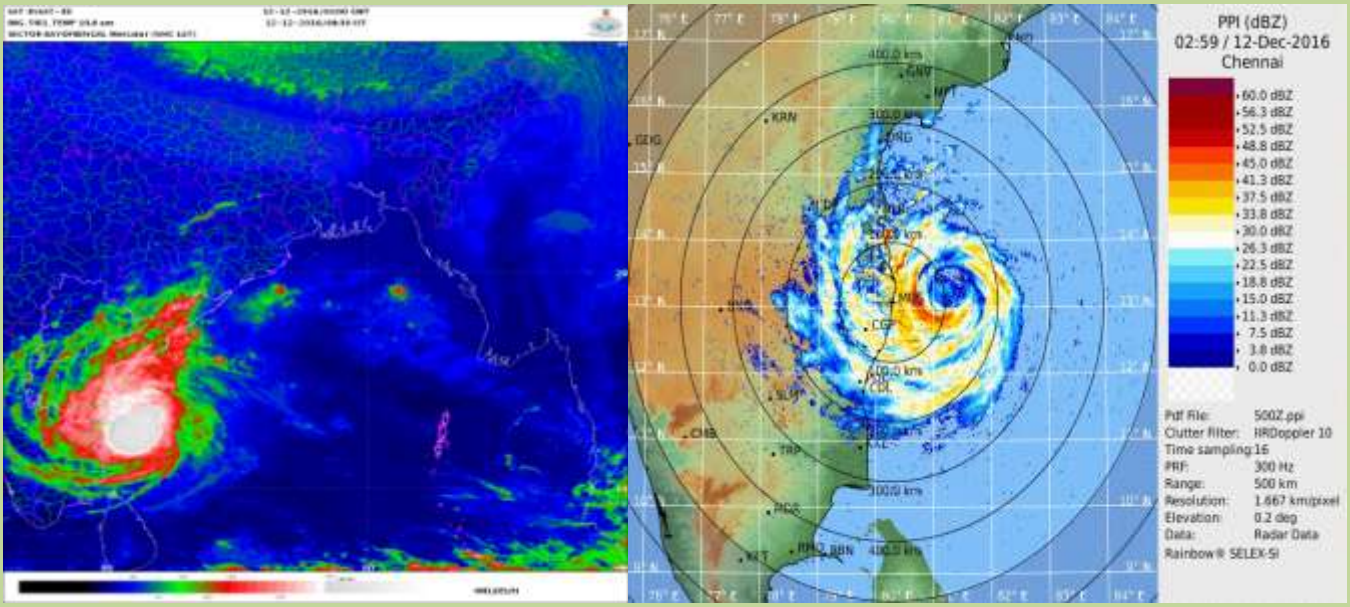
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Very Severe Cyclonic Storm,'Vardah' over the Bay of Bengal (06-13 December 2016): A Report



INSAT-3D enhanced colored IR imagery & DWR Chennai imagery based on 0300 UTC of 12th December

Cyclone Warning Division

India Meteorological Department

New Delhi

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Very Severe Cyclonic Storm 'Vardah' over the Bay of Bengal (06-13 December 2016)

1. Introduction

A low pressure area developed over south Andaman Sea & adjoining Sumatra in the morning of 4th December. It lay as a well marked low pressure area in the night of 5th over south Andaman Sea and adjoining southeast Bay of Bengal (BoB). Moving westwards, it concentrated into a depression (D) over southeast BOB in the afternoon of 6th December. Moving northwestwards initially and northwards thereafter, it intensified into a deep depression (DD) in the midnight of 7th December, into a cyclonic storm (CS) "**VARDAH**" in the morning of 8th and into a severe cyclonic storm (SCS) in the midnight of 9th. It then moved west-northwestwards and intensified further into a very severe cyclonic storm (VSCS) over westcentral and adjoining south BOB in the evening of 10th December. It then moved nearly westwards and reached its peak intensity of about 130 kmph on 11th December evening and maintained the same intensity till noon of 12th December. It weakened into an SCS at the time of landfall and crossed north Tamil Nadu coast near Chennai during 1500-1700 hrs IST of 12th December 2016 with a wind speed of 110 kmph gusting to 125 kmph. After the landfall, the SCS moved west-southwestwards and weakened into a CS in the evening, into a DD in the midnight of 12th and into D in the early morning of 13th. Continuing its west-southwestwards movement, it weakened into a well marked low pressure area in the forenoon of 13th December.

The observed track of the VSCS Vardah is shown in Fig.1. The salient features of the system are as follows.

(i) It was the first severe cyclonic storm of the year 2016.

(ii) Vardah was the fourth consecutive cyclone with recurving track after cyclones Roanu, Kyant and Nada during the year, as it changed its track from initial northwards movement to west-northwestwards and then west-southwestwards after landfall.

(iii) Unlike the previous two cyclones in the post-monsoon season, it crossed the coast with the cyclone intensity.

(iv) The peak maximum sustained wind speed of the cyclone was 130 kmph gusting to 145 kmph over westcentral BOB. However, the maximum sustained wind speed of the cyclone was 110 kmph gusting to 125 kmph at the time of landfall.

(v) The life period of cyclone was 159 hours (6.6 days) against the normal of 4.7 days over north Indian Ocean during post-monsoon season for VSCS category.

(vi) The track length of the cyclone was 1795 km.

(vii) The 12 hour average translational speed of the cyclone was 5.2 kmph against normal of 13 kmph over BOB for post-monsoon season. However, prior to landfall, the cyclone moved with a speed of about 15-20 kmph.

(viii) Lowest estimated central pressure (ECP) was 975.0 hPa with a pressure drop of 26 hPa.

(ix) The Accumulated Cyclone Energy (ACE) which is a measure of damage potential was about 5.99 X 10^4 $knot^2$.

(x) The Power Dissipation Index which is a measure of loss due to a CS was 3.61 X 10^6 $knot^3$.

(xi) There was rapid weakening of the system from 0600 to 1800 UTC of 12th Dec as the maximum sustained wind speed decreased from 70 knots to 30 knots during this period.

(xii) During genesis stage cyclone Vardah caused heavy to very heavy rainfall over Andaman & Nicobar Islands and squally wind speed reaching 50-60 kmph prevailed along and off Andaman & Nicobar Islands.

(xiii) It caused heavy to very heavy rainfall at many places with isolated extremely heavy rainfall over Chennai, Thiruvallur, Kanchipuram districts of Tamil Nadu and heavy to very heavy rainfall at a few places over Nellore district of Andhra Pradesh The maximum gale wind of about 100-110 kmph gusting to 125 kmph has been reported in these districts.

(xiv) The maximum storm surge of about 1 meter inundated low lying areas of Chennai, Thiruvallur districts of Tamil Nadu and Nellore district of Andhra Pradesh at the time of landfall.

Brief life history, characteristic features and associated weather along with performance of NWP and operational forecast of IMD are presented and discussed in following sections.

2. Monitoring of VSCS,'Vardah'

The cyclone was monitored & predicted continuously since its inception by IMD. The observed track of the cyclone over BoB during 06-13 December is presented in Fig.1. The best track parameters of the systems are presented in Table 1**.**

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) since its inception over south Andaman Sea on 6th December. At the genesis stage, the system was monitored mainly with satellite observations and buoy observations. From 12th December morning, the system was continuously monitored by Doppler Weather Radar at Chennai and Machilipatnam. Various national and international NWP models and dynamical-statistical models were utilized to predict the genesis, track and intensity of the cyclone. Tropical Cyclone Module, the digitized forecasting system of IMD was utilized for analysis and comparison of various models guidance, decision making process and warning product generation. IMD issued regular bulletins to WMO/ESCAP Panel member countries, National & State Disaster Management Agencies, general public and media since inception of the system over BOB.

3. Brief life history

3.1. Genesis

Under the influence of an upper air cyclonic circulation over northern parts of Sumatra & adjoining south Andaman Sea, a low pressure area formed over south Andaman Sea & adjoining Sumatra extending upto mid-tropospheric levels at 0300 UTC of 4th December. Moving west-northwestwards, it lay as a well marked low pressure area in the night of 5th over south Andaman Sea and adjoining southeast BoB. At 0900 UTC of

6th, the sea surface temperature (SST) was around 28-29˚C. The Ocean heat content was about 100-120 KJ/cm^2 over the well marked low pressure area. The low level convergence was about 20x10^{-5} second$^{-1,}$ the upper level divergence was around 30x10^{-5} second^{-1} and the low level relative vorticity was about 100x10^{-6} second^{-1} to the southwest of the system. The vertical wind shear of horizontal wind was moderate (5-15 knots) around the system centre and was increasing towards northwest and westcentral BoB. The Madden Julian Oscillation (MJO) index was in phase 2 with amplitude <1. The upper tropospheric ridge lay along 13^{0}N and east-southeasterly winds prevailed over the region of low pressure area in middle and upper tropospheric levels. Under these favourable environmental conditions, the well marked low pressure area over southeast BoB and adjoining south Andaman Sea moved west-northwestwards and concentrated into a depression (D) and lay centred at 0900 UTC of 6th over southeast BoB near latitude 8.5ºN and longitude 91.0ºE.

3.2. Intensification

At 1800 UTC of 7th, SST was around 28-29˚C, the ocean heat content was about 70-80 KJ/cm^2 over the depression. The low level convergence was about 20x10^{-5} second^{-1} to the east-northeast of the system centre, the upper level divergence was around 40x10^{-5} second^{-1} to the northeast and the low level relative vorticity was about 150x10^{-6} second^{-1} to the southeast of the system centre. The vertical wind shear of horizontal wind was moderate (10-20 knots) around the system centre and was increasing towards northwest and westcentral BoB. The MJO index lay in phase 2 with amplitude 1. Under these favourable environmental conditions, the system moved northwestwards initially & then northwards and concentrated into a deep depression **(DD)** at 1800 UTC of 7th over southeast BoB near latitude 10.8ºN and longitude 90.5ºE. At 0000 UTC of 8th, similar conditions prevailed and moving northwards, the system intensified into a cyclonic storm **(CS)** over southeast BoB near latitude 11.2ºN and longitude 90.5ºE. At 0000 UTC of 9th, similar thermal conditions prevailed. The low level convergence was about 20x10^{-5} second^{-1} to the east-northeast of the system centre, the upper level divergence was around 10x10^{-5} second^{-1} around the system centre and the low level relative vorticity increased to about 250x10^{-6} second^{-1} to the southeast of the system centre. The vertical wind shear of horizontal wind was high (20-25 knots) around the system centre. The MJO index lay in phase 2 with amplitude 1. Under these environmental parameters, the system moved nearly northwards, intensified gradually and lay over southeast BoB near latitude 12.1ºN and longitude 90.4ºE. At 1800 UTC of 9th, the SST was around 28-29˚C, the ocean heat content was about 70-80 KJ/cm^2 over the system. The low level convergence was about 50x10^{-5} second^{-1} at system centre, the upper level divergence was around 30x10^{-5} second^{-1} to west of the system centre and the low level relative vorticity was about 250x10^{-6} second^{-1} to the south of the system centre. The vertical wind shear of horizontal wind was high (20-25 knots) around the system centre. The MJO index lay in phase 2 with amplitude less than 1. Under these favourable environmental parameters, CS Vardah moved west-northwestwards and intensified into a severe cyclonic storm **(SCS)** over southeast BoB near latitude 12.3ºN and longitude 89.6ºE. At 1200 UTC of 10th, similar thermodynamical and large scale environmental conditions prevailed and the system moving west-northwestwards, concentrated into a very severe cyclonic storm **(VSCS)** and lay centered over westcentral and adjoining south BoB near latitude 13.2ºN and longitude 86.4ºE. At 0000 UTC of 11th, the low level convergence was about 40x10^{-5} second^{-1} to the southwest of the system centre, the upper level divergence was around 30x10^{-5} second^{-1} to southwest of the system centre. the low level relative vorticity was about 250x10^{-6} second^{-1} to the south-southwest of the system

centre. The vertical wind shear of horizontal wind was high (20-25 knots) around the system centre. The system intensified slightly and lay centered over westcentral and adjoining southwest BoB near latitude 13.3ºN and longitude 84.7ºE. The system continued its near westward journey, and at 0900 UTC of 12th, weakened slightly due to land interactions, lower SST about 26˚C, lower Ocean thermal energy less than 50 KJ/cm^2 and high vertical wind shear (20-25 knots) over westcentral & adjoining southwest BoB. Moving westwards, the system crossed north Tamil Nadu coast close to Chennai near 13.13^{0}N/80.3^{0}E during 0930-1130 UTC of 12th. Moving west-southwestwards, the system weakened into a CS over north Tamil Nadu near latitude 12.9ºN and longitude 79.5ºE at 1500 UTC of 12th, into a DD over north interior Tamil Nadu near latitude 12.7ºN and longitude 79.1ºE at 1800 UTC of 12th. It further weakened into a depression over north interior Tamil Nadu near at 0000 UTC of 13th and into a well marked low pressure area at 0300 UTC of 13th over north interior Tamil Nadu and adjoining south interior Karnataka.

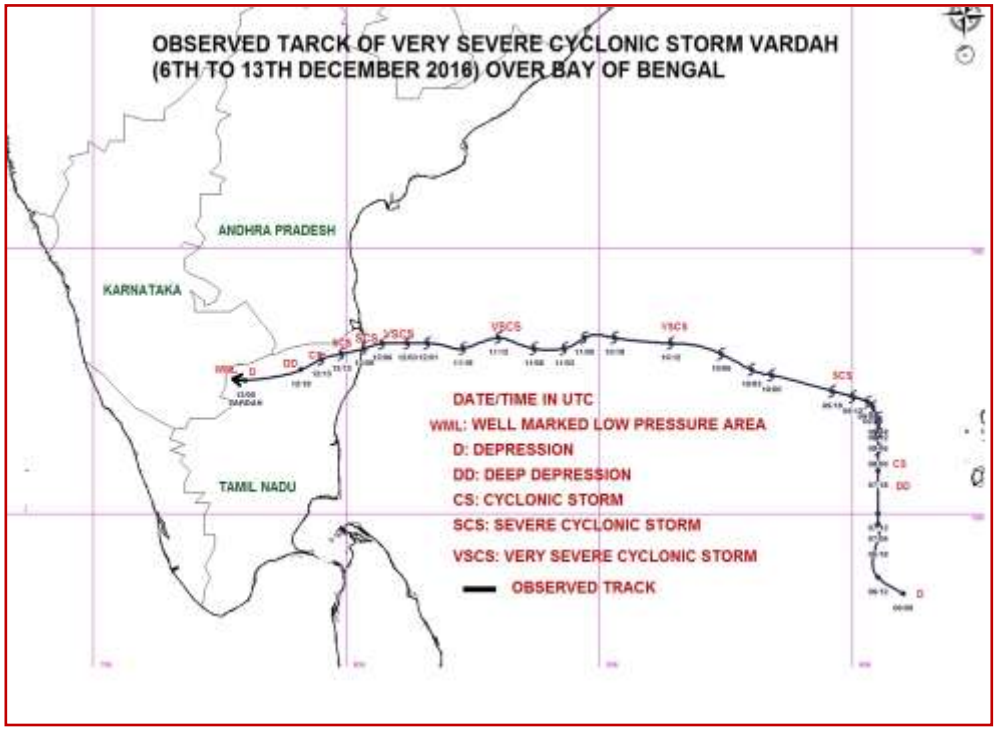


Fig.1 Observed track of VSCS,'Vardah' over BoB during 06-13 December 2016

Table 1: Best track positions and other parameters of the Very Severe Cyclonic Storm, 'Vardah' over the Bay of Bengal during 06-13 December, 2016

Date	Time (UTC)	Centre lat.^{0} N/ long.^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
06/12/2016	0900	8.5/91.0	1.5	1002	25	3	D
	1200	8.5/90.5	1.5	1002	25	3	D
	1800	9.5/90.5	1.5	1002	25	3	D
07/12/2016	0000	9.8/90.5	1.5	1002	25	4	D
	0300	9.8/90.5	1.5	1002	25	4	D
	0600	9.8/90.5	1.5	1002	25	4	D
	1200	10.0/90.5	1.5	1002	25	4	D
	1800	10.8/90.5	2.0	1000	30	5	**DD**
08/12/2016	0000	11.2/90.5	2.5	998	35	6	**CS**
	0300	11.5/90.5	2.5	998	35	7	CS
	0600	11.5/90.5	2.5	998	35	7	CS
	0900	11.5/90.5	2.5	998	35	7	CS
	1200	11.7/90.5	2.5	997	40	8	CS
	1500	11.7/90.5	2.5	997	40	8	CS
	1800	11.8/90.5	2.5	997	40	8	CS
	2100	12.0/90.5	2.5	997	40	8	CS
09/12/2016	0000	12.0/90.4	3.0	996	45	10	CS
	0300	12.1/90.4	3.0	996	45	10	CS
	0600	12.1/90.3	3.0	996	45	10	CS
	0900	12.2/90.3	3.0	996	45	10	CS
	1200	12.2/90.0	3.0	996	45	10	CS
	1500	12.2/89.9	3.0	994	45	12	CS
	1800	12.3/89.6	3.0	992	50	14	**SCS**
	2100	12.5/89.0	3.5	990	55	16	SCS
1012/2016	0000	12.6/88.4	3.5	990	55	16	SCS
	0300	12.7/88.0	3.5	990	55	16	SCS
	0600	13.0/87.4	3.5	990	55	16	SCS
	0900	13.1/86.8	3.5	988	60	18	SCS
	1200	13.2/86.4	4.0	984	65	22	**VSCS**
	1500	13.3/85.9	4.0	984	65	22	VSCS
	1800	13.3/85.3	4.0	984	65	22	VSCS
	2100	13.3/85.0	4.0	982	65	22	VSCS
11/12/2016	0000	13.3/84.7	4.0	980	70	24	VSCS
	0300	13.1/84.3	4.0	980	70	24	VSCS
	0600	13.1/83.7	4.0	980	70	24	VSCS
	0900	13.1/83.3	4.0	980	70	24	VSCS
	1200	13.3/83.0	4.0	980	70	24	VSCS
	1500	13.3/82.5	4.0	980	70	24	VSCS
	1800	13.1/82.3	4.0	980	70	24	VSCS
	2100	13.2/81.9	4.0	978	70	26	VSCS

12/12/2016	0000	13.2/81.6	4.0	975	70	26	VSCS
	0300	13.2/81.2	4.0	975	70	26	VSCS
	0600	13.2/80.7	4.0	975	70	26	VSCS
	0900	13.1/80.3	3.5	975	60	26	**SCS**
	Crossed North Tamil Nadu coast close to Chennai near 13.13^{0}N/80.3^{0}E during 0930-1130 UTC						
	1200	13.0/79.9	3.5	984	50	18	SCS
	1500	12.9/79.5	3.0	994	40	10	**CS**
	1800	12.7/79.1	2.0	1002	30	5	**DD**
13/12/2016	0000	12.5/78.0	1.5	1003	20	3	**D**
13/12/2016	0300	**Well Marked Low Pressure Area over north interior Tamil Nadu and south Interior Karnataka**					

The total precipitable water imageries (TPW) during 06th to 13th December are presented in Fig.2. These imageries indicate gradual incursion of cold, dry air from northwest into the system cutting off supply of cross equatorial moist air into the system on 12th completely. It led to rapid weakening of the system after landfall.

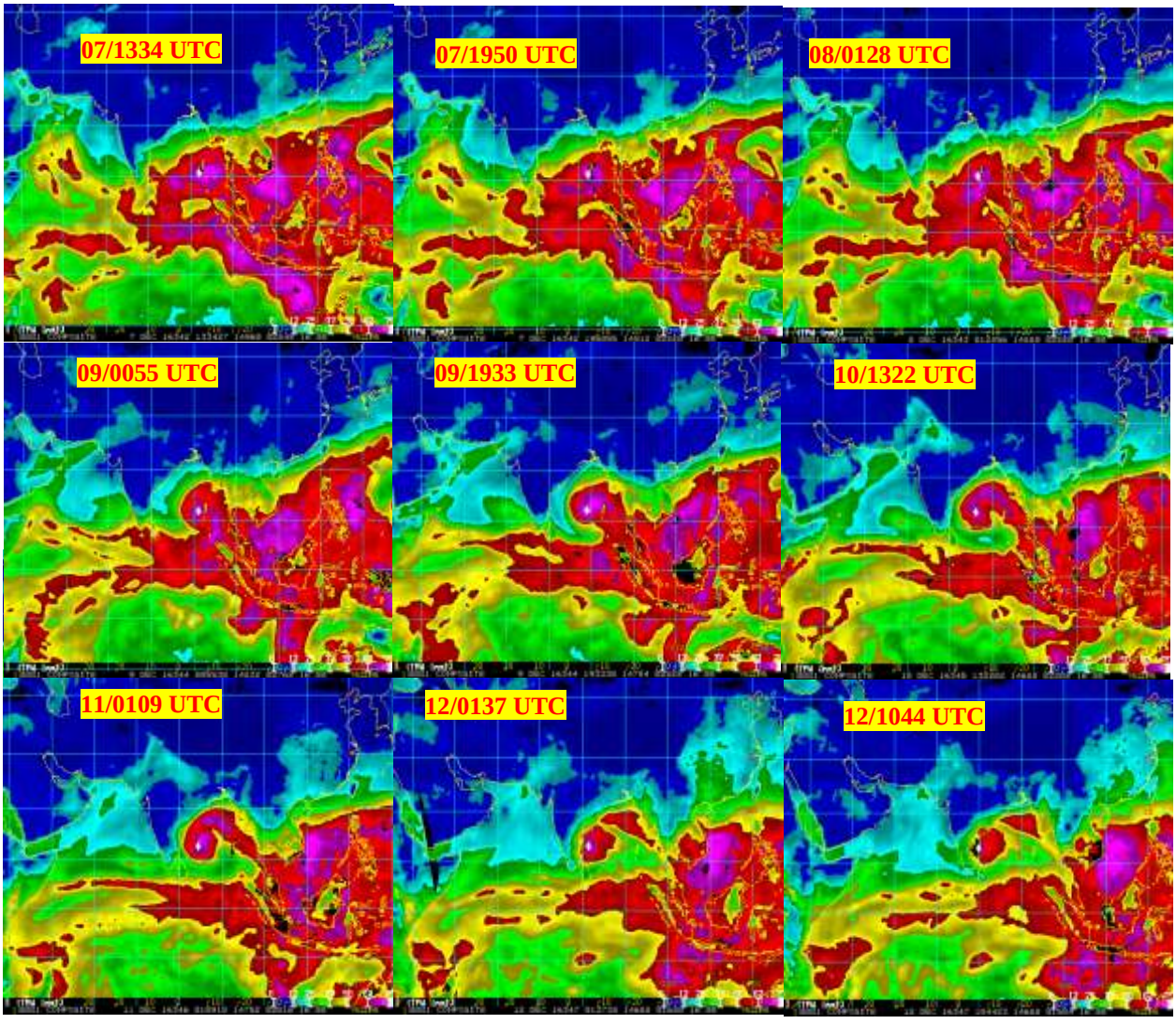


Fig. 2: Total Precipitable Water Imageries during 6th – 13th December, 2016

3.3 Movement

VSCS Vardah moved initially northwestwards and then northwards till midnight of 8th December. It then recurved and moved west-northwestwards till 0900 UTC of 12th and west-southwestwards after landfall close to Chennai coast. The six hourly movement of VSCS Vardah is presented in Fig.3. The system had a track length of about 1795 km during its life period.

The wind speed in middle and deep layer around the system centre is presented in Fig.4. It indicates that from 18th onwards, the middle to upper level steering flow was supporting the above direction and speed of movement. The west-southwesterly movement after the landfall was in association with an anti-cyclonic circulation lying to the northwest of the system centre. The initial slow northerly movement of the system was in association with the upper tropospheric ridge which lay very close to the north of the system centre.

Under the influence of middle and upper tropospheric trough, the wind shear around the system between 200 and 850 hPa levels also increased rapidly on 20th and 21st. As the wind shear was east-southeasterly, the convective cloud mass was sheared towards west-northwestwards of the system centre till 20th.

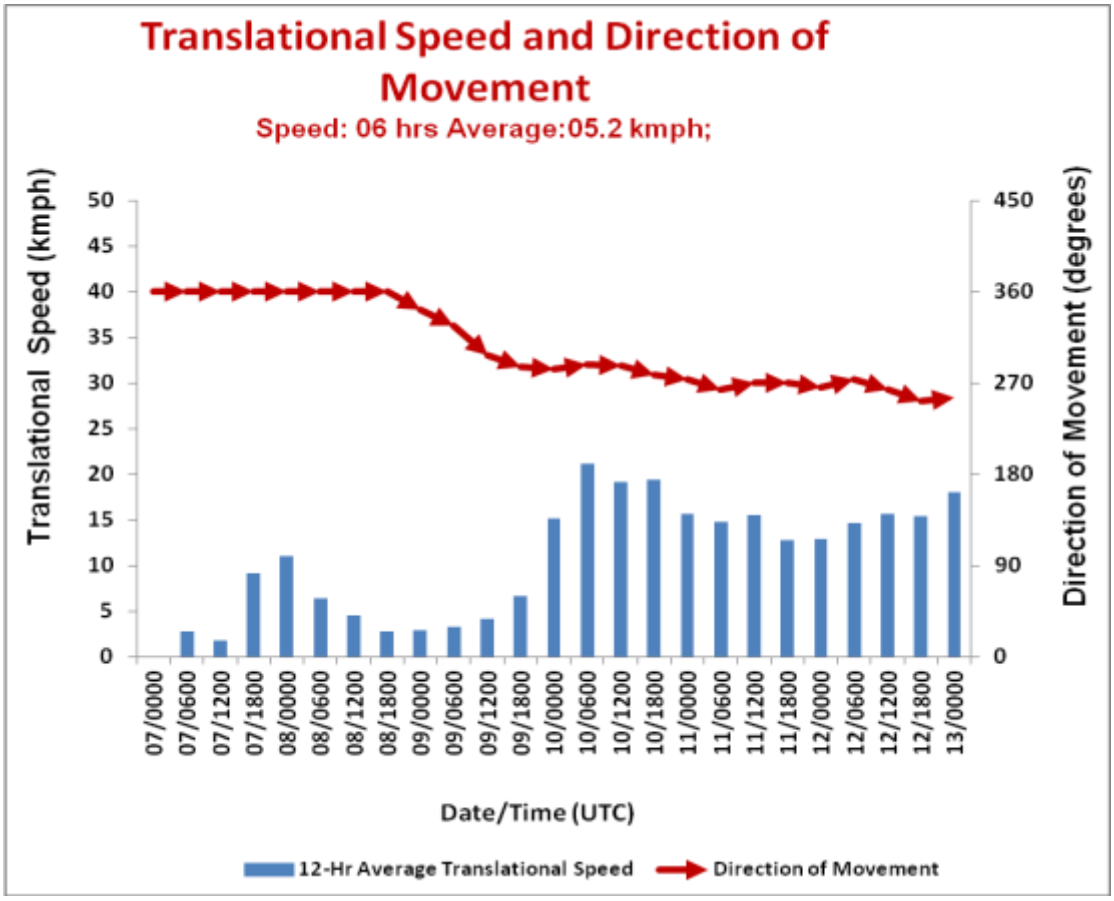


Fig.3 Twelve hourly average translational speed (kmph) and direction of movement in association with VSCS Vardah

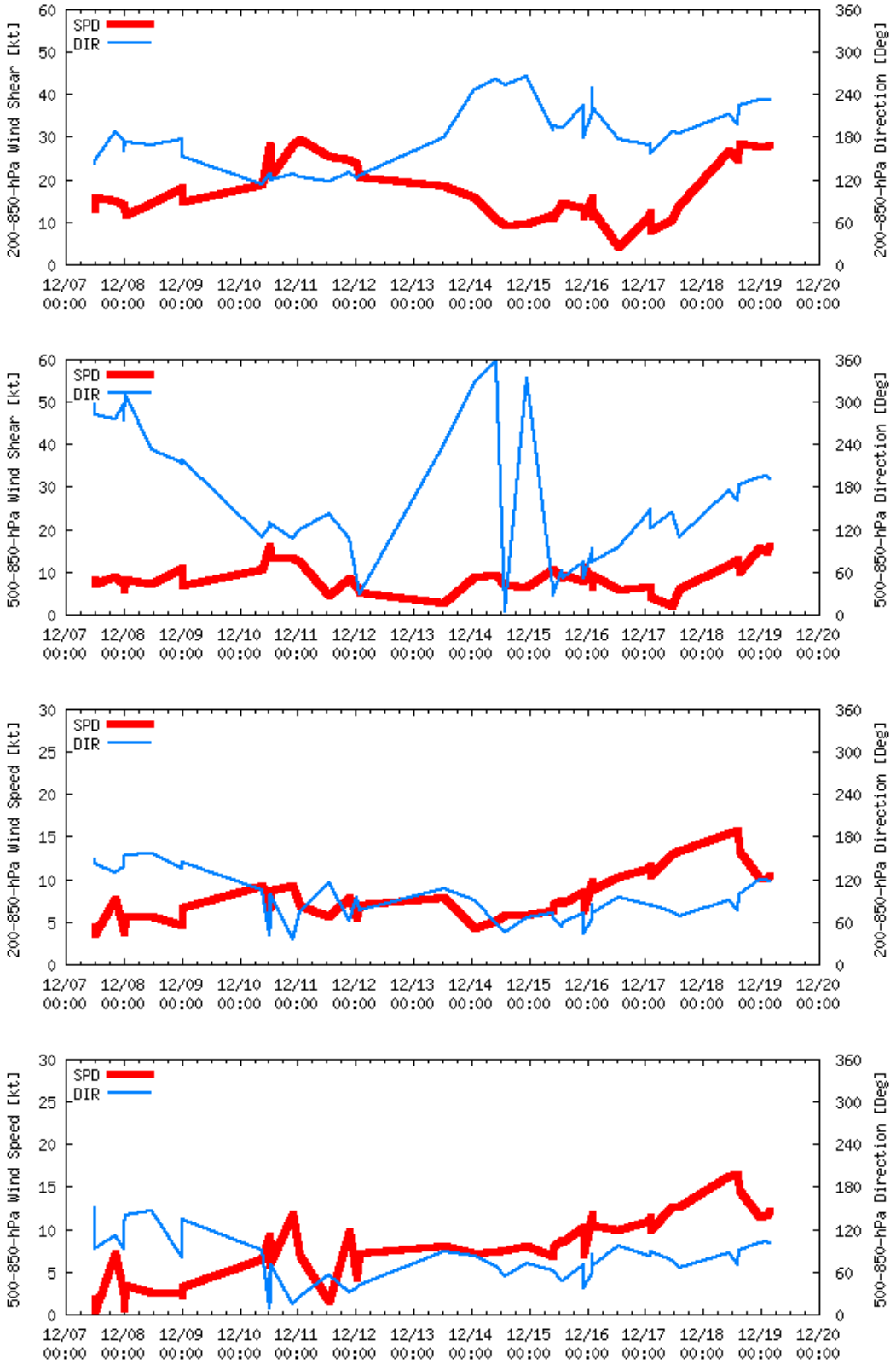


Fig.4 Wind shear and wind speed in the middle and deep layer around the system during 06th to 13th December 2016.

3.4 Landfall point and time

The plot of hourly observations is presented in Fig.5 during 0600-1200 UTC of 12th December. Veering of winds over NBK from northwesterly (0900 UTC) to southeasterly (1100 UTC) with calm winds at 1000 UTC indicating that the system has passed over NBK at 1000 UTC of 12th. Light winds over MBK at 1100 UTC and backing of winds from southwesterly at 1000 UTC to southeasterly at 1200 UTC suggest that the system passed over MBK at 1100 UTC.

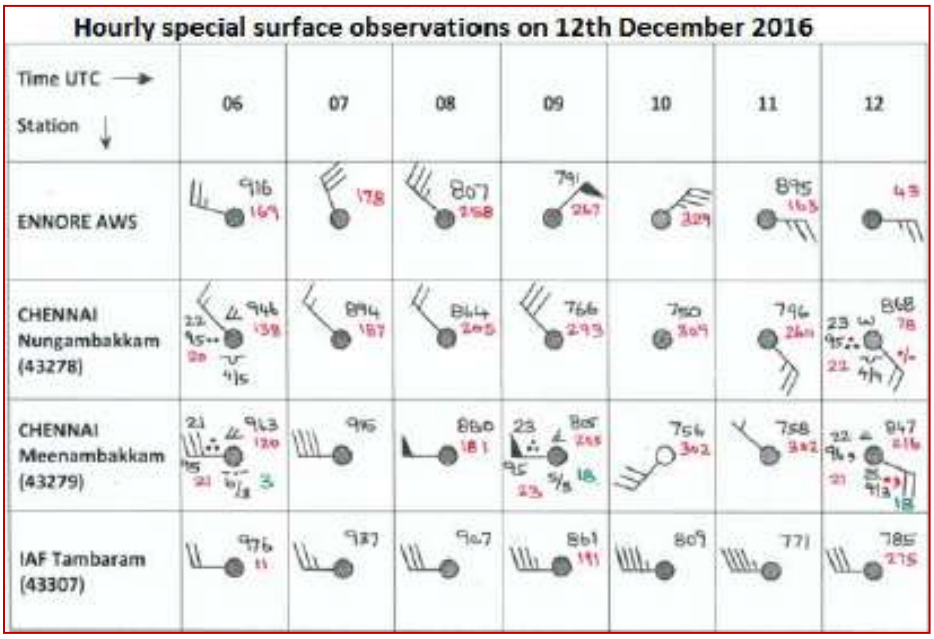


Fig.5: Hourly synoptic observations during 0600 -1200 UTC of 12th December, 2016

3.5. Maximum Sustained Surface Wind speed and estimated central pressure:

The lowest estimated central pressure and the maximum sustained wind speed are presented in Fig.6. The lowest estimated central pressure had been 976 hPa. The reported lowest mean sea level pressure has been 975.6 hPa recorded over Chennai at the time of landfall. The estimated maximum sustained surface wind speed (MSW) was 70 knots during 0000 UTC of 11th to 0600 UTC of 12th December. At the time of landfall, the ECP was 976 hPa and MSW was 60 knots (severe cyclonic storm). The ECP and Vmax graph indicate that the system intensified gradually till 0000 UTC of 11th, maintained its intensity till 0600 UTC of 12th and started weakening rapidly after landfall. There was rapid weakening of the system from 0600 to 1800 UTC of 12th Dec as the maximum sustained wind speed decreased from 70 knots to 30 knots during this period.

The hourly MSLP as recorded by Nungambakkam (NBK) (Chennai city) and Meenambakkam (MBK) (Chennai airport) is shown in Fig.7(a) which clearly indicates that the pressure fell gradually from 11th onwards. The minimum MSLP of 975 hPa and 975.6 hPa was recorded at NBK and MBK respectively at 1000 UTC. The lowest MSLP of 975.0 and 974.0 hPa has been recorded by the barograph at NBK and MBK respectively. At that time, the outermost pressure was 1002 hPa. Hence the pressure drop was 26-28 hPa at different stations in Chennai. Considering other stations surrounding Chennai, as

shown in Table 2, it is found that the lowest MSLP of 974.0 hPa was recorded over Chennai Airport at 1030 UTC. It indicates the cyclone Vardah crossed Tamil Nadu coast near Chennai around 1030 UTC.

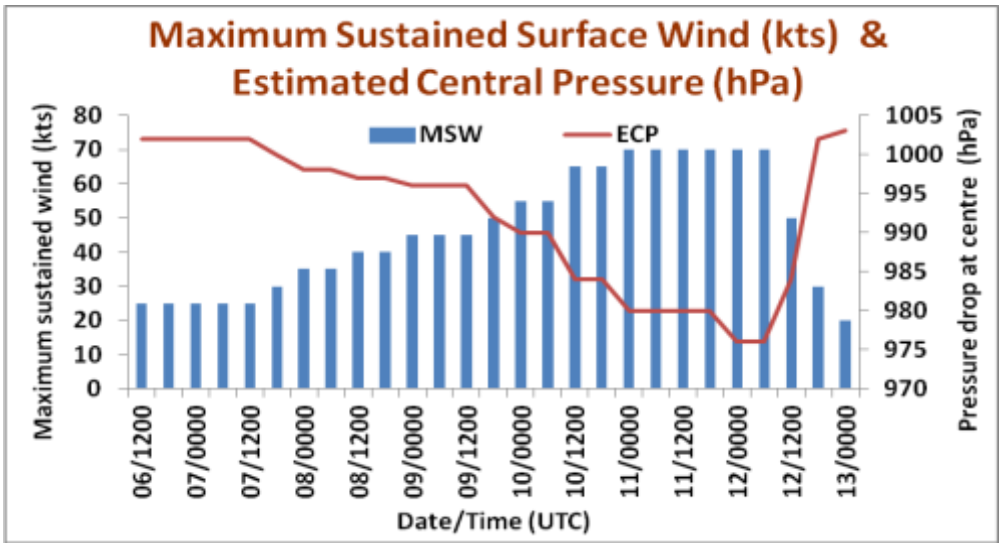


Fig.6 Lowest estimated central pressure and the maximum sustained wind speed

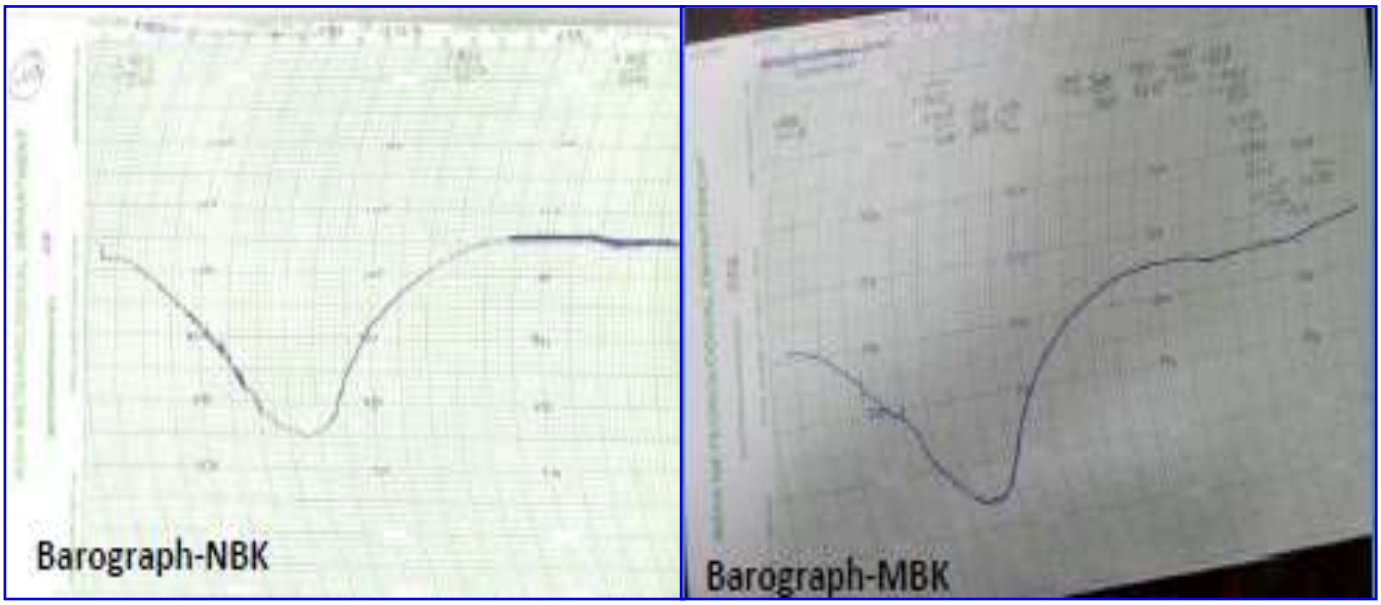


Fig.7(a): Barograph recordings at NBK and MBK on 12th December 2016

3.6. MSW based on pressure wind relationship:

The pressure drop at the centre was 28 hPa with lowest MSLP of 974 hPa over Chennai Airport (MBK) and the outermost pressure in the cyclone was 1002hPa. According to Mishra and Gupta formula, the MSW=14.2*SQRT (pressure drop) = 14.2*SQRT (28) = 75 knots. (139 kmph)

Table 2. Observational data recorded by manned observatories and AWS

Station/(lat./long.)	Lowest MSLP (hPa) and time of occurrence (UTC)	Wind Speed (kts/kmph) and time of occurrence (UTC)	Wind Direction (degree) and time of occurrence (UTC)
*Chennai (NBK)/ (13.1N/80.2E) (Manned)	975.0 at 1000 UTC	30 kts (56 kmph) at 0900 UTC	315
*Chennai (MBK)/ (12.98N/80.18E) (Manned)	975.6 at 1000 UTC	50kts (93 kmph) at 0900 UTC	270
*Chennai (NBK)/ (13.1N/80.2E) (AWS)	977 at 1000 UTC	11kts (20 kmph) at 0800 UTC	340
*Ennore Port/ (13.2N/80.3E) (AWS)	979.1 at 0900 UTC	48kts (89 kmph) at 0900 UTC	10
*Madhavaram Agro/ (13.2N/80.2E) (AWS)	977.3 at 1000 UTC	25kts (46 kmph) at 0800 UTC	350
*MBK-ISRO/ (13.0N/80.2E) (AWS)	978 at 1000 UTC	13kts (24 kmph) at 0700 UTC	200
**Chennai (NBK)/ (13.1N/80.2E) (Barograph)	975.0 at 1000 UTC	61 kts (114 kmph) at 0710 UTC	330
**Chennai (MBK)/ (12.98N/80.18E) (Barograph)	974.0 at 1030 UTC	65 kts 122 kmph during 0815-0820 UTC	315

***-3-minute average MSW, **-Instantaneous wind**

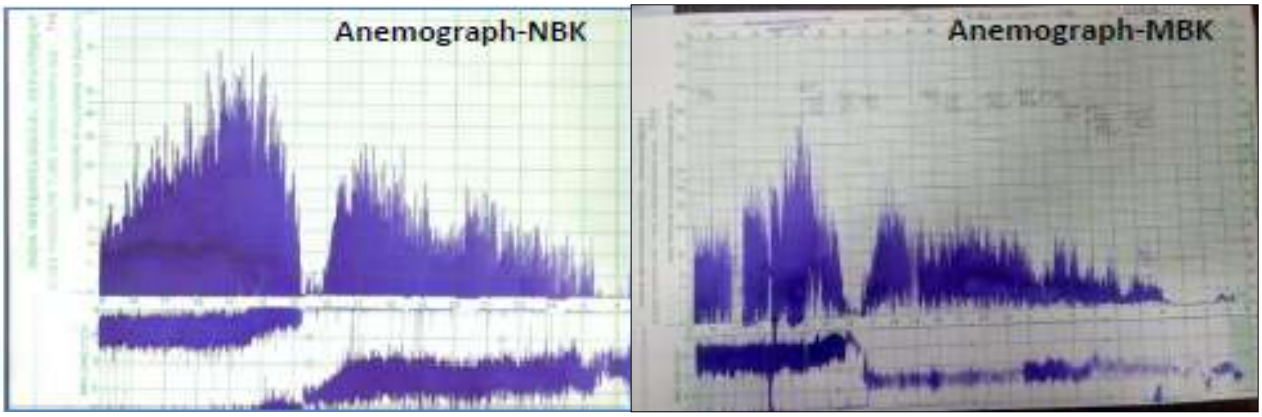


Fig.7(b): Anemograph recordings at NBK and MBK.

3.7. MSW over Chennai as measured by HWSR:

According to HWSR located at the ACWC, IMD, Chennai, one -minute average MSW was about 57.7 knots (107kmph) at 0800 UTC (1330 hours IST) (Fig.8).

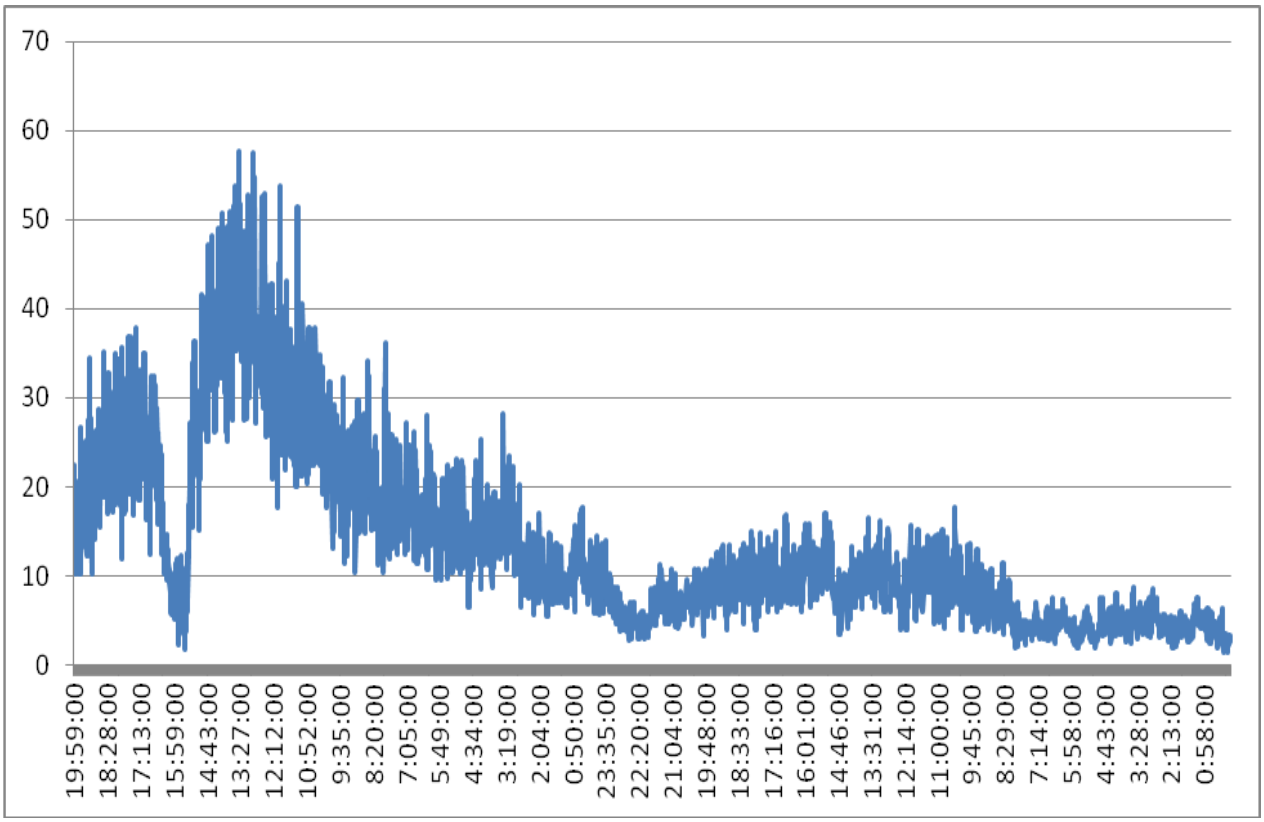


Fig.8: Wind speed recorded by HWSR Chennai on 12 October 2016

3.8 MSW based on observation by the DIWE, AWS and manned observatories:

From Table 2, the 3 minute maximum sustained surface wind of 50 knots has been reported by NBK followed by 48 knots by Ennore port. The Ennore port lies to the north of NBK at about 15 km. Hence it lay over the maximum wind region wnen the cyclone was crossing Chennai city. The maximum wnd in gustiness has been reported as 122 kmph over MBK followed by 114 kmph over NBK. The distance Indicator of Wind Equipment (DIWE) at NBK reported MSW of 87.6 knots at 0820 UTC (1350 IST) of 12th December. However, there is tunneling effect in the Chennai airport leading to this higher wind speed. ISRO, Sriharikota wind measuring tower reported 99 kmph winds in gustiness at 0900 UTC.

Considering the fact that, the VSCS, Vardah crossed coast over Chennai and moved west-southwestwards recording lowest MSLP over NBK at 1000 UTC and over MBK at 1030 UTC and MBK lies to the southwest of NBK, the concurrent MSW at 1000 and 1030 UTC of 12th Dec. over NBK and MBK has been examined and is presented in Table 3.

Table 3: Concurrent wind data during 1000 to 1030 UTC on 12th December

S. N.	**Source**	**Time (UTC)**	**Minimum MSLP (hPa)**
1.	Barograph (NBK)	1000 UTC (1530 IST)	975
2.	Barograph (MBK)	1030 UTC (1600 IST)	974
S. N.	**Concurrent wind**	**1000 UTC (1530 IST)**	**1030 UTC (1600 IST)**
1.	Manual (NBK)	Calm	---
2.	Manual (MBK)	30 kt	---

3.	Anemograph(NBK)	4 kmph (2 kt) /Ely	10 kmph / Ely
4.	Anemograph(MBK)	68 kmph (36.7 kt) / NWly	4 kmph / NNWly
5.	HWSR (NBK)	14.4 kt / NWly (Peak: 26.5 kt, NWly)	14.9 kt / NWly (Peak: 27.5 kt, WNWly)
6.	AWS (NBK)	11 kt / NWly	---
7.	AWS (Ennore Port)	37 kt / NEly	---
8.	Radar wind (surface)	28.8 m/s (55.8 kt)	**---**
9.	Runway-12 DWI	40.8 kt / NWly	6.5 kt / NNWly
10.	Runway-25 DWI	Not recorded due to power failure	
11.	Tambaram IAF	45 kt / W ly	---

3.10. MSW over Chennai based on radar:

The hourly radar observations from DWR Chennai are presented in Table 4.

As per Radar observations, maximum radial velocity of 51 m/s was recorded at 0500 UTC of 12th December in the direction of 103^{0} at a distance of 67 km at a height of 493 m above station level. As per the standard procedure the radial velocity has been converted to surface wind. Utilizing the mean wind speed profile, based on dropsonde observations over Atlantic Ocean in the eyewall region of cyclones, radar based radial wind observations at a given height has been converted initially into wind at 700 hPa level and then at surafce level. The wind is first converted to 700 hPa level as the WC-130J flies at this level and dropsonde is released into the cyclone field from this level. A suitable conversion factor for changing the radar wind at a given height to the 700 hPa level has been used based on Franklin etal, 2000 and Powel & Black (1990).

Table 4: DWR Chennai observations on 12th December

Date/Time (UTC)	Radial Velocity (m/s)	Azimuth (deg)	Range (deg)	Height (km)	Conversion Factor	W_{700} (m/s)	W_{10m} W_{700}x 0.73) (m/s)(kt) @1	W_{10m} (Outer Vortex) W_{700}x0.78) (m/s) (kts) @2	W_{10m} (Eye Wall) W_{700}x0.91) (m/s) (kts) @3	Remarks
12/0300	49.0	100.5	104.8	0.15	1.13	43.6	33.8 (65)	34.0 (66.)	39.7 (77.0)	-
12/0400	48.0	56.2	88.3	0.05	1.05	45.71	35.66 (70)	35.7 (69.2)	41.6 (80.7)	-
12/0500	51.0	103.5	67.3	0.493	1.21	42.15	32.88 (65)	32.9 (63.8)	38.4 (74.4)	-
12/0530	48.5	37.3	44.2	0.32	1.20	36.9	28.81 (60)	28.8 (55.8)	33.6 (65.1)	-
12/0650	37.67	8.5	40.0	0.0	-	-	-	-		Erroneous due to ground clutters
12/0800	42.47	8.6	28.2	0.2	1.15	36.9	28.80 (60)	28.8 (55.8)	33.6 (65.1)	-
12/0900	22.9	234	22.8	0.16	1.13	20.27	15.81	15.8	18.4	Not

							(30)	(30.7)	(35.8)	acceptable as point is over land
12/1000	28.8	230.6	30.3	0.0	-	-	-	-		Erroneous due to ground clutters
12/1100	29.9	187.1	26.6	0.19	1.15	26.0	20.3 (40)	20.3 (39.3)	39.3 (45.9)	-

@1: Powell and Black estimate (1990), @2: Franklin et al estimate (for winds in outer vortex) and @3: Franklin et al estimate (for winds in eye wall region)

3.10. Satellite based MSW over Chennai:

According to interpretation of satellite imageries, as per Dvorak technique by the IMD, the tropical cyclone intensity was T 4.0 on intensity scale. T4.0 corresponds to an MSW of about 65 knots (122 kmph). According to NOAA satellite estimates, the T number was 4.5 at 0230 UTC and 0830 UTC of 12th December, which was less than that estimated at 2030 UTC of 11th December (T5.0). It thus indicated the weakening trend of the cyclone while moving towards land on 12th December.

3.11.Best estimated wind speed at the time of landfall

Comprehensive analysis of all the observations is presented in Table 5. Considering all the inputs available based on surface synoptic observations, AWS, HWSR of IMD, wind profiler of SHAR, Sriharikota, Radar observations from DWR Chennai and satellite based observations, it is seen that the landfall occurred near Chennai city (NBK) and hence the MSW observed near the coast i.e. near NBK has been taken into consideration to estimate the intensity at the time of landfall. MBK which lies about 15 km to the southwest of NBK experienced the centre of the cyclone with lowest MSLP at 1030 UTC as compared to lowest pressure recorded at 1000 UTC by NBK. It is due to the fact that the cyclone moved west-southwest after landfall. Thus considering the MSW recorded over NBK and adjoining areas along the coast, MSW of 61 kts has been recorded over NBK (Table 3). HWSR Chennai reported MSW of 57.7 kts.

Considering the Radar observations taken at different heights, the MSW of 55-65 kts are estimated to be at the surface level based on various conversion factors utilised to convert the wind from a certain height to surface level (10m) (Table 3 & 4).

According to Mishra and Gupta formula, with lowest pressure of 974.0 hPa, the estimated MSW is found to be 75 kts which is not in agreement with actual observations of MSW. Hence this estimate has not been taken into consideration.

The observation from DIWE at MBK has not been considered as there is increased mean wind speed due to tunneling effect in the airport. Further, after the landfall there can be location specific modifications/ changes in the MSW due to variation in land use.

Considering all these observations and estimates, it has been concluded that the MSW associated with VSCS Vardah at the time of landfall was 60 kts.

Table 5: Analysis of all observations on 12th December

Station/(lat./long.)	Lowest MSLP (hPa) and time of occurrence (UTC)	Wind Speed (kts/kmph) and time of occurrence (UTC)
*Chennai (NBK)/ (13.1N/80.2E) (Manned)	975.0 at 1000 UTC	30 kts (56 kmph) at 0900 UTC
*Chennai (MBK)/ (12.98N/80.18E) (Manned)	975.6 at 1000 UTC	50kts (93 kmph) at 0900 UTC
*Chennai (NBK)/ (13.1N/80.2E) (AWS)	977 at 1000 UTC	11kts (20 kmph) at 0800 UTC
*Ennore Port/ (13.2N/80.3E) (AWS)	979.1 at 0900 UTC	48kts (89 kmph) at 0900 UTC
*MBK-ISRO/ (13.0N/80.2E) (AWS)	978 at 1000 UTC	13kts (24 kmph) at 0700 UTC
**Chennai (NBK)/ (13.1N/80.2E) (Barograph)	975.0 at 1000 UTC	61 kts (114 kmph) at 0710 UTC
**Chennai (MBK)/ (12.98N/80.18E) (Barograph)	974.0 at 1030 UTC	65 kts (122 kmph) during 0815-0820 UTC
Mishra and Gupta Formula	-	75 kts (139 kmph) at 0900 UTC
HWSR, IMD Chennai	-	57.7 kts (107 kph) at 0800 UTC
DIWE, NBK	-	87.6 kts at 0820 UTC
ISRO SHAR wind tower	-	54 kts (99 kmph) in gustiness at 0900 UTC
IMD, Satellite	-	T 4.0 at 0900 UTC(65 kts/122 kmph)
NOAA	-	T 4.5 (77 kts/143 kmph) at 0230 UTC & 0830 UTC
Radar (@1)	-	60 kts (111 kmph) at 0530 UTC
Radar (@2)	-	56 kts (104 kmph) at 0530 UTC (in outer vortex)
Radar (@3)	-	65 kts (120 kmph) at 0530 UTC (in eyewall region)

*-3-minute average MSW, **-Instantaneous wind, @1: Powell and Black estimate (1990), @2: Franklin et al estimate (for winds in outer vortex) and @3: Franklin et al estimate (for winds in eye wall region).

4. Climatological aspects

Considering the area of genesis (+/- 2^0 around the genesis point), the cliamtological tracks of the TCs (SCS and above) during 1891-2015 are presented in Fig.9. It indicates that climatologically, out of 19 cyclonic disturbances (depression and above), about half of them moved towards Tamil Nadu/ south Andhra Pradesh

coast. All these system crossed Tamil Nadu coast. Those which approach Andhra Pradesh coast weakened over the Sea.

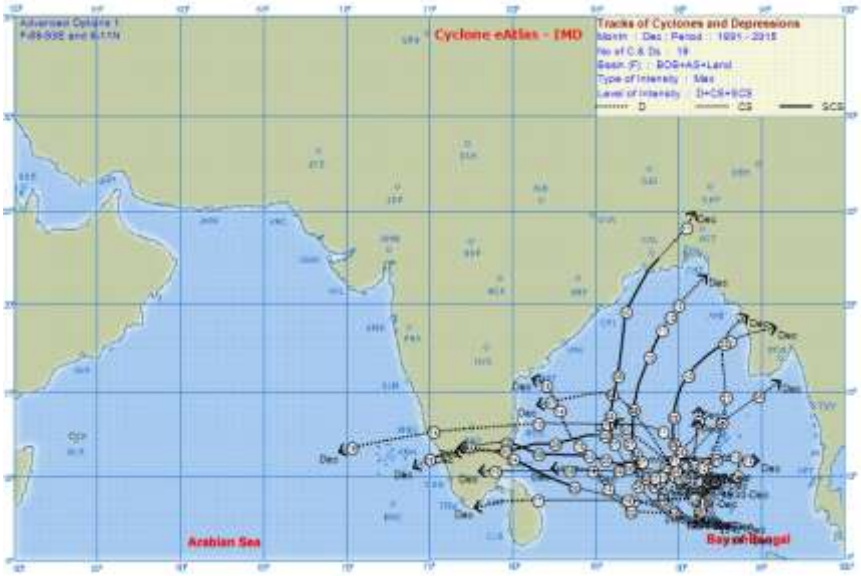


Fig 9. Climatological tracks of TCs (SCS and above) forming within +/- 2^0 around the genesis point during 1891-2015

5. Features observed through satellite and Radar

Satellite monitoring of the system was mainly done by using half hourly Kalpana-1 and INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7 & MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered.

5.1 INSAT-3D features

Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness tempearture imageries are presented in Fig.10. Intensity estimation using Dvorak's technique suggested that the system attained the intensity of T 1.5 on 0900 UTC of 6th. The cloud pattern was curved band type. Convection wrapped around western half of cyclonic circulation. Minimum Cloud Top Temperature (CTT) was minus 85.0^0C. Associated broken low and medium clouds with embedded intense to very intense convection lay over Andaman & Nicobar Islands and adjoining Andaman Sea & southeast BoB. At 1800 UTC of 7th, well defined banding features were seen. Banding wrapped 7 on log 10 spiral. The system attained the intensity of T2.0. Minimum CTT was minus 92.0^0C. Associated broken low and medium clouds with embedded intense to very intense convection lay over southeast and adjoining eastcentral BoB, western parts of Andaman Sea & Bay Islands. At 0000 UTC of 8th, the system intensified to T2.5. Convection showed central dense overcast (CDO) pattern. Minimum CTT was minus 93.0^0C. Associated broken low and medium clouds with embedded intense to very intense convection lay over southeast and adjoining eastcentral BoB, western parts of Andaman Sea & Bay islands. At 0000 UTC of 9th, the system attained the intensity of T 3.0. Convection showed CDO pattern. Minimum CTT was minus 93.0^0C. Associated broken low and medium clouds with embedded intense to very intense convection lay over southeast and adjoining eastcentral BoB. At 1800 UTC of 9th, the system intensified

to T 3.5. Convection showed CDO pattern. Minimum CTT was minus 93.0^{0}C. Associated broken low and medium clouds with embedded intense to very intense convection lay over southeast and adjoining eastcentral BoB between 9.5^{0}N & 15.0^{0}N and longitude 86.0^{0}E & 90.0^{0}E.

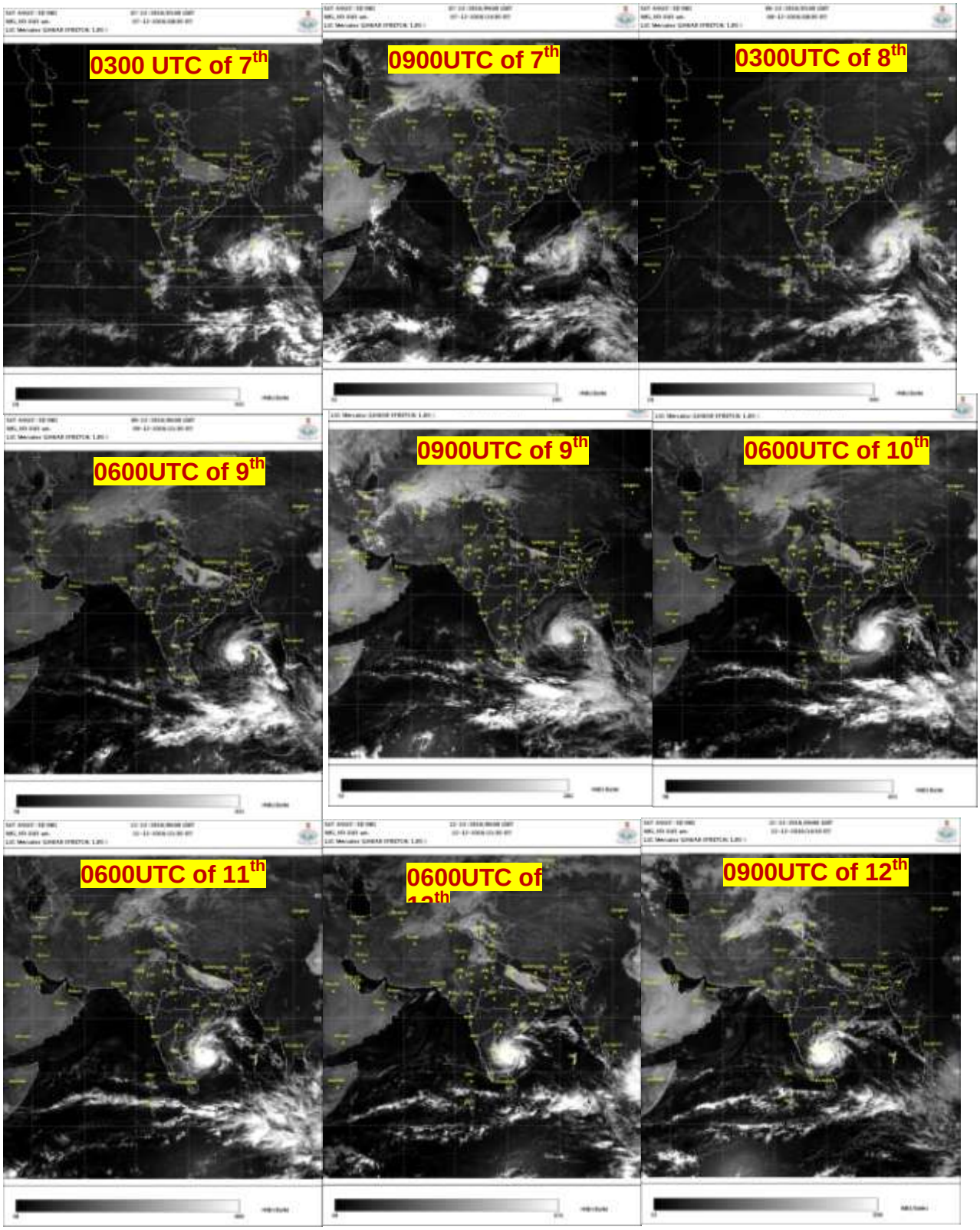


Fig. 10a: INSAT-3D visible imageries during life cycle of VSCS Vardah (06-13 December, 2016)

At 1200 UTC of 10th, the system intensified to T4.0. Convection showed curved band pattern with embedded CDO. Minimum CTT was minus 93.0^{0}C. Associated broken low and medium clouds with embedded intense to very intense convection lay over central BoB between 10.9^{0}N & 15.6^0 N and longitude 83.0^{0}E & 87.7^0 E. At 0000 UTC of 11th, the intensity of the system was T 4.0. Convection showed curved band pattern with embedded irregular CDO. Minimum CTT was minus 92.0^{0}C. Associated broken low and medium clouds with embedded intense to very intense convection lay over BoB between 10.0^{0}N & 16.0^{0}N and longitude 80.5^{0}E & 86.0^{0}E. At 0900 UTC of 12th, intensity of the system was T4.0. Cloud convection showed CDO pattern. Minimum CTT was minus 82.0^{0}C. Associated broken low and medium clouds with embedded intense to very intense convection lay over BoB between 11.0^{0}N & 15.0^{0}N, west of longitude 82^{0}E, south coastal Andhra Pradesh adjoining Rayalaseema and north coastal Tamil Nadu.

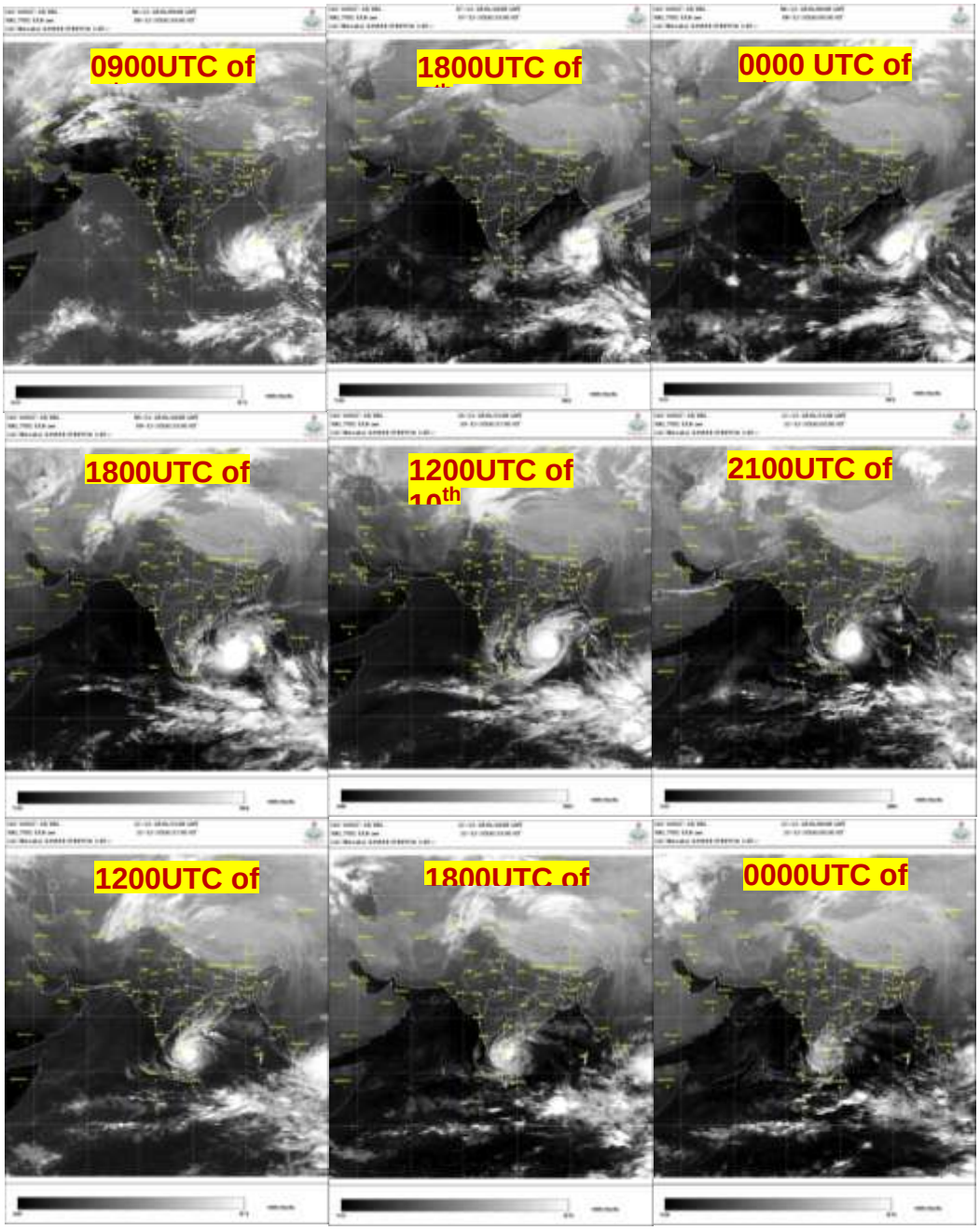


Fig. 10b: INSAT-3D IR imageries during life cycle of VSCS Vardah (06-13 December, 2016)

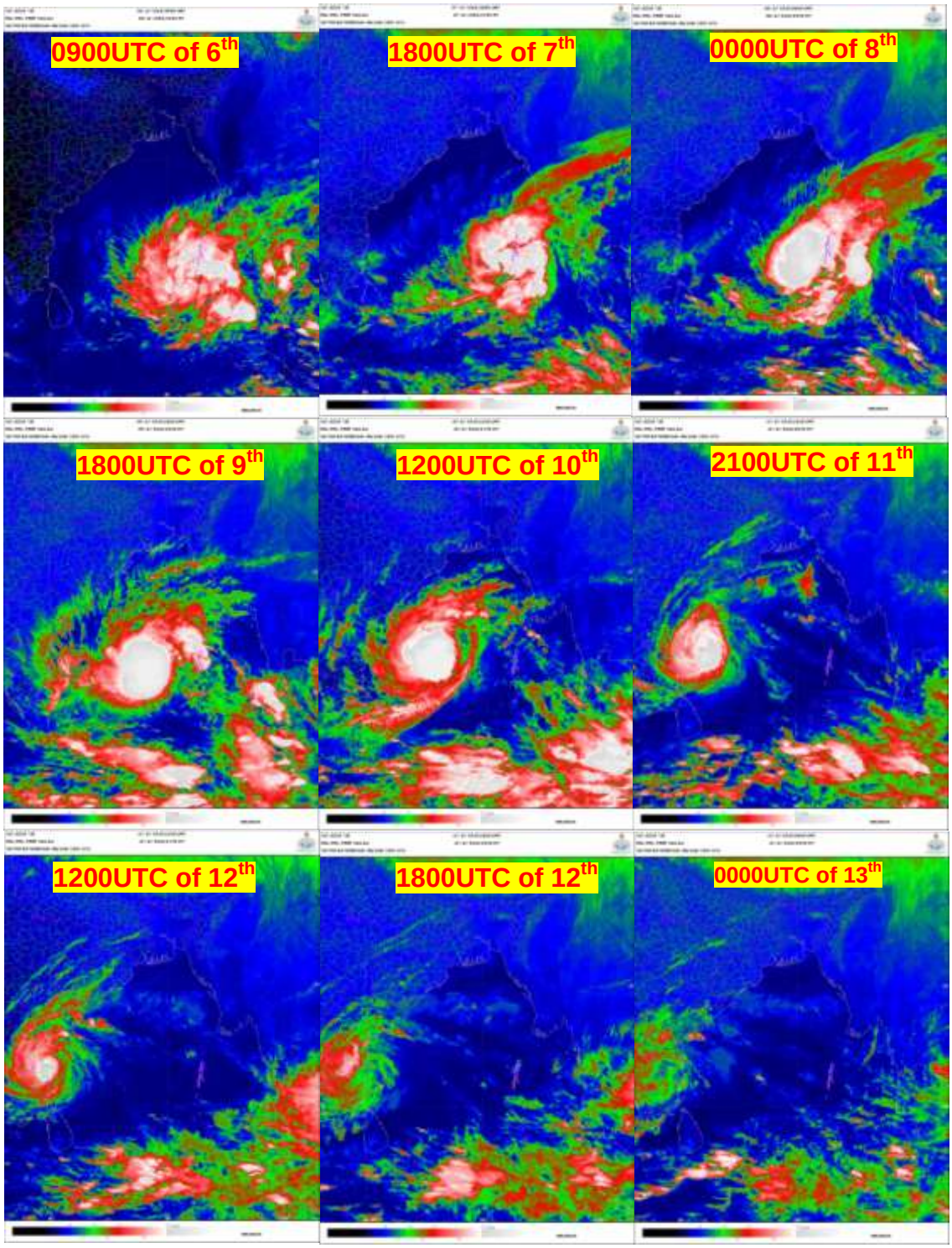


Fig. 10c: INSAT-3D enhanced colored imageries during life cycle of VSCS Vardah (06-13 December, 2016)

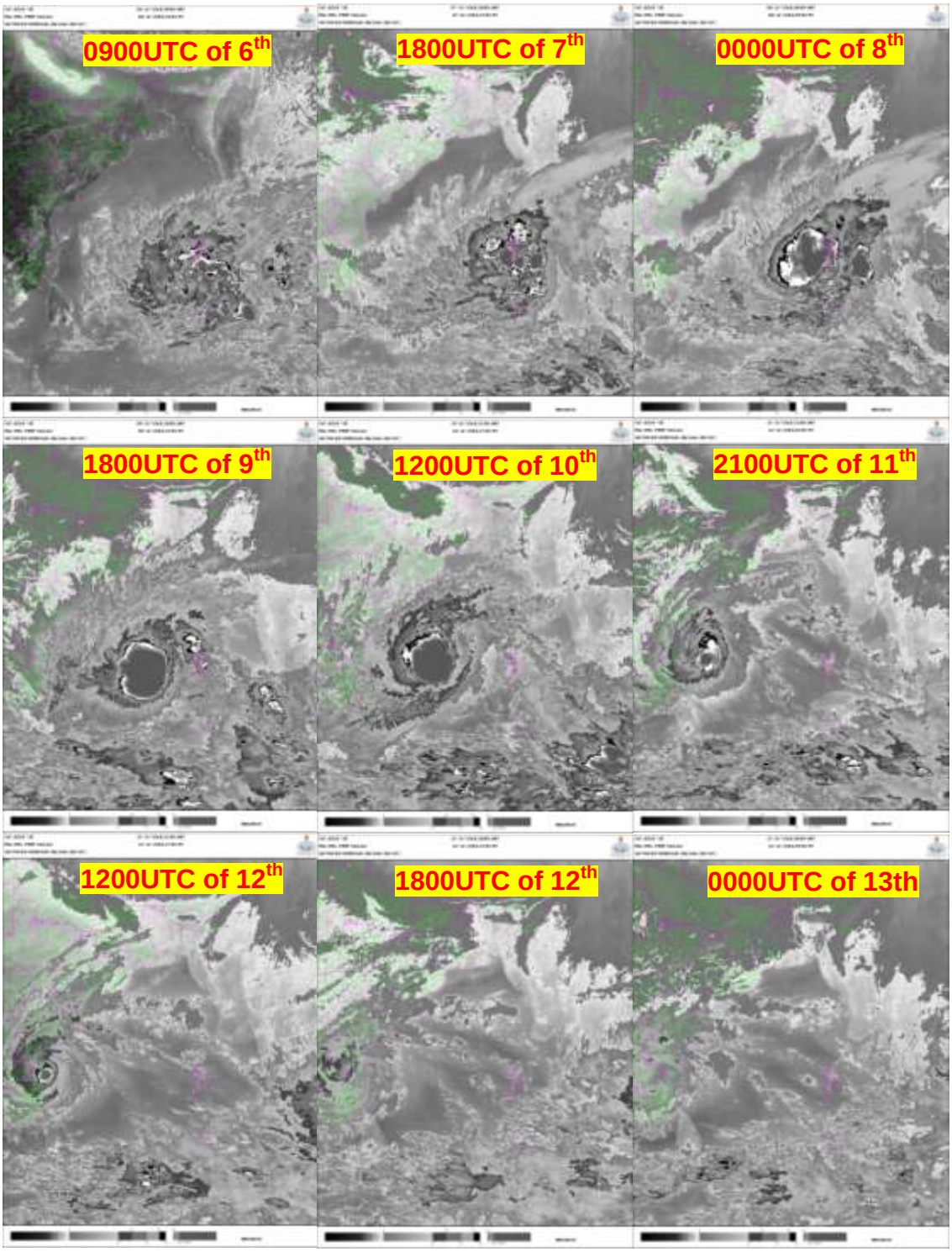


Fig. 10d: INSAT-3D cloud top brightness temperature imageries during life cycle of VSCS Vardah (06-13 December, 2016)

5.2 Microwave features

F-15, F-16, F-17, GPM and GCOM-W1 microwave imageries of the VSCS Vardah covering its life period from 06th to 13th December 2016 are presented in Fig.11. These imageries helped in understanding the internal structure of the system and better estimation of location of the system. It could indicate the region of intense convection and hence the rainfall. It also helped in understanding the large scale diurnal variation of the system.

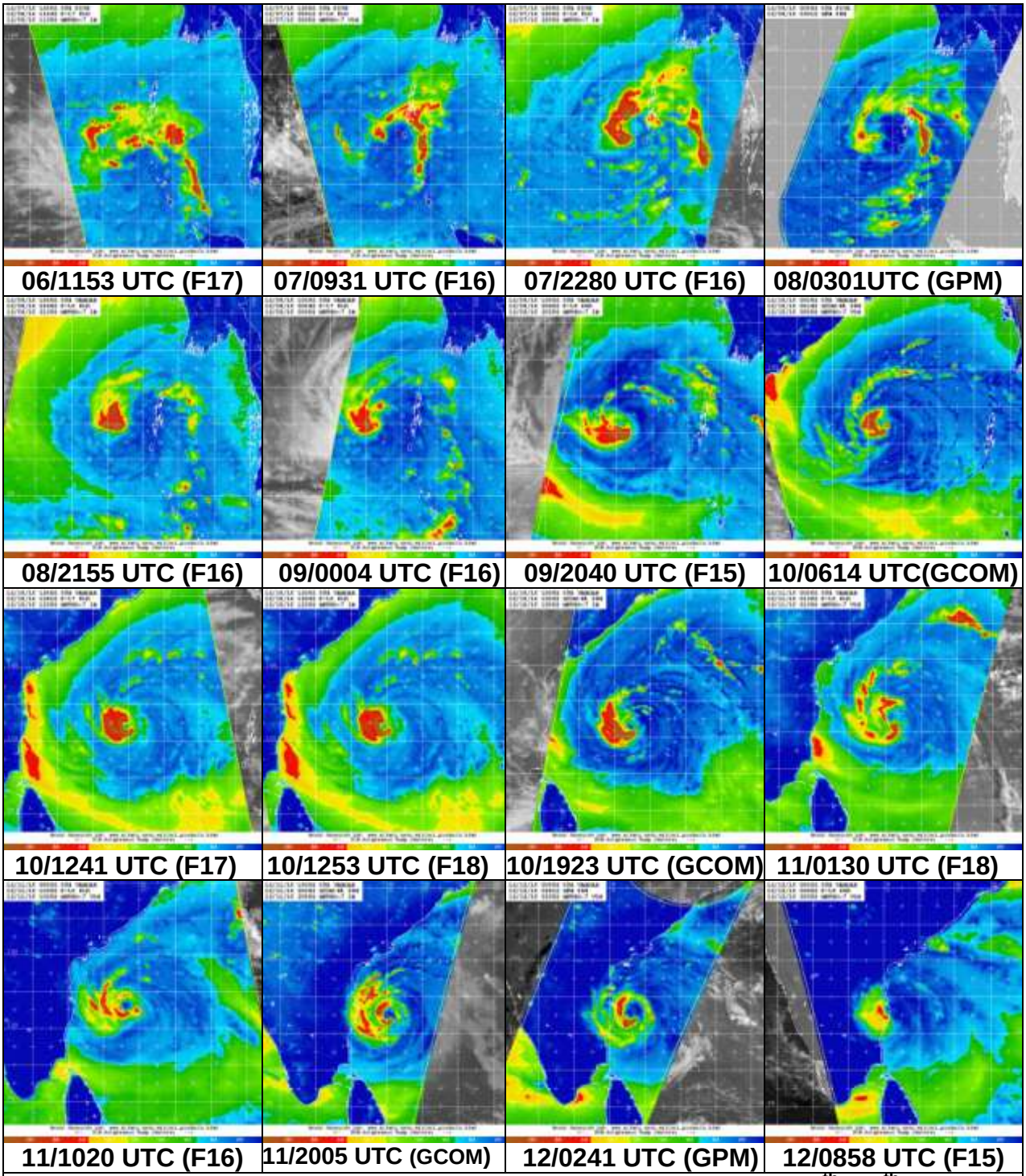


Fig. 11: Microwave imageries during life cycle of VSCS Vardah (06th- 13th December, 2016)

5.3. Features observed through Radar

As the system was moving along the east coast, it was tracked by DWR Chennai and Machillipatnama Typical Radar imageries from DWR Chennai on 12th December are presented in Fig. 12.

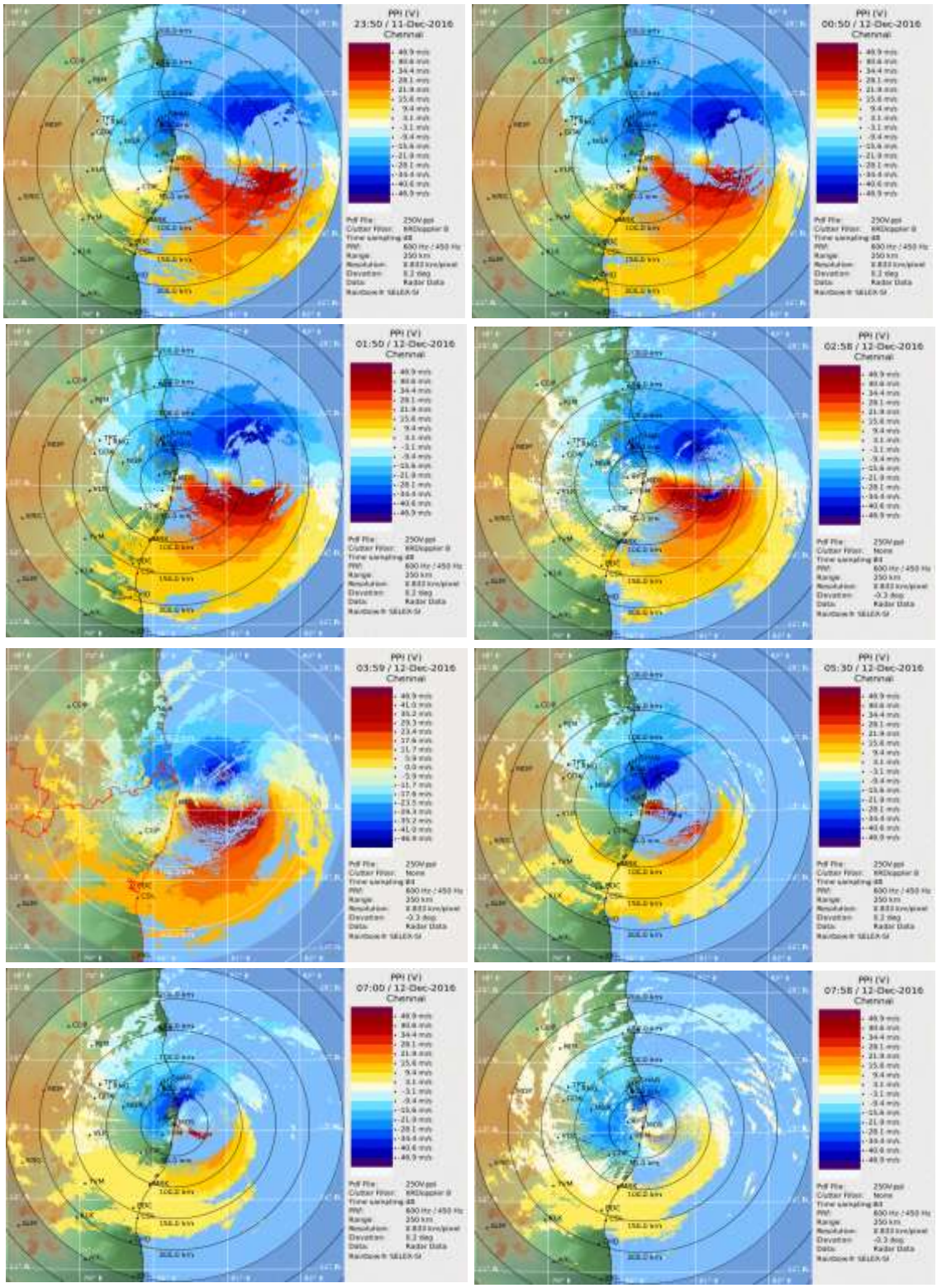


Fig. 12(a): Typical PPI (V) imageries during 11th & 12th December from DWR Chennai

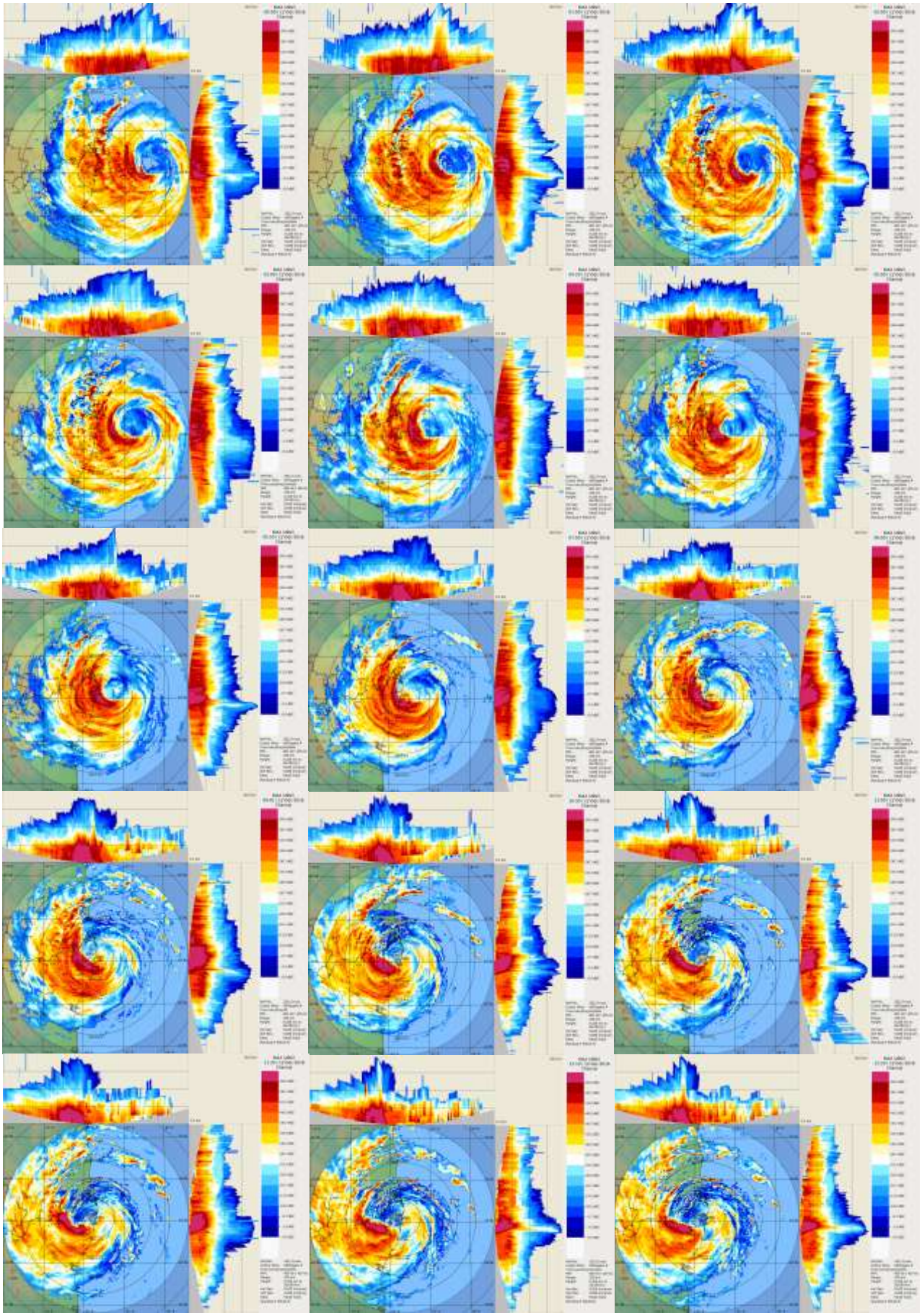


Fig. 12(b): Typical MAX (dBZ) imageries during 11th & 12th December from DWR Chennai

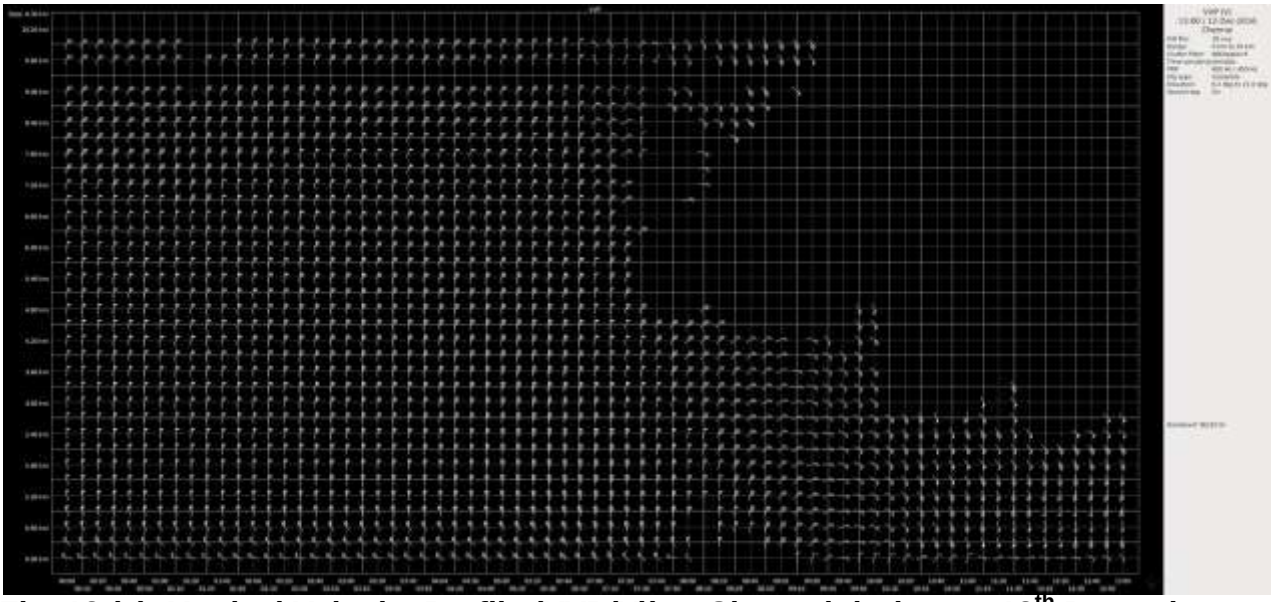


Fig. 12 (c): Vertical Velocity Profile (VVP(V)) at Chennai during on 12th December from DWR Chennai

6. Dynamical features

IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels are presented in Fig.13. GFS (T574) could simulate the genesis of the system and the associated circulation features during the life period of VSCS Vardah.

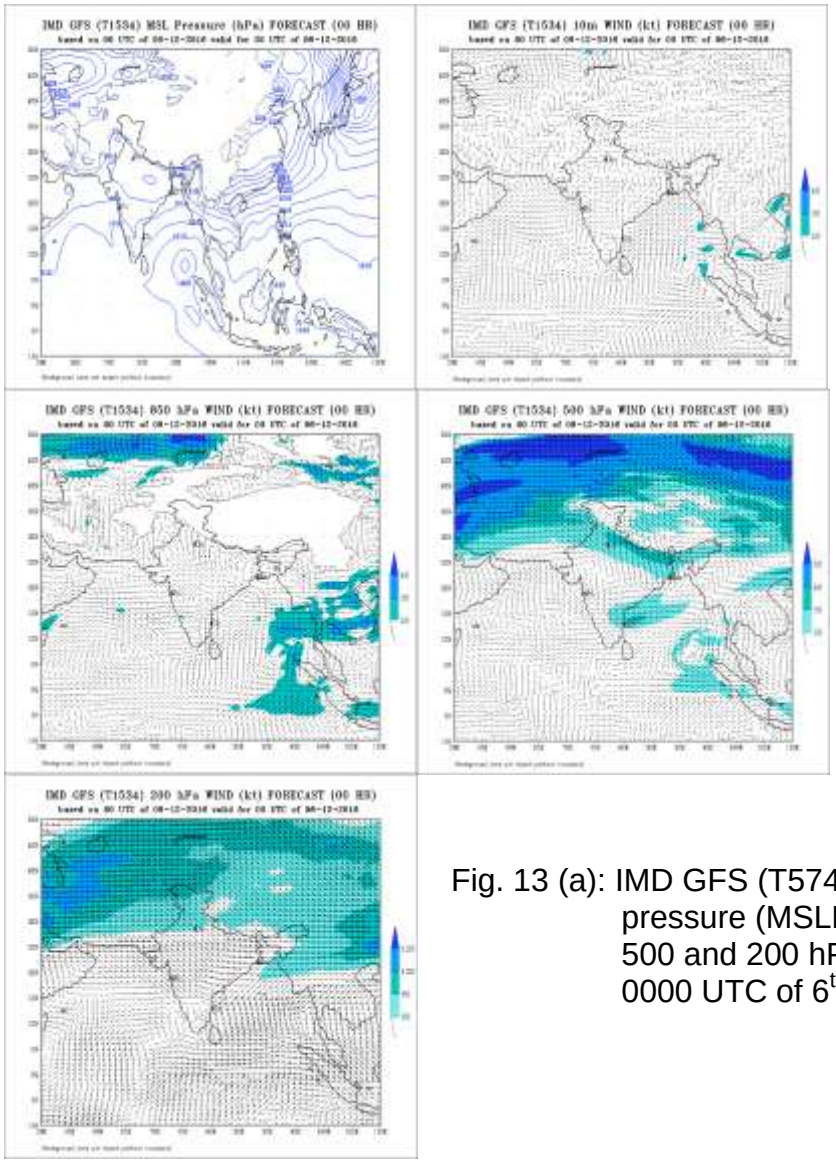


Fig. 13 (a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 6th December

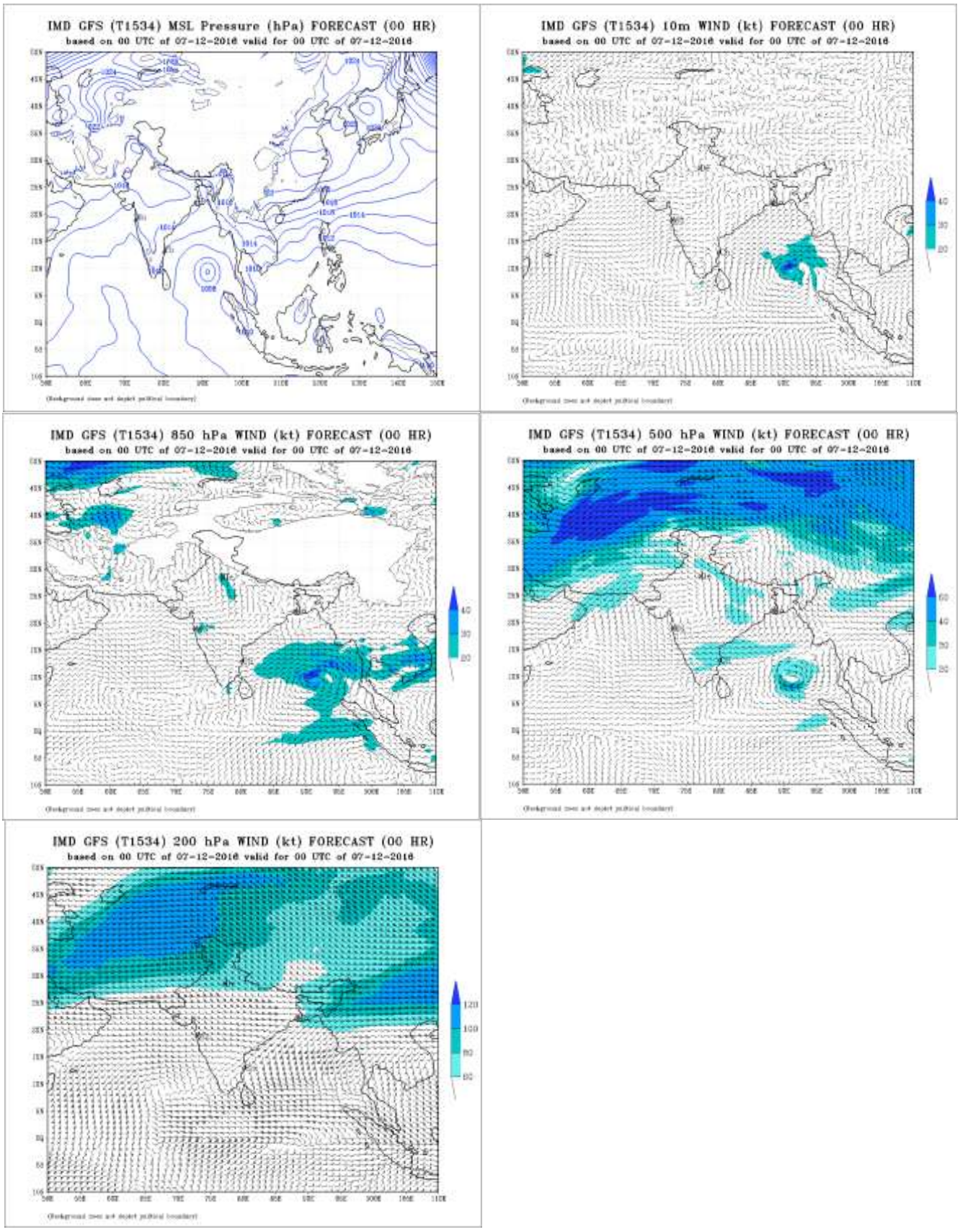
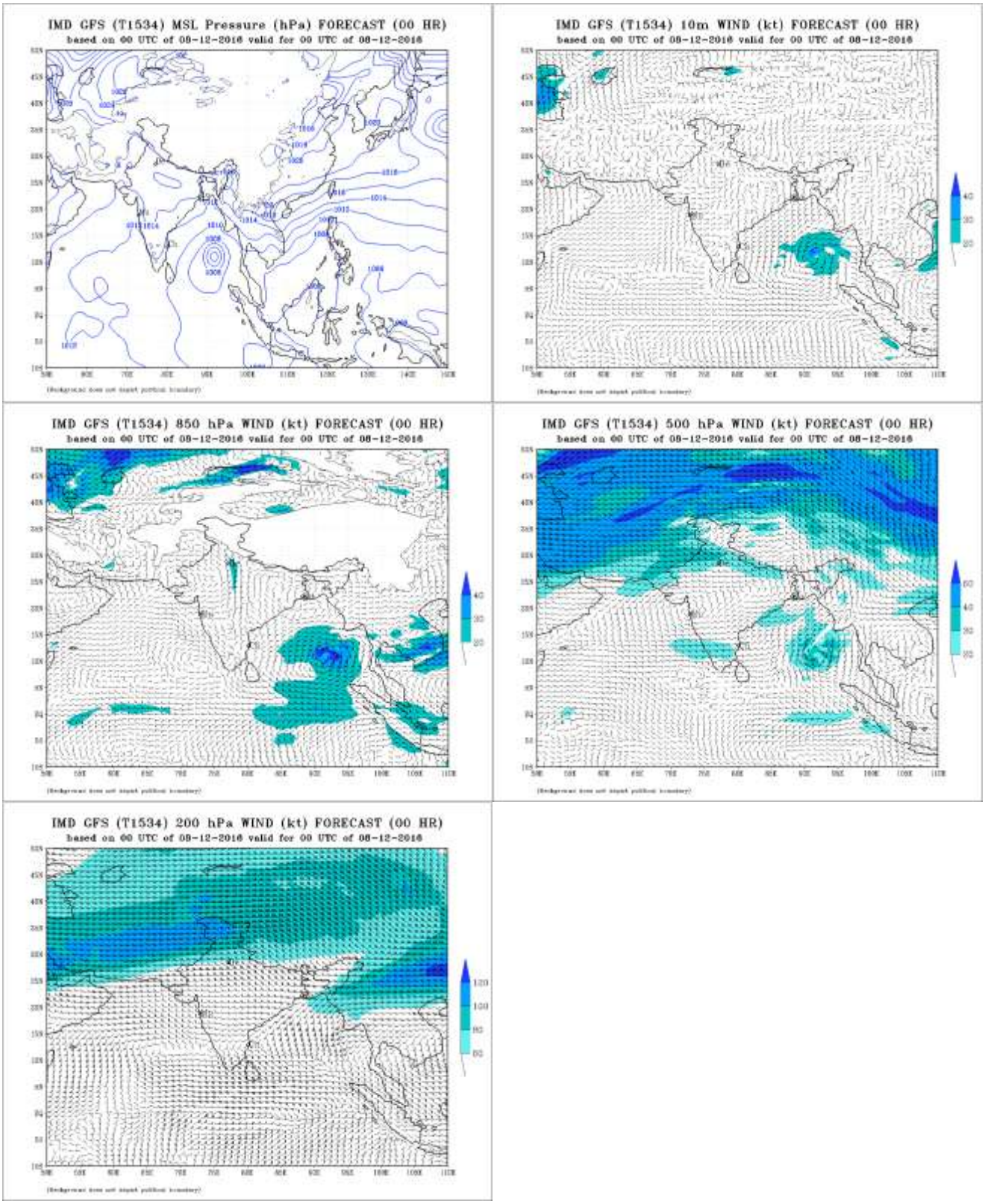


Fig. 13 (b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 7th December



F Fig. 13 (c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 8th December

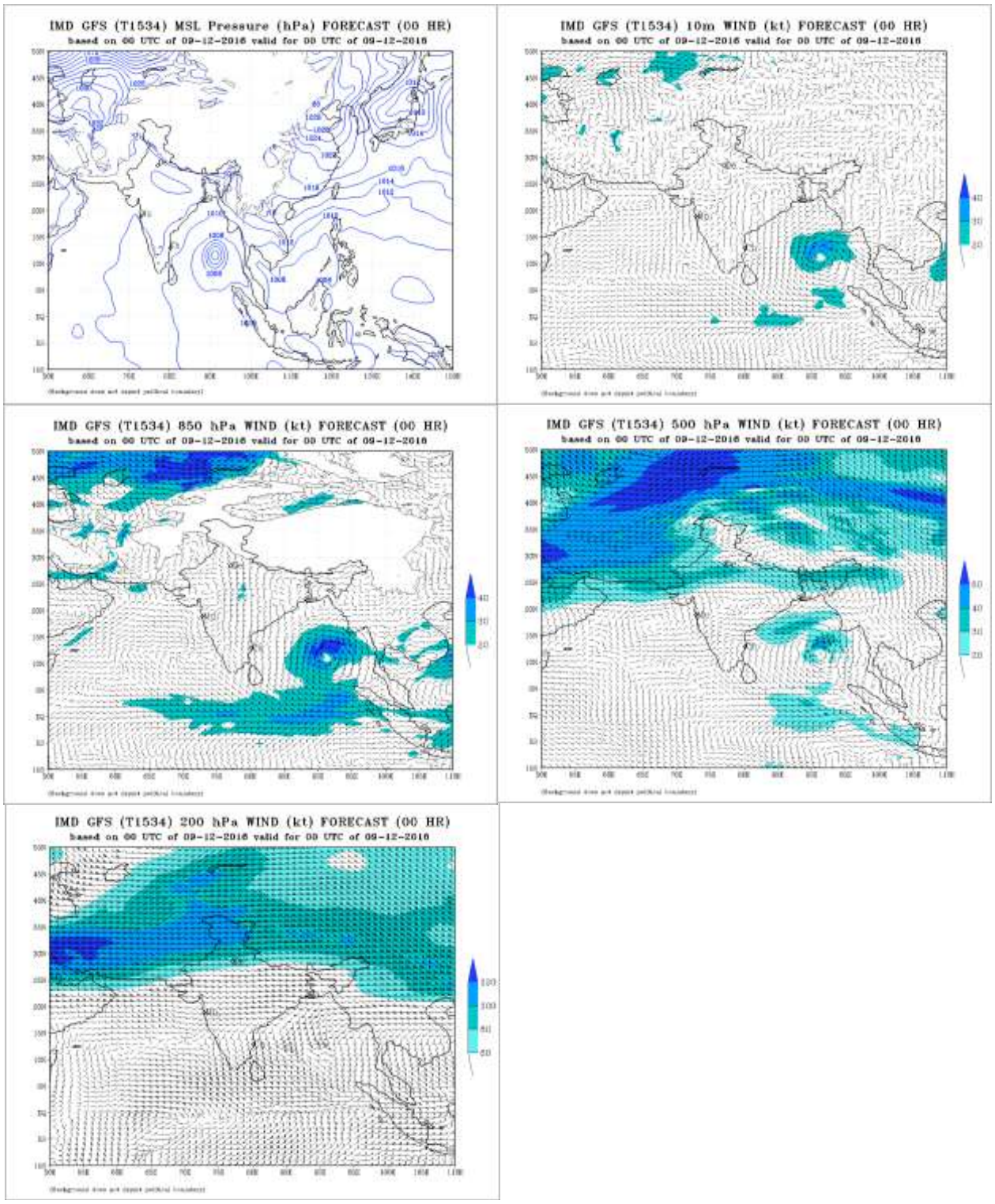


Fig. 13 (d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 9th December

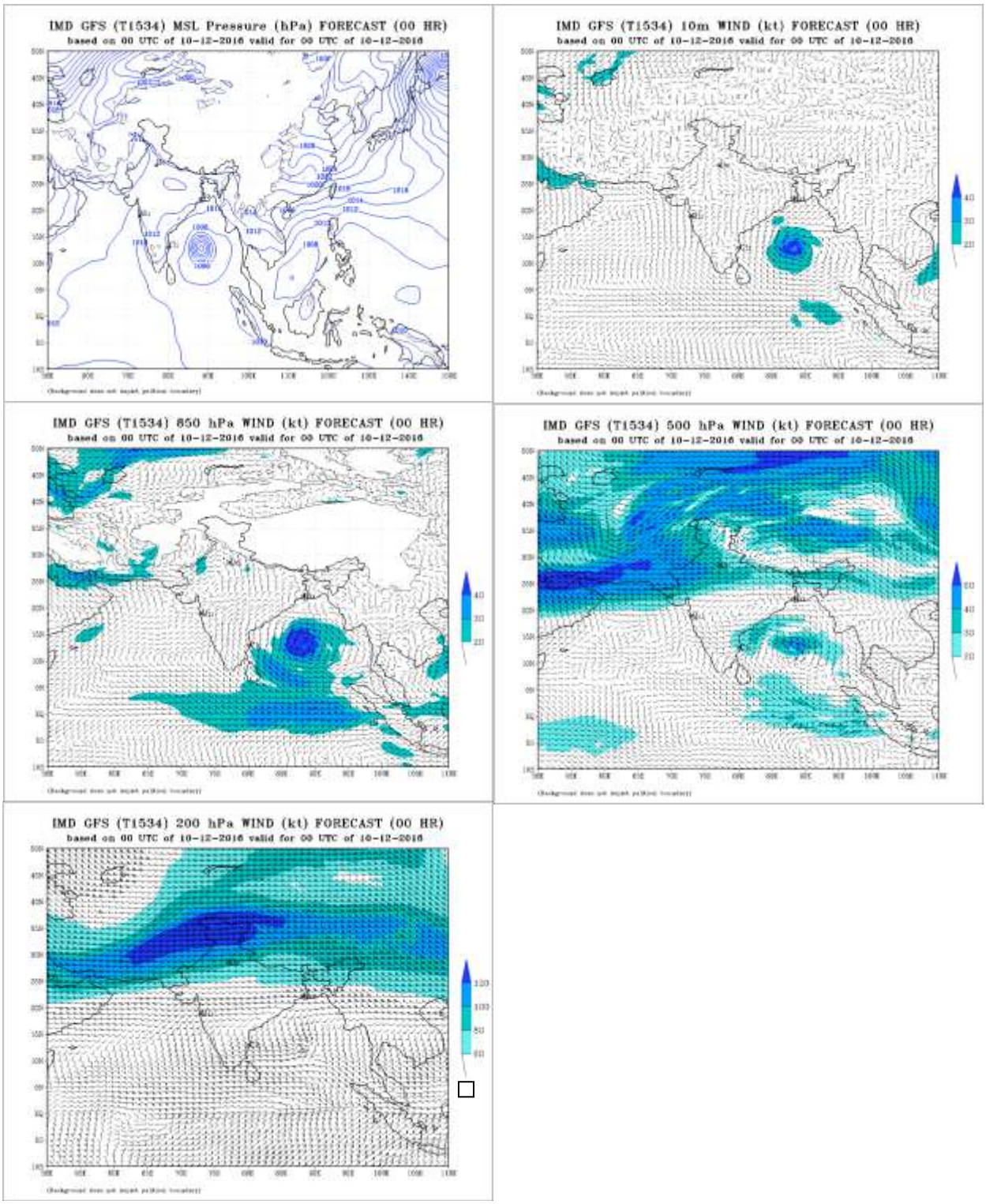


Fig. 13 (e): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 10th December

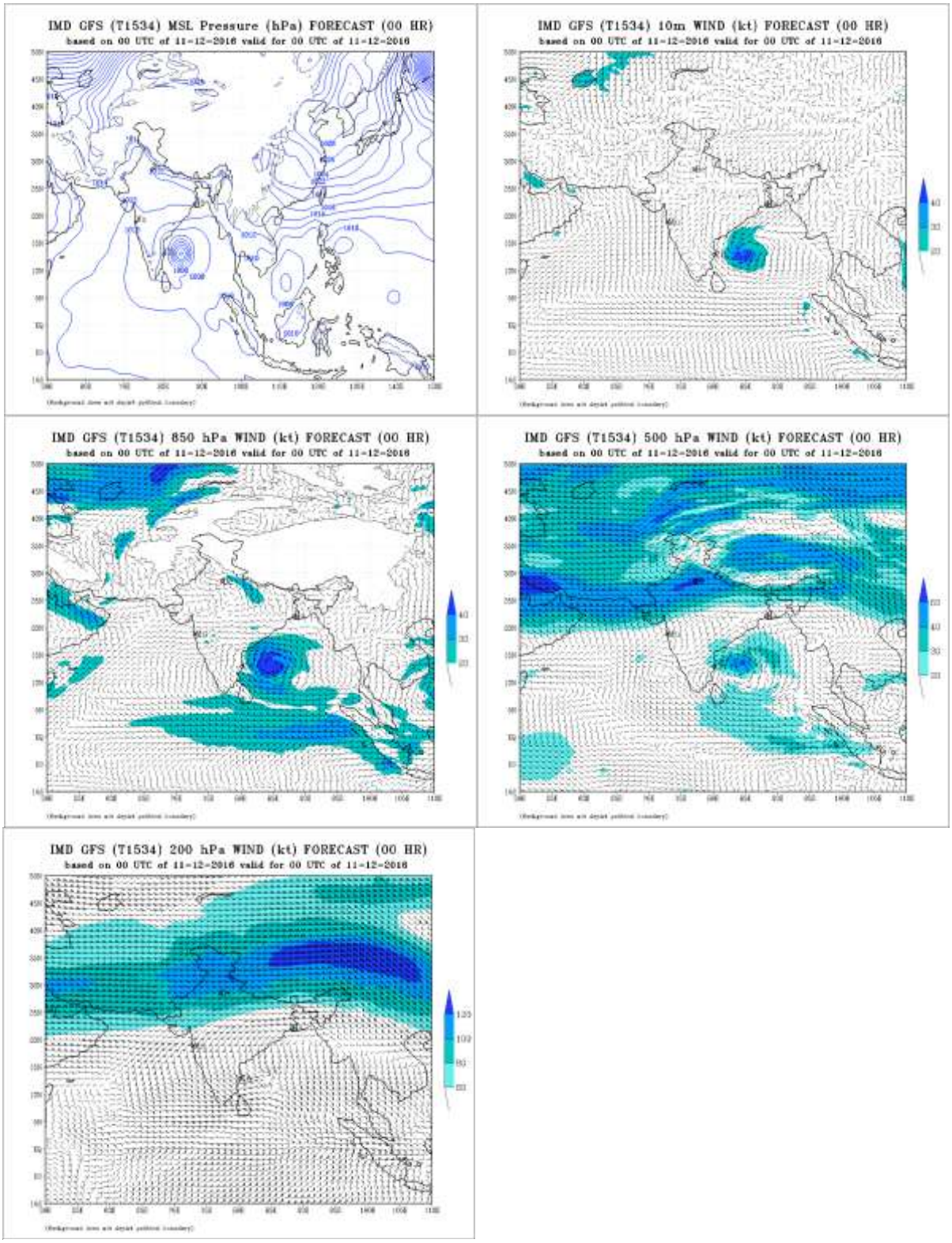


Fig. 13 (f): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 11th December

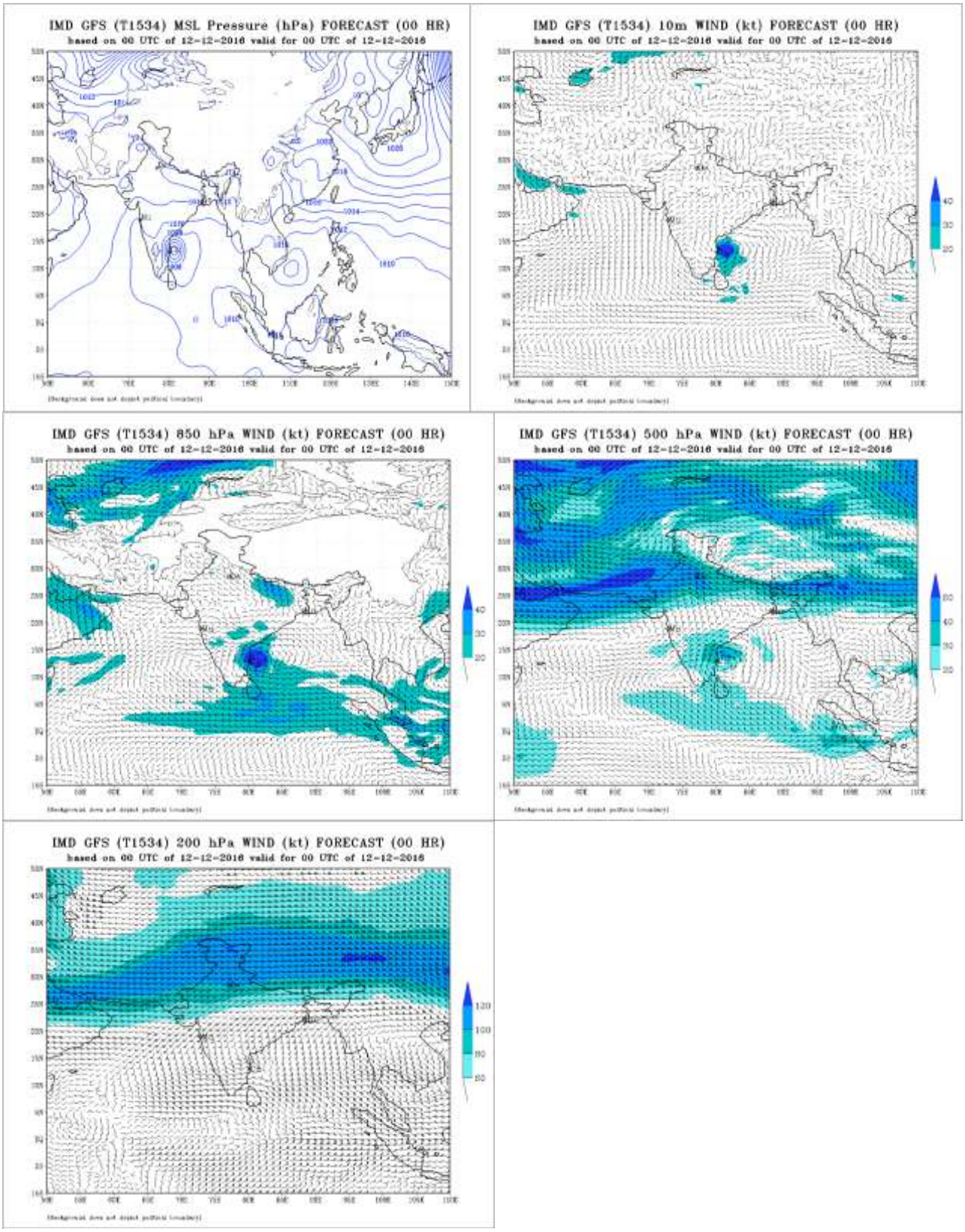


Fig. 13 (g): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 12th December

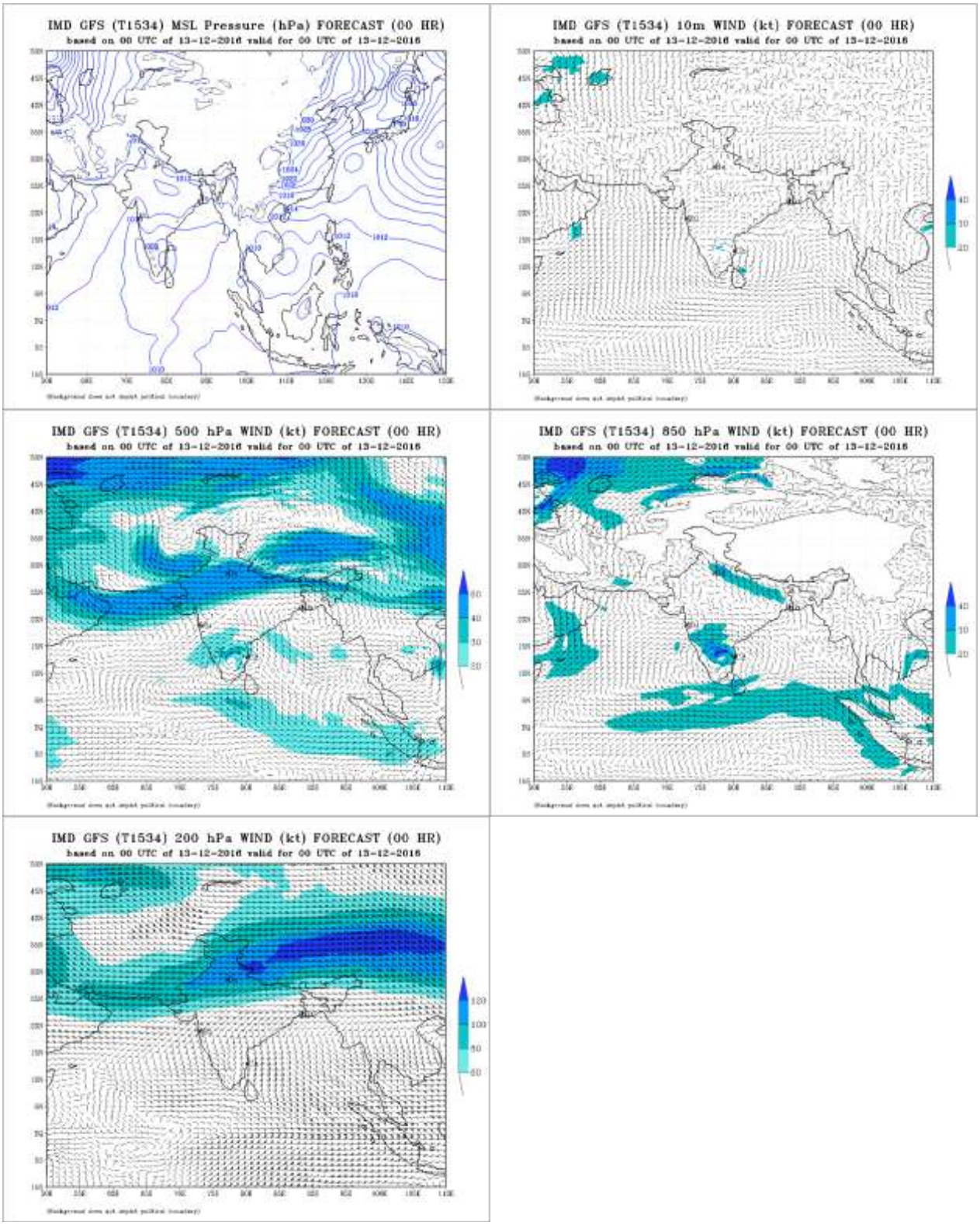


Fig. 13 (h): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 13th December

7. Realized Weather:

7.1 Rainfall:

Light to moderate rainfall at most places with heavy to very heavy falls at a few places over Andaman Islands and heavy rainfall at isolated places over Nicobar Islands were predicted during 7th -8th. Rainfall at most places with isolated heavy to very heavy falls over south coastal Andhra Pradesh, Rayalaseema, north coastal Tamil Nadu and Puducherry were predicted on 13th. Heavy to very heavy rainfall (7-19 cm) at a few places and isolated extremely heavy rainfall (≥ 20 cm) very likely over Chennai, Thiruvallur and Kanchipuram districts of Tamil Nadu and Nellore and Prakasam districts of Andhra Pradesh on 12th.

Heavy rainfall occurred at many places with very heavy falls at few places and isolated extremely heavy rainfall over Chennai, Kancheepuram, Tiruvallur, and Villupraum districts of Tamil Nadu. Heavy to very heavy rainfall occurred at a few places over Vellore, Krishnagiri, Tiruvannamalai districts of Tamil Nadu, Nellore district of coastal Andhra Pradesh and Chittor, Anantapuram & Cuddapah districts of Rayalaseema on 12th December. During genesis stage cyclone Vardah caused heavy to very heavy rainfall at a few places over Hut Bay, Maya Bandar, IAF Car Nicobar on 7th December and rainfall at many places with isolated extremely heavy rainfall occurred over Long Island, Port Blair of Andaman & Nicobar Islands on 8th December.

(Heavy rainfall distribution: Isolated places : <25%, A few places: 26-50%, Many places : 51-75%, Most places: 76-100% of total stations in the region;
Heavy rain : 64.5 – 115.5 mm, Very heavy rain: 115.6 – 200.4 mm, Extremely heavy rain: 200.5 mm or more).

Realized 24 hrs accumulated rainfall (≥7cm) ending at 0830 hrs IST of date due to the cyclone is presented below:

07.12.2016

ANDAMAN & NICOBAR ISLANDS: Hut Bay-17, Port Blair-12, Maya Bandar-9, IAF Carnicobar-7

08.12.2016

ANDAMAN & NICOBAR ISLANDS: Long Island-23, Port Blair-21, IAF Carnicobar-7

13.12.2016

Tamil Nadu:

Satyabama University (Kancheepuram)-38, Kattukuppam (Kancheepuram)-34, Kancheepuram (Kancheepuram)-28, Kalavai (Vellore)-23, Poonamallee (Tiruvallur)-22, Chembarabakkam (Tiruvallur)-21, Meenambakkam-20, Sriperumbudur (Kancheepuram)-17, Chembarambakkam (Tiruvallur)-16, Yercaud (Salem)-15, Alangayam (Vellore)-15, Tambaram (Kancheepuram)-14, Nugampakam-12, Vellore-11, Melalathur (Vellore)-9, Tirppattur-8, Poondi (Tiruvallur)-9, Mahabalipuram (Kancheepuram), Uthiramerur (Kancheepuram), Tirupattur (Vellore), Maduranthagam (Kancheepuram), Krishnagiri (Krishnagiri), Shoolagiri (Krishnagiri), Hosur (Krishnagiri), Vandavasi (Tiruvannamalai), Marakkanam (Villupraum), Vaniaymbadi (Vellore), Gudiyatham (Vellore) and Cheyyur (Kancheepuram) -7 each

Coastal Andhra Pradesh:

Atmakur (Nellore) 13, Vinjamur (Nellore) 12, Udayagiri (Nellore) 11, Sullurpeta (Nellore) 9, Kandukur (Prakasam) 9, Kavali (Nellore) 8, Nellore (Nellore) 8, Veligandla (Prakasam) 8, Rapur (Nellore) 7, Gudur (Nellore) 7, Venkatagiri (Nellore) 7, Shar (Nellore) 7

Rayalaseema:
Tirumalla (Chittor) 15, Puttur (Chittoor) 14, Nagari (Chittoor) 12, Chittoor 10, Kodur (Cuddapah) 10, Satyavedu (Chittoor) 10, Venkatagiri Kota (Chittoor) 9, Palasamudram (Chittoor) 9, Nambulipulikunta (Anantapuram) 7, Thottambedu (Chittoor) 7, Tirupati Aero (Chittoor) 7, Atlur (Cuddapah) 7, Rajamet (Cuddapah) 7, Mandapalle (Chittoor) 7, Kuppam (Chittoor) 7, Pakala (Chittoor) 7, Sambepalle (Cuddapah) 7, Royachoti (Cuddapah) 7.

Rainfall associated with the system is depicted in Fig 14 based on IMD-NCMRWF GPM merged gauge rainfall data.

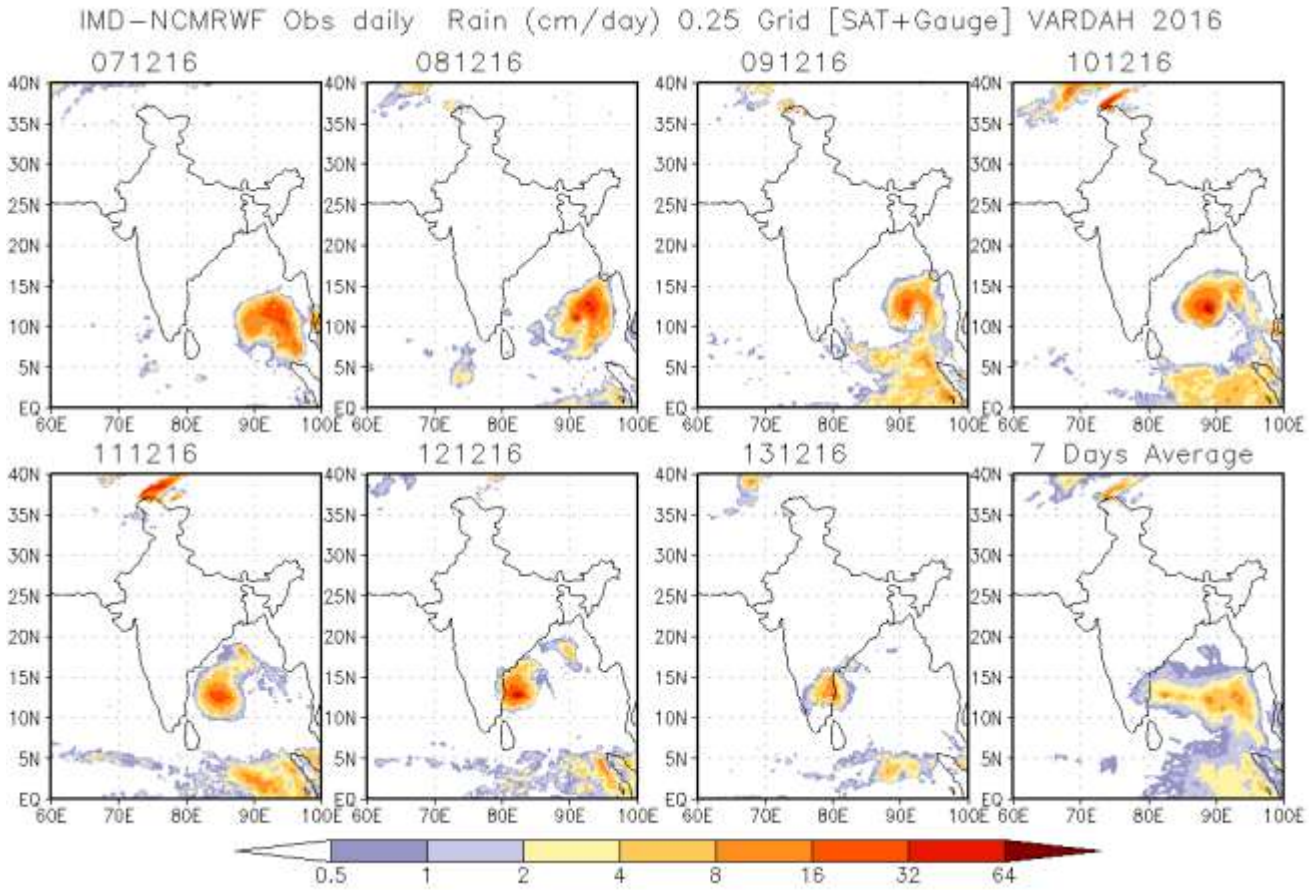


Fig.14: IMD-NCMRWF GPM merged gauge rainfall during 7th – 13th and 7 days average rainfall (cm/day)

On 7th & 8th, heavy to very heavy rainfall was observed over south Andaman Sea and adjoining southeast BoB to the northeast of system centre. On 9th the region of heavy to very heavy rainfall shifted from northeast to northwest sector. On 10th, 32 cm rainfall was observed in southeast BOB over the entire region around the centre. On 11th, 16-32 cm rainfall was observed over southwest BoB. On 12th, around 30 cm rainfall was observed in the right forward sector of the system near north Tamil Nadu and adjoining south Andhra Pradesh. On 13th, 4-8 cm rainfall was observed over north interior Tamil Nadu and south interior Karnataka. 7 days average rainfall plot indicate that during initial stage 4-8 cm average rainfall was observed over south Andaman Sea and southeast BoB within 10-14 degree North. However, in the later part of the week, 2-4 cm rainfall was observed between 10-14 degree North over southwest BoB.

8. Damage due to VSCS Vardah

Andaman Islands

As per media report, Cyclone Vardah wreaked havoc in the remote islands of Andaman like Diglipur, Rangat and Billyground that witnessed a flood-like situation due to torrential rains. Landslides were reported along the Andaman Trunk Road, while several houses and crops have been damaged in areas located in the northern and central Andaman. There was no power in several areas for two days due to the snapping of power cables. More than 1,400 tourists were stranded on the Havelock and Neil Islands of the Archipelago. However, no casualty was reported from Andaman & Nicobar Islands.

Tamil Nadu

Loss of Human Lives

The cyclone prompted India's largest evacuation in 2 years of 16000 people. 24 deaths related to the cyclone have been reported in the state of Tamil Nadu.

Infrastructure damage

Cyclone Vardah caused colossal damage to infrastructure like roads, bridges, reservoirs, tanks, drinking water supply, school & public health buildings, electrical installations, habitats such as huts & houses, crops, cattle losses. The state Government estimated the damage to the tune of Rs 22,573 crores (The Hindu dated the 28th December, 2016).

Crop damage

Severe Crop damages occurred in Tiruvallur, Kanchipuram, Vellore and Tiruvannamalai districts of north Tamil Nadu. There was damage to paddy, groundnut, blackgram, greengram and coconut causing a loss of nearly 33 % in these districts in an area of 34206.13 Hectare. The estimated loss of Agriculture produce valued Rs. 35571 Crore. The detailed loss is given in table:

S.No.	Crop	Total Area damaged in Hectares	Production Loss (MT)	Avg. Market Price/MT (Rs.)	Value of the produce Lost (Rs. in crores)
1.	Paddy	33980.86	220876	16000	35340.09
2.	Millets	58.44	2507	15000	37.60614
3.	Pulses	41.8	314	80000	25.08
4.	Sugarcane	44.82	41683	2300	95.86998
5.	Oilseeds	63.06	145	50000	72.519
6.	Perennial crops Coconut	16.62	-	-	0.20775
	Total	34206.10	22547		35571.37287

District wise Details of Area affected by Cyclone "Vardah"

(a) Tiruvallur:

Due to Cyclone Vardah, the Paddy crop cultivated in Tiruvallur district was severely affected in 11 blocks. Out of the total area (87000 Hectare) cultivated in the district,

45518 Hectare Paddy was severely affected. In this 32241 Hectare Paddy was affected with >33% crop damage. And also 16.62 Hectare Coconut was also affected. The trees were totally uprooted from the field. Totally 32257.62 Hectare area was affected with >33% crop damage which includes 2700.40 Hectare area of SF/MF and 5237 Hectare of Other farmers. 37370 farmers were affected due to this Vardah cyclone.

The total Assistance sought for Tiruvallur district is Rs.4355.53 lakhs @ Rs.13500/ Hectare to Paddy crop and Rs.18000/ Hectare to Coconut crop.

(b) Kanchipuram:

Due to Cyclone Vardah, the crops viz., Paddy, Ground nut and Pulses crops cultivated in Kanchipuram district were severely affected in 13 blocks. Out of the total area cultivated (49500 Hectare) in the district, 6002.20 Hectare area under agricultural crops was severely affected. In this, Paddy --1625.70 Hectare, Ground nut --54 Hectare and Pulses --35 Hectare were affected with >33% crop damage. In total 1714.70 Hectare area was affected with >33% crop damage which includes 1679.20 Hectare area of SF/MF and 35.50 Hectare of other farmers. 2398 farmers were affected due to this Vardah cyclone.

The total Assistance sought for Kanchipuram district is Rs.231.483 lakhs @ Rs.13500/ Hectare to annual crops.

(c) Vellore:

The crops viz., Paddy, Millets, Ground nut Pulses and Sugarcane crops cultivated in Vellore district were severely affected in 15 blocks. Out of the total area (1, 24, 800 Hectare) cultivated in the district, 780.12 Hectare agricultural crops were severely affected. Due to cyclone Vardah, Paddy --101.16 Hectare, Millets --58.44 Hectare, Groundnut --9.06 Hectare, Pulses -- 6.8 Hectare, Sugarcane -- 44.82 Hectare and Coconut -- 0.53 Hectare were affected with >33% crop damage. In total 220.81 Hectare area was affected with >33% crop damage which was belonging to SF/MF only. 498 farmers were affected due to this Vardah cyclone.

The total Assistance sought for this affected area of Vellore district is Rs.29.81 lakhs @ Rs.13500/ Hectare to annual crops.

(d) Tiruvannamalai:

Due to Cyclone Vardah, the Paddy and Sugarcane crops cultivated were severely affected in Arani block of in Tiruvannamalai district. Out of the total area cultivated under Paddy (57300 Hectare) in the district, 139 Hectare area was severely affected. In this, 13 Hectare Paddy area cultivated by 48 numbers of SF/MF was affected with >33% crop damage.

The total Assistance sought for Tiruvannamalai district is Rs.1.76 lakhs @ Rs.13500/ Hectare to Paddy crop.

Andhra Pradesh

Loss of Human Lives

Two persons were killed in Chittoor district of Andhra Pradesh due to cyclone Vardah as heavy rains lashed the region (NDTV, 13th December, 2016).


Fig. 14 (a): Uprooted Poles and Trees in Chennai City (Business Line, 12th December)

Fig. 14 (b): Blown away profiler wind sheets at district

Damaged banana plantation in Vellore VGP Theme Park

Fig. 14 (c): Flying car in Chennai City

Storm Surge near Chennai Coast


Fig. 14 (d): Heavy Rainfall over Chennai

9. Performance of operational NWP models

IMD operationally runs a regional models, WRF for short-range prediction and one Global model T574L64 for medium range prediction (7 days). The WRF-VAR model is run at the horizontal resolution of 27 km, 9 km and 3 km with 38 Eta levels in the vertical and the integration is carried up to 72 hours over three domains covering the area between lat. 25^0S to 45^0 N long 40^0 E to 120^0 E. Initial and boundary conditions are obtained from the IMD Global Forecast System (IMD-GFS) at the resolution of 23 km. The boundary conditions are updated at every six hours interval.

Global models are also run at NCMRWF. These include GFS and unified model adapted from UK Meteorological Office. Apart from the observations that are used in the earlier system, the new observations assimilated at NCMRWF include (i) Precipitation rates from SSM/I and TRMM (ii) GPSRO occultation (iii) AIRS and AMSRE radiances (iv) MODIS winds. Additionally ASCAT ocean surface winds and INSAT-3D AMVs are also assimilated. NCUM (N768/L70) model features a horizontal resolution of 17km and 70 vertical levels. It uses 4D-Var assimilation and features no cyclone initialization/relocation. NCUM is a grid point model which has a Non-hydrostatic dynamics with a deep atmosphere suitable for all scales. It has semi-implicit time integration with 3D semi-Lagrangian advection, terrain following height coordinates and high order advection. It features mass-flux for shallow convection with convective momentum transport, non-local mixing and entrainment for boundary layer. (For additional details refer to http://www.ncmrwf.gov.in/). NCMRWF Ensemble Prediction System (NEPS) is a global medium-range probabilistic forecasting system adapted from UK MET Office. The configuration consists of four cycles of assimilation corresponding to 00Z, 06Z, 12Z 18Z and 10-day forecasts are made using the 00Z initial condition. The N400L70 forecast model consists of 800x600 grid points on the horizontal surface and has 70 vertical levels. Horizontal resolution of the model is approximately 33 km in the midlatitudes. The 10-day control forecast run starts with N768L70 analysis of the deterministic assimilation forecast system and 44 ensemble members start from different perturbed initial conditions consistent with the uncertainty in initial conditions. The initial perturbations are generated using Ensemble Transform Kalman Filter (ETKF) method (Bishop et al., 2001). An important component common to both the deterministic (NCUM) and ensemble model (NEPS) is that they do not use any TC relocation in the analysis. However, the ACCESS-TC model features TC relocation. The Met Office bi-variate approach to tracking TCs is used in the real-time to track the location of the CS 'Vardah'. This method is in contrast to the earlier operational National Centers for Environmental Prediction (NCEP) who use any or all of MSLP, 850 hPa and 700 hPa RV and geopotential height to track tropical cyclones (Marchok, 2002). The bi-variate method identifies TCs by examination of the 850RV field but then fixes the TC center to the nearest local MSLP minimum (Hamming,2016). This is the adopted method in Met Office UK. The key advantage of the method is that it gives a strong signal of the approximate center of the TC even for weak systems and does not depend on the '*tcvitals*' information for tracking.

IMD also makes use of NWP products prepared by some other operational NWP centres like, ECMWF (European Centre for Medium Range Weather Forecasting), GFS (NCEP), JMA (Japan Meteorological Agency). Hurricane WRF (HWRF) model and Ensemble prediction system (EPS) has been implemented at the NWP Division of the IMD HQ for operational forecasting of cyclones.

In addition to the above NWP models, IMD also run operationally dynamical statistical models. The dynamical statistical models have been developed for (a) Cyclone Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction, (d) Rapid intensification and I Predicting decay in intensity after the landfall. Genesis potential parameter (GPP) is used for predicting potential of cyclogenesis (T3.0) and forecast for potential cyclogenesis zone. The multi-model ensemble (MME) for predicting the track (at 12h interval up to 120h) of tropical cyclones for the Indian Seas is developed applying multiple linear regression technique using the member models IMD-GFS, IMD-WRF, GFS (NCEP), ECMWF and JMA. The SCIP model is used for 12 hourly intensity predictions up to 72-h and a rapid intensification index (RII) is developed and implemented for the probability forecast of rapid intensification (RI). Decay model is used for prediction of intensity after landfall. In this report performance of the individual models, MME forecasts, SCIP, GPP, RII and Decay model for cyclone ROANU are presented and discussed.

9.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for Vardah

Figure 15 (a-e) shows the predicted zone of cyclogenesis. Grid point analysis and forecasts of GPP correctly predicted the cyclogenesis zone over southwest Bay of Bengal 96 hrs before its formation.

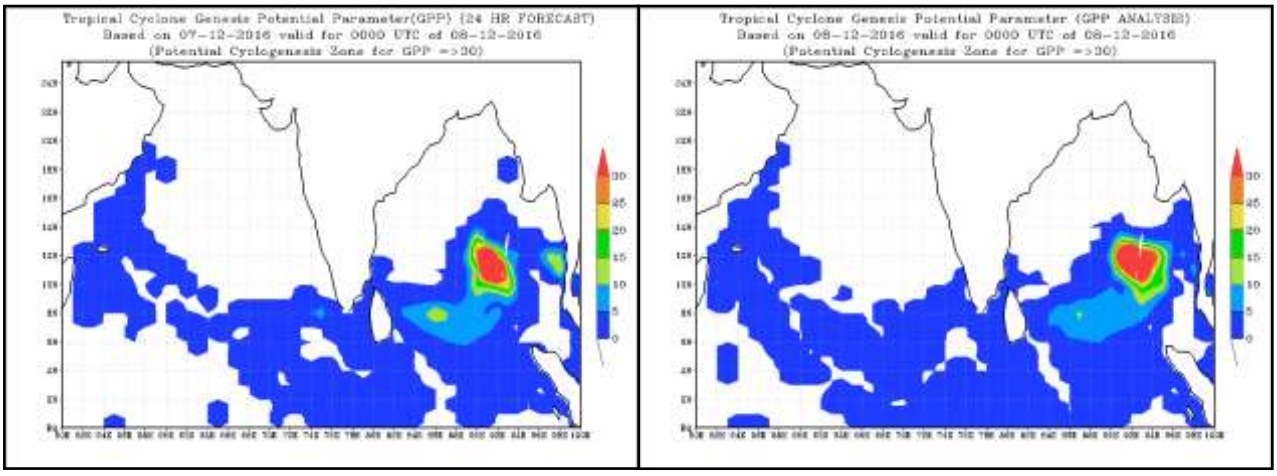


Figure 15 (a-b): Predicted zone of cyclogenesis based on 0000 UTC of 8th and 7th December for 8th December 2016.

Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages (T No. 1.0, 1.5, 2.0) of development. Conditions for: (i) Developed system:

Threshold value of average GPP ≥ 8.0 and (ii) Non-developed system: Threshold value of GPP < 8.0. The forecasts of GPP (Fig. 16) showed potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0).

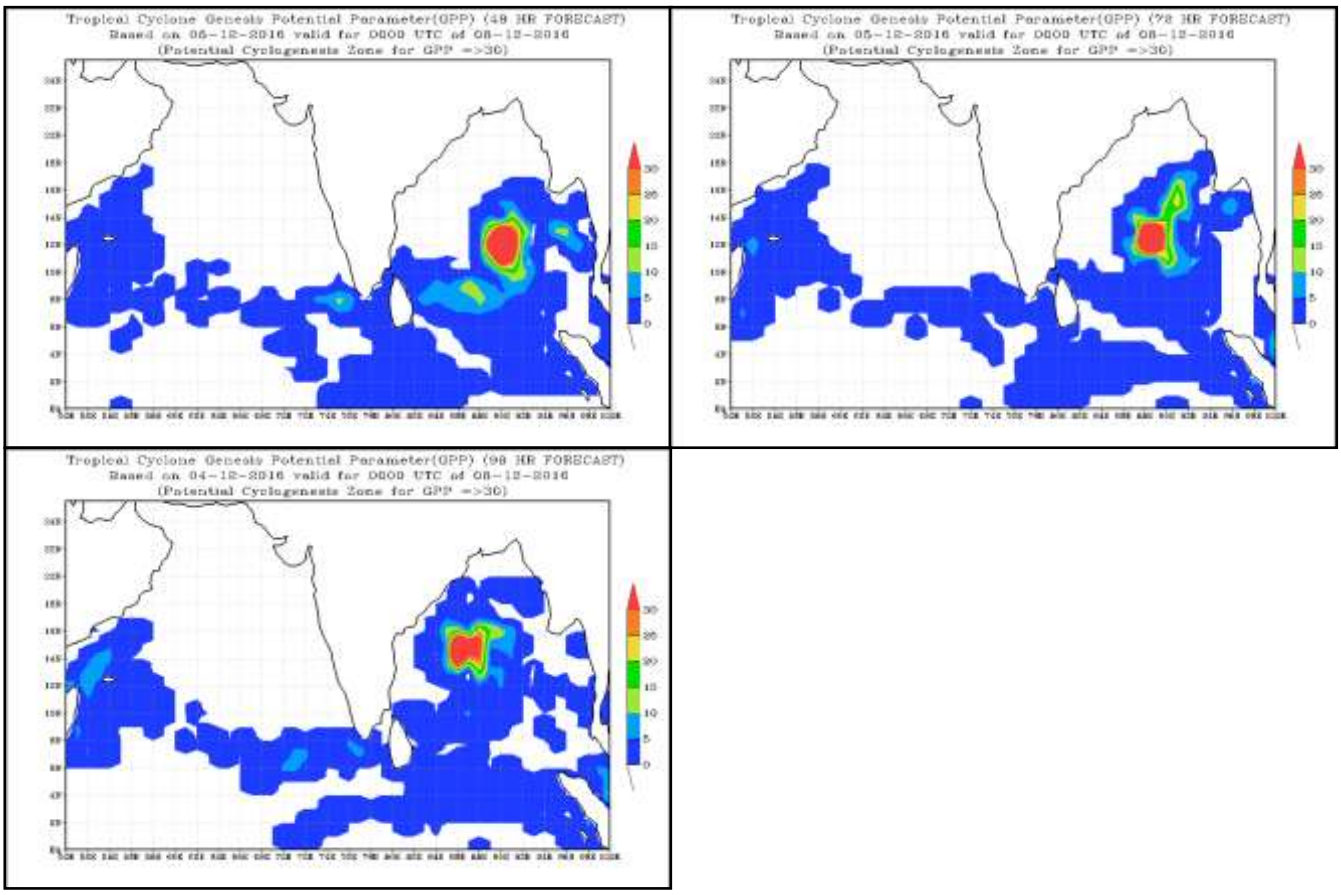


Fig. 15 (c-e): Predicted zone of cyclogenesis based on 0000 UTC of 6th, 5th and 4th December for 8th December 2016.

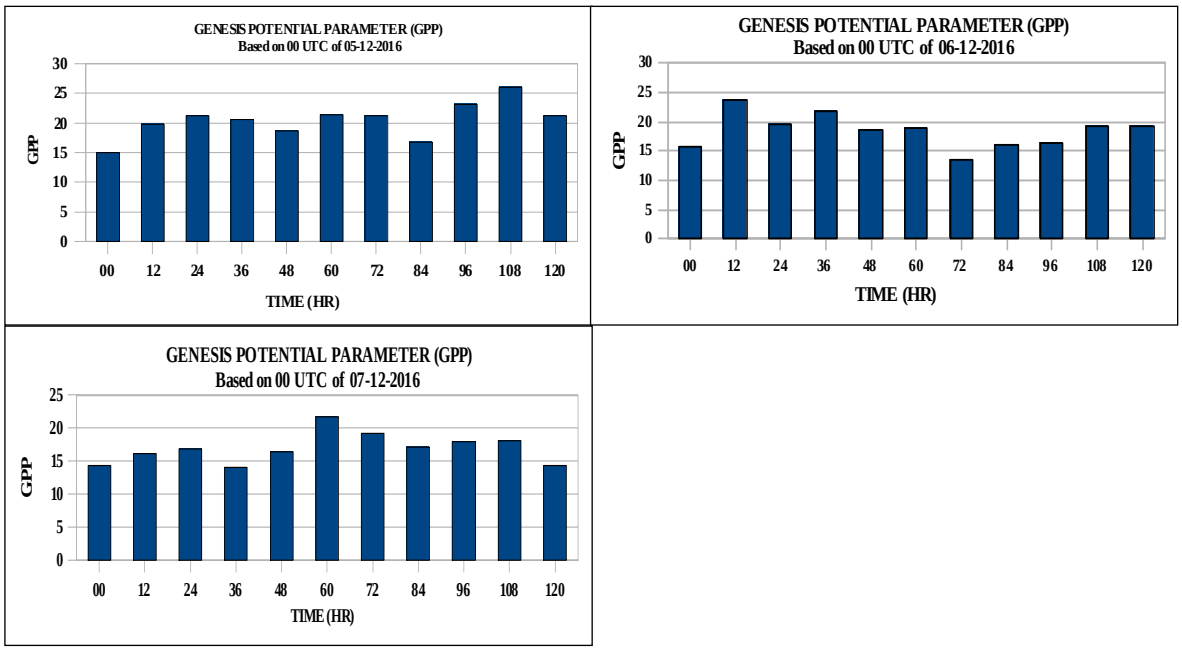


Fig. 16: Area average analysis and forecasts of GPP based on 0000 UTC of 5th -7th December, 2016

9.2 Track prediction by NWP models

Track prediction by various NWP models is presented in Fig.17. Based on initial conditions of 0000 UTC of 7th December, ECMWF, WRF-VAR, UKMO, JMA, MME and HWRF showed dissipation over sea. Only NCEP-GFS and IMD GFS were showing landfall of system over south Andhra Pradesh between Ongole and Machillipatnam in the early hours of 12th. All models were showing anticlockwise recurving track.

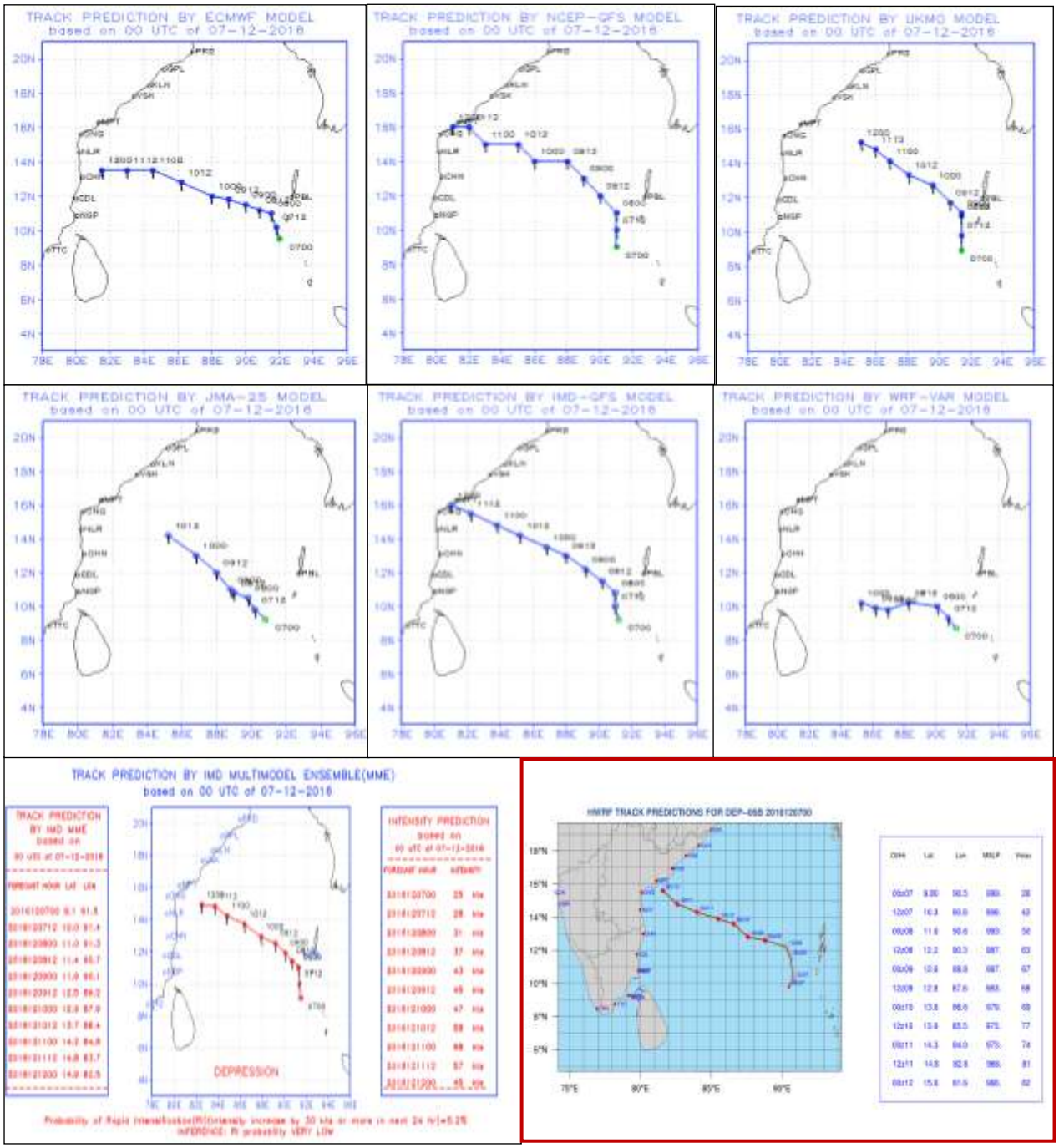


Fig. 17 (a): NWP model track forecast based on 0000 UTC of 7th December

Based on the initial conditions of 0000 UTC of 8th December, JMA, WRF-VAR and HWRF predicted weakening over the sea. All other models predicted landfall between Nellore to Machillipatnam. Time of landfall also varied from early hours of 12th to early hours of 13th. All models unanimously predicted anticlockwise recurving track.

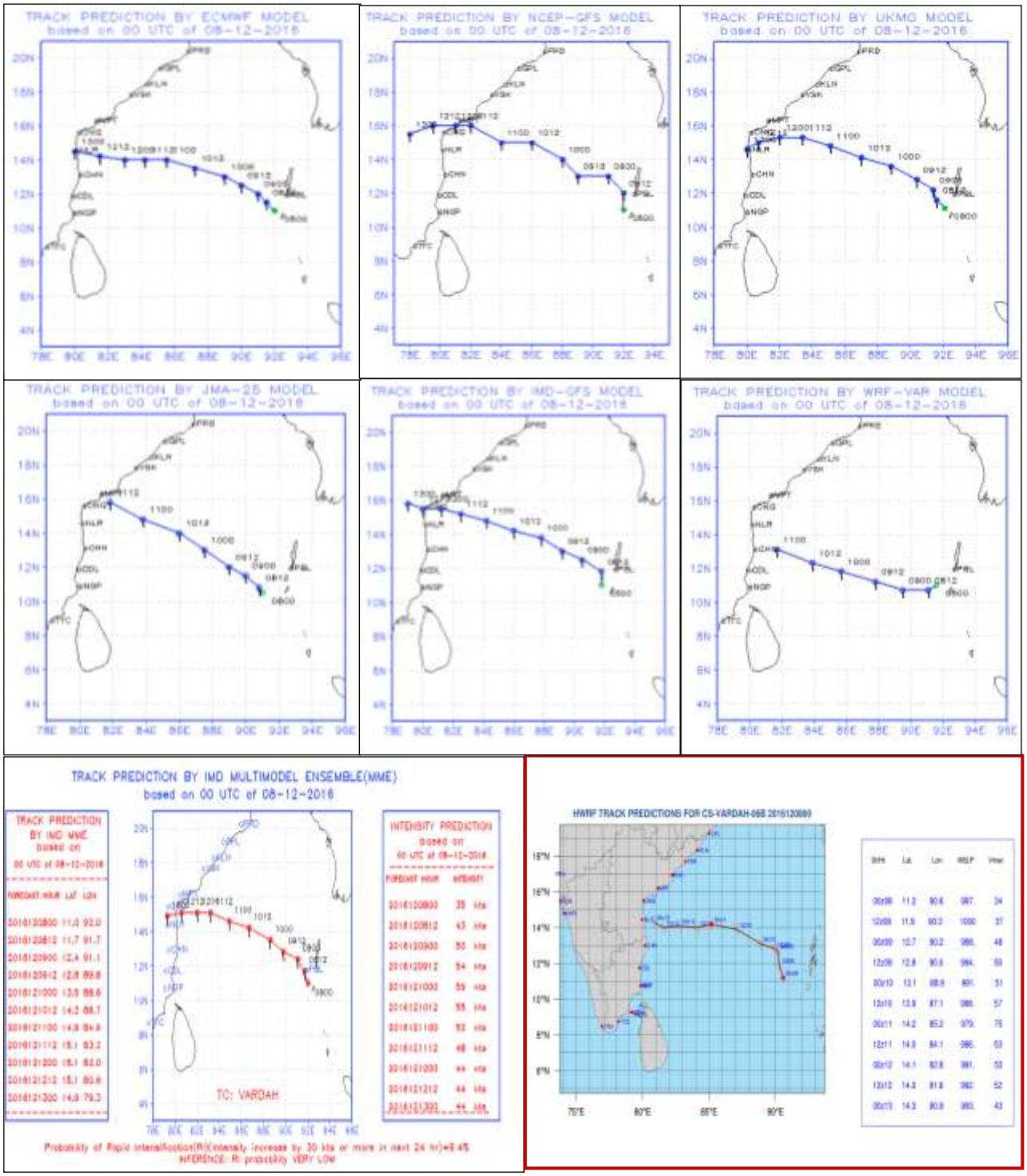


Fig. 17 (b): NWP model track forecast based on 0000 UTC of 8th December

Based on initial conditions of 0000 UTC of 9th, JMA and WRF-VAR predicted weakening over the sea. All other models predicted landfall over south Andhra Pradesh between Nellore to Machillipatnam. Time of landfall also varied from 1200 UTC of 12th to 0000 UTC of 13th. All models unanimously predicted anticlockwise recurving track.

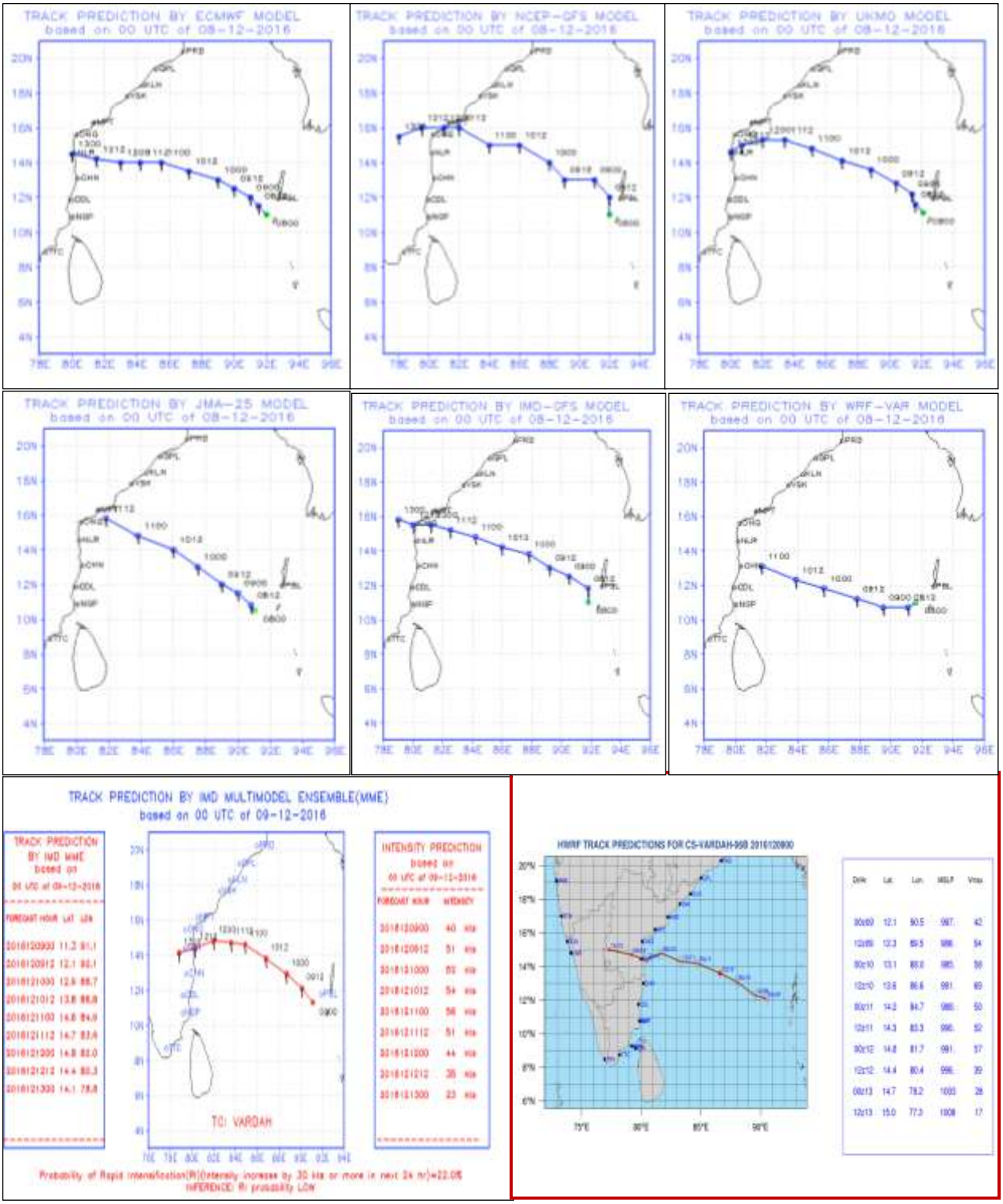


Fig. 17 (c): NWP model track forecast based on 0000 UTC of 9th December

Based on initial conditions of 0000 UTC of 10th December, all models predicted landfall between Chennai and Nellore. NCEP-GFS predicted landfall close to Chennai.

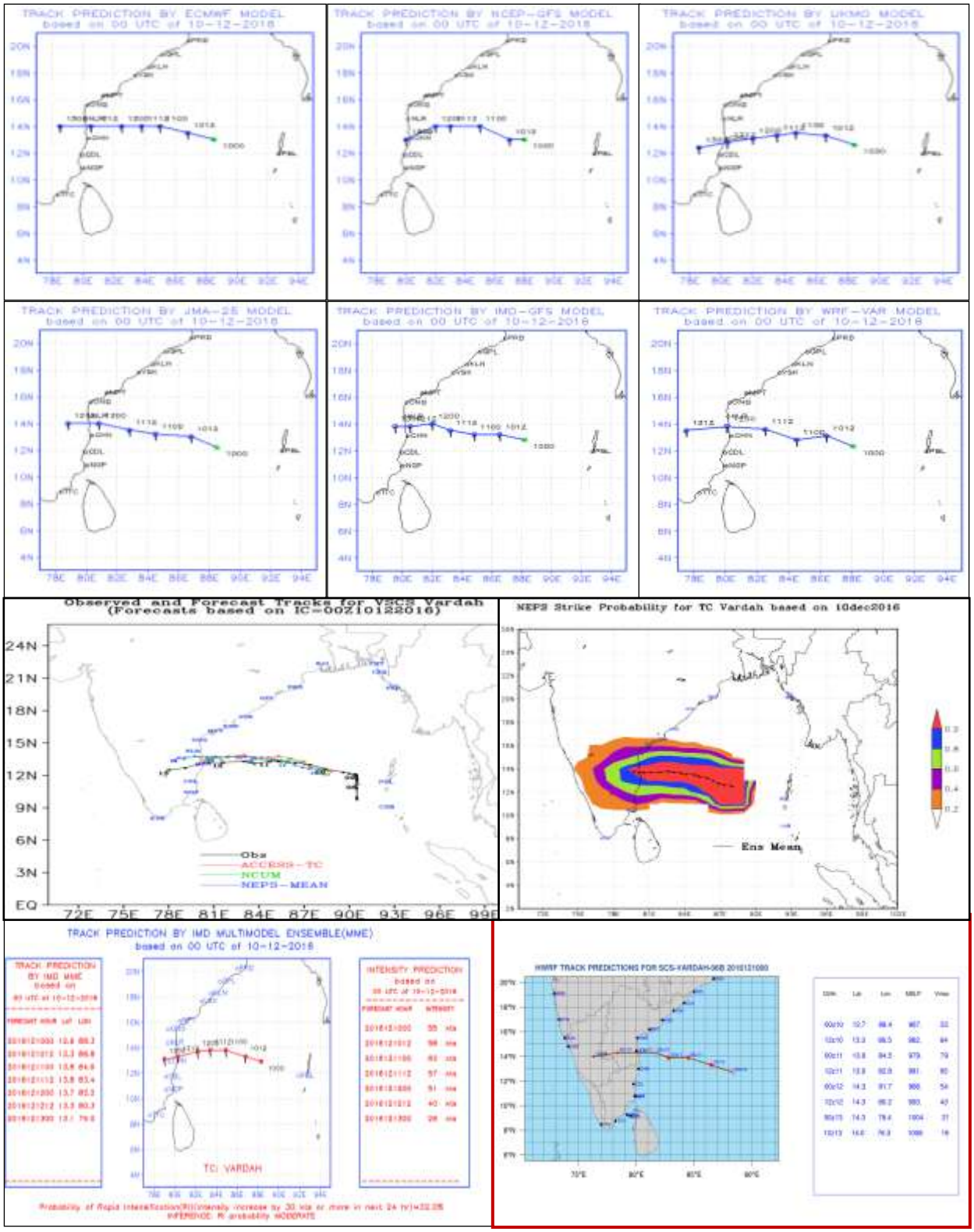


Fig. 17 (d): NWP model track forecast based on 0000 UTC of 10th December

Based on initial conditions of 0000 UTC of 11th December, most of the models predicted landfall over Chennai. JMA, WRF-VAR and HWRF were predicting landfall north/south of Chennai. Predicted time of landfall was around evening of 12th.

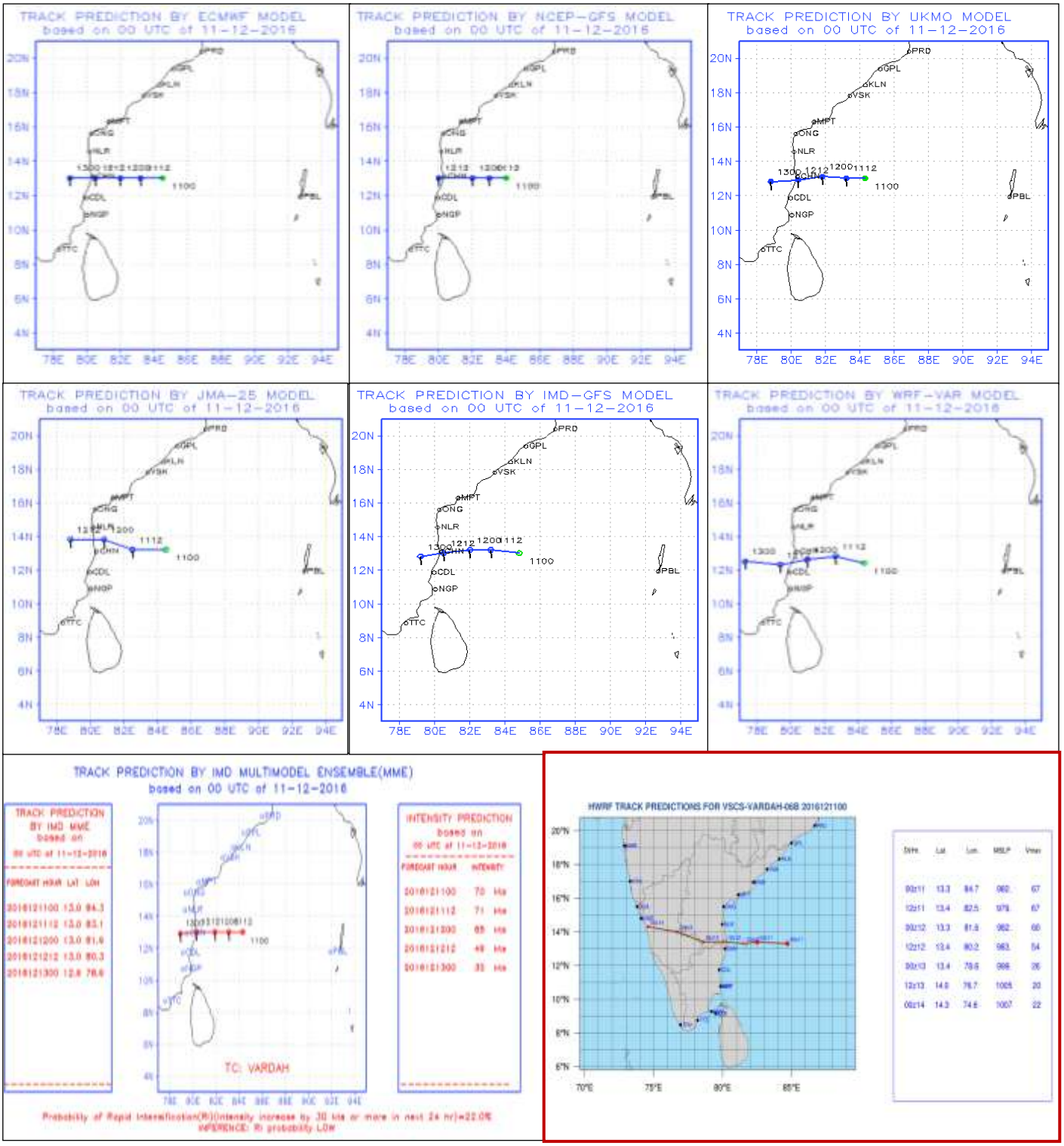


Fig. 17 (e): NWP model track forecast based on 0000 UTC of 11th December

Based on initial conditions of 0000 UTC of 12th December, all models unanimously showed landfall over Chennai around evening of 12th. HWRF also predicted emergence of Vardah over eastcentral Arabian Sea as a depression.

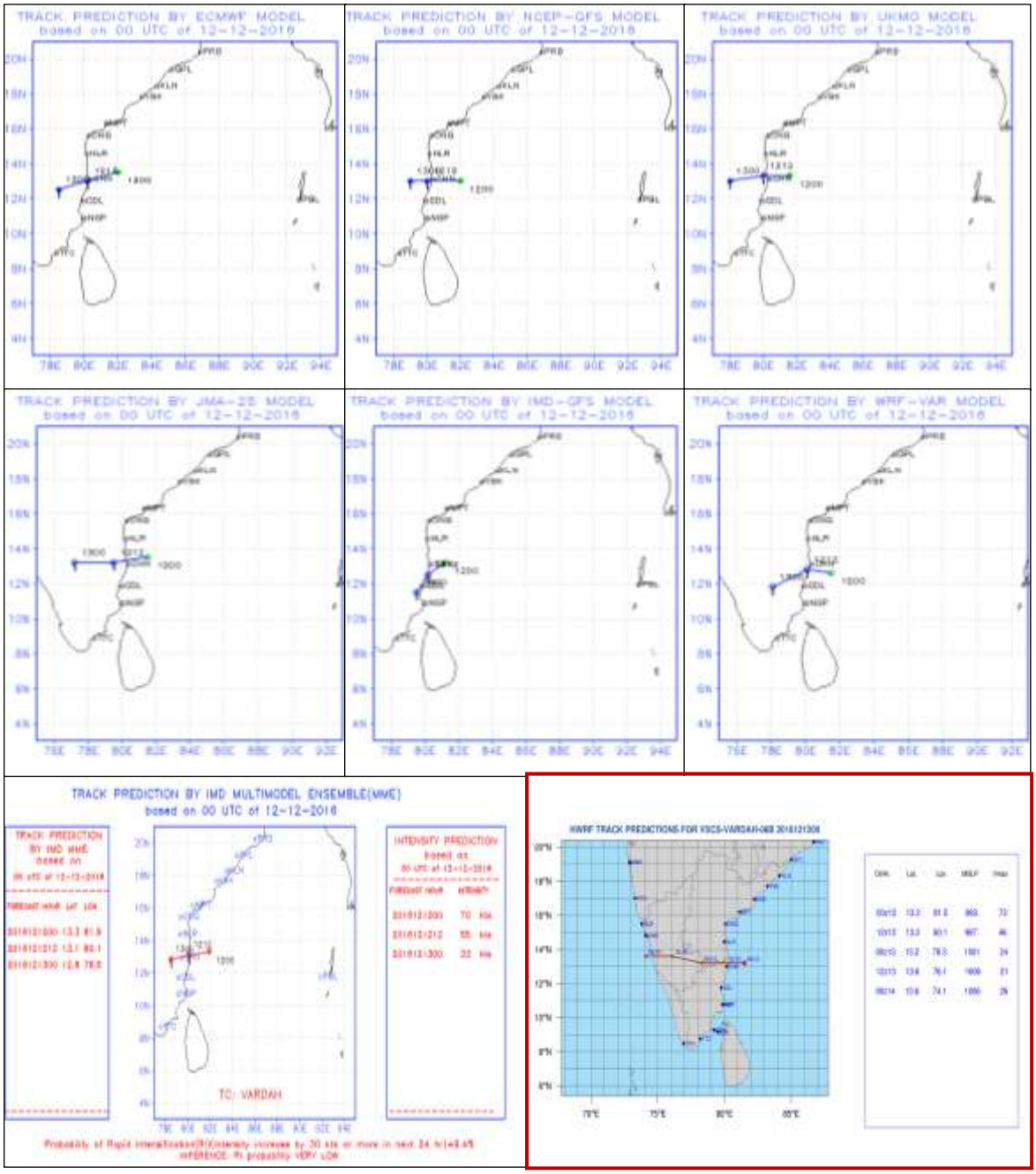


Fig. 17 (f): NWP model track forecast based on 0000 UTC of 12th December

Hence to conclude, most of the models predicted anticlockwise recurving track and landfall between north Tamil Nadu and south Chennai. From 10th onwards most of the models were predicting landfall close to Chennai around evening of 12th. HWRF also predicted emergence of system over eastcentral AS.

Ensemble Prediction System

The probabilistic and deterministic track forecast by National Centre for Environment Prediction (NCEP) and UK Meteorological Office (UKMO) and consolidated forecast by these centres based on initial conditions of 1200 UTC of 8th December are presented in Fig. 18 (a). UKMO predicted 20-40% and 5-20 % strike probability over north Tamil Nadu close to Chennai and south Andhra Pradesh respectively. NCEP members showed 60-80% strike probability over south Andhra Pradesh coast. All members ensemble showed 20-40% strike probability over south Andhra Pradesh coast and 5-20% over north Tamil Nadu.

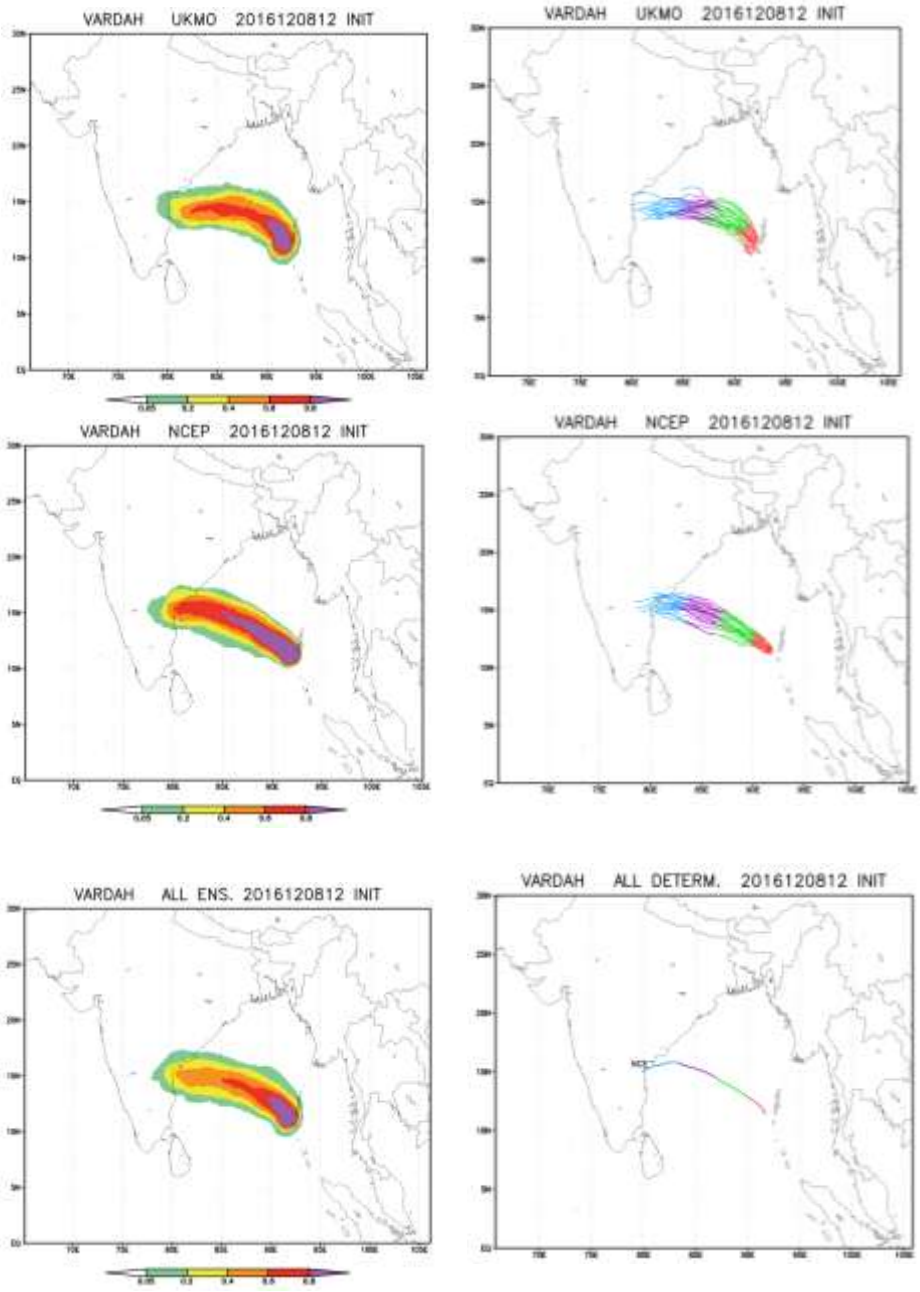


Fig. 18 (a): EPS track and strike probability forecast based on 1200 UTC of 8th December.

UKMO and NCEP probabilistic and deterministic tracks based on 0000 UTC of 9th December are presented in Fig. 18 (b). UKMO ensemble members predicted 40-60 % strike probability over north Tamil Nadu close to Chennai. However, NCEP ensemble members predicted 60-80 % strike probability over south Andhra Pradesh coast. All ensemble members were predicting 40-60 % strike probability over south Andhra Pradesh coast.

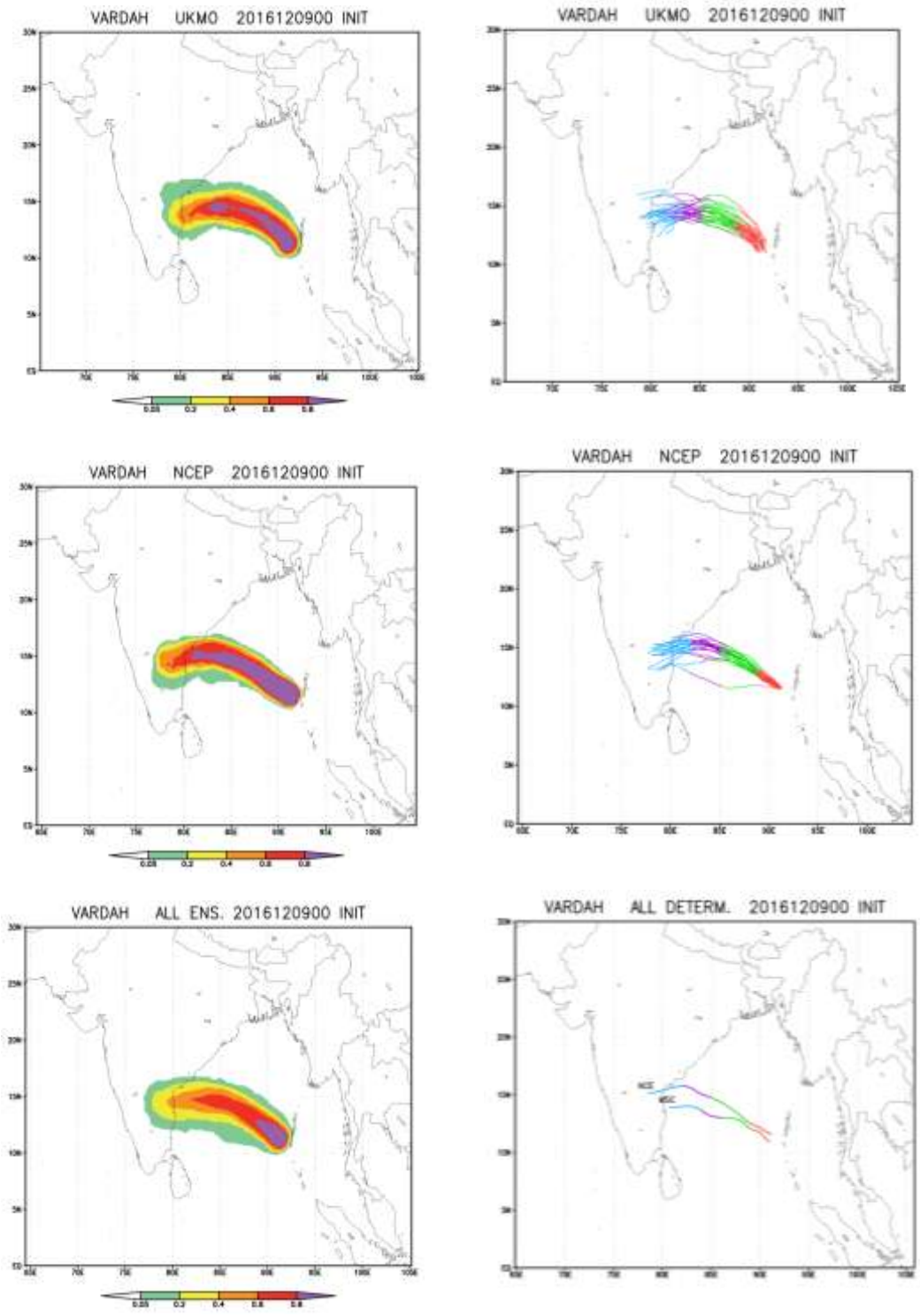


Fig. 18 (b): EPS track and strike probability forecast based on 0000 UTC of 9th December, 2016

UKMO and NCEP probabilistic and deterministic tracks based on 0000 UTC of 10th are presented in Fig. 18 (c). Ensembles from UKMO predicted 40-60 % strike probability over north Tamil Nadu. Ensembles from NCEP predicted 60-80 % strike probability over north Tamil Nadu. All ensemble members were predicting 40-60 % strike probability over north Tamil Nadu.

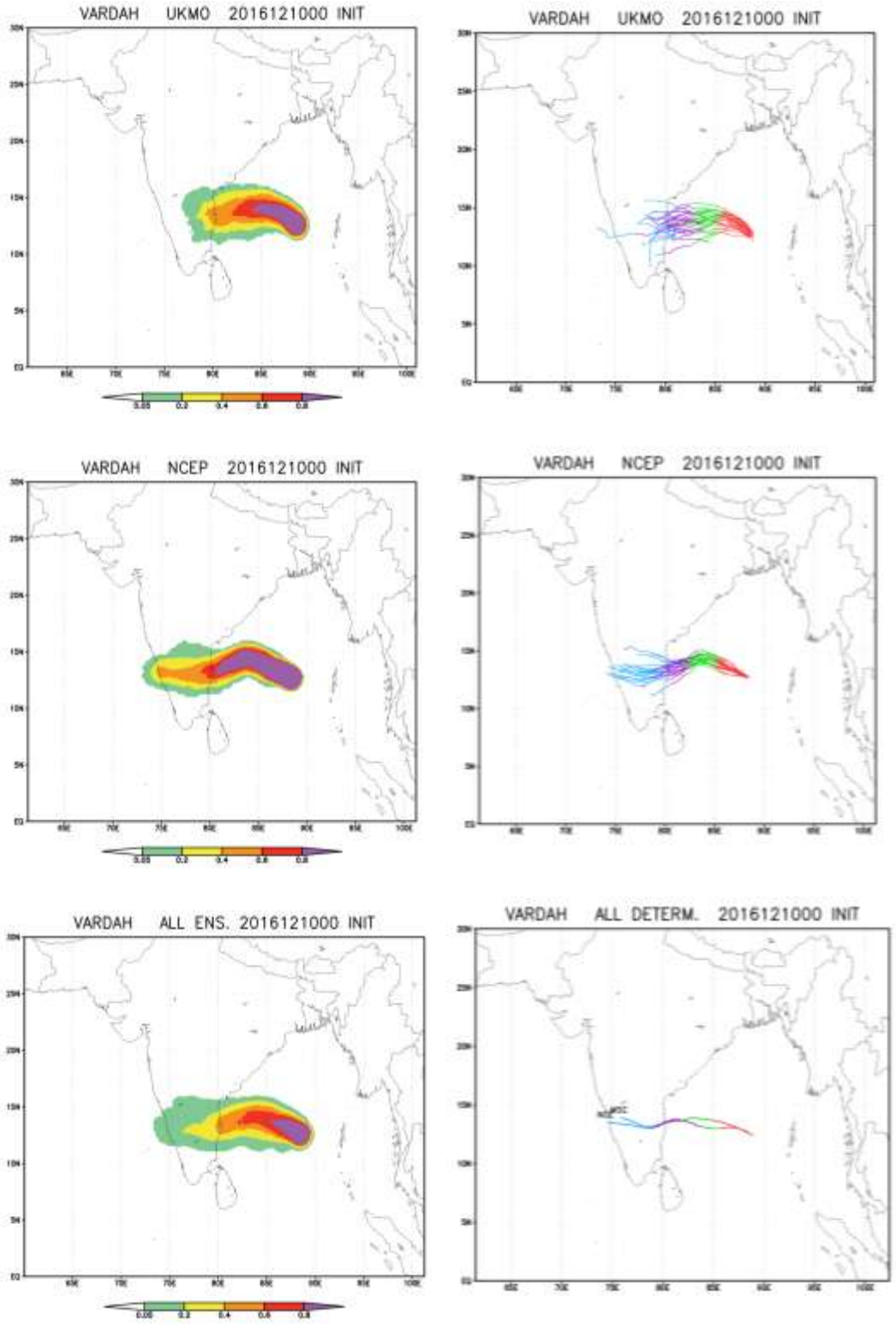


Fig. 18 (c): EPS track and strike probability forecast based on 0000 UTC of 10th December, 2016

Based on initial conditions of 0000 UTC of 11th (Fig. 18 (d)), both UKMO and NCEP members showed >80% strike probability over north Tamil Nadu close to Chennai. All ensemble members were predicting 60-80 % strike probability over north Tamil Nadu close to Chennai.

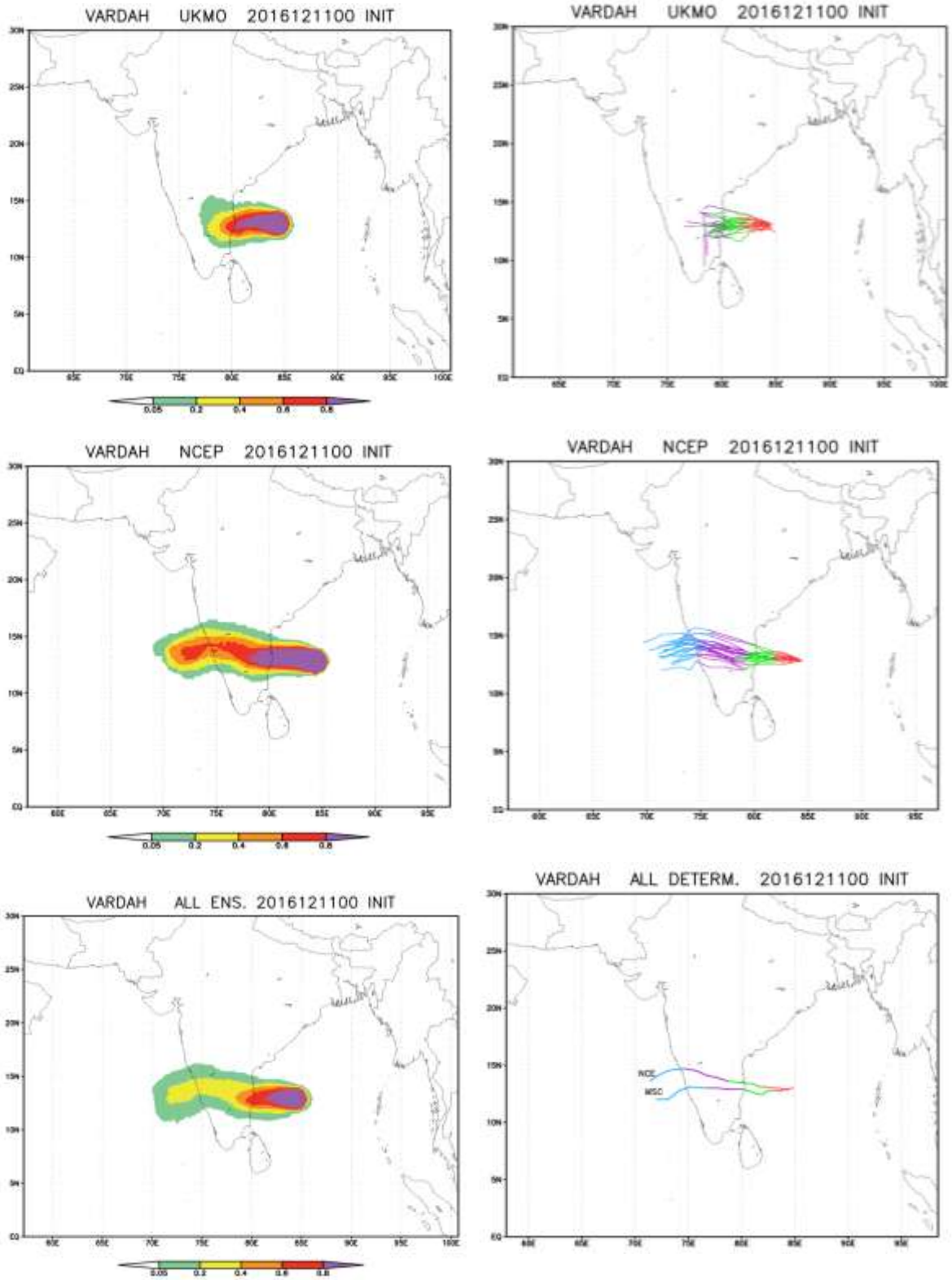


Fig. 18 (d): EPS track and strike probability forecast based on 0000 UTC of 11th December, 2016

Based on initial conditions of 0000 UTC of 12th (Fig.18 (e)) UKMO, NCEP and all ensemble members showed >80% strike probability over north Tamil Nadu close to Chennai.

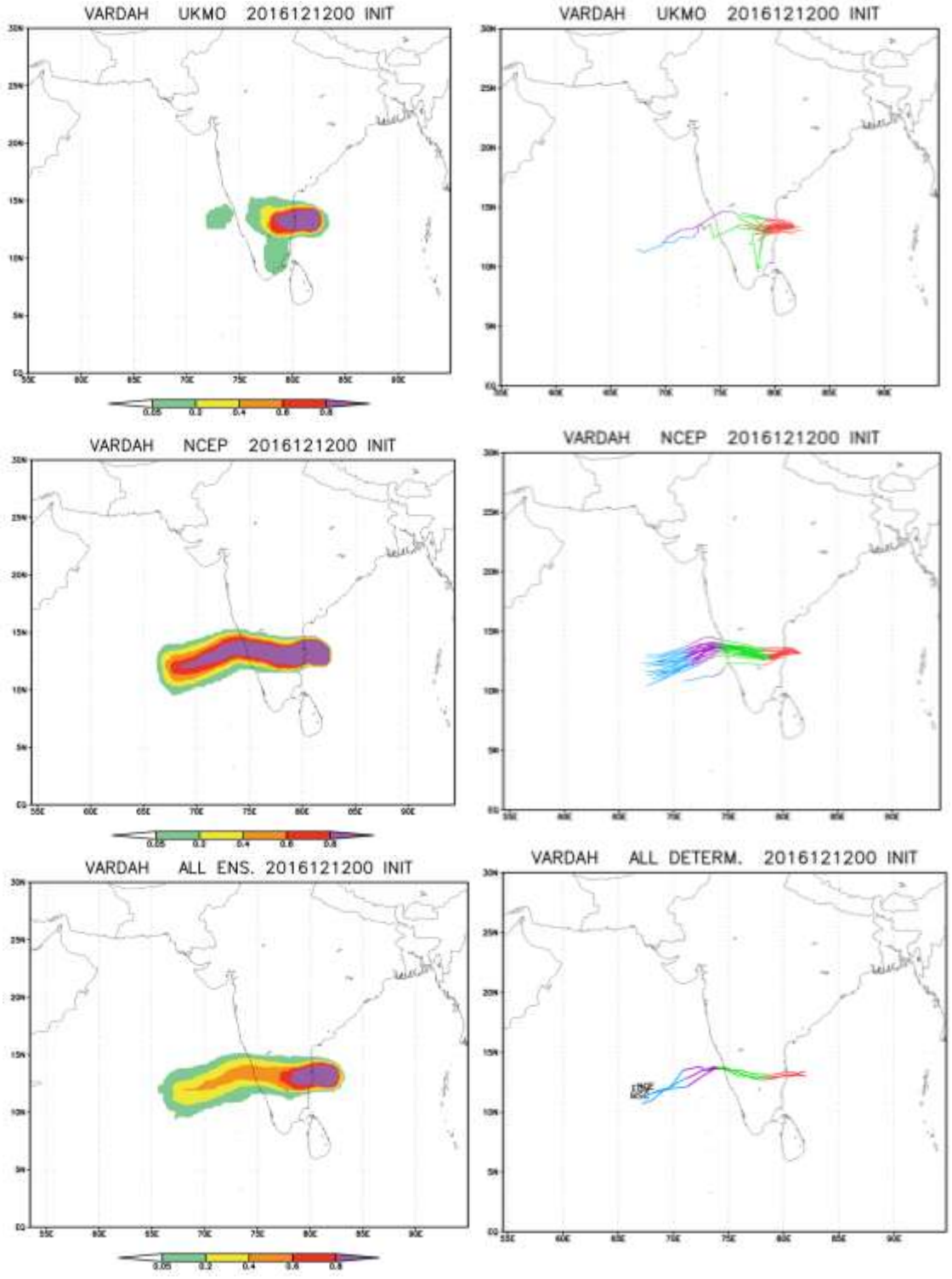


Fig. 18 (e): EPS track and strike probability forecast based on 0000 UTC of 12th December, 2016.

Overall forecast by NCEP members was closer to observed landfall point as compared to UKMO members.

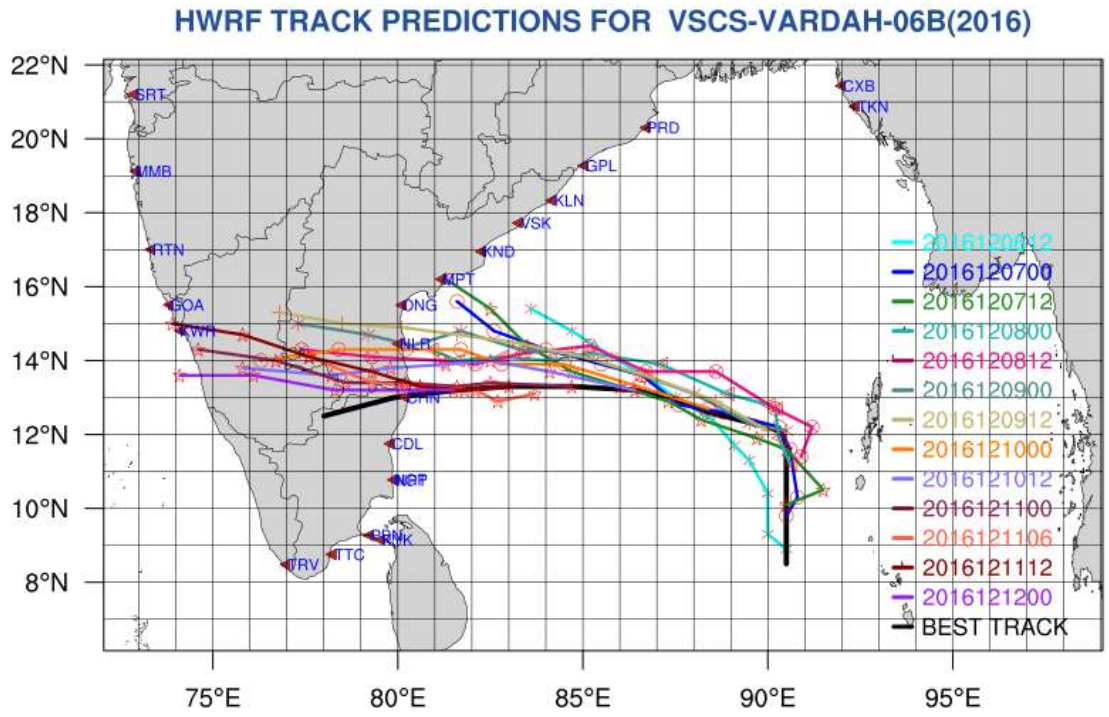


Fig. 19: Observed track and track forecast by HWRF based on initial conditions during 1200 UTC of 6th to 12th December

It is seen that HWRF could predict accurately anticlockwise recurvature of the system. HWRF predicted landfall between Chennai and Nellore. HWRF could also predict emergence of system over eastcentral AS.

9.3 Track and intensity forecast errors by various NWP Models

The average track forecast errors (Direct Position Error) in km at different lead period (hr) of various models are presented in Table 6. The average cross track errors (CTE) and along track errors (ATE) are presented in Table 7 (a-b). From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of UKMO were significantly less for all lead periods. Average track errors of IMD-MME were the least for 24 and 48 hours lead period.

Table 6. Average track forecast errors (Direct Position Error (DPE)) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	120hr
IMD-GFS	61(10)	76(10)	86(9)	115(8)	153(7)	195(6)	210(5)	239(4)	269(2)	350(2)
IMD-WRF	71(10)	109(10)	136(9)	190(8)	284(6)	325(4)	***	***	***	***
JMA	65(10)	76(10)	100(8)	140(7)	196(6)	261(5)	303(4)	***	***	***
NCEP	60(10)	87(10)	112(9)	170(8)	199(7)	266(6)	270(5)	248(4)	327(2)	326(2)
UKMO	67(10)	72(10)	100(9)	119(8)	130(7)	162(6)	205(5)	203(4)	301(2)	378(2)
ECMWF	58(10)	63(10)	83(9)	103(8)	116(7)	138(6)	143(5)	146(4)	120(2)	172(2)

IMD-HWRF	58(25)	64(23)	97(21)	144(19)	175(17)	179(15)	183(13)	201(11)	224(9)	316(7)
IMD-MME	55(10)	67(10)	88(9)	112(8)	132(7)	155(6)	177(5)	170(4)	214(2)	257(2)
NCUM	170	231	313	313	311	274	252			
ACCESS-TC	67	92	128	151	175	228	-			
NEPS-Mean	111	167	193	254	226	274	261			

( ): Number of forecasts verified; -: No forecast issued

Table 7 (a). Average cross-track forecast errors (CTE) in km

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**84hr**	**96hr**	**108hr**	**120hr**
IMD-GFS	55	31	31	80	117	147	158	202	231	322
IMD-WRF	43	82	117	137	170	176	***	***	***	***
JMA	44	47	72	94	149	190	200	***	***	***
NCEP	49	54	68	136	139	192	205	188	276	301
UKMO	56	64	74	91	104	139	181	187	260	296
ECMWF	52	45	41	67	87	115	110	115	89	134
IMD-HWRF	45	43	41	91	107	138	111	126	147	215
IMD-MME	49	51	52	86	103	130	160	163	213	244

Table 7 (b). Average along-track forecast errors (ATE) in km

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**84hr**	**96hr**	**108hr**	**120hr**
IMD-GFS	13	63	73	62	85	112	102	108	105	123
IMD-WRF	46	59	54	121	198	209	***	***	***	***
JMA	37	57	62	97	115	177	209	***	***	***
NCEP	22	57	68	70	117	134	132	121	157	98
UKMO	29	23	50	59	58	60	71	60	137	235
ECMWF	18	36	65	63	59	64	80	69	80	109
IMD-HWRF	53	51	88	112	138	113	145	156	172	234
IMD-MME	16	36	56	51	59	63	58	36	20	71

Above tables show that DPE was largely contributed by ATE, that is errors in speed of movement of the storm, whereas CTE shows that forecast tracks were close to the observed track.

- : No forecast issued

Landfall point and time forecast errors are presented in Table 8 and 9. 24hr landfall point forecast error was the least by IMD GFS followed by JMA & IMD-MME and NCEP GFS. 48 hr landfall point forecast error was the least by IMD MME followed by ECMWF and NCEP GFS.

Table 8: Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Forecast Lead Time (hour) →	10:30	22:30	34:30	46:30	58:30	70:30	82:30	106:30	130:30
Based on	12Dec/00z	11Dec/12z	11 Dec/00z	10Dec/12z	10Dec/00z	09Dec/12z	09Dec/00z	08Dec/00z	07Dec/00z
IMD-GFS	77	11	13	19	64	110	198	264	328
IMD-WRF	41	137	52	43	77	187	74	**	**
JMA	37	13	75	86	97	265	209	**	**
NCEP	22	18	13	18	18	209	209	328	328
UKMO	22	22	18	41	37	143	176	175	**
ECMWF	26	22	13	13	97	75	41	156	**
IMD-HWRF	8	30	30	75	130	198	153	**	**
IMD-MME	11	13	14	11	19	119	119	143	208

Landfall Point Error: Landfall Forecast Point- Actual Landfall Point, **: No forecast issued

Table-9. Landfall time forecast errors (hour) at different lead time (hr)
('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	10:30 hr	22:30 hr	34:30 hr	46:30 hr	58:30 hr	70:30 hr	82:30 hr	106:30 hr	130:30 hr
Based on	12Dec/00z	11Dec/12z	11 Dec/00z	10Dec/12z	10Dec/00z	09Dec/12z	09Dec/00z	08Dec/00z	07Dec/00z
IMD-GFS	+01:30	+14:30	+03:30	+07:30	+04:30	+03:30	+00:30	+00:30	-10:30
IMD-WRF	+01:30	+07:30	-02:30	-02:30	-10:30	-10:30	-13:30	***	***
JMA	-02:30	-05:30	-06:30	-05:30	-05:30	+01:30	-10:30	***	***
NCEP	-00:30	+10:30	-00:30	+10:30	+11:30	+13:30	+00:30	-10:30	-10:30
UKMO	+01:30	+03:30	+02:30	+02:30	+01:30	+09:30	+01:30	+12:30	***
ECMWF	+01:30	+06:30	+03:30	+06:30	+03:30	+08:30	+06:30	+12:00	***
IMD-HWRF	+00:30	+04:30	+00:30	+04:30	+01:30	+01:30	+02:30	***	***
IMD-MME	+01:30	+06:30	+01:30	+06:30	+01:30	+08:30	+01:30	+00:30	+05:30

Landfall Time Error: Landfall Forecast Time- Actual Landfall Time
- : No forecast issued

The intensity forecast s of IMD-SCIP model and HWRF model are shown in Table 10. The errors were relatively higher in case of HWRF. The probability of rapid intensification (RI) index of IMD is shown in Table 11. It correctly predicted no RI for cyclone, Vardah.

Table 10: Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of SCIP model (Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	120hr
IMD-SCIP (AAE)	4.2(10)	6.2(9)	8.9(8)	10.6(7)	10.0(6)	16.2(5)	18.0(4)	17.3(3)	9.5(2)	25(1)
IMD-HWRF (AAE)	7.5(25)	9.4 (23)	11.0 (21)	15.5 (19)	12.2 (17)	13.6 (15)	14.5 (13)	12.5 (11)	11.0 (9)	14.4 (7)
IMD-SCIP (RMSE)	5.0	7.3	11.0	14.1	14.4	17.2	19.6	20.5	10.1	25.0
IMD-HWRF (RMSE)	8.8 (25)	11.2(23)	13.7 (21)	17.8 (19)	15.2 (17)	15.8 (15)	16.4 (13)	15.2 (11)	12.8 (9)	17.8 (7)

( ) : No of forecasts verified

Table 11: Probability of Rapid intensification

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes(kt) occurred in 24h
00/07.12.2016	5.2 %	VERY LOW	10
00/08.12.2016	9.4 %	VERY LOW	10
12/08.12.2016	9.4 %	VERY LOW	5
00/09.12.2016	22.0 %	LOW	10
12/09.12.2016	22.0 %	LOW	20
00/10.12.2016	32.0 %	MODERATE	15
12/10.12.2016	22.0 %	LOW	5
00/11.12.2016	22.0 %	LOW	0
12/11.12.2016	9.4%	VERY LOW	-20

9.4. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model are presented in fig.15. It indicates that the HWRF model could predict the occurrence of rainfall over Andaman & Nicobar Islands based on initial conditions of 08^{th} -10^{th}. It could not capture rainfall over north Tamil Nadu. Occurrence of heavy to very rainfall over Andhra Pradesh coast was also over predicted. However, it could capture occurrence of heavy rainfall over south interior Karnataka and emergence of system in eastcentral Arabian Sea.

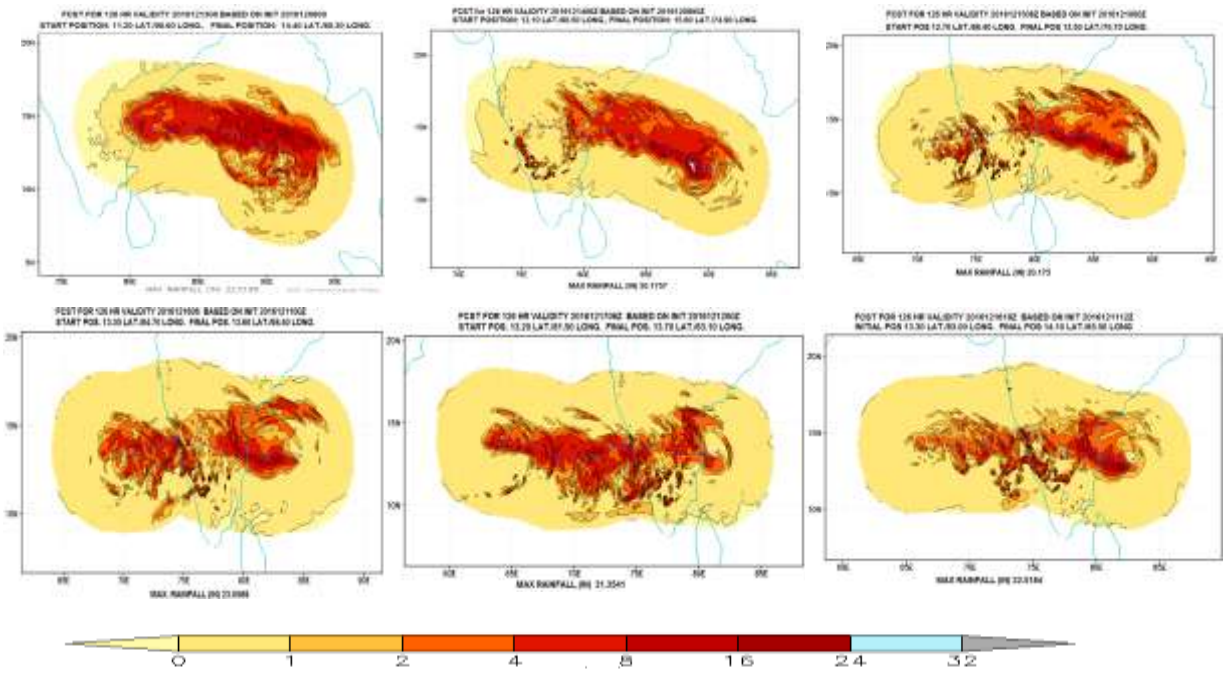


Fig.15: 126 hour heavy rainfall forecast by HWRF based on initial conditions of 0000 UTC of 8th-12th December and 1200 UTC of 11th December.

10.5 Storm surge forecast

IMD predicted storm surge forecast based on guidance from Indian National Centre for Ocean Information Services (INCOIS) Advance Circulation (ADCIRC) model and Indian Institute of Delhi. IMD predicted Storm surge of about 1m height above astronomical tide at the time of landfall over low lying areas of Chennai and Tiruvallur districts of Tamil Nadu and Nellore district of Andhra Pradesh at the time of landfall.

10.6 Ocean State Forecast by INCOIS

INCOIS issues ocean state forecast based on the bulletins issued by IMD. The forecast and observed wave heights at Gopalpur, Vishakhapatnam and Pondicherry are presented in the Fig. 16.

The Pondicherry, Visakhapatnam and Gopalpur buoys showed around 2-2.5 m waves in connection with the cyclone VARDAH (since these 3 locations were not in the close vicinity of the VSCS VARDAH, the wave heights were comparably less). The waves at Pondicherry showed a diurnal cycle, but no high waves (less than 1.5m) attributable to the cyclone. The forecast and observed wave heights at Visakhapatnam, Gopalpur and Pondicherry are presented in the Figure 20.

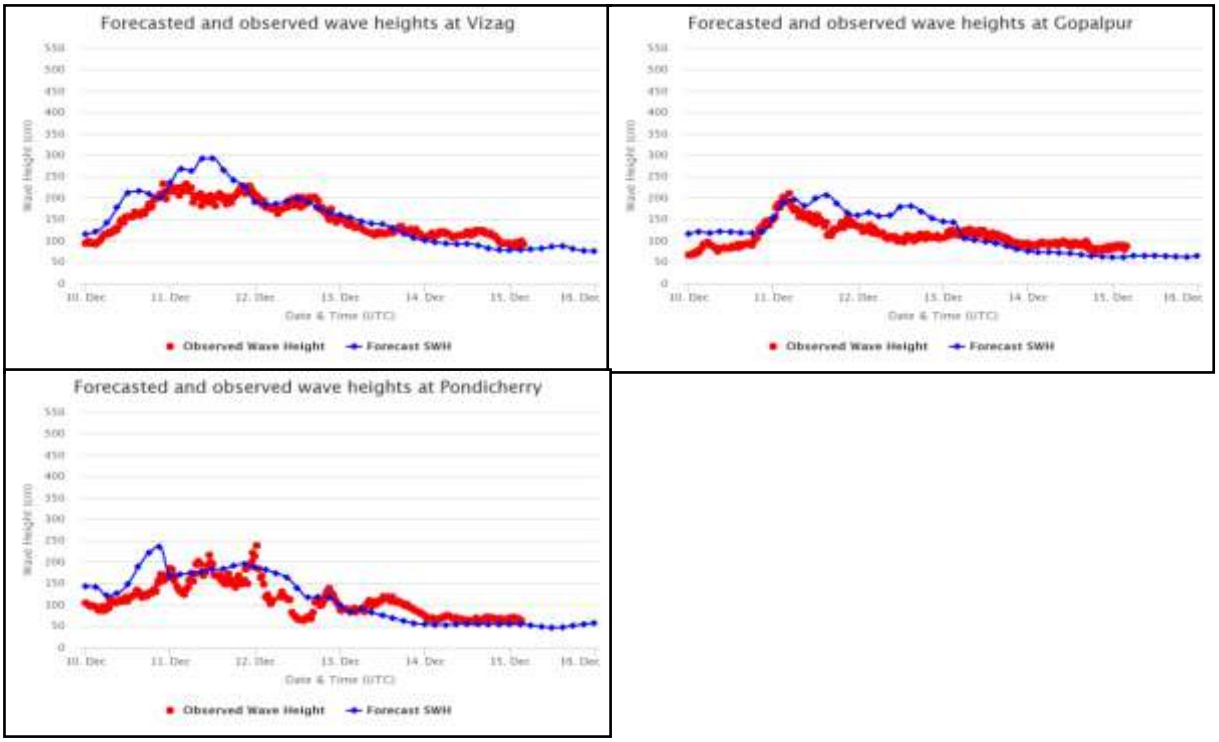


Fig.16 The forecast and observed wave heights during 10th to 16th December 2016

10. Operational Forecast Performance

Forecast Performance

(i) The first information regarding genesis of depression over southeast BOB on 6th December was issued by RSMC New Delhi on 3rd December with probability of 51-75% (about 72 hours in advance).

(ii) The first bulletin indicating the landfall of cyclone between Ongole and Chennai by afternoon/evening of 12th December was issued based on 1730 hours IST observations of 10th (48 hours prior to landfall).

(iii) The bulletin indicating landfall of cyclone close to Chennai around afternoon of 12th December was issued based on 0530 hours IST observations of 11th (36 hours prior to landfall).

(iv) There was almost zero error in landfall forecast issued 12 hrs before landfall and about 66 km in the forecast issued 36 hrs before landfall.

(v) The track forecast error for 24, 48 and 72 hrs lead period were 94, 141 and 197 km respectively, which is significantly less than the average track forecast errors of recurving cyclones in last five years. The track forecast skill is about 61%, 75% and 76% for 24, 48 and 72 hrs lead period respectively, which are higher than the long period average (LPA) during 2011-15.

(vi) The absolute intensity (wind) forecast error for 24, 48 and 72 hrs lead period are 8.4, 10.5 and 12.1 knots against the LPA of 12, 15 and 18 knots respectively.

(vii) The surface wind at the time of landfall over Chennai was predicted to be 100-110 kmph gusting to 120 kmph 12 hrs in advance and 80-90 kmph gusting to 100 kmph 24-36 hrs in advance against the actual wind speed of about 100-110 kmph gusting to 120 kmph.

(viii) The heavy to very heavy rainfall alongwith the isolated extremely heavy rainfall over north coastal districts of Tamil Nadu and adjoining districts of Andhra Pradesh as well as the storm surge of 1 meter above the astronomical tide were also predicted 48 hrs in advance

(ix) The heavy to very heavy rainfall over Andaman & Nicobar Islands and squally wind speed reaching 50-60 kmph prevailed along and off Andaman & Nicobar Islands were predicted 72 hrs in advance. Regular bulletins were issued to disaster management agencies of Andaman & Nicobar Islands and central level during the period.

(x) Every three hourly TC Advisories were issued to central & state level disaster managers, media general public and WMO/ESCAP member countries.

(xi) On the day of landfall hourly bulletins about the location and intensity of the cyclone were issued.

(xii) The numerical weather prediction (NWP) and dynamical statistical models provided reasonable guidance with respect to its genesis, track and intensity of the system.

10.1 Operational Genesis forecast

- The first information regarding genesis of depression over southeast BOB on 6th December was issued by RSMC New Delhi on 3rd December with probability of 51-75%.
- The first bulletin indicating the landfall of cyclone between Ongole and Chennai by afternoon/evening of 12th December was issued based on 1730 hours IST observations of 10th (48 hours prior to landfall).
- The bulletin indicating landfall of cyclone close to Chennai around afternoon of 12th December was issued based on 0530 hours IST observations of 11th (36 hours prior to landfall).

10.2. Operational landfall forecast error and skill

The operational landfall forecast errors and skill are presented in Table 12. The landfall point error (LPE) has been about 11, 154 and 264 km against long period average (LPA) based on 2011-15 of 56, 94 and 106 km for 24, 48 and 72 hours lead period respectively. For 12 hour lead period, the landfall point error was almost zero. The LPE has been significantly lower than the LPA for 24 hours lead period and comparable to LPA for 48 and 72 hours lead period. The landfall time error (LTE) has been 5.0, 6.0 and 4.5 hours against the LPA of 4.2, 4.7 and 2.4 hours for 24, 48 and 72 hours lead period respectively. An example of forecast track along with cone of uncertainty and quadrant wind distribution around the centre of cyclone issued on 0000 UTC of 11th December and observed track is presented in Fig.17.

Table 12: Landfall Point and Time Error in association with VSCS Vardah

Lead Period (hrs)	Base Time	Landfall Point (^{0}N/^{0}E)		Landfall Time (hours)		Operational Error		LPA error (2011-15)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	11/1800	13.1/80.3	13.1/80.3	12/1000	12/1030	0	0.5	36.5	2.5
24	11/0600	13.0/80.3	13.1/80.3	12/0530	12/1030	11	5.0	56.3	4.2
36	10/1800	13.7/80.3	13.13/80.3	12/0700	12/1030	66	3.5	60.6	4.7
48	10/0600	14.5/80.2	13.1/80.3	12/0530	12/1030	154	6.0	93.5	4.7
60	09/1800	14.6/80.2	13.1/80.3	12/1230	12/1030	165	2.0	95.2	3.9
72	09/0600	15.5/80.2	13.1/80.3	12/1500	12/1030	264	4.5	105.7	2.4

LPE: Landfall Point Error, LTE: Landfall Time Error, LPA: Long Period Average,
LPE= Forecast Landfall Point-Actual Landfall Point,
LTE= Forecast Landfall Time-Actual Landfall Time

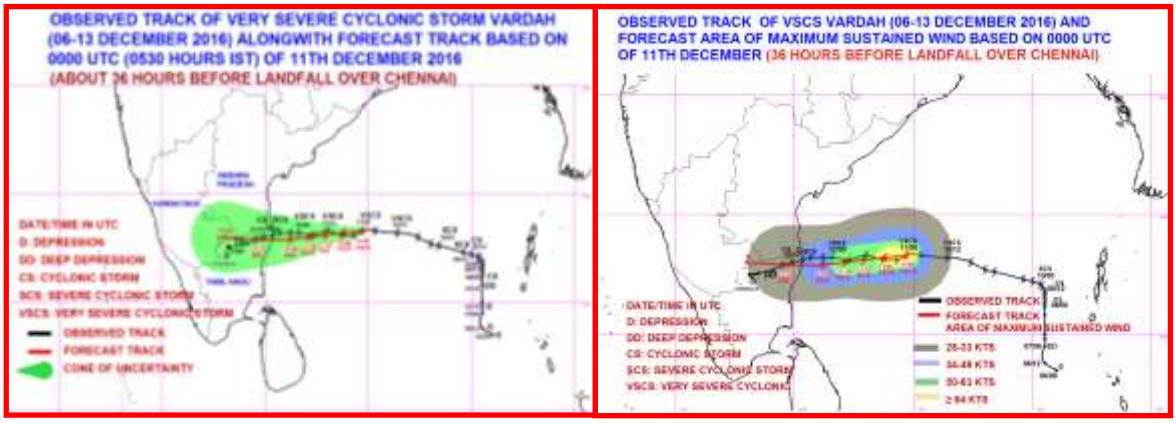


Fig.17: Observed track of VSCS Vardah (06-13 Dec, 2016) and forecast track based on 0000 UTC of 11th Dec alongwith (a) Cone of uncertainty and (b) Quadrant wind distribution

10.3 Operational track forecast error and skill

The operational average track forecast errors and skills (compared to climatological and persistence (CLIPER) forecasts) are shown in Table 13. The track forecast errors for 24, 48 and 72 hours lead period have been 94, 141 and 197 km against the long period average (LPA) of 98, 146 and 183 km respectively. The track forecast errors were less than the LPA for all 24 & 48 hours lead periods despite the fact that Vardah followed a recurving track. For 72 hours lead period, it was slightly more than LPA. However, the skill in operational track forecast compared to CLIPER forecast has been higher than long period average for all lead periods.

Table 13: Average Track forecast error in association with VSCS VARDAH

Lead Period (hrs)	N	Average track forecast error (km)	Skill (%)	LPA (2011-15)	
				Track forecast error (km)	Skill (%)
12	20	48.6	56.0	59.1	41.4
24	18	94.4	61.4	97.5	48.5
36	16	117.7	70.1	120.0	58.1
48	14	140.6	74.6	145.5	62.7

60	12	172.7	75.6	160.4	67.8
72	10	196.8	76.1	183.2	69.3
84	08	233.4	71.7	-	-
96	6	292.6	73.0	-	-
108	4	344.1	72.1	-	-
120	2	438.3	70.4	-	-

N: No. of observations verified, LPA: Long Period Average (2011-15)
LPA not available for 84-120 hr forecasts, as this forecast was introduced from 2013 only.

10.4 Operational Intensity forecast error and skill

The operational intensity forecast errors and skill compared to persistence forecast in terms of absolute error (AE) and root mean square error (RMSE) are presented in Table 14. The operational AE in intensity forecast has been significantly less than LPA as it was about 8.4, 10.5 and 12.1 knots against LPA of 11.5, 16.9 and 17.6 knots for 24, 48 and 72 hours lead period. Similarly, operational RMSE in intensity forecast has been about 10.5, 12.7 and 13.2 knots against LPA of 15.1, 22.1 and 22.5 knots for 24, 48 and 72 hours lead period respectively. The skill in intensity forecast with reference to AE is about 36%, 82% and 73% against the LPA of 36%, 56% and 67% respectively for 24, 48 and 72 hours lead period.

Table 14: Average Intensity forecast error in association with VSCS VARDAH

Lead Period (hrs)	N	Average Intensity Error (kts)		Skill (%) in intensity forecast		LPA Intensity forecast Error (kts) (2011-15)	
		AE	RMSE	AE	RMSE	AE	RMSE
12	20	4.9	6.0	7.6	44.0	7.1	9.5
24	18	8.4	10.5	20.7	39.0	11.5	15.1
36	16	9.1	10.8	35.1	52.6	14.8	19.6
48	14	10.5	12.7	41.1	60.1	16.9	22.1
60	12	10.6	13.2	42.1	59.7	17.7	22.6
72	10	12.1	13.2	36.5	54.2	17.6	22.5
84	08	12.7	15.0	38.6	49.0	-	-
96	6	12.6	14.4	54.3	47.7	-	-
108	4	9.5	13.1	82.3	78.7	-	-
120	2	5.0	5.0	93.9	94.3	-	-

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2011-15). LPA not available for 84-120 hr forecasts, as this forecast was introduced from 2013 only.

10.5. Adverse weather forecast verification

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Table 15-17. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table – 15(a) Verification of Heavy Rainfall Forecast

Date/Time (UTC)	Heavy rainfall warning issued	Realised 24-hour heavy rainfall ending at 0300 UTC of date
06.12.2016 0900	Heavy to very heavy falls at a few places over Andaman and Nicobar Islands during next 48 hrs.	**Andaman & Nicobar Islands** **07-10 Dec. 2016** Heavy to very heavy rainfall at a few places over Andaman and Nicobar Islands. Isolated extremely heavy rainfall on 8th Dec. **Tamil Nadu, South coastal Andhra Pradesh, Rayalaseema** **13.12.2016** Heavy rainfall at many places with very heavy falls at few places and isolated extremely heavy rainfall over Chennai, Kancheepuram, Tiruvallur, districts of Tamil Nadu. Isolated Heavy to very heavy rainfall at a few places over Villipuram, Vellore, Krishnagiri, Tiruvannamalai districts of Tamil Nadu, Nellore district of coastal Andhra Pradesh and Chittor, Anantapuram & Cuddapah districts of Rayalaseema. **14.12.2016** Isolated heavy rainfall over south coastal Andhra Pradesh
07.12.2016 0300	Heavy to very heavy falls at a few places over Andaman Islands and heavy rainfall at isolated places over Nicobar Islands during next 24 hrs. isolated heavy falls over Andaman and Nicobar Islands during subsequent 24 hours.	
08.12.2016 0300	Heavy to very heavy falls at a few places over Andaman Islands and heavy rainfall at isolated places over Nicobar Islands during next 24 hrs and isolated heavy falls over Andaman & Nicobar Islands during subsequent 24 hours. Isolated heavy falls over coastal Andhra Pradesh is very likely to commence from 11th December evening.	
09.12.2016 0300	Isolated heavy falls over coastal Andhra Pradesh is very likely to commence from 11th December evening.	
10.12.2016 0300	Isolated heavy to very heavy falls over south coastal Andhra Pradesh to commence from 11th December evening for subsequent 36 hrs.	
10.12.2016 1200	Isolated heavy to very heavy falls over south coastal Andhra Pradesh and adjoining areas of north coastal Tamil Nadu to commence from 11th December evening for subsequent 36 hrs.	
11.12.2016 0300	Isolated heavy to very heavy falls over south coastal Andhra Pradesh, north coastal Tamil Nadu and Puducherry to commence from 11th December evening for subsequent 36 hrs. The rainfall intensity will increase gradually becoming heavy to very heavy rainfall (7-19 cm) at a few places and isolated extremely heavy rainfall (≥ 20 cm) over Chennai, Thiruvallur and Kanchipuram districts of Tamil Nadu and Nellore and Prakasam districts of Andhra Pradesh on 12th December	
12.12.2016 0300	Do	
13.12.2016 0300	Isolated heavy falls over north interior Tamil Nadu and adjoining areas of south interior Karnataka & north Kerala during next 12 hrs.	

Based on the Table 15(a), the contingency table (Table 15 b) has been prepared and skill scores are calculated. The same are presented in Table 15 (c) for 24 and 48 hr forecasts.

Table 15 (b): Contingency Table for verification of 24 and 48 hr Heavy to Very Heavy Rainfall Forecast for VSCS Vardah

Heavy to very heavy rainfall							Extremely heavy rainfall					
Observed	24 hr forecast			48 hr forecast			24 hr forecast			48 hr forecast		
	Forecast		Total	Forecast		Total	Forecast		Total	Forecast		Total
	Yes	No		Yes	No		Yes	No		Yes	No	
Yes	3	1	**4**	2	3	**5**	1	0	1	1	0	1
No	0	4	**4**	0	6	**6**	1	6	7	1	9	10
Total	**3**	**5**	**8**	**2**	**9**	**11**	2	6	8	2	9	11

Table - 15(c): Skill scores for 24 and 48 hr heavy rainfall forecast

Skill Parameter	Heavy to Very Heavy Rainfall Forecast		Extremely Heavy Rainfall Forecast	
	24 hr forecast	48 hr forecast	24 hr forecast	48 hr forecast
Probability of detection (POD)	0.8	0.4	1.0	1.0
False alarm rate (FAR)	0.0	0.0	0.5	0.5
Missing rate (MR)	0.3	0.6	0.0	0.0
Correct non-occurrence (C-NON)	1.0	1.0	0.9	0.9
Critical success index (CSI)	0.8	0.4	0.5	0.5
Bias for occurrence	0.8	0.4	2.0	2.0
Percentage correct (PC)	87.5	72.7	87.5	90.9
True Skill Score	0.8	0.4	0.9	0.9
Heidke skill score (HSS)	0.8	0.4	0.6	0.6

From table 15 (c), it is seen that probability of detection (POD) of heavy rainfall during life cycle of VSCS Vardah was 0.8 and 0.4 respectively for 24 and 48 hours lead period respectively with false alarm (FAR) of 0.0 and 0.0. The Percentage Correct (PC) was about 87.5% and 72.7 % respectively for 24 and 48 hours lead period. For extremely heavy rainfall forecast, the POD was 1.0 and 1.0 respectively for 24 and 48 hours lead period respectively with FAR of 0.5 and 0.5. The PC was about 87.5% and 90.9 % respectively for 24 and 48 hours lead period.

Table 16. Verification of Gale Wind Forecast

Date/ Time(UTC)	Gale wind Forecast	Recorded wind speed
06.12.2016 0900	Squally winds speed reaching 40-50 kmph gusting to 60 kmph over Andaman & Nicobar Islands and adjoining sea areas during next 48 hrs.	Andaman & Nicobar Islands: 50-60 kmph on 8th. Wind observations on 12th December: Chennai High wind speed recorder: 57.7 kts (107 kmph) (0800 UTC),
07.12.2016 0300	Do	
08.12.2016 0300	Squally winds speed reaching 45-55 kmph gusting to 65 kmph over Andaman Islands & adjoining sea areas during next 24 hrs and Nicobar Islands & adjoining sea areas during next 12 hrs.	

	Squally winds speed reaching 40-50 kmph gusting to 60 kmph would prevail along and off Andhra Pradesh coast commencing from 11th December night.	Dynes Pressure Tube Anemograph, Chennai: 114 kmph ISRO, Sriharikota: 99 kmph (0900 UTC), Chennai NBK Barograph recorded 61 kts (114 kmph) (0710 UTC), Chennai MBK recorded 65 kts (122 kmph) (0815-0820 UTC).
09.12.2016 0300	Squally winds speed reaching 35-45 kmph gusting to 55 kmph over Andaman and Nicobar Islands & adjoining sea areas during next 12 hrs and gradually decrease thereafter. Squally winds speed reaching 40-50 kmph gusting to 60 kmph along and off Andhra Pradesh coast commencing from 11th December night.	
10.12.2016 0300	Squally winds speed reaching 40-50 kmph gusting to 60 kmph along and off Andhra Pradesh and adjoining north Tamil Nadu coasts commencing from 11th December night.	
11.12.2016 0000 (36 hours in advance)	Squally winds speed reaching 40-50 kmph gusting to 60 kmph along and off Andhra Pradesh and adjoining north Tamil Nadu coasts commencing from 11th December night. It will gradually increase becoming 80-90 kmph gusting to 100 kmph during the time of landfall along and off Chennai, Thiruvallur and Kanchipuram districts of Tamil Nadu, Puducherry and Nellore and Prakasam districts of Andhra Pradesh.	
12.12.2016 0300	Gale winds speed reaching 100-110 kmph gusting to 120 kmph during next 12 hours along & off Chennai, Thiruvallur and Kanchipuram districts of Tamil Nadu and Nellore and Prakasam districts of Andhra Pradesh. Squally wind speed reaching 50-60 kmph gusting to 70 kmph along and off remaining districts of north Tamilnadu & Puducherry and south Andhra Pradesh coasts during the same period.	

Table 17. Verification of Storm Surge Forecast issued by IMD

Date/ Time(UTC)	**Storm Surge Forecast**	**Recorded storm surge**
11.12.2016 0000 UTC (36 hours in advance)	Tidal wave of about one meter height above the astronomical tide to inundate low lying areas of Chennai, Thiruvallur and Kanchipuram districts of Tamil Nadu and Nellore districts of Andhra Pradesh during the time of landfall.	Storm Surge of height 1m above the astronomical tide occurred near Pulicat lake at 1200 hours IST of 12th December. The astronomical tide at that time was 0.47 m and hence the total tidal wave was 1.47 m.
12.12.2016 0300 UTC	Tidal wave of about one meter height above the astronomical tide to inundate low lying areas of Chennai, Thiruvallur and Kanchipuram districts of Tamil Nadu and Nellore districts of Andhra Pradesh during the time of landfall.	

11. Bulletins issued by IMD

11.1 Bulletins issued by Cyclone Warning Division, New Delhi

Bulletins issued by Cyclone Warning Division, New Delhi

- **Track, intensity and landfall forecast:** IMD continuously monitored, predicted and issued bulletins containing track, intensity, and landfall forecast upto120 hrs or till the system weakened into a low pressure area. The above forecasts were issued from the stage of deep depression onwards along with the cone of uncertainty in the track forecast.
- **Cyclone structure forecast for shipping and coastal hazard management** The radius of maximum wind and radii of MSW ≥28 knots, ≥34 knots, ≥50 knots and ≥64 knots wind in four quadrants of cyclone was issued every six hourly giving forecast for +06, +12, +18, +24, +36, +48, +60, +72, +84 and +120 hrs lead period.
- **Diagnostic and prognostic features of cyclone:** The prognostics and diagnostics of the systems were described in the RSMC bulletins and tropical cyclone advisory bulletins.
- **TC Vital:** Tropical cyclone vitals were prepared every six hourly from deep depression stage onwards and provided to various NWP modeling groups in India for generation/relocation of vortex in the model so as to improve the track and intensity forecast by the numerical models.
- **Tropical cyclone forecasts and adverse weather warning bulletins:** The tropical cyclone forecasts alongwith expected adverse weather like heavy rain, gale wind and storm surge were issued with every three hourly update during cyclone period to the central, state and district level disaster management agencies including MHA NDRF, NDMA, Andhra Pradesh, Tamil Nadu, Puducherry and Andaman & Nicobar Islands. The bulletin also contained the expected damage and suggested action by disaster managers and general public. These bulletins were also issued to Railways, surface transport, Defence including Indian Navy & Indian Air Force, Ministry of Agriculture, Ministry of Information and Broadcasting etc.
- **Warning graphics:** The graphical display of the observed and forecast track with cone of uncertainty and the wind forecast for different quadrants were disseminated by email and uploaded in the RSMC, New Delhi website (http://rsmcnewdelhi.imd.gov.in/) regularly. Typical graphical products displaying track with cone of uncertainty and wind distribution forecast are presented in Fig 3.
- **Hourly update:** On the day of landfall, hourly updates of cyclone position, landfall point & time and associated MSW at the time of landfall was issued by email and SMS to disaster managers, press and electronic media and registered general public.
- **Warning and advisory through social media:** Daily updates were uploaded on facebook and tweeter regularly during the life period of the system.

- **Press release and press briefing:** Press and electronic media were given daily updates since inception of system and hourly updates on the day of landfall through press release, e-mail, website and SMS.
- **Warning and advisory for marine community:** The three/six hourly bulletins were issued by the cyclone warning division at New Delhi and cyclone warning centres of IMD at Chennai, Kolkata, Visakhapatnam and Bhubaneswar to ports, fishermen, coastal and high sea shipping community
- **Advisory for international civil aviation :** The Tropical Cyclone Advisory Centre (TCAC) bulletin for international civil aviation were issued every six hourly to all meteorological watch offices in Asia Pacific region for issue of significant meteorological information (SIGMET). It was also sent to Aviation Disaster Risk Reduction (ADRR) centre of WMO at Hong Kong.

Bulletins issued by Cyclone Warning services of IMD in association with the system are given in Table 18 (a-b).

Table 18 (a): Bulletins issued by Cyclone Warning Division, India Meteorological Department

S.N.	Bulletin	No. of Bulletins	Issued to
1	National Bulletin	49	1. IMD's website 2. FAX and e-mail to Control Room NDM, Cabinet Secretariat, Minister of Sc. & Tech, Secretary MoES, DST, HQ Integrated Defence Staff, DG Doordarshan, All India Radio, DG-NDRF, Director Indian Railways, Indian Navy, IAF, Chief Secretary- Andaman & Nicobar Islands, Andhra Pradesh, Tamil Nadu, West Bengal, Odisha, Telengana, Puducherry, Karnataka.
2	Hourly updates on the day of landfall	10	Hourly updates were issued from 0830 IST to 1730 IST till the landfall of cyclone for disaster managers, media and general public by email.
3	Bulletin from DGM, IMD	6	From 8th (intensification to cyclone) to 13th December (weakening into a well marked low pressure area) by email to disaster managers and senior government officers.
4	Press Release	6	From 8th -13th December based on 0830 hours IST observations by email to disaster managers, senior government officers, chief secretaries of Andaman & Nicobar Islands, Andhra Pradesh, Tamil Nadu, West Bengal, Odisha, Telengana, Puducherry, Karnataka, media by email. Put up on website: www.rsmcnewdelhi.imd.gov.in, www.imd.gov.in
5	RSMC Bulletin for WMO/ ESCAP Panel	45	1. IMD's website 2. All WMO/ESCAP member countries through GTS and E-mail.

	countries		3. Indian Navy, IAF by E-mail
6	Tropical Cyclone Advisory Centre Bulletin (Text & Graphics)	20	1. Met Watch offices in Asia Pacific regions though GTS to issue Significant Meteorological information for International Civil Aviation 2. WMO's Aviation Disaster Risk Reduction (ADRR), Hong Kong through ftp 3. RSMC website
7	Tropical Cyclone Vital Statistics (Coded and Textual)	20	Modelling group of IMD, National Centre for Medium Range Weather Forecasting Centre (NCMRWF), Indian National Centre for Ocean Information Services (INCOIS), Indian Institute of Technology (IIT) Delhi, IIT Bhubaneswar etc.
8	Cyclone Warnings through SMS	1,48,211 by IMD	SMS through (i) IMD network for disaster managers (1023) since inception to weakening of cyclone and (ii) IMD's public registration using Department of Electronics and Information Technology network (1,47,188) :(2-3 times a day whenever there was significant change in intensity/track/landfall point) and hourly on the day of landfall.(ii) INCOIS: 64,710 and (iii) Kisan Portal: 4,05,939
9	Cyclone Warnings through Social Media	Once daily	Cyclone Warnings were uploaded on Social networking sites like Face book and Tweeter since inception to weakening of system

Table-18 (b): Bulletins issued by ACWC Chennai/ACWC Kolkata/CWC Bhubaneswar (BBN)/ CWC Visakhapatnam (VZK)

S.No.	Type of Bulletin Number	No. of Bulletins issued by			
		ACWC Chennai	ACWC Kolkata	CWC BBN	CWC VZK
1.	Sea Area Bulletins	14	36	-	-
2.	Coastal Weather Bulletins	10	WB Coast- 16 A & N Coast- 16	14	24
3.	Fishermen Warnings issued	20	WB Coast- Nil A & N Coast- 23	24	26
4.	Port Warnings	10	WB Coast- 9 A & N Coast- 27	22	16
5.	Heavy Rainfall Warning	7	A & N Ids- 3	10	NIL
6.	Gale Wind Warning	NIL	NIL.	08	NIL
7.	Information & Warning issued to State Government and other Agencies	7	Govt. of WB- 8 Govt. of A & N-5	23	4
8.	SMS	24	NIL	1600	320

12. Summary and Conclusion:

The VSCS Roanu formed from a low pressure area over south Andaman Sea and adjoining Sumatra on 4th December and concentrated into a depression in the afternoon of 6th. The system gradually intensified into a CS at 0000 UTC of 8th, an SCS at 1800 UTC of 9th and VSCS at 1200 UTC of 10th. The system had anticlockwise recurvature and crossed north Tamil Nadu cosat close to Chennai during 0930-1130 UTC of 12th.

IMD utilised all its resources to monitor and predict the genesis, track and intensification of VSCS Vardah. The forecast of its genesis (formation of Depression) on 6th December, its track, intensity, point & time of landfall, were predicted well with sufficient lead time. For 24, 48 and 72 hrs lead period, the operational landfall point error was 11, 154 & 264 km; track forecast error was 94, 141 & 197 km and intensity forecast error based on absolute error was 8, 11 & 12 kts. Adverse weather was also accurately predicted for Andaman & Nicobar Islands during genesis stage and for north Tamil and south Andhra Pradesh coasts during landfall time.

14. Acknowledgements:

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