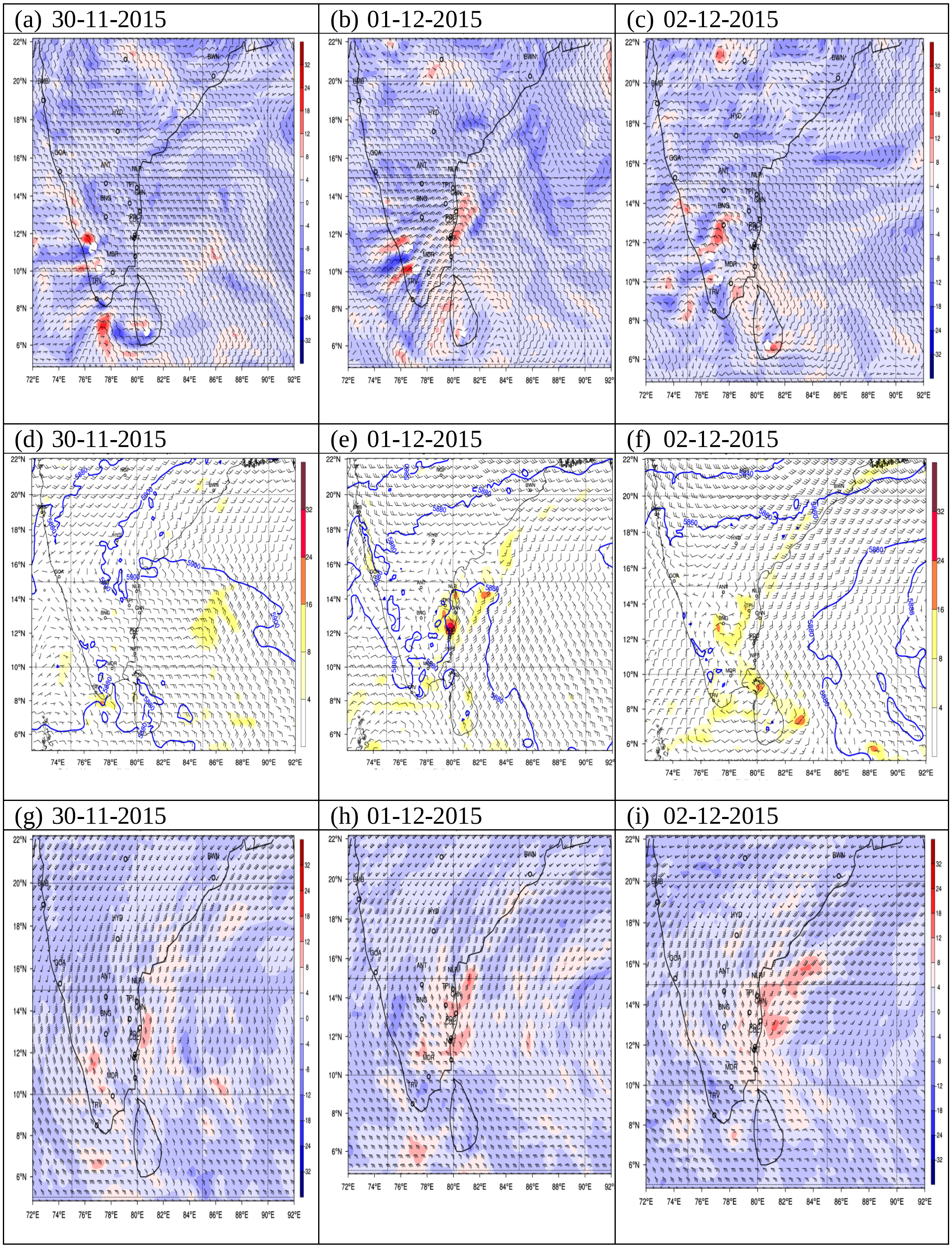


Figure 37. The analyses valid at 00 UTC. (a), (b) and (c) for wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa level, (d), (e) and (f) for wind and relative vorticity at 500 hPa and (g), (h) and (i) for wind and divergence at 200 hPa on 30 November, 01 and 02 December 2015 respectively.

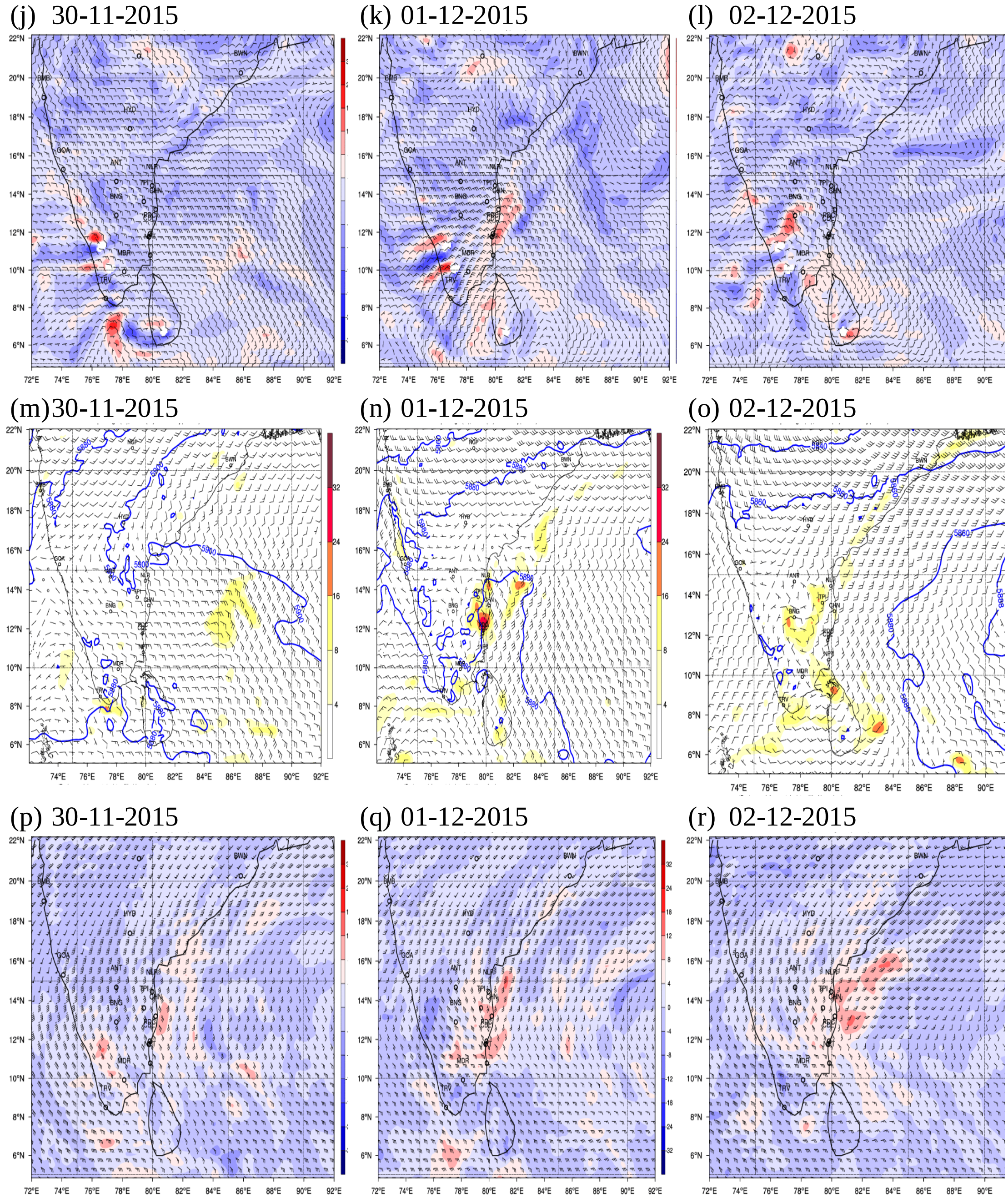


Figure 38. The analyses valid at 00 UTC. (a), (b) and (c) for wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa level, (d), (e) and (f) for wind and relative vorticity at 500 hPa and (g), (h) and (i) for wind and divergence at 200 hPa on 30 November, 01 and 02 December 2015 respectively.

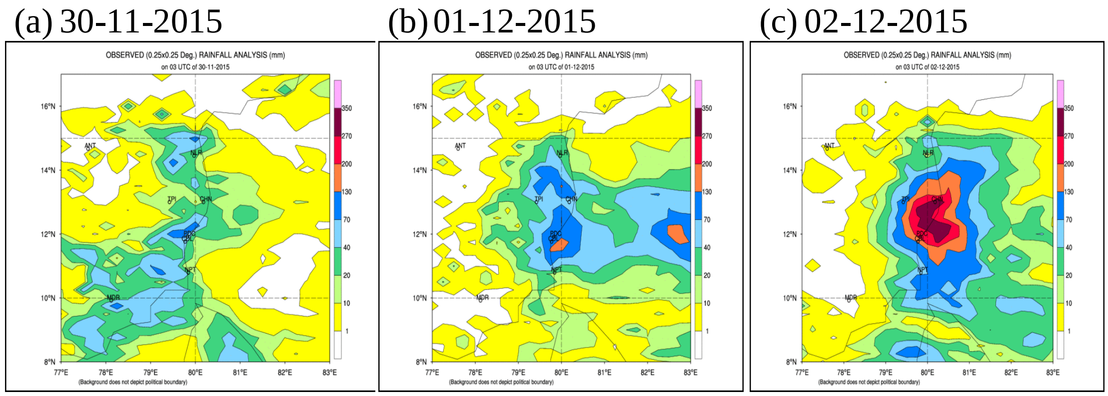


Figure 39. Observed rainfall analyses (0.25°x0.25°) valid at 03 UTC on (a) 30-11-2015, (b) 01-12-2015 and (c) 02-12-2015.

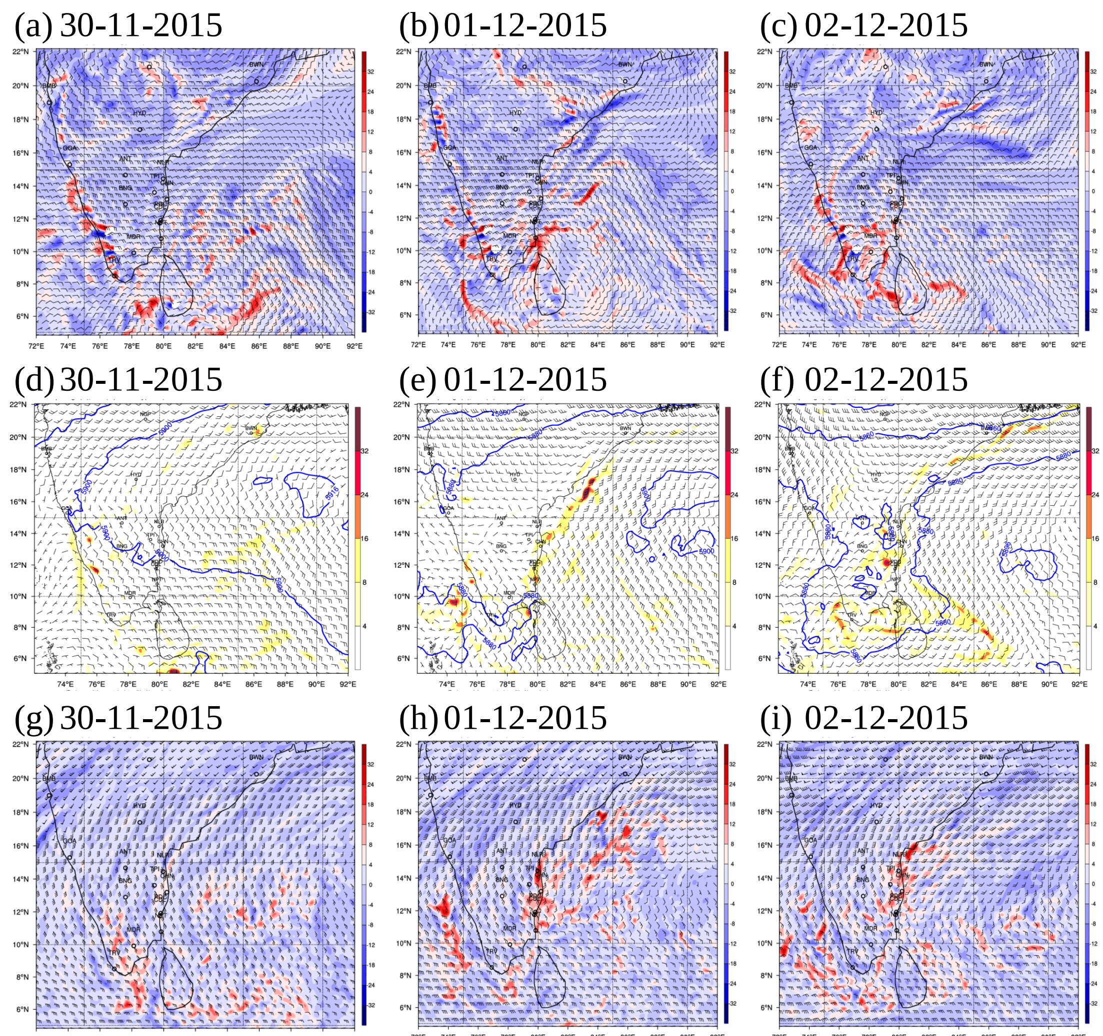


Figure 40. The 24 hour WRF forecasts valid at 00 UTC. (a), (b) and (c) for wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa level, (d), (e) and (f) for wind and relative vorticity at 500 hPa and (g), (h) and (i) for wind and divergence at 200 hPa on 30 Nov., 01 and 02 December 2015 respectively.

(a) 30-11-2015 (b) 01-12-2015 (c) 02-12-2015

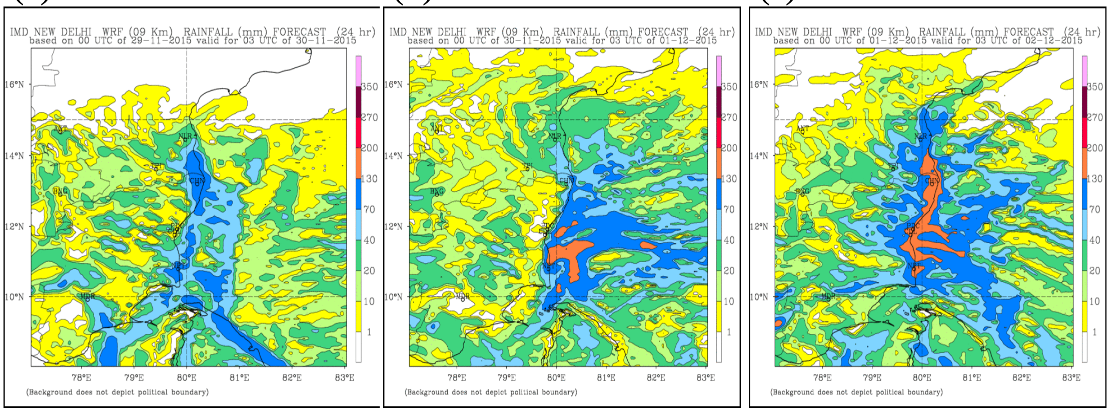


Figure 41. The WRF model 24 hour rainfall forecasts valid at 03 UTC on (a) 30-11-2015, (b) 01-12-2015 and (c) 02-12-2015.

The forecast charts of 24 hour (figure 25) show that there is a development of prominent slow moving cyclonic circulation in lower troposphere over the extreme southern tip peninsular India and Sri Lanka from 30 November to 02 December 2015 whereas the analyses show the development over the region with slight northward movement. The 48 hour forecast (figure 27) also portray the lower tropospheric circulation features similar to 24 hour forecast. There are patches of higher cyclonic vorticity over the region but do not describe any circulation feature. The persisting upper-air divergence over the area oriented along southerly wind in north-south direction can be seen in both 24 and 48 hour forecasts (in figures 26 and 28). Consequently, the rainfall belts are along the Tamilnadu coast with north-south alignment. The forecast rainfall distribution mainly confined near sea shore and coverage over land area is less compared to observation. The amount of observed rainfall during 01^{st} and 02^{nd} December is under-predicted by the model. The increasing trend of rainfall from 01^{st} to 02^{nd} December is captured by the model forecasts but missed the intense activity on 02^{nd} December.

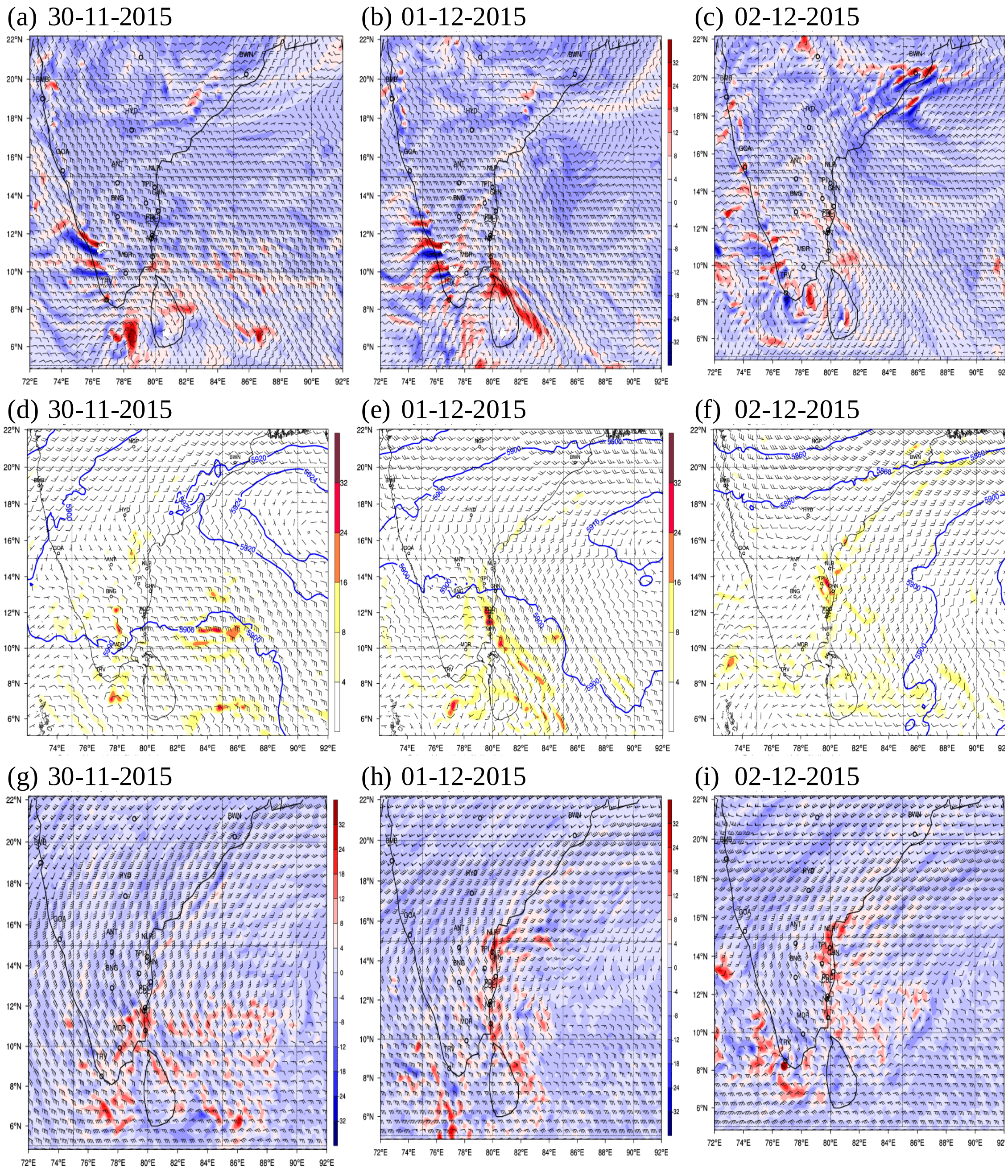


Figure 42. The 48 hour WRF forecasts valid at 00 UTC. (a), (b) and (c) for wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa level, (d), (e) and (f) for wind and relative vorticity at 500 hPa and (g), (h) and (i) for wind and divergence at 200 hPa on 30 Nov., 01 and 02 December 2015 respectively.

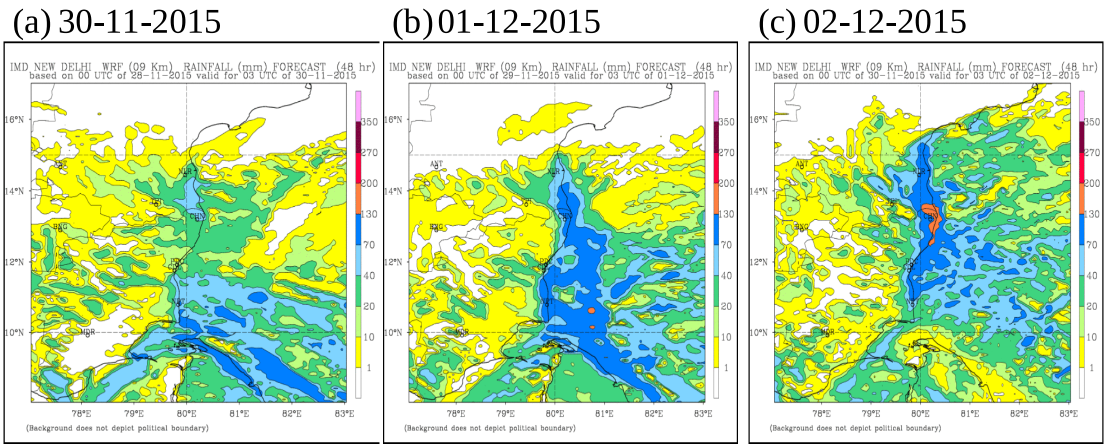


Figure 43. The WRF model 48 hour rainfall forecasts valid at 03 UTC on (a) 30-11-2015, (b) 01-12-2015 and (c) 02-12-2015.

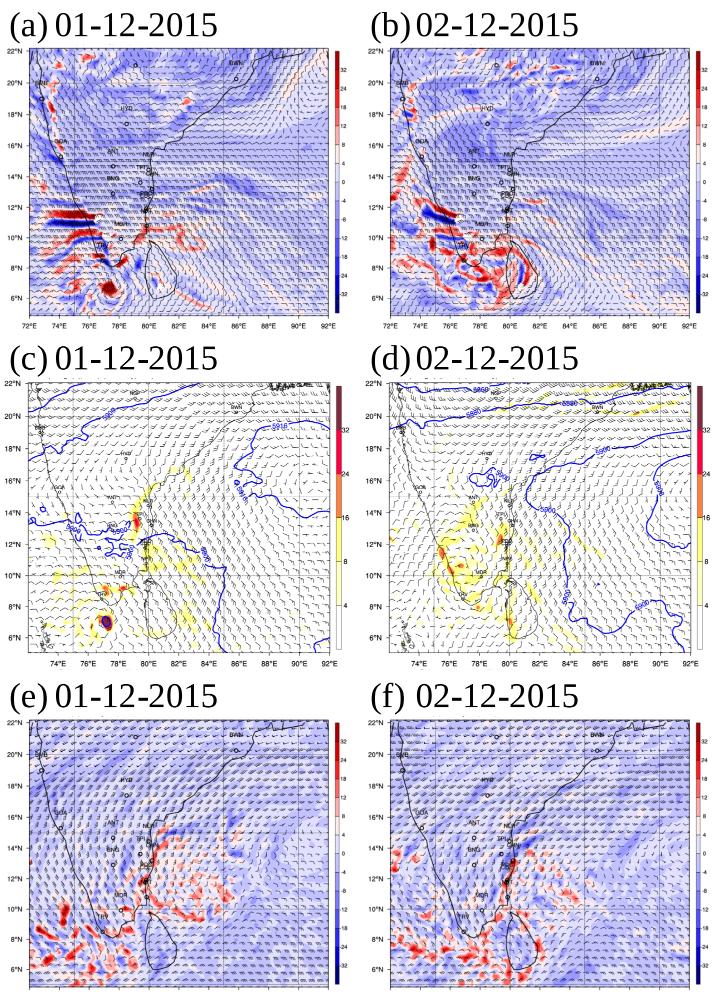


Figure 44. The 72 hour WRF forecasts valid at 00 UTC. (a) and (b) for wind and relative vorticity (x 10^{-5} s^{-1}) at 850 hPa level, (c) and (d) for wind and relative vorticity at 500 hPa and (e) and (f) for wind and divergence at 200 hPa on 01 and 02 December 2015 respectively.

(a) 01-12-2015 (b) 02-12-2015

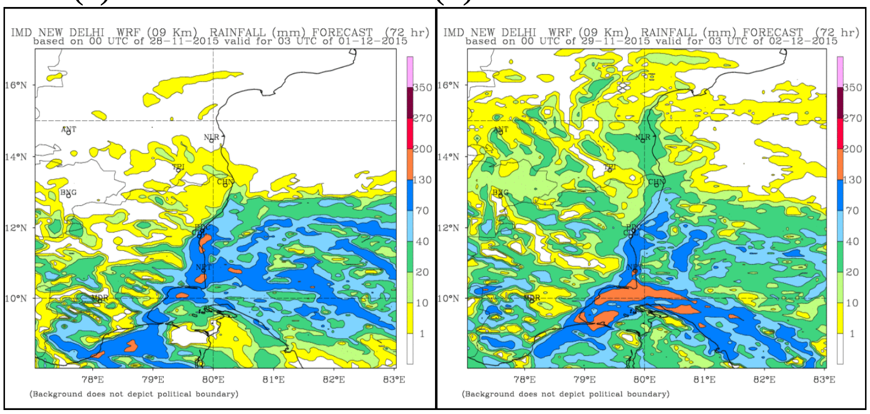
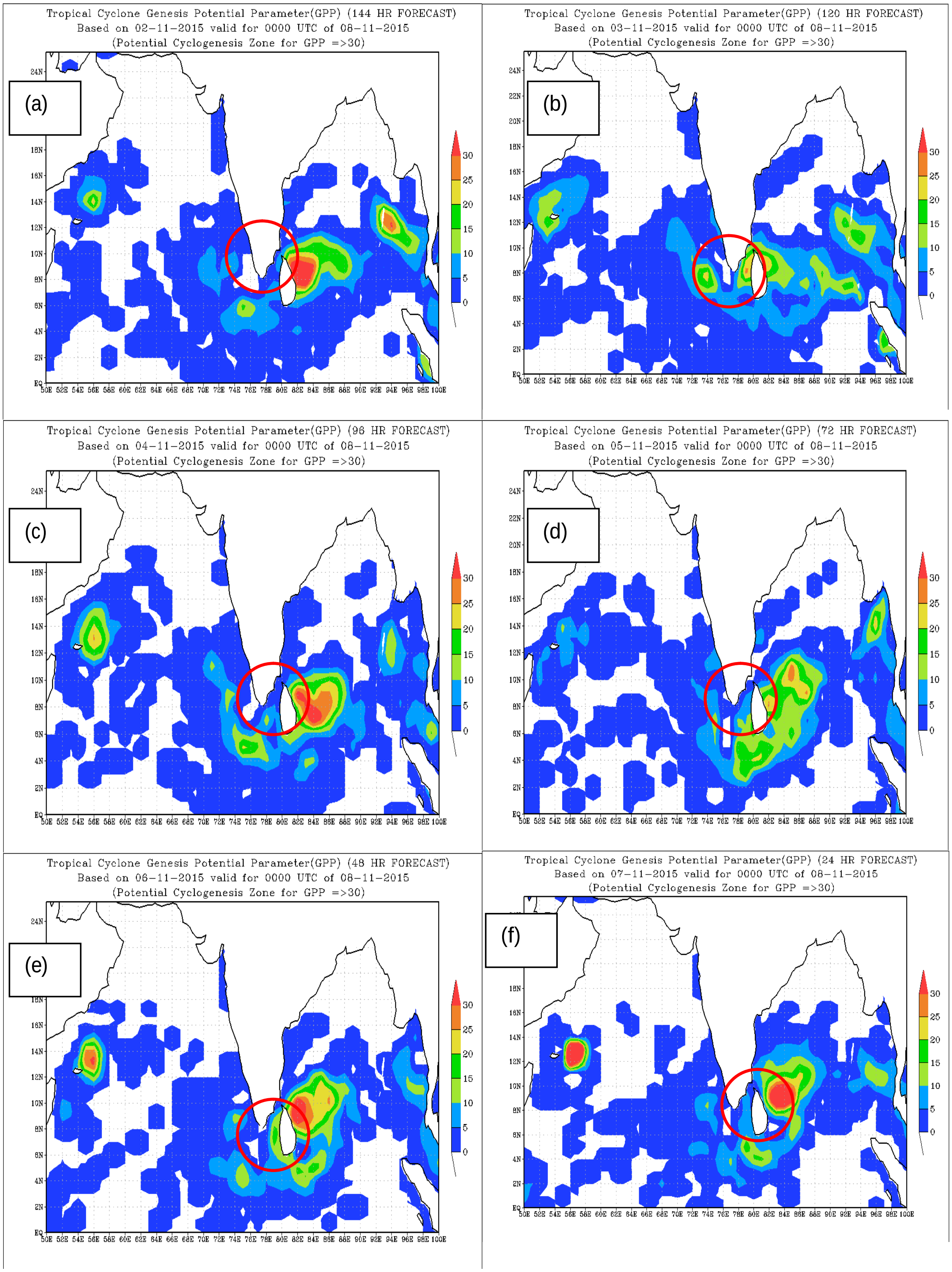


Figure 45. The WRF model 72 hour rainfall forecasts valid at 03 UTC on (a) 01-12-2015 and (b) 02-12-2015.

The 72 hour forecasts for 01st and 02nd December have been plotted in figure 29 and 30. The circulation in the forecast is stronger than the analysis. The southward shift of the whole system can also be observed. The area of maximum rainfall is also shifted southward and at the same time the north-south orientation of rainfall zone is missed by the model rather model rainfall is more aligned in east-west direction.

6. Performance of Genesis Potential Parameter (GPP) for cyclogenesis guidance

6.1. Deep Depression over the Bay of Bengal during 08-10, November 2015



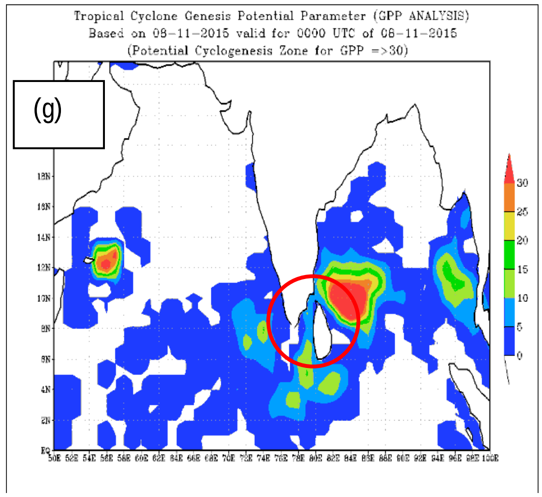


Figure 46(a-g): Predicted zone of cyclogenesis

6.2. Well Marked Low Pressure Area over the Bay of Bengal during 15-18, November 2015

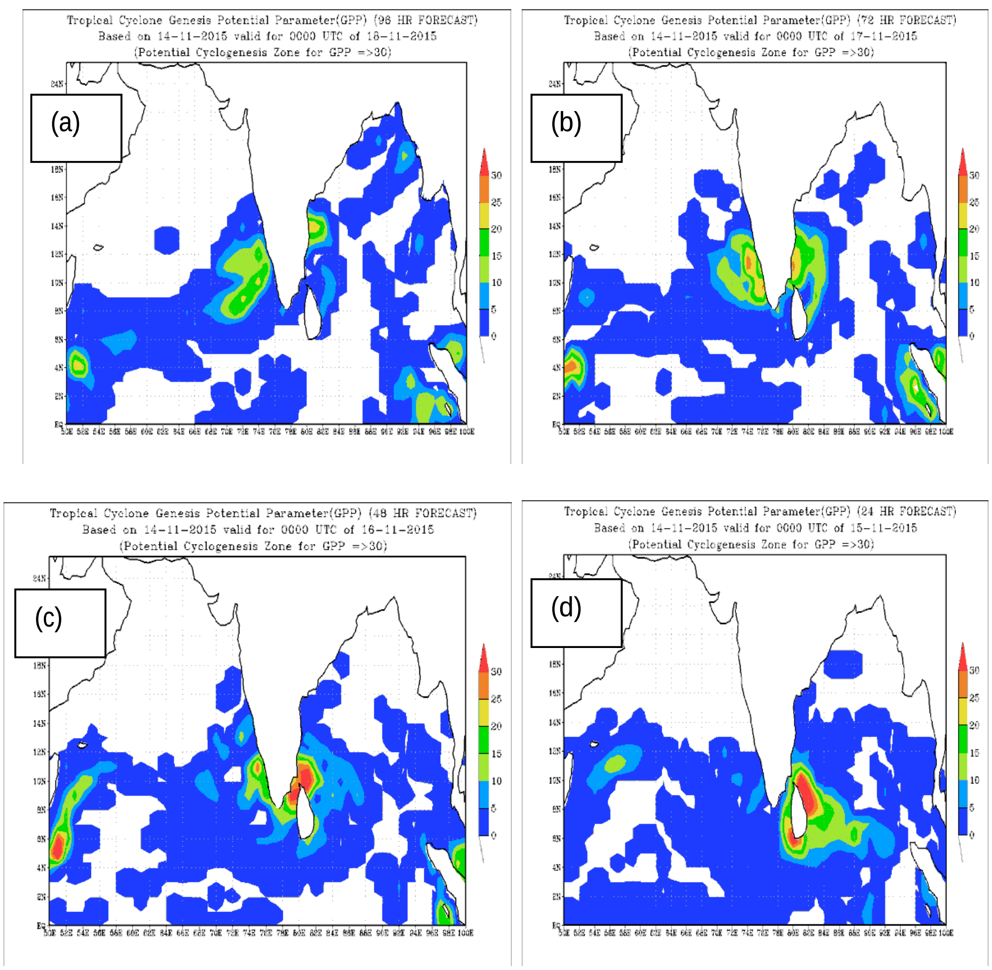
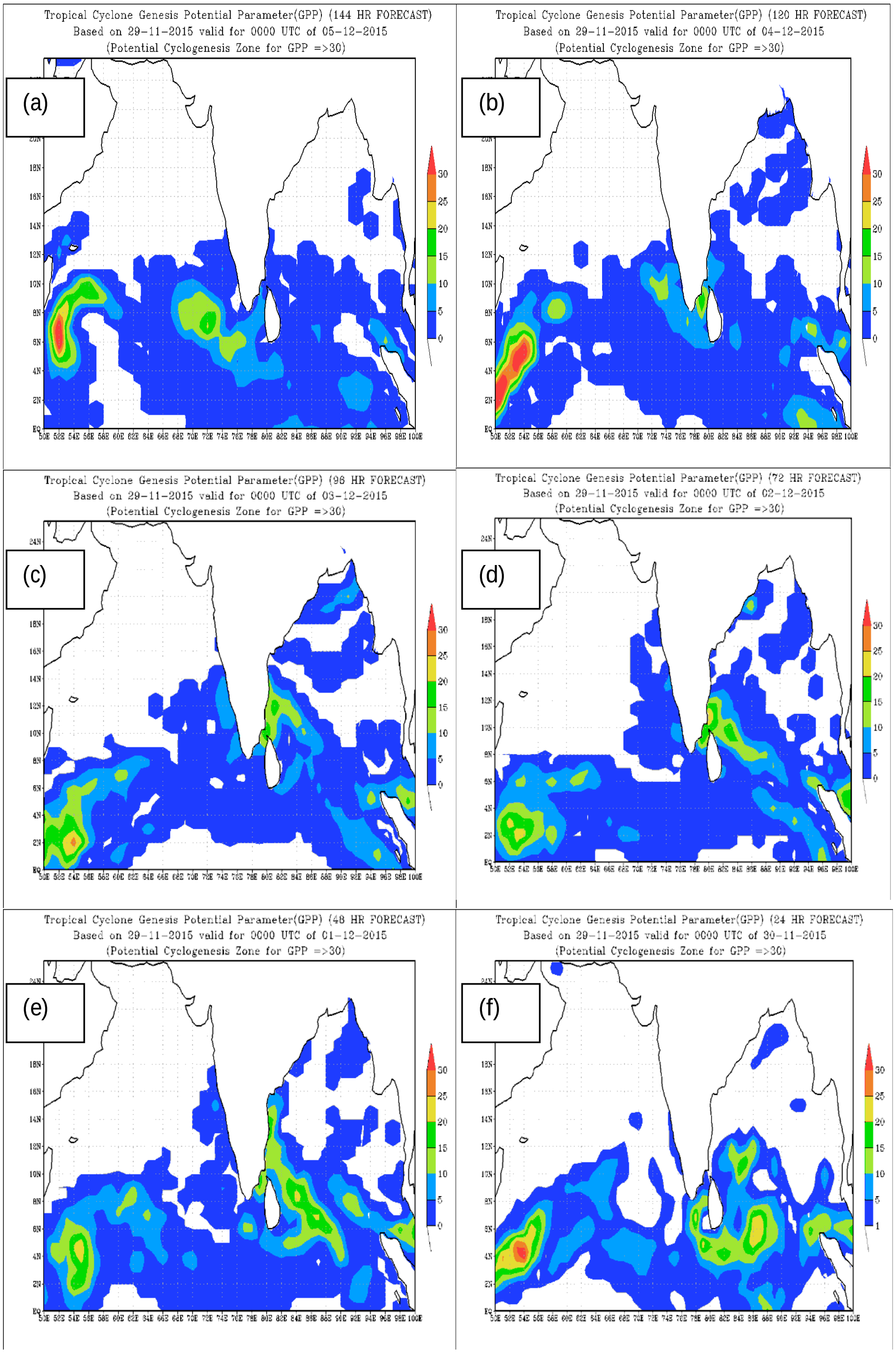


Figure 47(a-d): Predicted zone of cyclogenesis

6.3. Low Pressure Area over Bay of Bengal during 30 November-04 December 2015



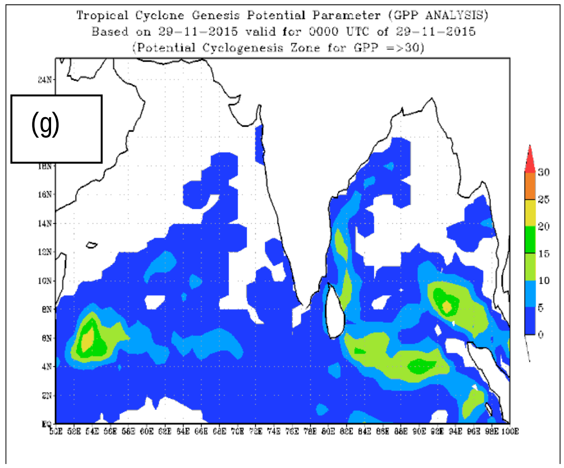


Figure 48(a-g): Predicted zone of cyclogenesis

6. Limitations and future scope

In view of the growing operational demand user specific nowcast / forecast, the new initiative shall cover following components:

(i) Development of Indian WRF including meso-scale data assimilation ingesting optimal local observations and Block level forecasts.

(ii) Rapid updates of high resolution rainfall analysis and forecasts for the entire country

(iii) GIS based rainfall analysis and forecasts for river basins

(iv) On line access to NWP data

Annexure I : Detailed specification of IMD GFS and WRF models

***Global Forecast System* (GFS)**:

Global Forecast System (GFS, based on NCEP) at T574L64 resolution has been implemented at IMD HQ on IBM based High Power Computing Systems 22 Km in the tropics) in spectral≈(HPCS). In horizontal, it resolves 574 waves (triangular truncation. The model has 64 vertical levels (hybrid; sigma and pressure). This new higher resolution global forecast model and the corresponding assimilation system are adopted from NCEP, USA. The GFS at IMD Delhi involves 4 steps as given below :

Step 1 - *Data Decoding and Quality Control*: First step of the forecast system is data decoding. It runs 48 times in a day on half-hourly basis, as soon as GTS data files are updated at regional telecom hub (RTH) of global telecom system (GTS), at IMD, New Delhi.

Steps 2 – *Pre-processing of data (PREPBUFR)* : Runs 4 times a day at 0000 UTC, 0600 UTC, 1200 UTC and 1800 UTC. List of data presently being preprocessed for Global Forecast System are :

- Upper air sounding,TEMP, GPS and PILOT
- Land surface – SYNOP, SYNOP MOBIL & AWS
- Marine surface - SHIP
- Drifting buoy - BUOY
- Sub-surface buoy - BATHY
- Aircraft observations - AIREP & AMDAR
- Automated Aircraft Observation - BUFR (ACARS)
- Airport Weather Observations - METAR
- Satellite winds - SATOB
- High density satellite winds - BUFR (EUMETSAT & Japan)
- Wind profiler observations - BUFR (US/Europe)
- Surface pressure Analysis - PAOB (Australia)

- Radiance (AMSU-A, AMSU-B, HIRS-3 and HIRS-4, MSU, IASI, SSMI, AIRS, AMSRE, GOES, MHS)
- GPS Radio occultation 15.Rain Rate (SSMI and TRMM)
- Rain Rate (SSMI and TRMM)

Step 3 - *Global Data Assimilation (GDAS) cycle* : The Global Data Assimilation (GDAS) cycle runs 4 times a day (00, 06, 12 and 18 UTC). The assimilation system is a global 3-dimensional variational (3D VAR) technique, based on NCEP's Grid Point Statistical Interpolation (GSI) scheme. Step 4 – Forecast Integration for 7 days and post-processing The model forecasts are post-processed at the standard pressure level for generation of graphical outputs, which are called model forecast field at the given forecast time.

MESO-SCALE MODELLING AND ASSIMILATION SYSTEM (WRF-VAR):

The regional mesoscale analysis system WRF (ARW) was implemented on the HPCS at HQ of IMD, Delhi with its all components namely, pre-processing programs (WPS and REAL), data assimilation program (WRF-Var), boundary condition updating (update_bc) and forecasting model (WRF) and NCL for display. The pre-processed observational data from GTS and other sources prepared for the Global Forecast System in the BURF format (PREPBUFR of step 2 in GFS) is also used in case of WRF assimilation.

In the WRF-Var assimilation system, all conventional observations over a domain (200S to 450N; 400E to 1150E) which merely cover Regional Specialized Meteorological Centre (RSMC), Delhi region are considered to improve the first guess of GFS analysis. Assimilation is done with 27 km horizontal resolution and 38 vertical eta levels. The boundary conditions from GFS forecasts run at IMD are updated to get a consistency with improved mesoscale analysis. WRF model is then integrated for 75 hours with a nested configuration (27 km mother and 9 km child domain) and with full physics (including cloud microphysics, cumulus, planetary boundary layer and surface layer parameterization). The post-processing programs ARW post and WPP are also installed on HPCS to generate graphical plots and grib2 out for MFI-SYNERGIE system respectively. WRF at 3 km resolution was implemented for National Capital Region of Delhi Region. High resolution WRF has been in operational at other ten regional centres.

WRF Data assimilation (WRFDA) is a unified variational data assimilation system built within the software framework of the Weather Research and Forecasting (WRF-ARW) model. WRFDA system based variational data assimilation technique, increments the first guess state of the atmosphere using observations through the iterative minimization of a prescribed cost (or penalty) function. The cost function represents the cumulative differences between the analysis and observations/first guess which weighted/penalized according to their perceived error statistics. WRFDA system is capable to utilize observations (conventional/non-conventional) from different platforms with is inherent to variational method.

The regional mesoscale analysis system WRFDA is installed on High performance Computing (HPC) system at IMD, Delhi with its different components i.e. preprocessing program (WPS and REAL), assimilation program (WRFDA), boundary condition update (update_bc) and forecasting model (WRFARW). The processed observational data from different sources are assimilated in WRFDA system to improve the first guess GFS analysis. Assimilation is done with 27 km horizontal resolution and 38 vertical eta levels. Usable cold-start mode of assimilation is presently adopted for WRFDA system. WRFDA takes first guest from global analysis and produces modified mesoscale analysis in each specified time (00 and 12 UTC) of operational run. Using update_bc component of WRFDA, the boundary conditions from GFS forecasts are each time suitably updated to get a consistency with improved mesoscale analysis. WRF-ARW model is then integrated for 75 hours with a nested configuration (27 km mother and 9 km child domain). The forecast model is configured with full physics (including cloud microphysics, cumulus, planetary boundary layer and surface layer parameterization) as well. The whole WRF-ARW forecasting process has been scheduled to provide forecasts at 00 UTC and 12 UTC daily.

The forecasts from 9 km nested domain are further down scaled up to 3 km to prepare IC and BC for WRF-ARW model run at higher resolution of 3km. The nestdown component of the system can be utilized as many times as possible to generate the IC and BC for many number sub-domains inside the area covered by 9 km domain. Although the triple nest configuration (27, 9 and 3 km) of WRF-ARW model is the most suitable choice to generate forecast at 8 higher resolution, but the scope is restricted to a few number of child domains at 3km with some rigidity in the nested configuration of the model. At the same time, the triple nest model can only be run on single system with all child nests, which in turn prohibits the use of several computing system simultaneously at a time installed at different regional centers in IMD. Triple nest also increase computing load on the HPC at IMD-HQ and slows down the forecasting schedule for RSMC (Regional Specialised Meteorological Centre, New Delhi) and India region. On the other hand, as the nestdown utility generates separate set of IC and BC for several sub-domains, it provides the scope for further modification and improvement of those inputs through nest step of assimilation using additional local observations at higher resolution.

The post-processing programs *WPP* (WRF Post Processor) and NCL (NCAR Command Language) graphics package have been utilized for the preparation of meteograms and graphics from all classes of forecasts at three 9 different resolutions (27, 9 and 3 km). WPP program converts WRF forecasts to grib2 format for further utilization in MET (Model Evaluation Tools) package and operational SYNERGIE forecasting system in IMD. All other graphics products have been generated through NCL scripting.

The inputs to WRFDA-WRF-ARW system are mainly of three different class i.e. static or slow-varying geographical characteristics data and day-to-day operational global analysis and forecasts and observations. WRFDA system also takes error statistics information for background and observation updated every month. The background error statistics has been computed using gen_be utility of the system from past WRF forecasts for a specified month.