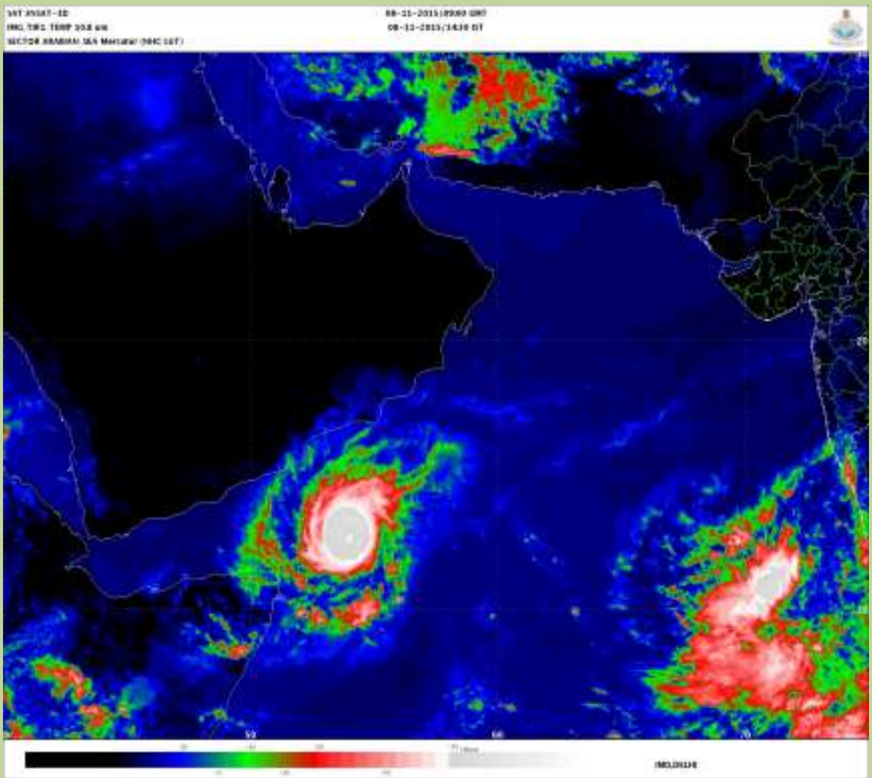
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
EARTH SYSTEM SCIENCE ORGANISATION
INDIA METEOROLOGICAL DEPARTMENT

Extremely Severe Cyclonic Storm,'Megh' over the Arabian Sea (05-10 November 2015): A Report



INSAT-3D enhanced colored imagery based on 0900 UTC of 8th November

Cyclone Warning Division

India Meteorological Department

New Delhi

DECEMBER 2015

Extremely Severe Cyclonic Storm, 'Megh' over the Arabian Sea (05-10 November 2015)

1. Introduction

A depression formed over the eastcentral Arabian Sea (AS) at 0000 UTC of 5th November from a low level circulation over Lakshadweep and neighbourhood. It moved westwards/west-southwestwards and intensified into a cyclonic storm (CS) at 1200 UTC of 5th November. It continued its west-southwestward movement and intensified into a severe cyclonic storm (SCS) at 0600 UTC of 7th, into a very severe cyclonic storm (VSCS) at 1500 UTC of 7th and rapidly intensified into an extremely severe cyclonic storm (ESCS) at 0300 UTC of 8th. Maintaining its peak intensity for a short period of about 6 hrs, it weakened gradually into a VSCS at 0000 UTC of 9th. From 0600 UTC of 9th, it exhibited west-northwestward movement, weakened rapidly into an SCS at 2100 UTC of 9th, into a CS at 0300 UTC of 10th and deep depression (DD) at 0600 UTC of 10th. It recurved northeastwards from 0300 UTC of 10th and crossed Yemen coast near latitude 13.4°N and longitude 46.1°E around 0900 UTC 10th as a DD. Continuing its northeastwards movement, it weakened into a depression at 1500 UTC of 10th and into a well marked low pressure area over Yemen and neighborhood at 1800 UTC of 10th.

The salient features of the system are as follows.

i. ESCS Megh occurred just after a week of formation of ESCS, Chapala over Arabian Sea. Also, ESCS Megh has been the first back to back cyclone after Chapala that reached Gulf of Aden and crossed Yemen within a week.
ii. ESCS Megh was the second ESCS after Chapala crossing Yemen coast in the satellite era. Chapala crossed Yemen coast close to the southwest of Riyan near 14.1^{0}N/48.65^{0}E during 0100-0200 UTC as a VSCS (with maximum sustained wind speed (MSW) of 65 knots) and Megh crossed Yemen coast near 13.4°N/46.1°E around 0900 UTC as a DD (with MSW of 30 knots).
iii. Unlike Chapala, ESCS Megh was a small core system with a pin hole eye.
iv. Megh maintained the intensity of ESCS for 18 hours (0803-0821) unlike Chapala which maintained the intensity of ESCS for 78 hours (3003-0209). The peak intensity in Megh was 95 knots for a period of 3 hours (0806-0809) against 115 knots for a period of 15 hours (3009-3100) in case of Chapala.
v. Lowest estimated central pressure (ECP) was 964 hPa with a pressure drop of 44 hPa unlike Chapala where it was 940 hPa with a pressure drop of 66 hPa.
vi. Like Chapala, ESCS Megh also experienced rapid intensification on 0000 UTC of 7th when its MSW increased from 45 knots to 85 knots at 0000 UTC of 8th (rise in wind speed 40 knots in 24 hours). During same period the ECP fell from 994 hPa to 974 hPa (20 hPa fall in 24 hours).
vii. ESCS Megh experienced rapid weakening over Gulf of Aden from 1800 UTC of 9th (MSW 65 knots) to 0600 UTC of 10th (MSW 35 knots), i.e. Megh experienced a fall in MSW by 30 knots in 12 hours.

viii. The ESCS Megh moved west to west-southwestwards throughout its life period till landfall over Yemen. While, ESCS Chapala moved initially north-northwestwards and then west-southwestwards to Yemen.

ix. Both ESCS Chapala and Megh could intensify upto the stage of ESCS under favourable environmental conditions, mainly low vertical wind shear (5-10 knots) around the system centre and the forward sector of the storm.

x. The system had the longest track length after VSCS Phet in 2010, as it travelled a distance of about 2307 km during its life period.

xi. The Accumulated Cyclone Energy (ACE) was about 8.2×10^4 $knot^2$ which is also the maximum after VSCS Phet in 2010 and ESCS Chapala in 2015 over the Arabian Sea.

xii. The Power Dissipation Index was 6.07×10^6 $knot^3$ which is the maximum after VSCS Phet in 2010 and ESCS Chapala in 2015 over the Arabian Sea.

xiii. The ESCS Megh had a life period of 5.7 days against long period average of 4.7 days in post-monsoon season for VSCS/ESCS over Arabian Sea)

xiv. The westward movement of the cyclone away from the Indian coasts was predicted from the first bulletin itself i.e. on 5th November 2015 (0300 UTC). Every three hourly Tropical Cyclone Advisories were issued to WMO/ESCAP member countries, Yemen and Somalia.

xv. The numerical weather prediction (NWP) and dynamical statistical models provided reasonable guidance with respect to its genesis and track. However, most of the NWP and dynamical statistical models except HWRF could not predict the landfall and rapid intensification/ weakening of ESCS Megh.

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 ESCS,'Megh'

The cyclone was monitored & predicted continuously since its inception by IMD. The forecast of its genesis on 5th November, its track, intensity, landfall over Yemen were predicted with sufficient lead time. The observed track of the cyclone over AS during 5th - 10th November is presented in fig.1.

At the genesis stage, the system was monitored mainly with satellite observations. Various national and international NWP models and dynamical-statistical models including IMD's and NCMRWF's global and meso-scale models, dynamical statistical models for genesis and intensity 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.

3. Brief life history

3.1. Genesis

An upper air cyclonic circulation in lower levels lay over southeast AS and adjoining Lakshadweep area on 1st November. It moved west-nothwestwards and lay over eastcentral AS on 2nd. It persisted over the same region on 3rd and extended upto mid-tropospheric levels. Under its influence, a low pressure area formed over eastcentral AS on 4th. On 0000 UTC of 5th, the winds were higher over the northeastern sector. The sea surface temperature (SST) was 29^{0}C and the ocean thermal energy (OTE) was about 60-80 KJ/cm^{2} around system centre. The vertical wind shear was about 5-10 knots (low) around the system centre. The low level relative vorticity was 50 KJ/cm^{2}. Lower level convergence was $5X10^{-5}s^{-1}$ and upper level divergence was $10X10^{-5}s^{-1}$. Vorticity at 850 hPa was 50 $X10^{-5}s^{-1}$. The low level relative vorticity and convergence had increased during previous 12 hrs. The upper tropospheric ridge at 200 hpa level ran along 16^{0}N. There was favourable poleward and westward outflow in association with the anti-cyclonic circulation lying to the northeast of the system centre alongwith this ridge. All these conditions led to intensification of the low pressure area into a depression at 0000 UTC of 5th. Considering the large scale features, the Madden Jullian Oscillation Index was in phase -2 over west-equatorial Indian Ocean with amplitude greater than 2. The Indian Ocean Dipole was positive, indicating higher warming over west equatorial Iindian Ocean, which helped in maintaining the warmer SST over AS even after passage of ESCS Chapala.

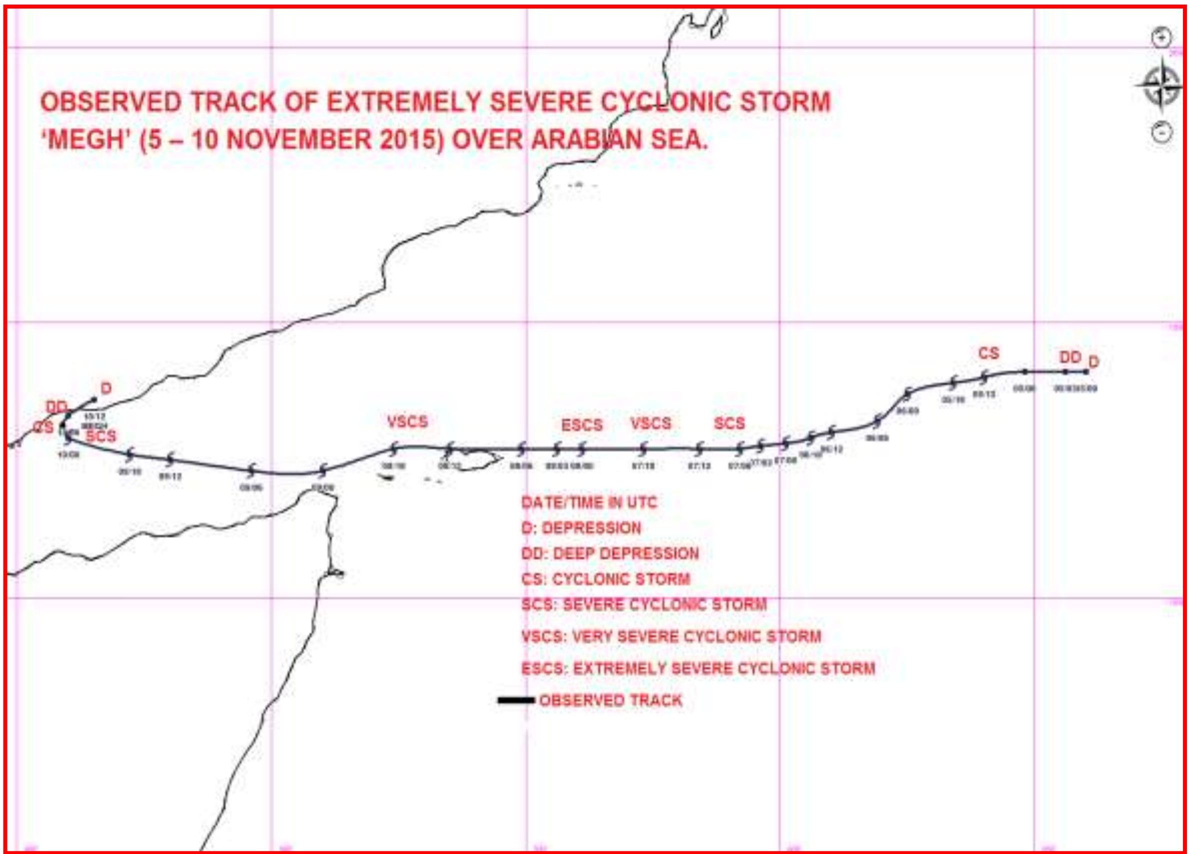


Fig.1 Observed track of ESCS,'Megh' over AS during 5th-10th November 2015

3.2 Intensification

Similar environmental conditions prevailed and the system intensified into a CS at 1200 UTC of 5th. Due to favourable large scale environmental features like MJO Index and weak vertical wind shear, the system experienced rapid intensification from 0300 UTC of 7th when its maximum sustained wind speed increased from 45 knots to 90 knots at 0300 UTC of 8th (rise in wind speed by 45 knots in 24 hours). During same period the ECP fell from 994 hPa to 968 (fall of 26 hPa in 24 hours). On 0300 UTC of 7th, the low level relative vorticity was 150 x 10^{-5} sec-1, convergence was 5-10 x 10^{-5} sec-1, and divergence was 30 x 10^{-5} sec-1. The SST around the system centre was 29°C. The OTE was about 35-50 KJ/cm^2 around system centre and 50-75 KJ/cm2 to west-southwest of the system centre The vertical wind shear was about 10 knots (low) around the system centre during the period of rapid intensification. The system reached its peak intensity (95 kt) at 0600 UTC of 8th.

The system started weakening from 1200 UTC of 8th. At 1200 UTC, the low level relative vorticity was 150 x 10^{-5} sec^{-1} and convergence was 20 x 10-5 sec-1. The upper level divergence decreased and was about 10 x 10^{-5} sec^{-1}. The SST around the system centre was 28°C. The OTE was 40-50 KJ/cm^2 around the system centre and then showed decreasing trends towards Gulf of Aden. The vertical wind shear was about 10 knots around the system centre. The low vertical wind shear was mitigating the adverse impact of cold and dry air intrusion from northwest. However, the system started weakening as it passed very close to Gulf of Aden around 0600 UTC of 8th and suffered land interaction. Also, it moved over an area with lower OTE over Gulf of Aden. Enhanced rapid weakening was observed from 1800 UTC of 9th due to land interaction with rugged terrain of Yemen, lower OTE over Gulf of Aden and dry air incursion. The system started weakening from 1200 UTC of 8th, the rate of weakening was slow till 1800 UTC of 9th. During this period the system passed close to the northern border of Socotra Island, moved into colder Gulf of Aden and the track was close to northern tip of Somalia, but the low vertical wind shear inhibited the adverse effect of cold and dry air from northwest in weakening the wall cloud region. It indicates that the internal dynamics played a significant role in maintaining intensity of the system apart from the external dynamics including environmental conditions. From 2100 UTC of 9th, the system exhibited rapid weakening as it lay over western part of Gulf of Aden and had interaction with rugged terrain of Yemen. It rapidly weakened from 65 kts at 1800 UTC of 9th to 30 kts at 0600 UTC of 10th just before landfall. The best track parameters of the systems are presented in Table 1**.** The total precipitable water imageries (TPW) during 5th to 10th November are presented in fig.2 to show the role of TPW on intensification and weakening. The vertical wind shear during the life period of the system is shown in fig.3 to illustrate its impact on intensification and weakening.

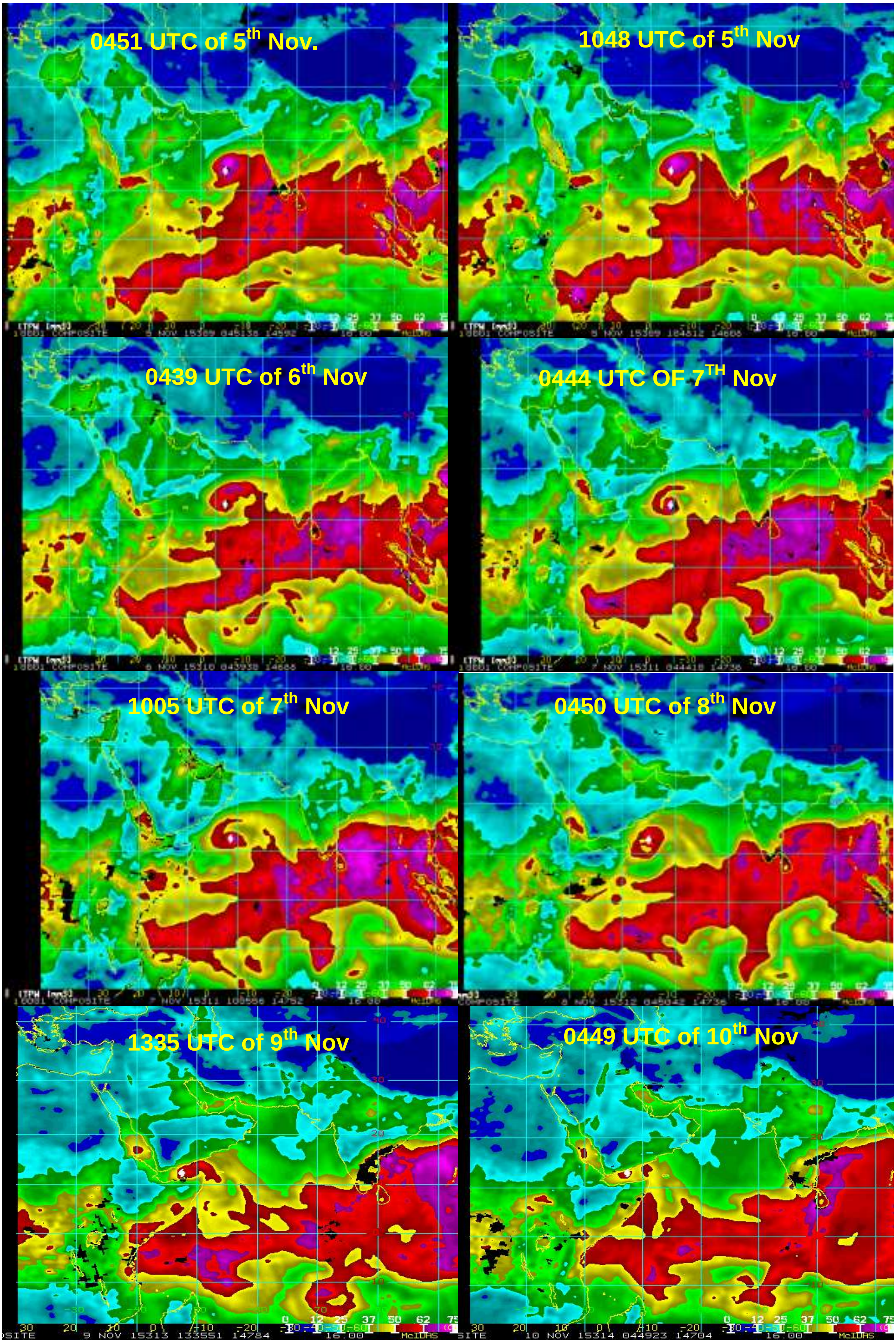


Fig.2 Total precipitable water imageries during 5th to 10th November 2015

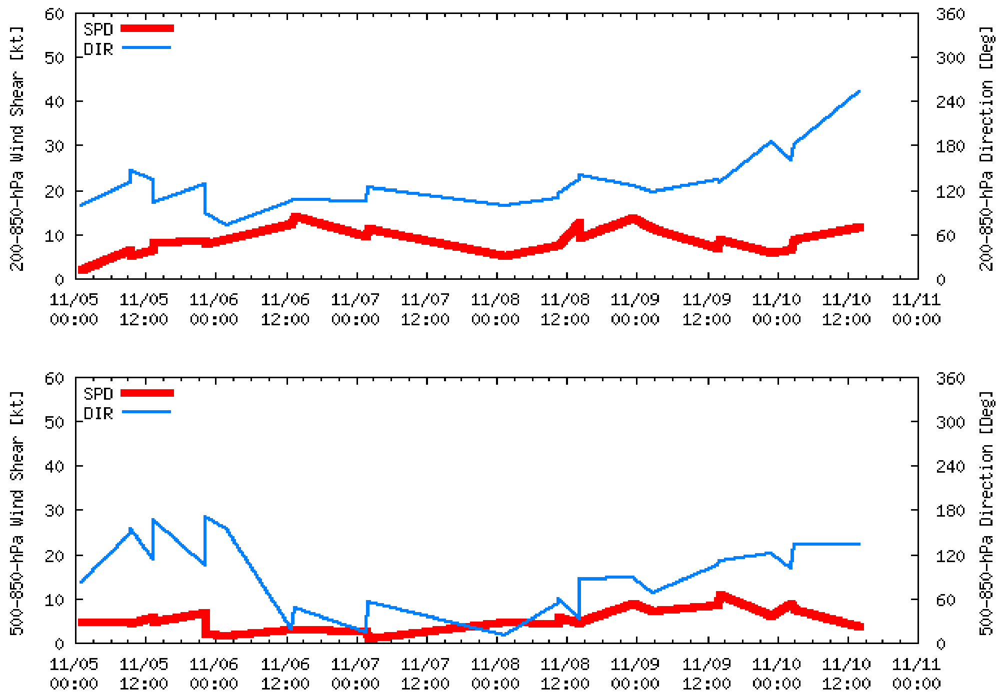


Fig.3 Wind shear and wind speed in the middle and deep layer around the system during 05th to 10th Nov 2015.

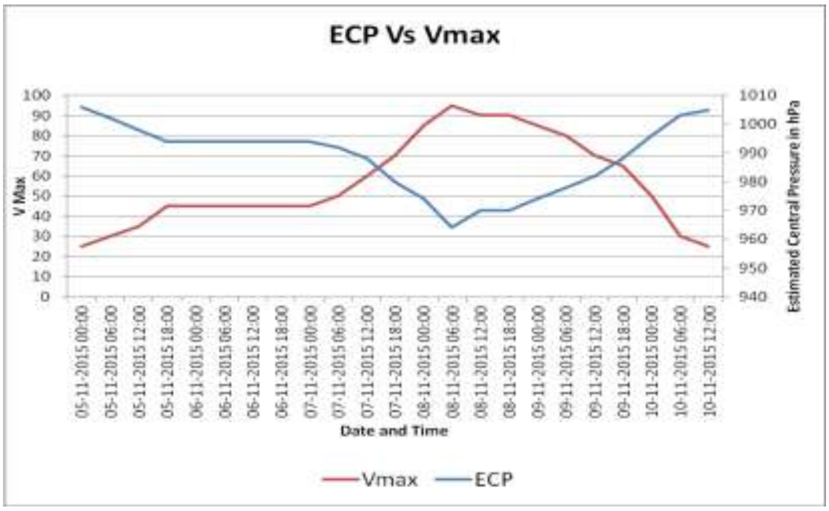


Fig.4 Lowest estimated central pressure and the maximum sustained wind speed

3.3. MSW and estimated central pressure (ECP)

The lowest ECP and the MSW speed during the life cycle of ESCS Megh are presented in fig.4. The lowest ECP has been 964 hPa. The highest MSW speed was 95 knots during 0600 - 0900 UTC of 8th November. At the time of landfall, the ECP was 1003 hPa and MSW was 30 knots (deep depression) due to weakening of the system over Gulf of Aden. The figure also indicates that rapid intensification of the system commenced from 0300 UTC of 7th and continued upto 0600 UTC of 8th. It is mainly attributed to low vertical wind shear (05-10 kts) around the system centre and the forward sector of the system accompanied with favourable upper level divergence due to radial outflow. Also the large scale features like IOD and MJO were favouring amplification of the convection.

3.4. Translational Speed and direction of movement

The six hourly translational speed and direction of movement of ESCS is presented in fig.5(a).

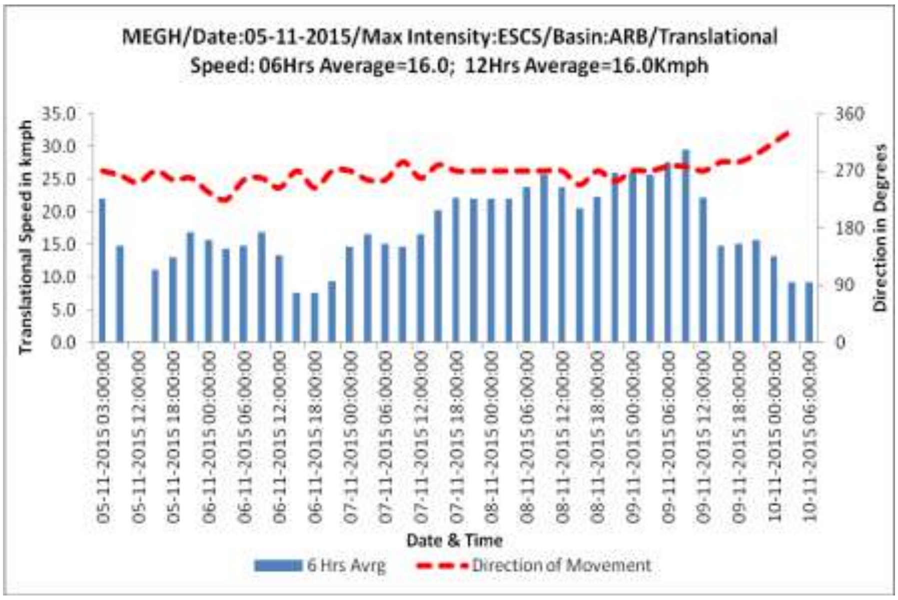


Fig.5(a).Six hours average translational speed and direction of movement in association with ESCS Megh

The average translational speed of the system during entire life cycle was 16 kmph. However, on 8th and 9th November it moved with an average translational speed of 22.0 kmph and reached maximum of 29.6 kmph at 1200 UTC of 9th. It the decreased sharply till 1500 UTC of 9th (14.8 kmph). It moved slowly till 0000 UTC of 10th and then decreased sharply.

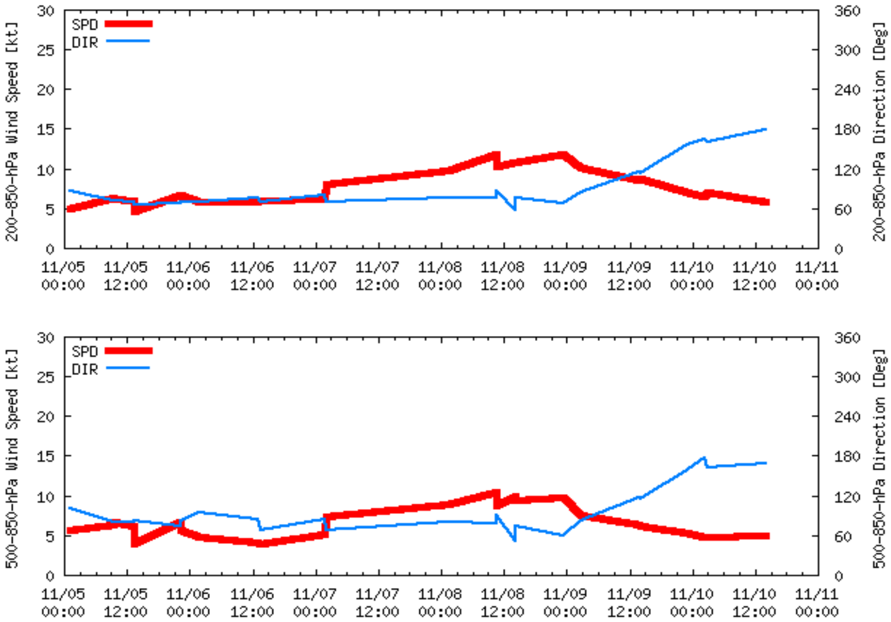


Fig.5(b).Wind speed and direction in the middle and deep layer around the system during 05th to 10th Nov 2015.

ESCS Megh moved west to west-southwestwards till 10th November, then recurved northeastwards and crossed Yemen coast. The upper tropospheric ridge was running along 16.0^{0}N in association with anti-cyclonic circulation lying to the northeast of the system centre. Under its influence, the system moved west/west-southwestwards till 0900 UTC of 9th November. Thereafter, the system started recurving northwards as the anticyclonic circulation moved northeastwards gradually from 9th with the ridge extending southwestwards towards northern tip of Somalia adjacent to Gulf of Aden on 0600 UTC of 10th leading to northeastwards recurvature. Continuing its northeastwards movement, the system crossed Yemen coast near lat. 13.4^{0}N/long.46.1^{0}E. To examine the steering flow, the mean wind speed and direction in middle and deep layer around the cyclone field is shown in Fig.5 (b). It indicates that the ESCS Megh was steered by middle to upper tropospheric winds.

The system had the longest track length after VSCS Phet in 2010 as it travelled a distance of about 2307 km during its life period (Chapala-2250 km).

To summarise, the genesis and intensification of the system just after the passage of ESCS Chapala, can be attributed to the favourable environmental conditions like vertical wind shear and large scale features like IOD and MJO.

Table1: Best track positions and other parameters of Extremely Severe Cyclonic Storm (ESCS) 'MEGH' over the Arabian Sea during 05-10 November, 2015

Date	Time (UTC)	Centre lat.° N/ long. ° E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
05-11-2015	0000	14.1/66.0	1.5	1006	25	3	**D**
	0300	14.1/65.6	1.5	1004	25	4	D
	0600	14.1/64.8	2.0	1002	30	5	**DD**
	1200	14.0/64.0	2.5	998	35	7	**CS**
	1500	13.9/63.7	2.5	996	40	8	CS
	1800	13.9/63.4	3.0	994	45	10	CS
	2100	13.8/63.0	3.0	994	45	10	CS
06-11-2015	0000	13.7/62.5	3.0	994	45	10	CS
	0300	13.5/62.2	3.0	994	45	10	CS
	0600	13.2/61.9	3.0	994	45	10	CS
	0900	13.1/61.5	3.0	994	45	10	CS
	1200	13.0/61.0	3.0	994	45	10	CS
	1500	12.9/60.8	3.0	994	45	10	CS
	1800	12.9/60.6	3.0	994	45	10	CS
	2100	12.8/60.4	3.0	994	45	10	CS
07-11-2015	0000	12.8/60.1	3.0	994	45	10	CS
	0300	12.8/59.6	3.0	994	45	10	CS

	0600	12.7/59.2	3.0	992	50	12	**SCS**
	0900	12.6/58.8	3.5	990	55	16	SCS
	1200	12.7/58.4	3.5	988	60	18	SCS
	1500	12.6/57.9	4.0	984	65	22	**VSCS**
	1800	12.7/57.3	4.0	980	70	26	VSCS
	2100	12.7/56.7	4.5	976	80	32	VSCS
08-11-2015	0000	12.7/56.1	4.5	974	85	36	VSCS
	0300	12.7/55.5	5.0	968	90	40	**ESCS**
	0600	12.7/54.9	5.0	964	95	44	ESCS
	0900	12.7/54.2	5.0	964	95	44	ESCS
	1200	12.7/53.5	5.0	970	90	40	ESCS
	1500	12.7/52.9	5.0	970	90	40	ESCS
	1800	12.5/52.4	5.0	970	90	40	ESCS
	2100	12.5/51.7	5.0	970	90	40	ESCS
09-11-2015	0000	12.3/51.0	4.5	974	85	36	**VSCS**
	0300	12.3/50.3	4.5	976	80	32	VSCS
	0600	12.3/49.6	4.5	978	80	30	VSCS
	0900	12.4/48.8	4.0	980	75	28	VSCS
	1200	12.5/48.0	4.0	982	70	26	VSCS
	1500	12.5/47.6	4.0	986	65	22	VSCS
	1800	12.6/47.2	4.0	988	65	20	VSCS
	2100	12.7/46.8	3.5	990	60	18	**SCS**
10-11-2015	0000	12.9/46.4	3.0	996	50	14	SCS
	0300	13.1/46.2	3.0	998	40	12	**CS**
	0600	13.3/46.1	2.0	1003	30	5	**DD**
	0900	**System crossed Yemen coast near Lat. 13.4°N/Long. 46.1°E around 0900 UTC**					
	1200	13.6/46.5	1.5	1005	25	3	**D**
	1800	**Weakened into a well marked low pressure area over Yemen and neighbourhood**					

D: Depression, DD: Deep Depression, CS: Cyclonic Storm, SCS: Severe Cyclonic Storm, VSCS: Very Severe Cyclonic Storm, ESCS: Extremely Severe Cyclonic Storm

4. Climatological aspects

Climatologically, the severe cyclonic storms crossing Yemen coasts are very rare. Prior to Megh and Chapala, one SCS (May 1960) crossed Yemen coast during 1891-2014. The track of the SCS crossing Yemen coast is shown in Fig.6.

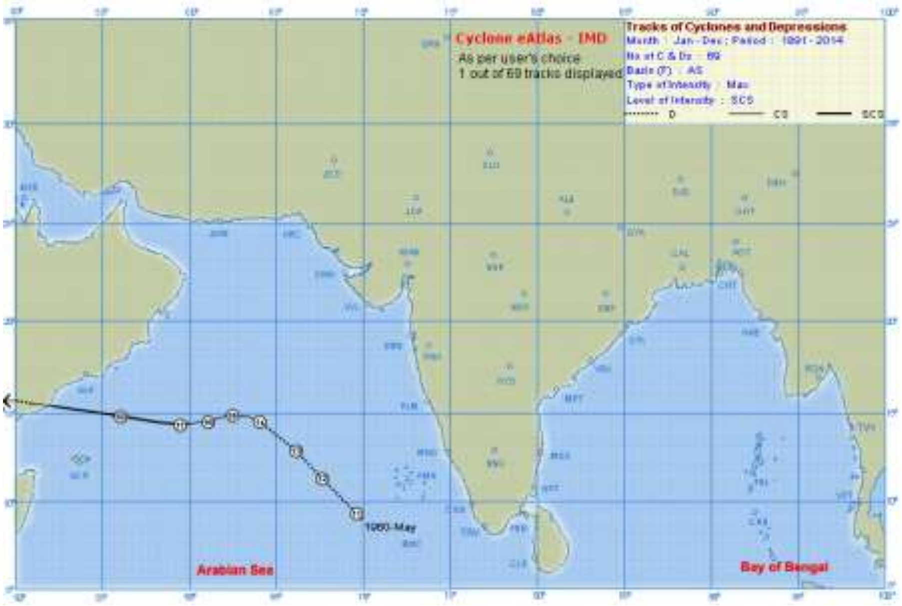


Fig. 6 Track of Severe cyclonic storm over Arabian Sea during the period 1891-2014 that crossed Yemen coast.

5. Features observed through satellite

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 and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered. Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness tempearture imageries are presented in fig.7-9.

5.1 INSAT-3D features

Intensity estimation using Dvorak's technique suggested that the system attained the intensity of T 1.5 on 0000 UTC of 5$^{th.}$ Associated broken low and medium clouds with embedded moderate to intense convection lay over AS between latitude 12.0^{0}N to 17.5^{0}N and longitude 63.0^{0}E to 69.5^{0}E. Lowest cloud top temperature (CTT) was -81^{0}C. The cloud pattern was curved band type. Convection wrapped 0.5 on log 10 spiral. At 0600 UTC of 5^{th,} the system intensified to T2.0. At 1200 UTC of 5th, the depth of convection increased, the lowest CTT was -83^{0}C and system intensified to T2.5. At 1800 UTC of 5th convection further organised and the system intensified to T3.0. Convection wrapped 0.6 on log10 spiral. The system maintained its intensity till 0300 UTC of 7th. At 0600 UTC of 7th, convection further organised and intensity was T3.0. Associated broken low and medium clouds with embedded intense to very intense convection lay over the area between latitude 10.5^{0}N to 15.0^{0}N and longitude 57.0^{0}E to 61.0^{0}E. Lowest CTT was -80°C. Ragged eye was seen. The system further intensified to T3.5 at 0900 UTC of 7th. The convection showed eye pattern. Ragged eye was seen in visible imagery. Lowest CTT in wall cloud region was -81°C. Area of convection extended between latitude 10.5^{0N} to 15.0^{0}N and longitude 56.5^{0}E to 60.5^{0}E. The system further intensified to T5.0 at 0300 UTC of 8th. Area of convection extended between latitude 11.0^{0}N to 14.5^{0}N and longitude

54.0^{0}E to 57.0^{0}E. Eye was seen in both visible and IR imageries. Lowest CTT in wall cloud region was -85°C. From 1200 UTC of 8th, the system started weakening. Lowest CTT in wall cloud region was -84°C. The clouds started disorganising. At 1430 UTC, the system lost its distinct eye feature in IR imagery. Thereafter the system underwent rapid weakening from 1800 UTC of 9th.

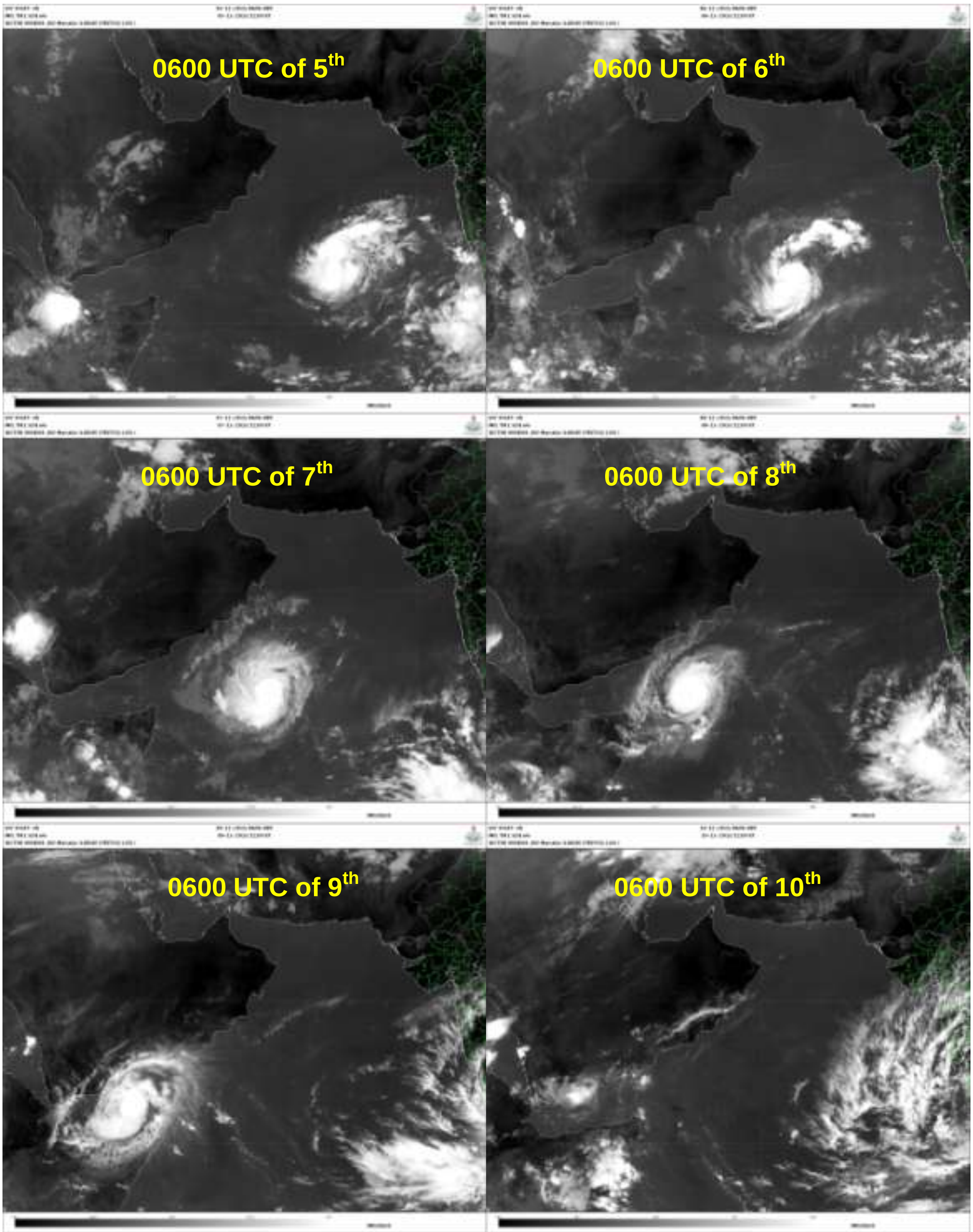


Fig. 7 INSAT-3D IR imageries based on 0600 UTC of 5th to 10th November 2015

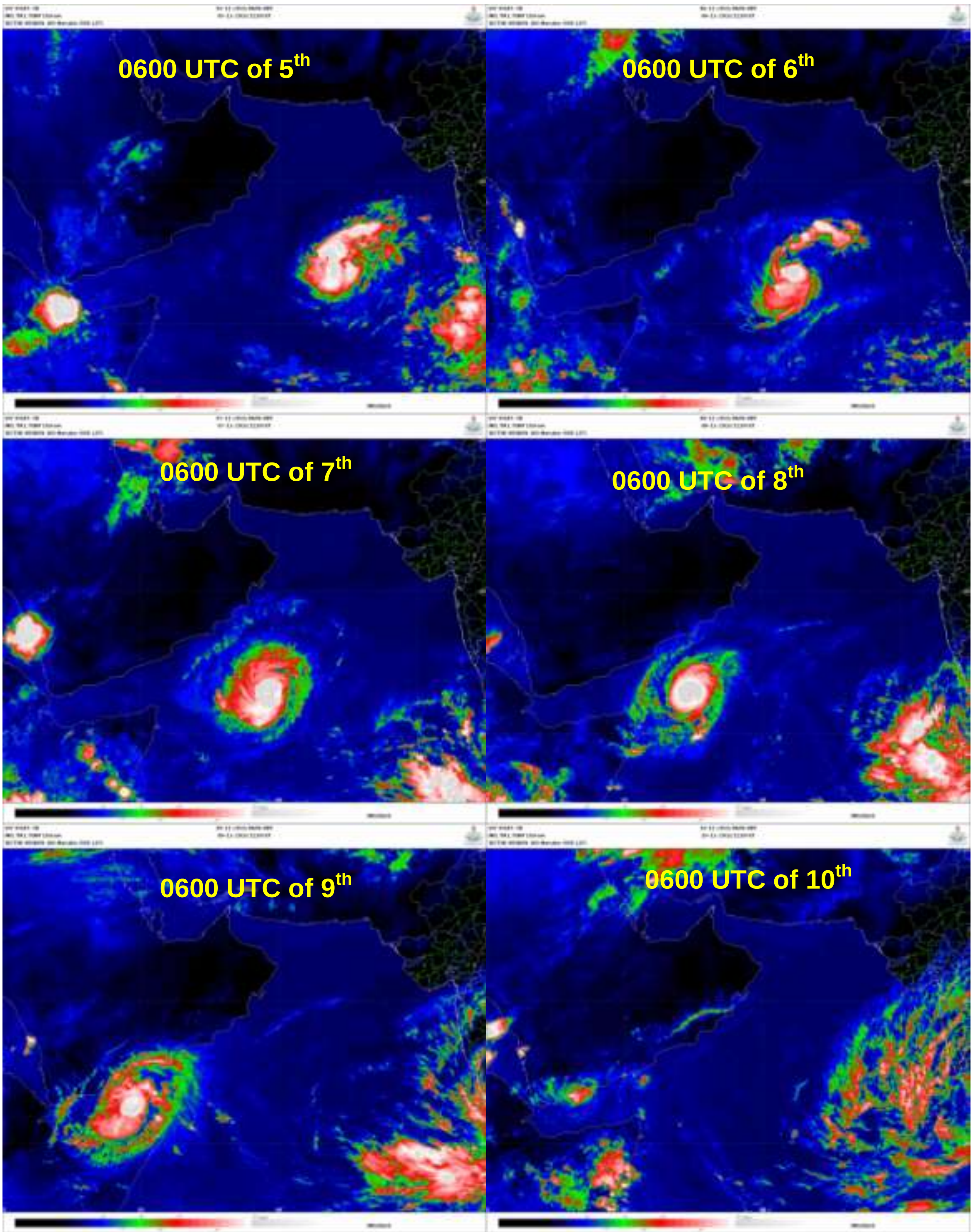


Fig.8 INSAT-3D enhanced colored imageries based on 0600 UTC of 5th to 10th November 2015

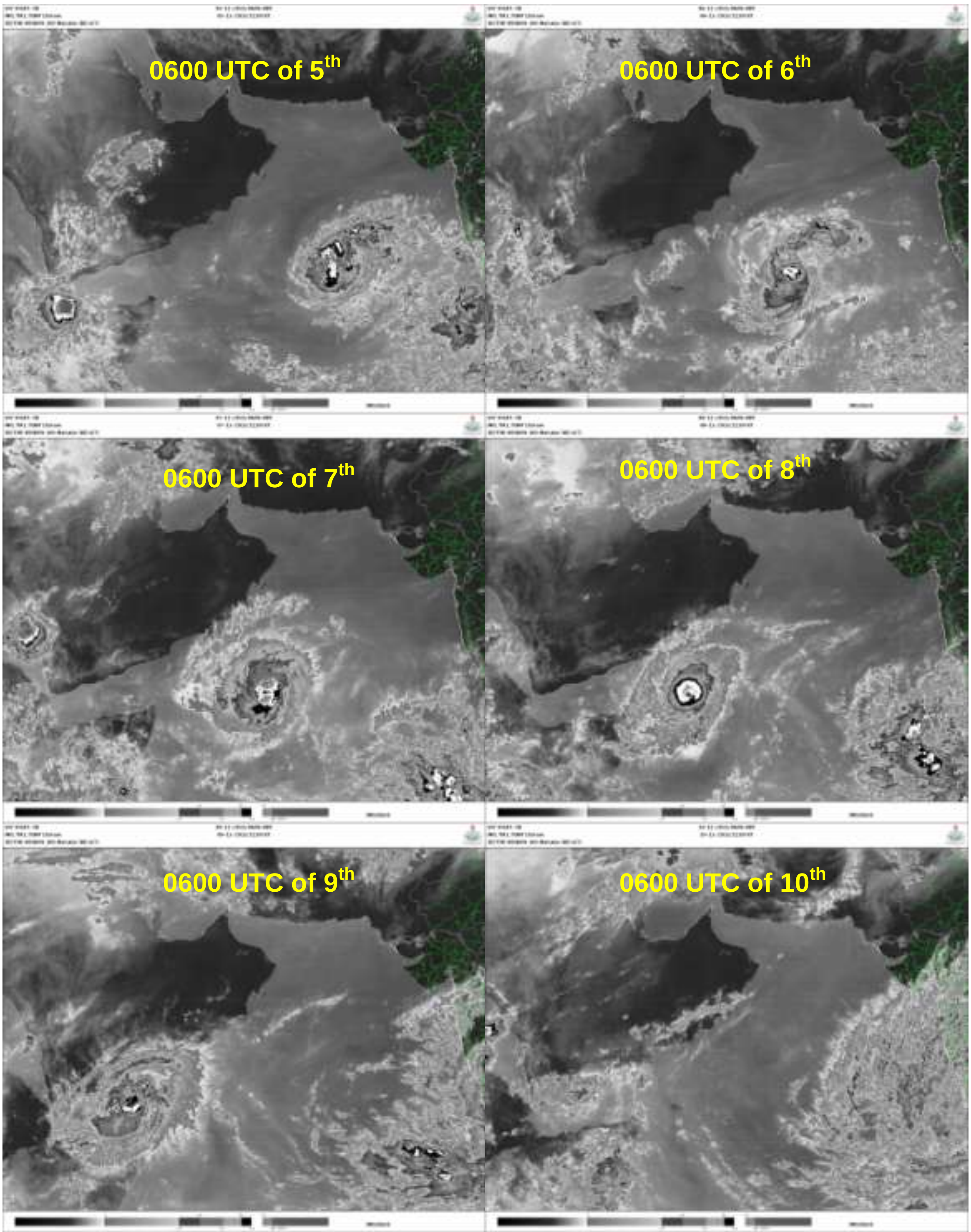


Fig.9 INSAT-3D cloud top brightness temperature imageries based on 0600 UTC of 5th to 10th November 2015

5.2 Microwave features

SSMIS, AMSR2 and WINDSAT(37) microwave imageries of the ESCS Megh covering its life period from 05th to 10th November 2015 are presented in Fig.10 .

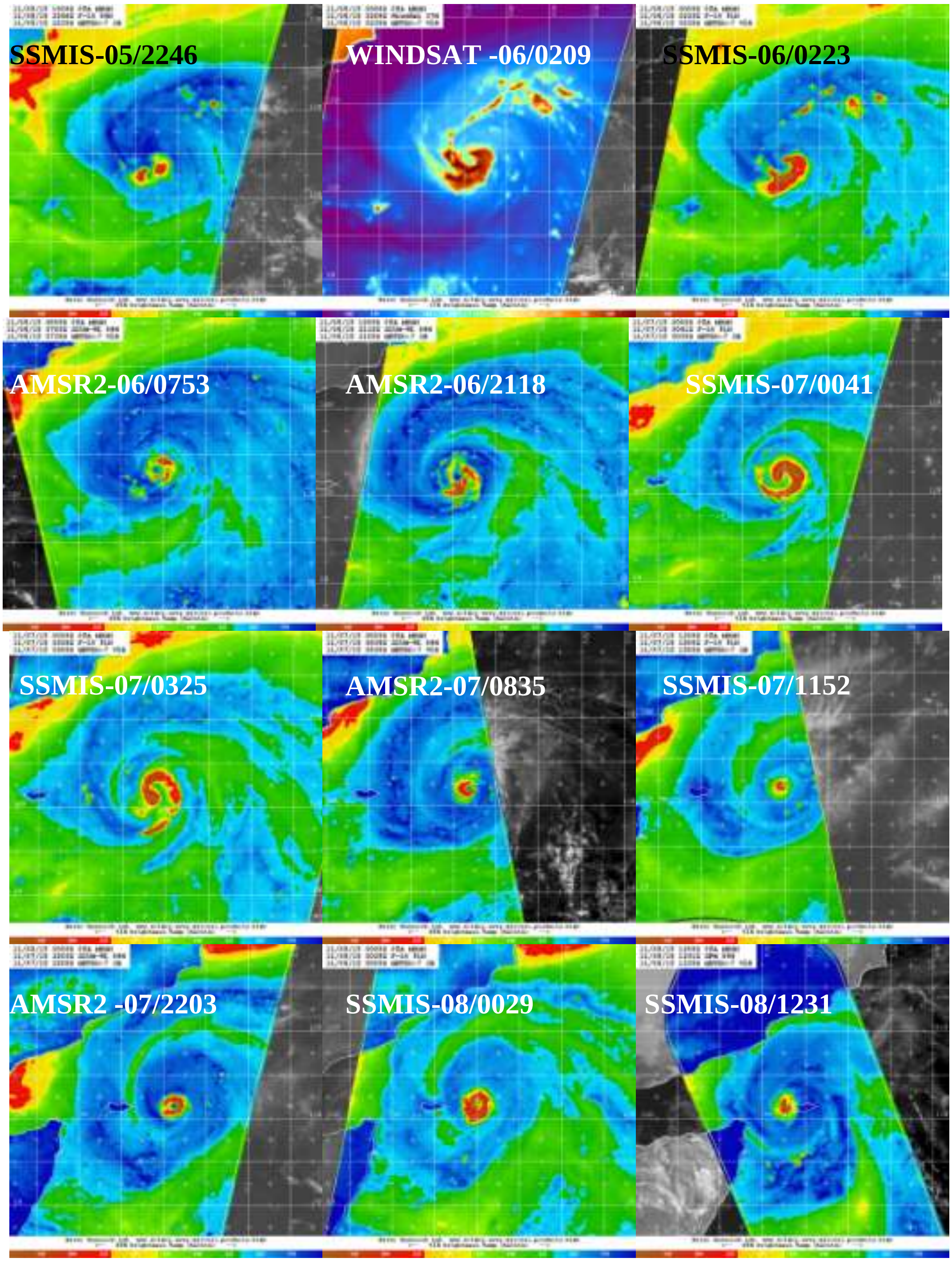


Fig. 10 Typical microwave imageries during 5th to 8th November 2015 in association with ESCS Megh.

On 05th and 06th, organisation of convective clouds along curved band is seen. On 06th/0753 UTC, formation of eye and development of wall cloud are observed. On 07th, the wall cloud region developed further and expanded. It is observed to spiral inwards cyclonically and completely covering the eye by 08th/0029 UTC. However, by 08th/1231

UTC, the eye-wall opened and the eye became exposed. Subsequently, disorganisation of convective clouds took place, eye became ill-defined and the system underwent rapid weakening on 09th (from T.5.0 at 09/0000 UTC to T 2.5 at 10/0000 UTC).

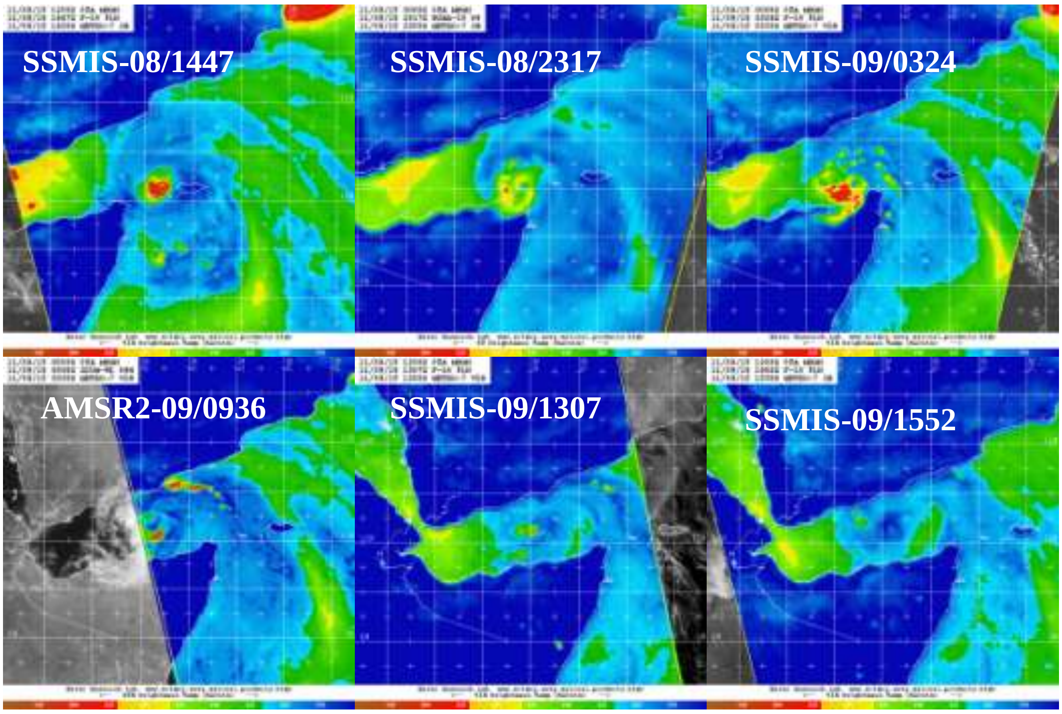


Fig.10 (contd.) Typical microwave imageries during 8th to 9th November 2015 in association with ESCS Megh.

6. Surface wind structure

The surface wind structure during the life period of ESCS, Megh based on multi-satellite surface wind developed by CIRA, USA is shown in Fig. 11. It can be seen that the radius of 34 kt (outer core size) winds was higher in northeast (NE) sector. It was maximum of about 125 nm during its mature stage. Also in the radius of 50 kt/64 kt (inner core size), the winds were higher in the northeastern sector as compared to the other sector. The size of the system was maximum, especially in northeast quadrant at 0600 UTC of 9th November, while the intensity was decreasing gradually. Then it decreased sharply to 63 nm at 1200 UTC of 9th. The size then remained same upto 1800 UTC of 9th Nov. and then gradually decreased. The change in the inner core (R50) was similar to that of R34 and the temporal variation in R64 was less. The radius of maximum winds (RMW) remained almost same till 1800 UTC of 6th November. It then decreased gradually reaching minimum of 8nm at 1800 UTC of 8th, as the cyclone experienced rapid intensification from 0300 UTC of 7th to 0300 UTC of 8th. It then increased with weakening of the system from 1200 UTC of 8th. It was one of the lowest RMW, as the cyclone was associated with one of the smallest eye or a pin hole eye.

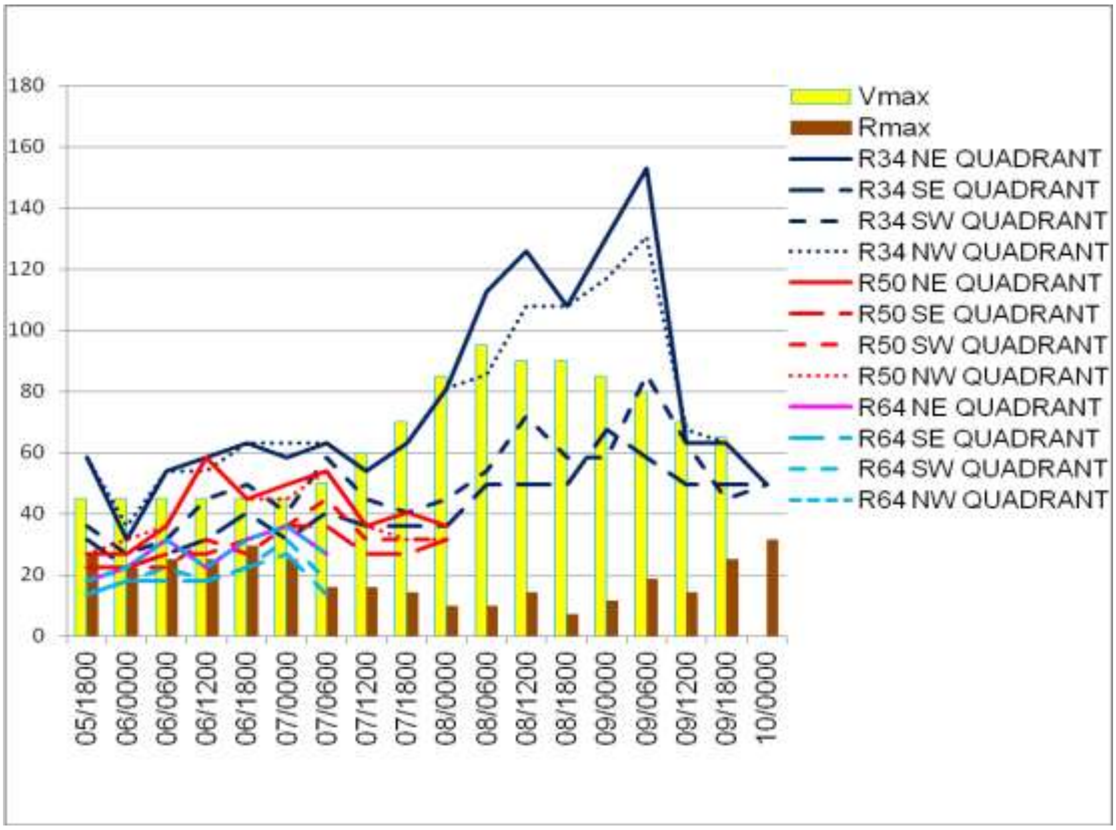


Fig. 11: Radius 34 knot (R34), radius of 50 knot (R50) & radius of 64 knot (R64), estimated maximum sustained surface winds (Vmax in knots) and Radius of Maximum winds (Rmax in nautical mile) based on multi-satellite surface wind (http://rammb.cira.colostate.edu/)

7. Dynamical features

To analyse the dynamical features, the mean sea level pressure (MSLP), 10 metre wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 5th to 10th November are presented in fig. 12 (a-f). From the analysis of MSLP and 10m wind, it is observed that the GFS model underestimated the intensification of the system. However, it could detect the genesis at 0000 UTC of 5th November with the formation of 2 closed isobars at the interval of 2 hPa and ECP of 1008 hPa against the best track ECP of 1006 hPa. It could detect the movement towards Yemen coast across the Gulf of Aden, but could not predict the landfall. Though the centre based on GFS analysis lay to the south of the best track. The rapid intensification on 7th and rapid weakening on 10th could not be detected. The associated cyclonic circulation extended upto mid-tropospheric levels. Considering the upper tropospheric wind analysis, ridge over AS ran along 15.0^{0}N throughout the life period at 200 hPa level. At 500 hPa level, it ran along 18.0^{0}N during 5th to 7th and along 20.0^{0}N during 8th to 10th November. Under the influence of this ridge, northerly to northeasterly winds prevailed over the cyclone field leading to west-southwestwards movement of the system. From the GFS analysis, it can be concluded that the system was steered west-southwestwards by the lower mid-tropospheric winds. However, on 10th November the system recurved northeastwards which can be associated with the upper tropospheric flow at 200 hPa level.

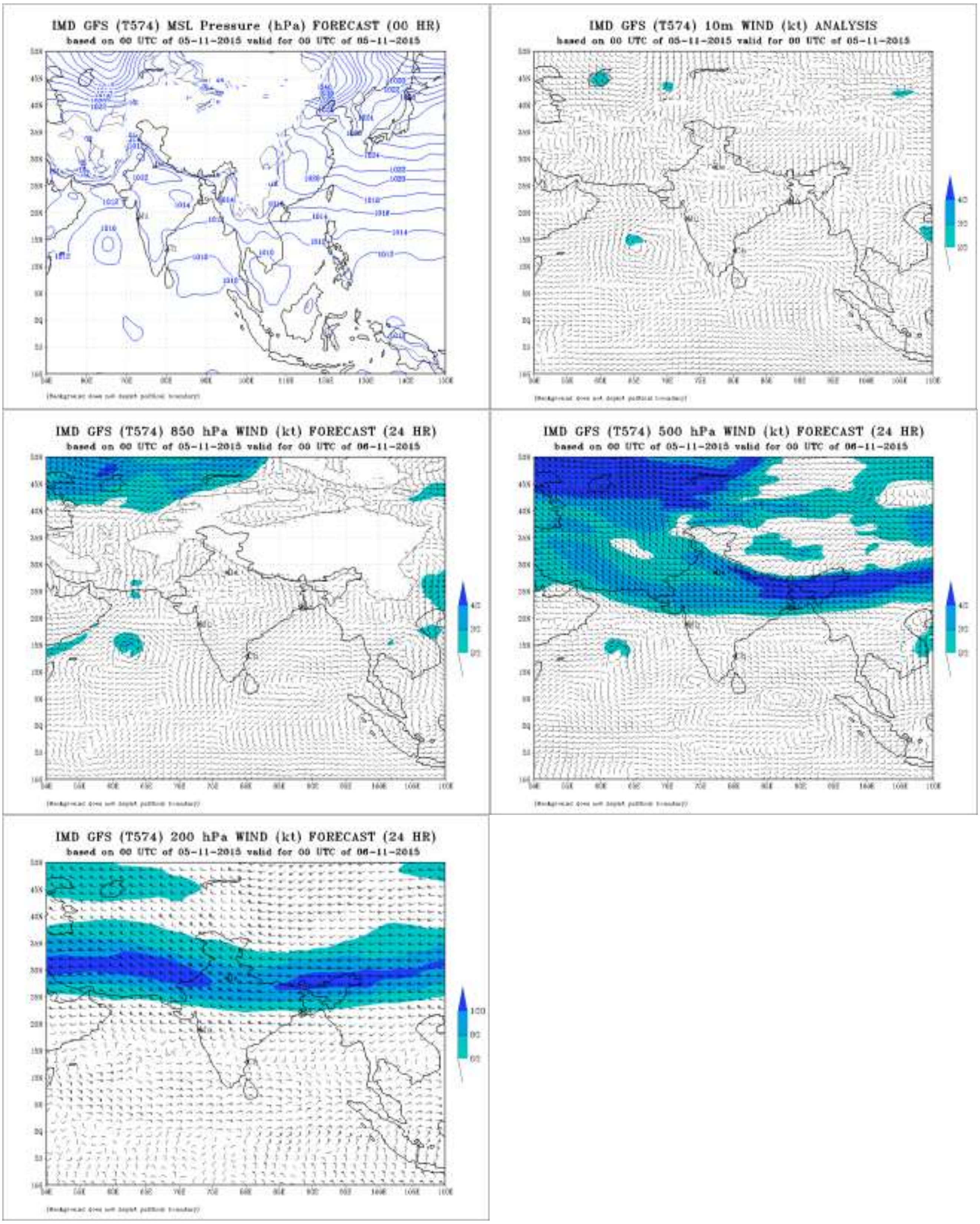


Fig.12(a) IMD GFS analysis of MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 5th November.

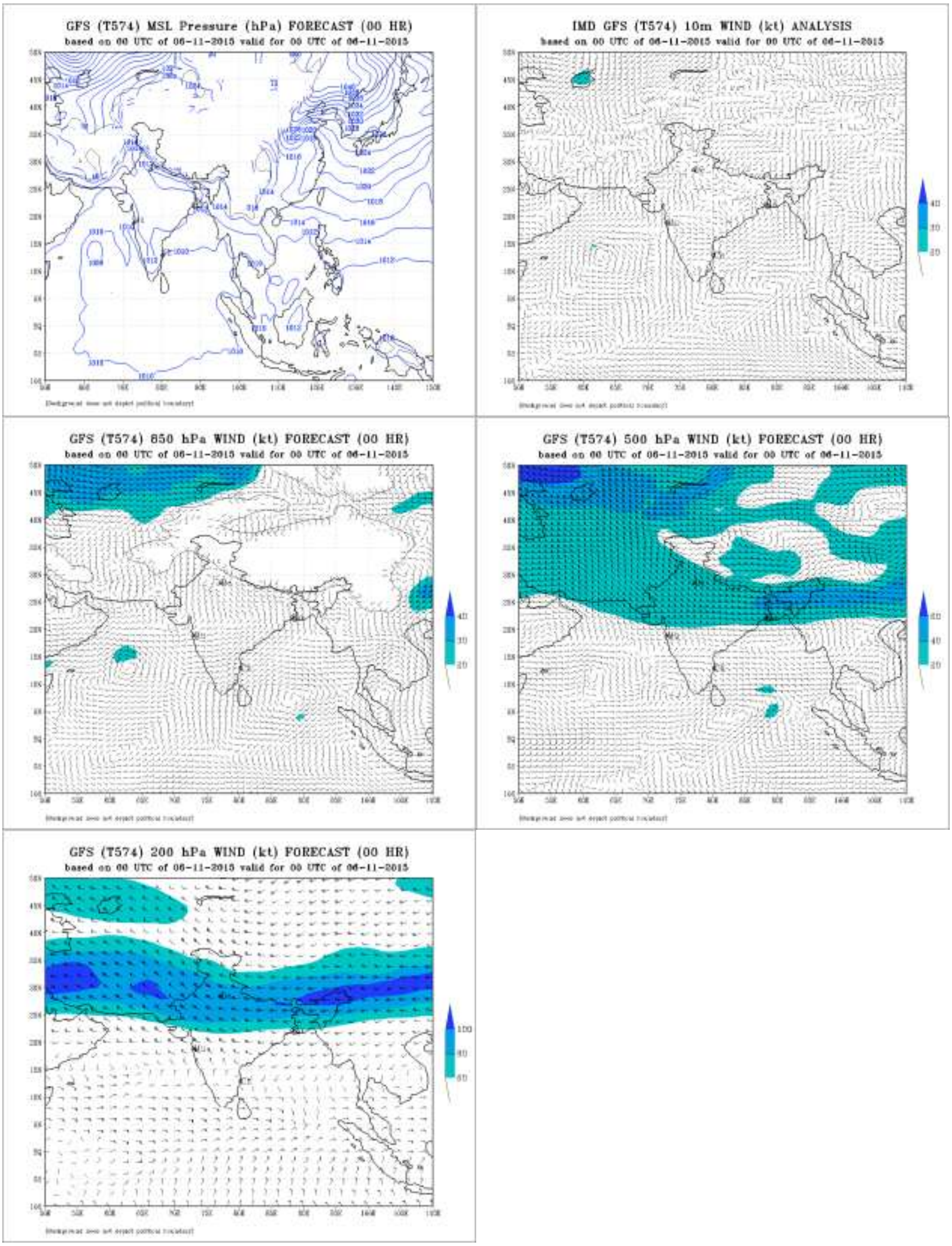


Fig.12(b) IMD GFS analysis of MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 6th November.

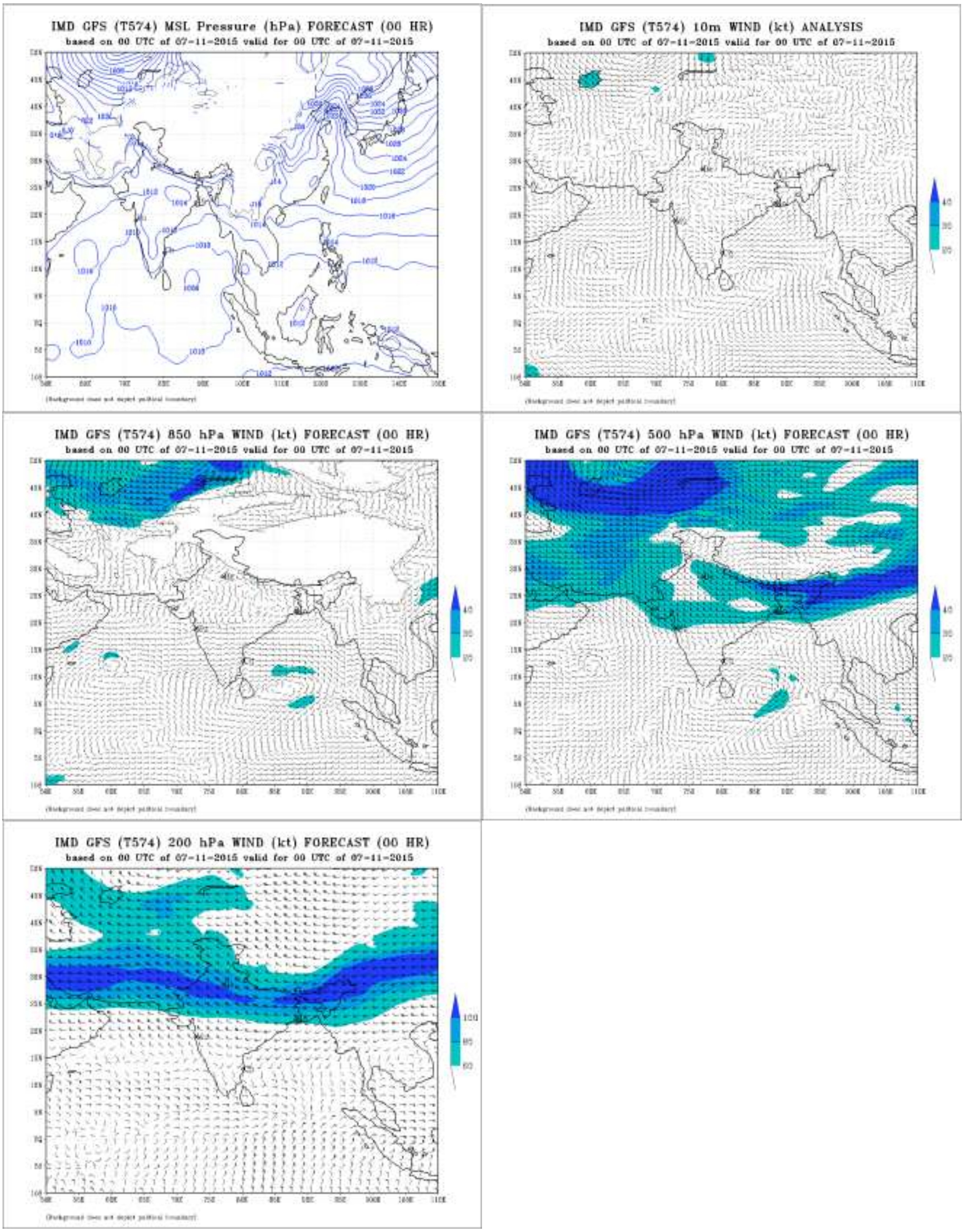


Fig.12(c) IMD GFS analysis of MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 7th November.

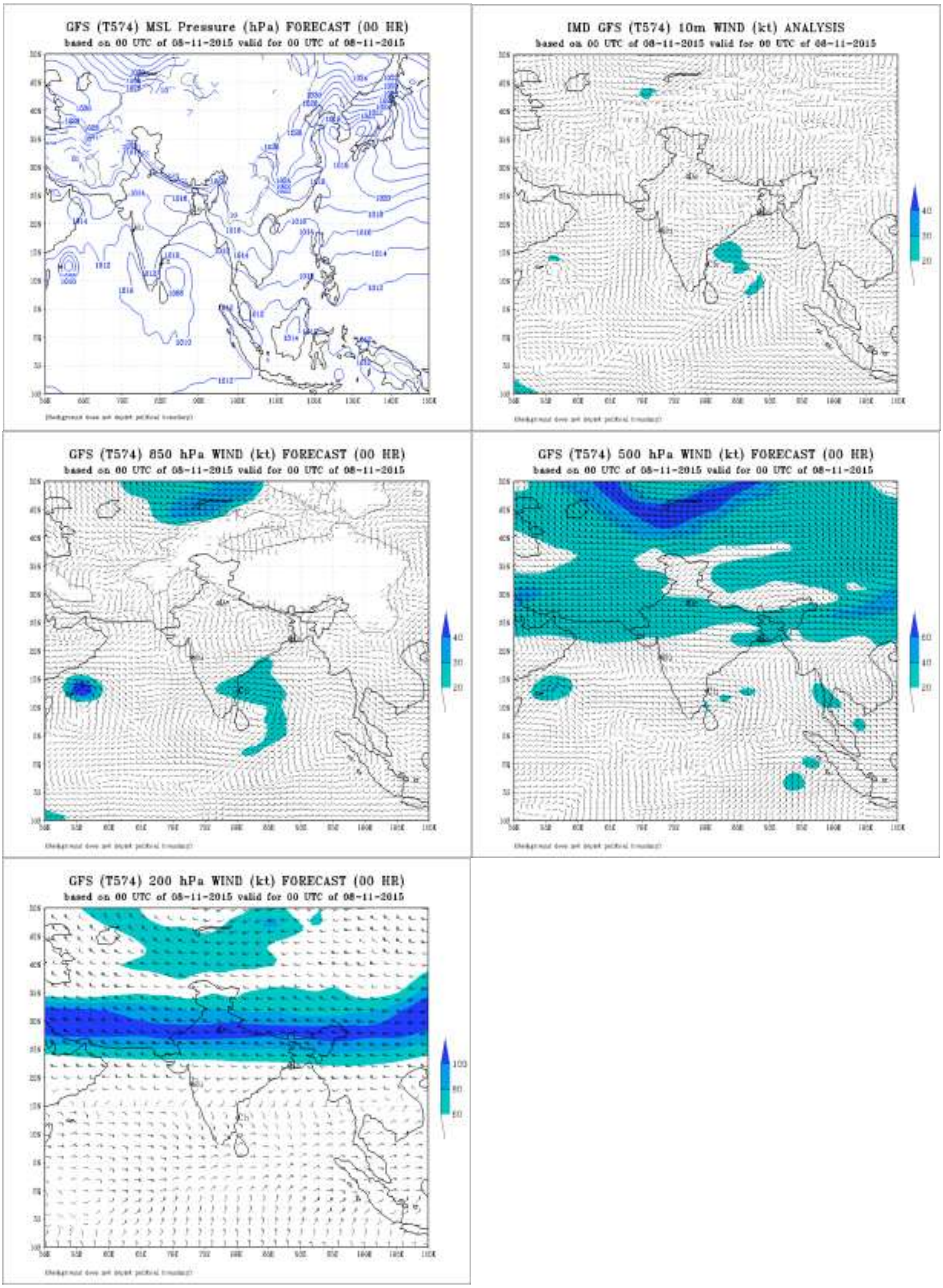


Fig.12(d) IMD GFS analysis of MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 8th November.

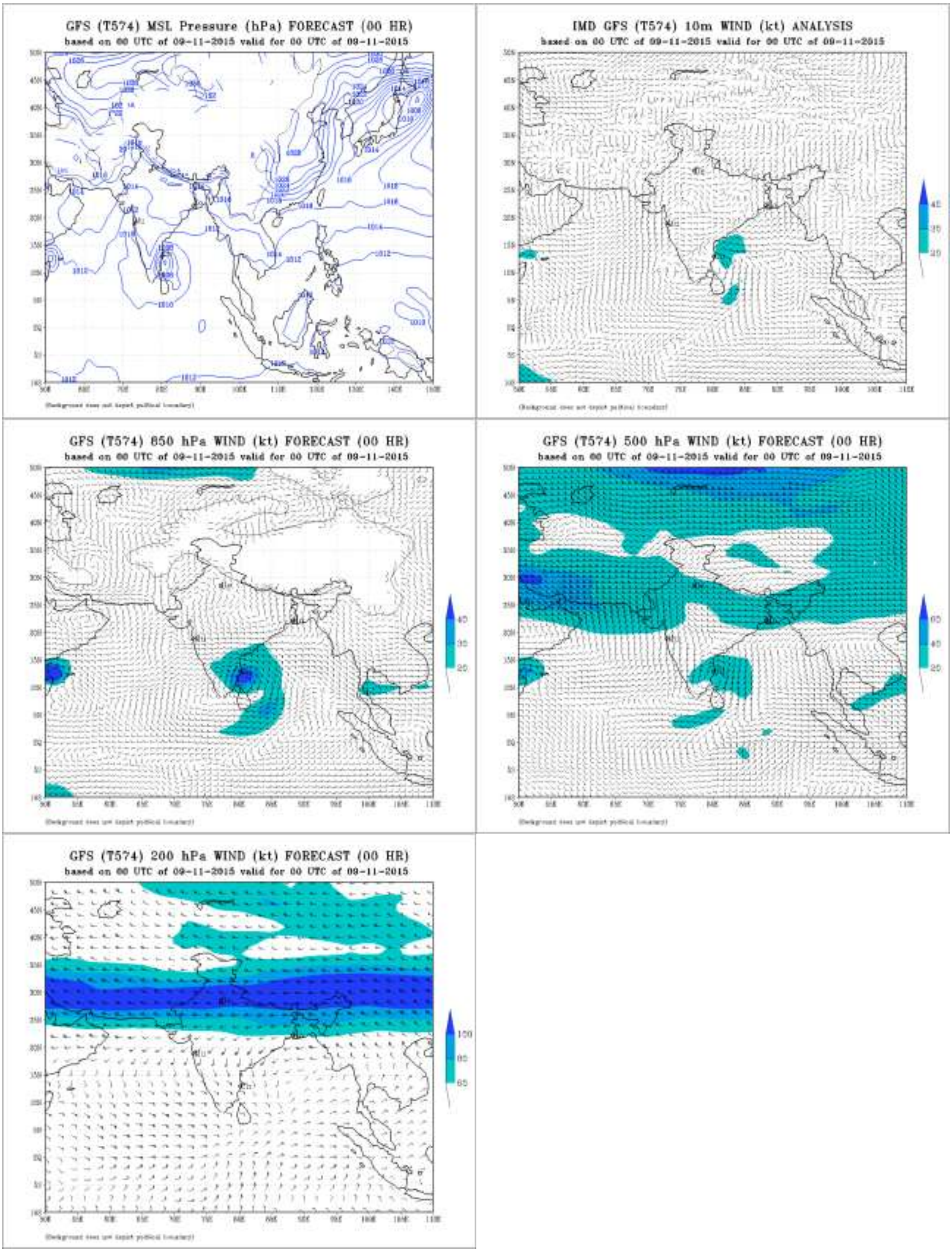


Fig. 12(e) IMD GFS analysis of MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 9th November.

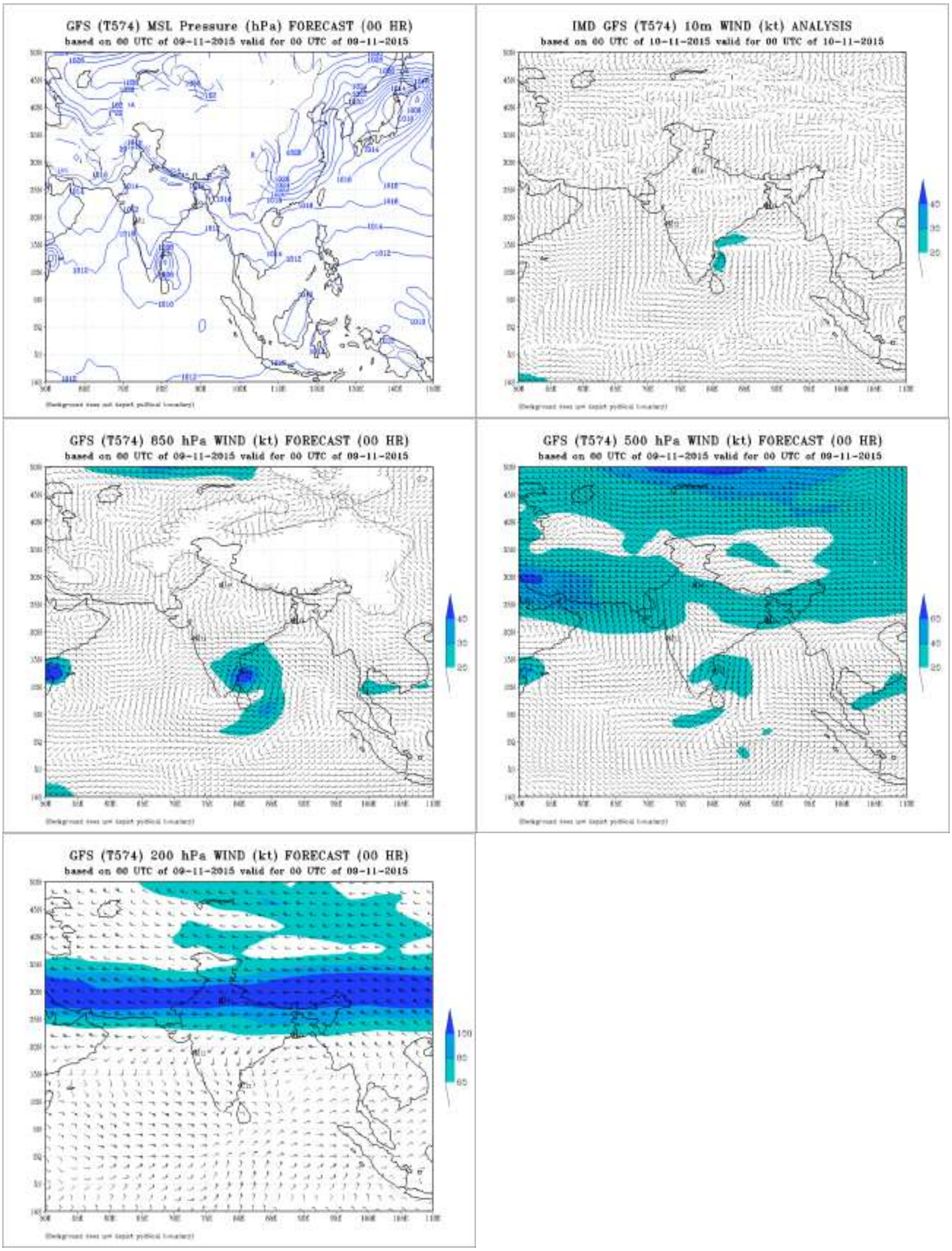


Fig.12(f) IMD GFS analysis of MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 10th November.

8. Realized Weather:

8.1 Rainfall:

Rainfall associated with the system is depicted in Fig13 based on IMD-NCMRWF GPM merged gauge rainfall data

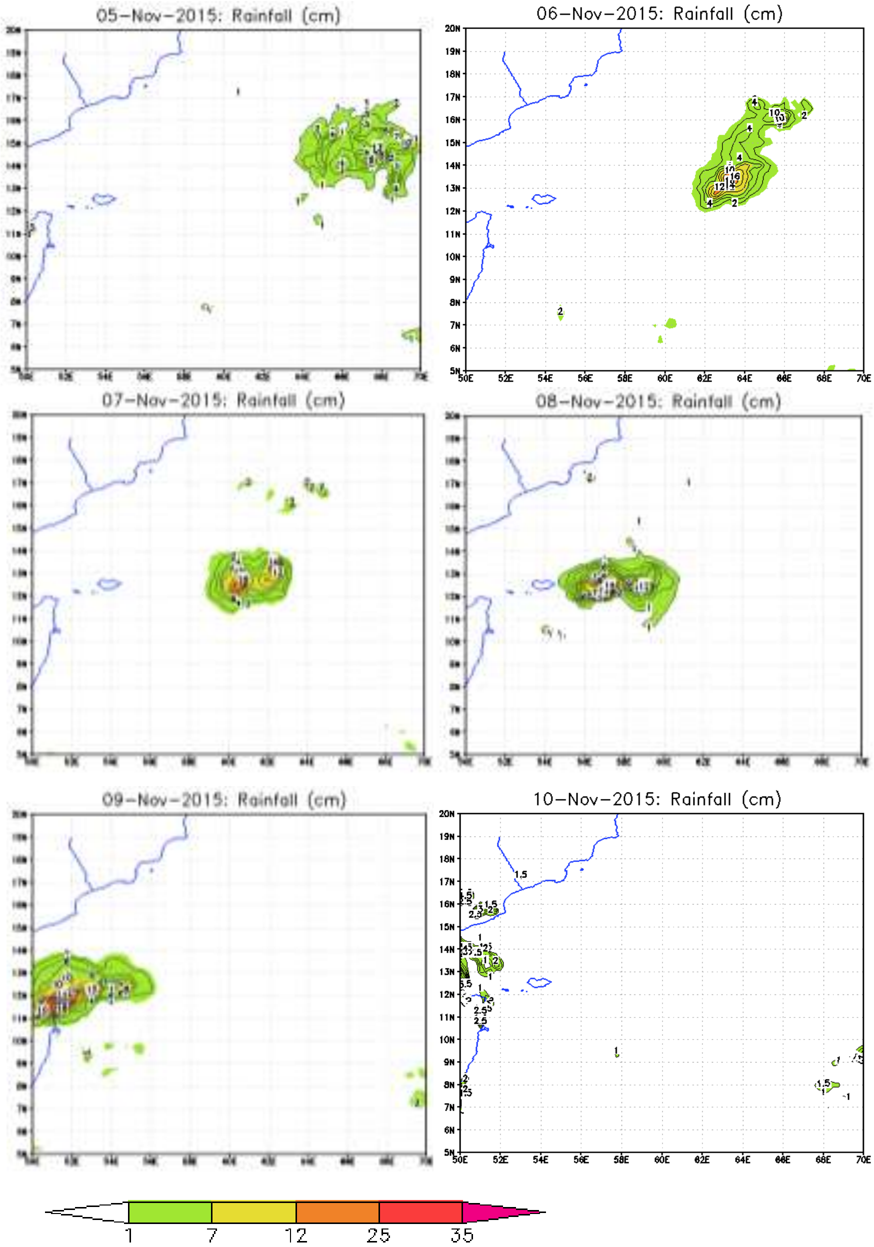


Fig.13 IMD-NCMRWF GPM-gauge merged 24-hr rainfall as on 0300 UTC of the date indicated in each plot for the period 05-10 November 2015

During the initial stage of formation of the system, on 5th November, rainfall belt was east-west oriented and the rainfall maximum was observed to the northeast of the system centre. Similar pattern was observed on 6th November with extension of rainfall belt from southwest to northeast. Subsequently, with the organisation of the system, convection became more and more organised and rainfall was symmetric about the centre on 7th and 8th November. However, gradually the rainfall maximum shifted to the southwest with gradual weakening of the system from 8th and west-southwestwards movement, the rainfall belt was elongated towards west-southwest from east-northeast. As a result the northern tip of Somalia experienced haevy rainfall on 9th. The rainfall almost decreased on 9th and 10th due to rapid weakening of the system.

9. Damage due to ESCS Megh

As per media and press report, ESCS Megh caused extensive devastation, killing at least eighteen people and injuring dozens of others. More than 500 houses were completely destroyed and another 3,000 were damaged. In addition, hundreds of fishing boats were damaged and more than 3,000 families were displaced. The typical damage photographs over Socotra Island are presented in fig. 14.

Yemini Island, Socotra lashed by high winds and torrential rains

Dragon's blood tree is seen on the ground after Megh hits Socotra Island

Fig. 14 Typical damage photographs over in asssociation with ESCS Megh over Socotra Island

10. Performance of operational NWP models

IMD operationally runs a regional model, WRF for short-range prediction and one global forecast system (GFS) model (T574L64) for medium range prediction (7 days). In addition, Hurricane WRF (HWRF) model (5 days) and Ensemble prediction system (EPS) based on TIGGE has been implemented at the NWP Division of the IMD HQ for operational forecasting of cyclones.

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^o S to 45^o N long 40^o E to 120^o 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. The QLM model (resolution 40 km) is used for cyclone track prediction in case of cyclone situation in the north Indian Ocean. 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).

Under Indo-US joint collaborative program, IMD adapted Hurricane-WRF model for Tropical Cyclone track and intensity forecast for North Indian Ocean region for its operational requirements. The basic version of the model HWRFV (3.2+) which was operational at EMC, NCEP, USA was ported on IMD IBM P- 6/575 machine with nested domain of 27 km and 9 km which has been upgraded to 3 km horizontal resolution in 2015 and 42 vertical levels with outer domain covering the area of 800x800 and inner domain 60x60 with Center of the system adjusted to the Center of the observed cyclonic storm. The outer domain covers most of the north Indian Ocean and the inner domain mainly covering the cyclonic vortex which moves along the movement of the system. The model has special features such as vortex initialization, coupled with Ocean model to take into account the changes in SST during the model integration, tracker and diagnostic software to provide the graphic and text information on track and intensity prediction for real-time operational requirement.

As part of WMO Program to provide a guidance of tropical cyclone (TC) forecasts in near real-time for the WMO/ESCAP panel Member Countries based on the TIGGE Cyclone XML (CXML) data, IMD implemented JMA supported software for real-time TC forecast over North Indian Ocean (NIO) during 2011. The Ensemble and deterministic forecast products from ECMWF (50+1 Members), NCEP (20+1 Members), UKMO (23+1 Members) and MSC (20+1 Members) are available near real-time for NIO region for named TCs. These Products includes: Deterministic and Ensemble TC track forecasts, Strike Probability Maps, Strike probability of cities within the range of 120 kms 4 days in advance. The JMA provided software to prepare Web page to provide guidance of tropical cyclone forecasts in near real-time for the WMO/ESCAP panel Members. The forecast products are made available in real time.

In addition to the above NWP models, IMD also runs 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 decaying intensity after the landfall. Genesis potential parameter (GPP) is used for predicting potential of cyclogenesis (T-3.0) 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 used 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 during ESCS Megh are presented and discussed.

Global models are also run at NCMRWF. These include GFS (T574/L64) and unified model adapted from UK Meteorological Office (NCUM). 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 (N512/L70) model features a horizontal resolution of 25km and 70 vertical levels. It uses 4D-Var assimilation and features no cyclone initialization/relocation. At NCMRWF the Global Ensemble Forecast System (NGEFS) provides analysis and forecast run out to 10 days based on 20 perturbed forecasts. The results of these models guidance are presented and discussed in following sections.

10.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for Megh

The predicted zone of cyclogenesis is presented in fig.15 (a-d).

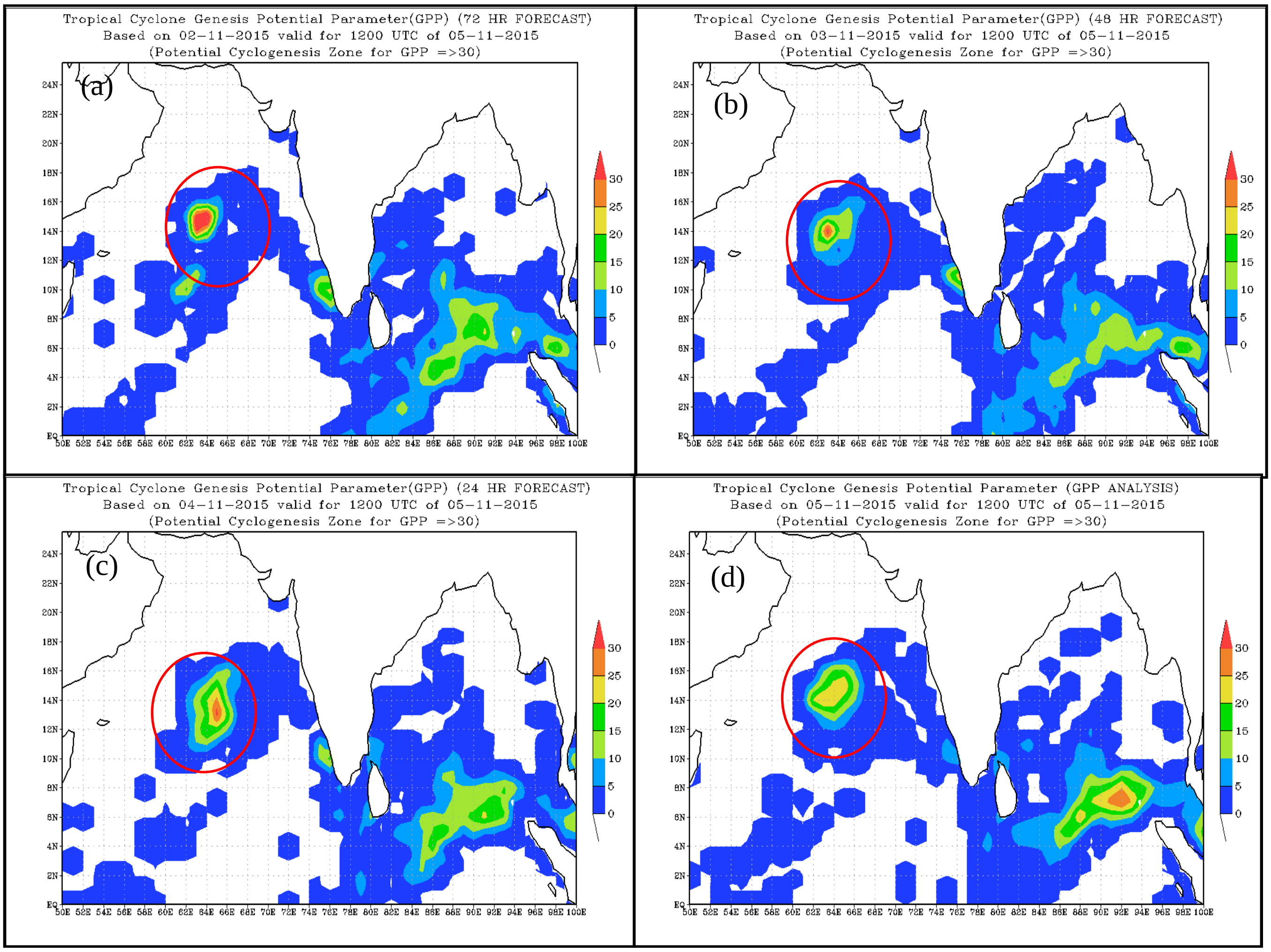


Fig. 15 (a-d): Predicted zone of cyclogenesis based on dynamical statistical model of IMD.

Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis. Grid point analysis and forecasts of GPP showed a weak cyclogenesis zone 72 hrs before its formation.

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) of development.

Conditions for: (i) Developed system (T 3.0): Threshold value of GPP ≥ 8.0

(ii) Non-developed system (T<3.0): Threshold value of GPP < 8.0

Area analysis and forecasts of GPP is presented in fig.16. Based on 0000 UTC of 5th November, it shows that the GPP ≥ 8.0 indicated its potential to intensify into a cyclone at early stages of development (T 1.5) during next 24 hours but incorrectly showed weakening for subsequent hours up to 72 hours. Though the system intensified into a cyclone (T 2.5) at 1200 UTC of 5th and intensified into a cyclone (T 3.0) at 1800 UTC of 5th.

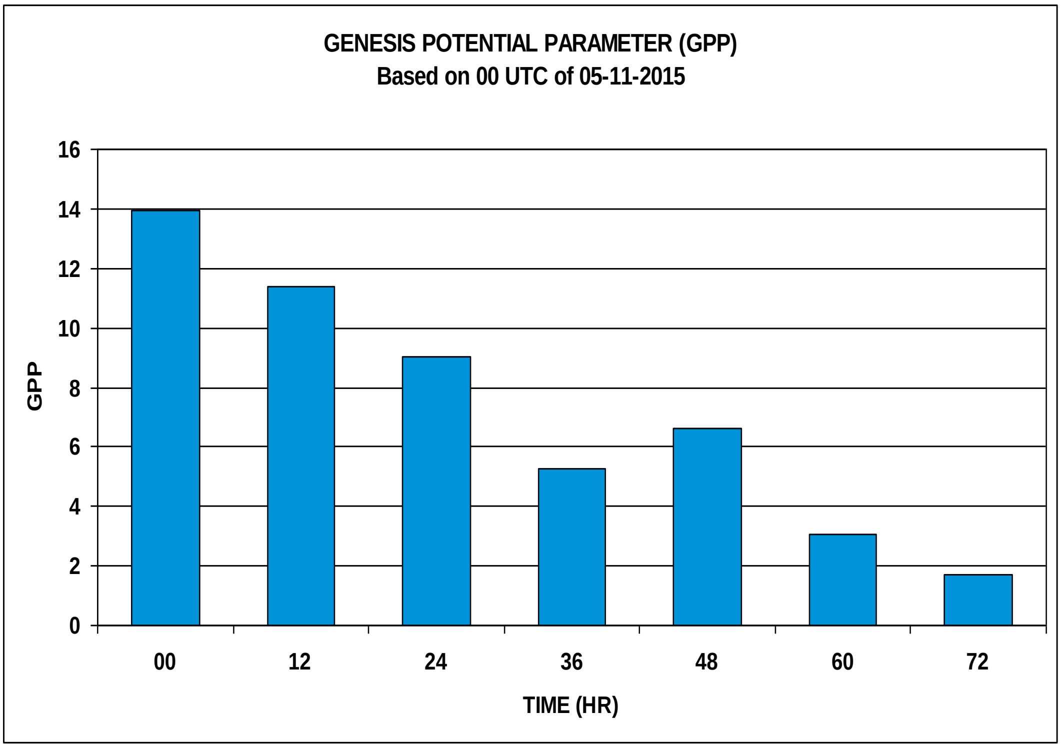


Fig. 16 Area average analysis and forecasts of GPP based on 0000 UTC of 5th November 2015

10.2 Track prediction by NWP models

NWP guidance for track forecast was provided by IMD-HWRF, IMD-WRF, JMA, NCEP-GFS, UKMO, ECMWF and IMD'S Multi model ensemble (MME) technique and NCMRWF GEFS models. Track prediction by various NWP models is presented in fig. 17

0000 UTC analysis of 5th November showed west-southwestwards movement by all models. Also, all models were showing weakening of the system over AS without landfall over any coast.

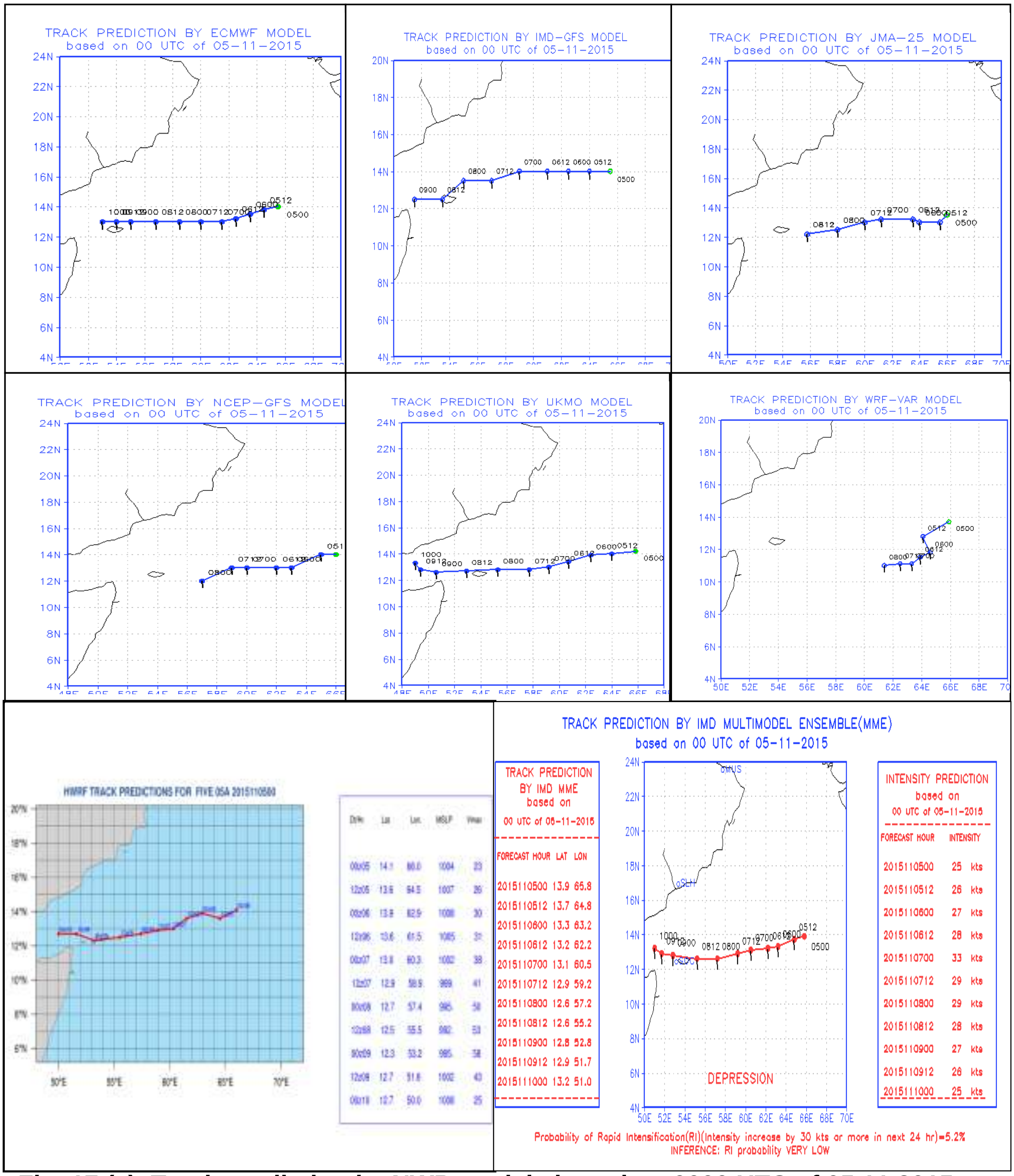


Fig. 17 (a). Track prediction by NWP models based on 0000 UTC of 05.11.2015

Based on 1200 UTC of 5th Nov initial conditions, only HWRF model showed landfall of the system near 13.5^{0}N over Yemen coast. Only HWRF and ECMWF models were showing that the system would pass near north of Socotra Island. Rest of the models were showing movement of system near south of Socotra Island. All models were unanimous about the west-southwestwards movement of the system.

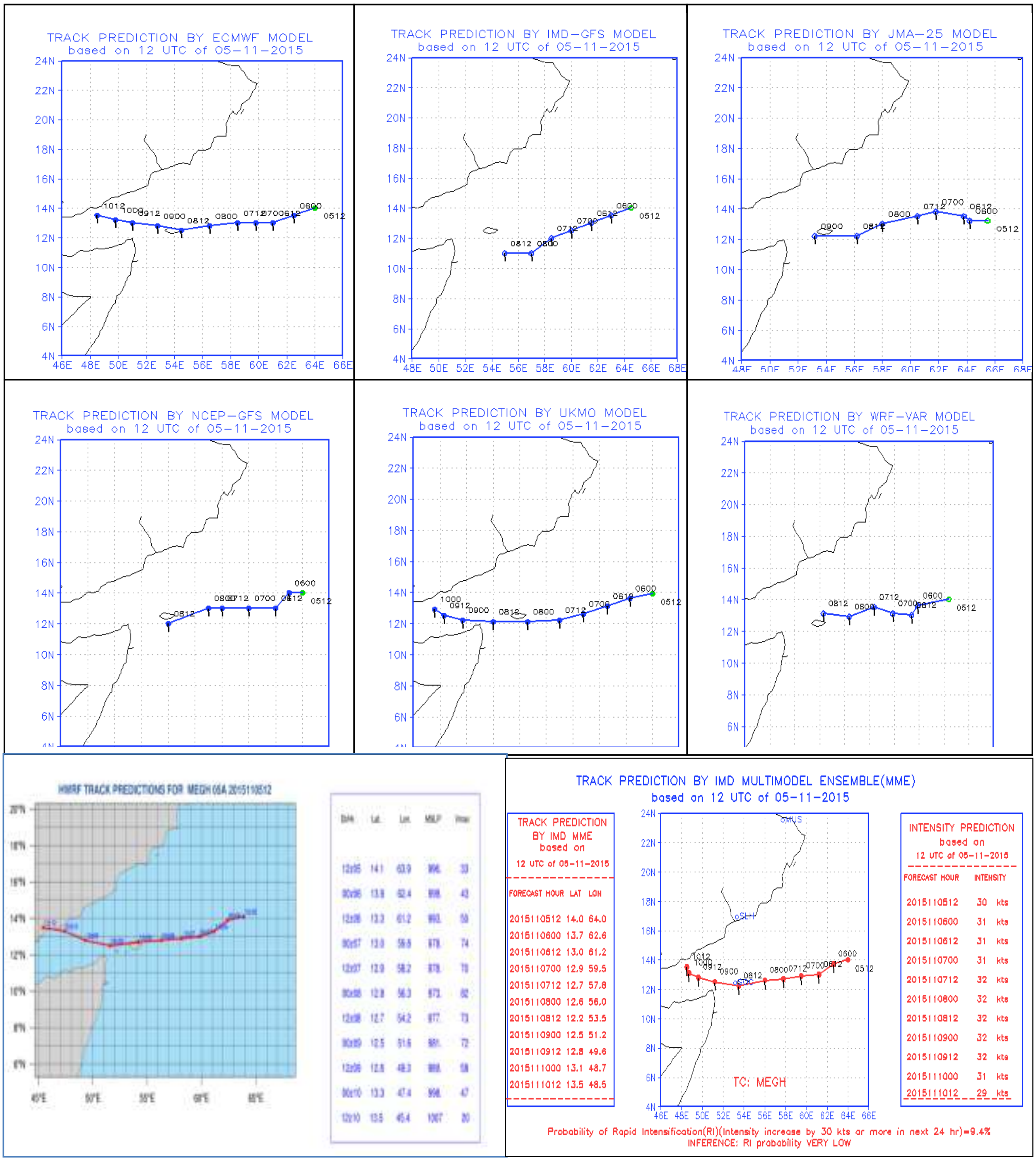


Fig.17 (b). Track prediction by NWP models based on 1200 UTC of 05.11.2015

Based on 0000 UTC of 6th November initial conditions, various models except HWRF continued to show weakening of the system over the sea. Only HWRF model was showing landfall over Yemen near 13.6^{0}N around 0000 UTC of 10th and NGFS over north Somalia.

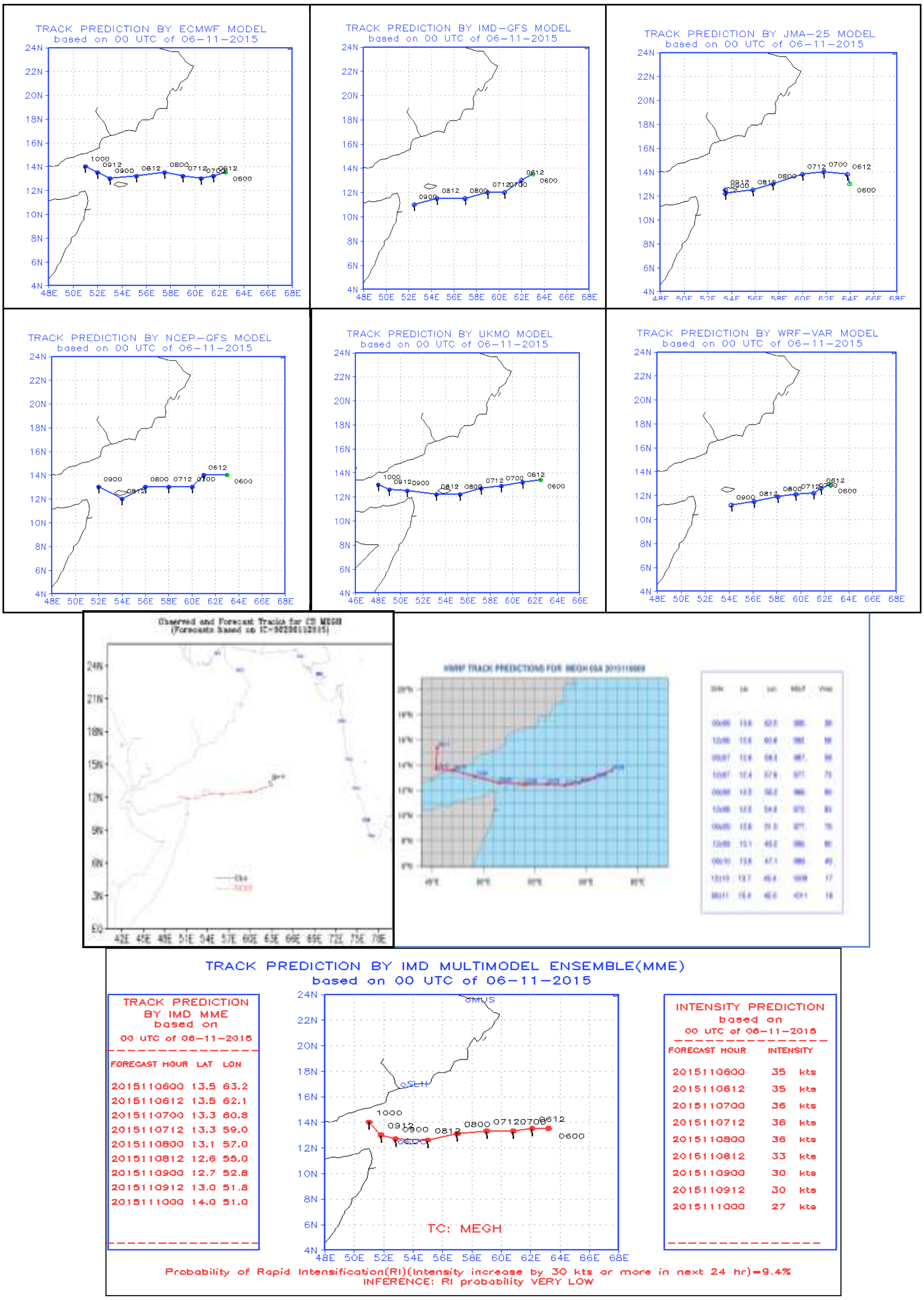


Fig.17(c) Track prediction by NWP models based on 0000 UTC of 06.11.2015

Based on 1200 UTC of 6th November initial conditions, various models except HWRF continued to show weakening of the system over sea. Only HWRF was showing landfall over Yemen near 13.6^{0}N and WRF-VAR was showing landfall over Somalia.

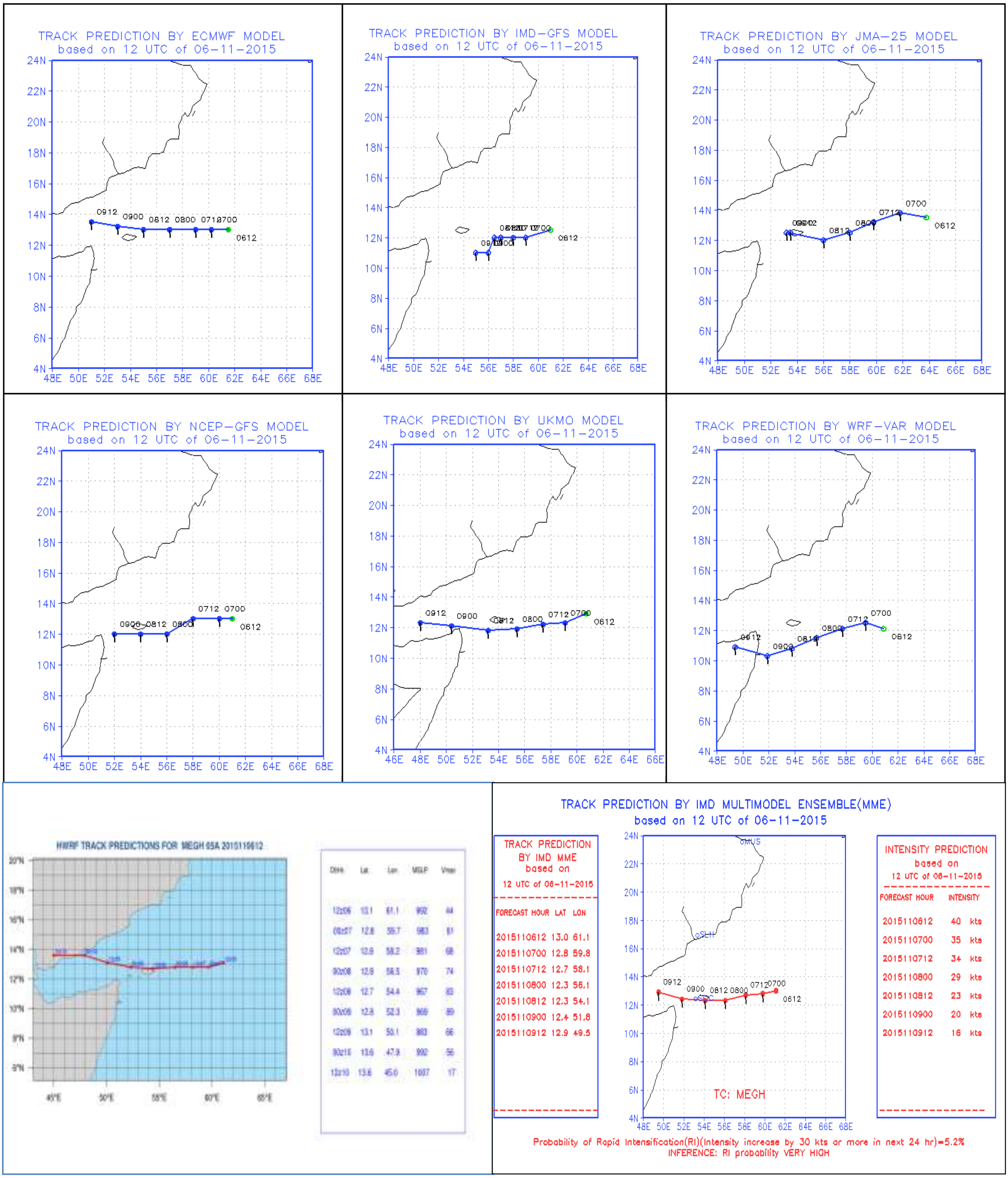


Fig.17 (d). Track prediction by NWP models based on 1200 UTC of 06.11.2015

Based on 0000 UTC of 7th November initial conditions, by various models except HWRF continued to show weakening of the system over sea without landfall. Only HWRF was showing landfall over Yemen near 13.5^{0}N at 0300 UTC of 10th. Only HWRF and ECMWF models were showing the movement of system close to north of Socotra Island.

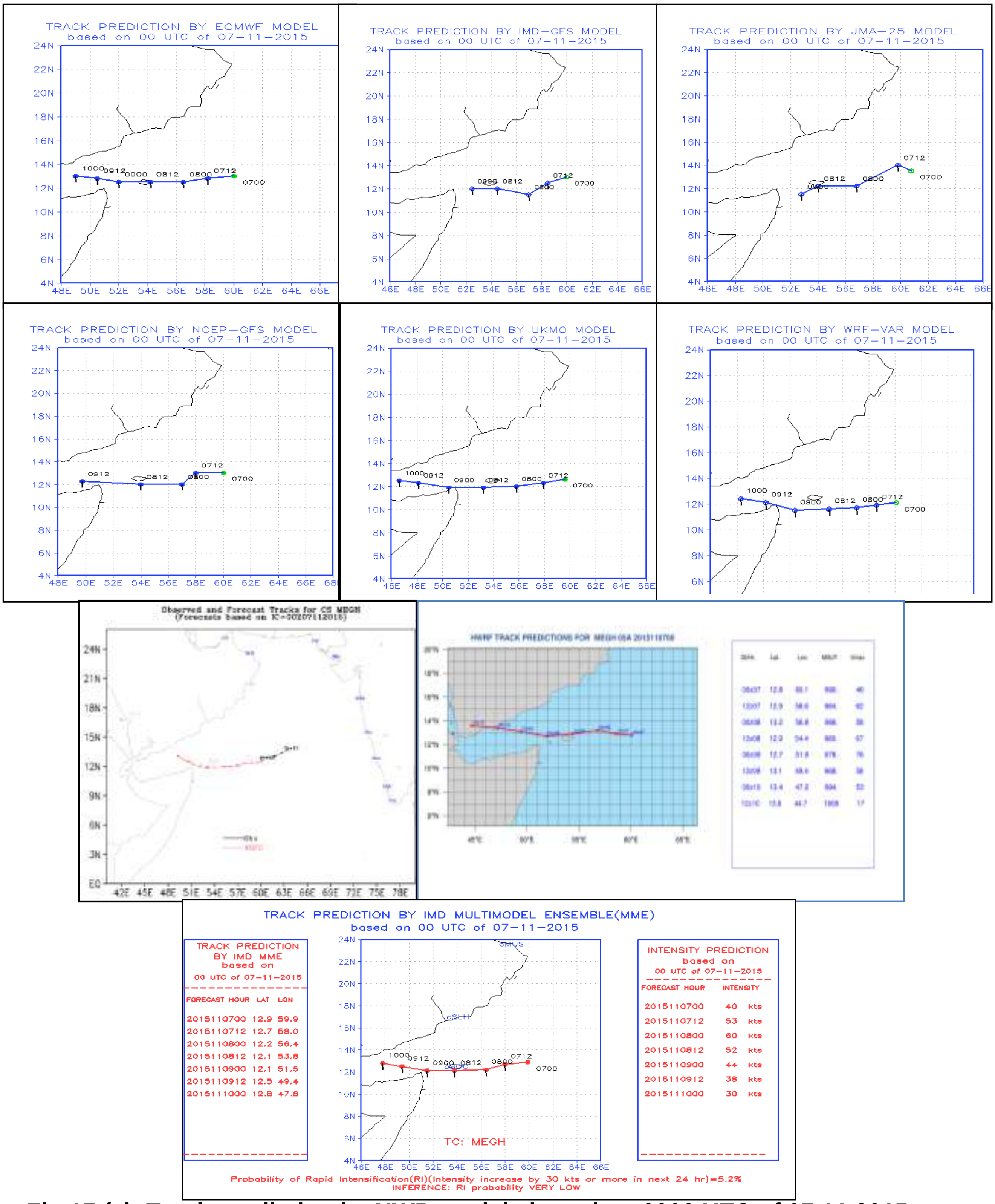


Fig.17 (e). Track prediction by NWP models based on 0000 UTC of 07.11.2015

Based on 1200 UTC of 7th November initial conditions, various models except HWRF continued to show weakening of the system over sea. Only HWRF was showing landfall over Yemen near 13.5^{0}N at 1200 UTC of 10th and north-northwestwards recurvature of the system thereafter. Only HWRF and ECMWF were showing the movement of system close to north of Socotra Island. UKMO and NCEP GFS also predicted landfall over the northern tip of Somalia and JMA over northeast Somalia.

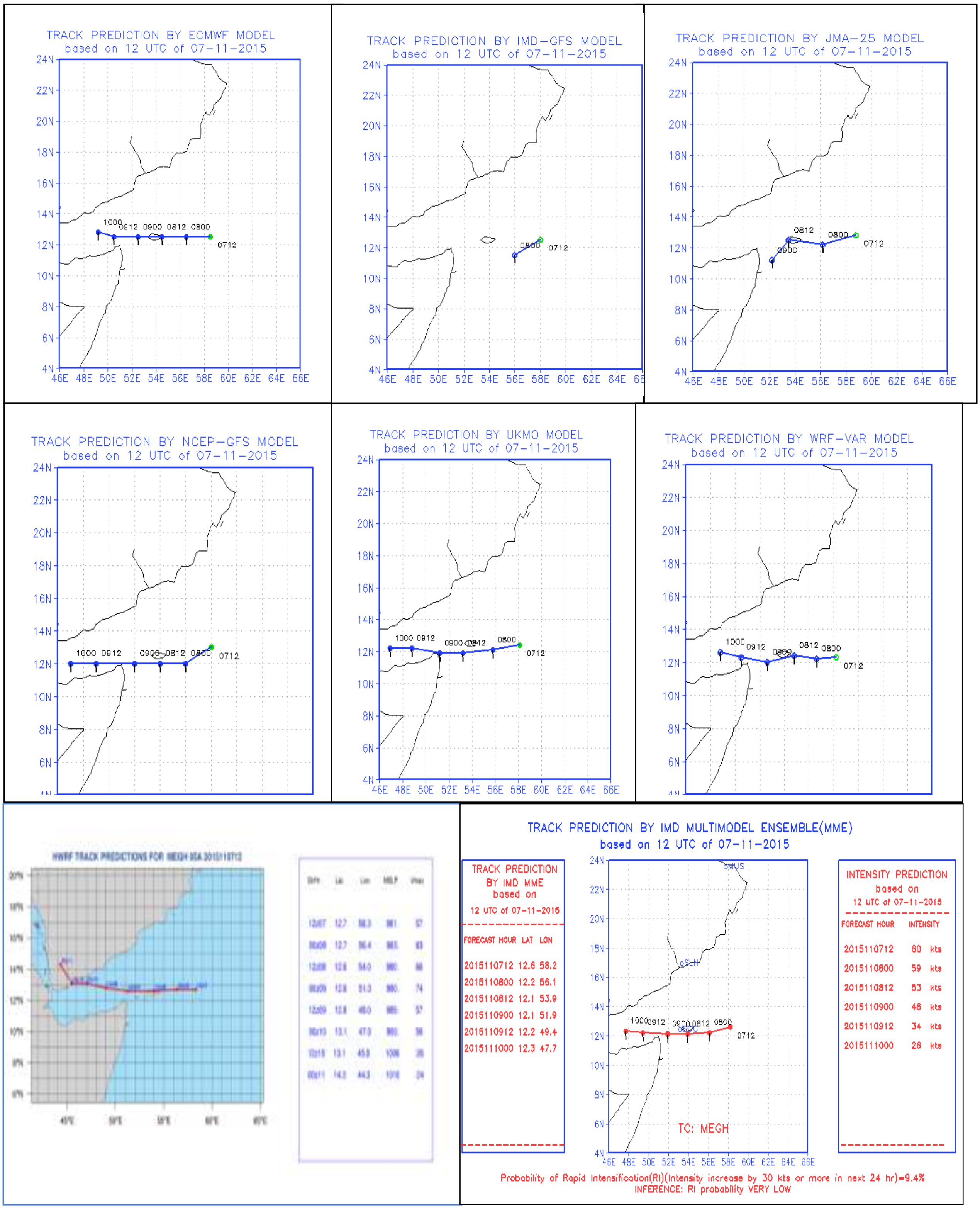


Fig. 17 (f). Track prediction by NWP models based on 1200 UTC of 07.11.2015

Based on 0000 UTC of 8[th] November initial conditions, HWRF showed landfall over Yemen near 13.4^{0}N at 0000 UTC of 10[th] and westwards movement till 1200 UTC and north-northwestwards recurvature of the system thereafter. All other models were showing weakening of the system over Sea with UKMO and WRF showing landfall over Somalia.

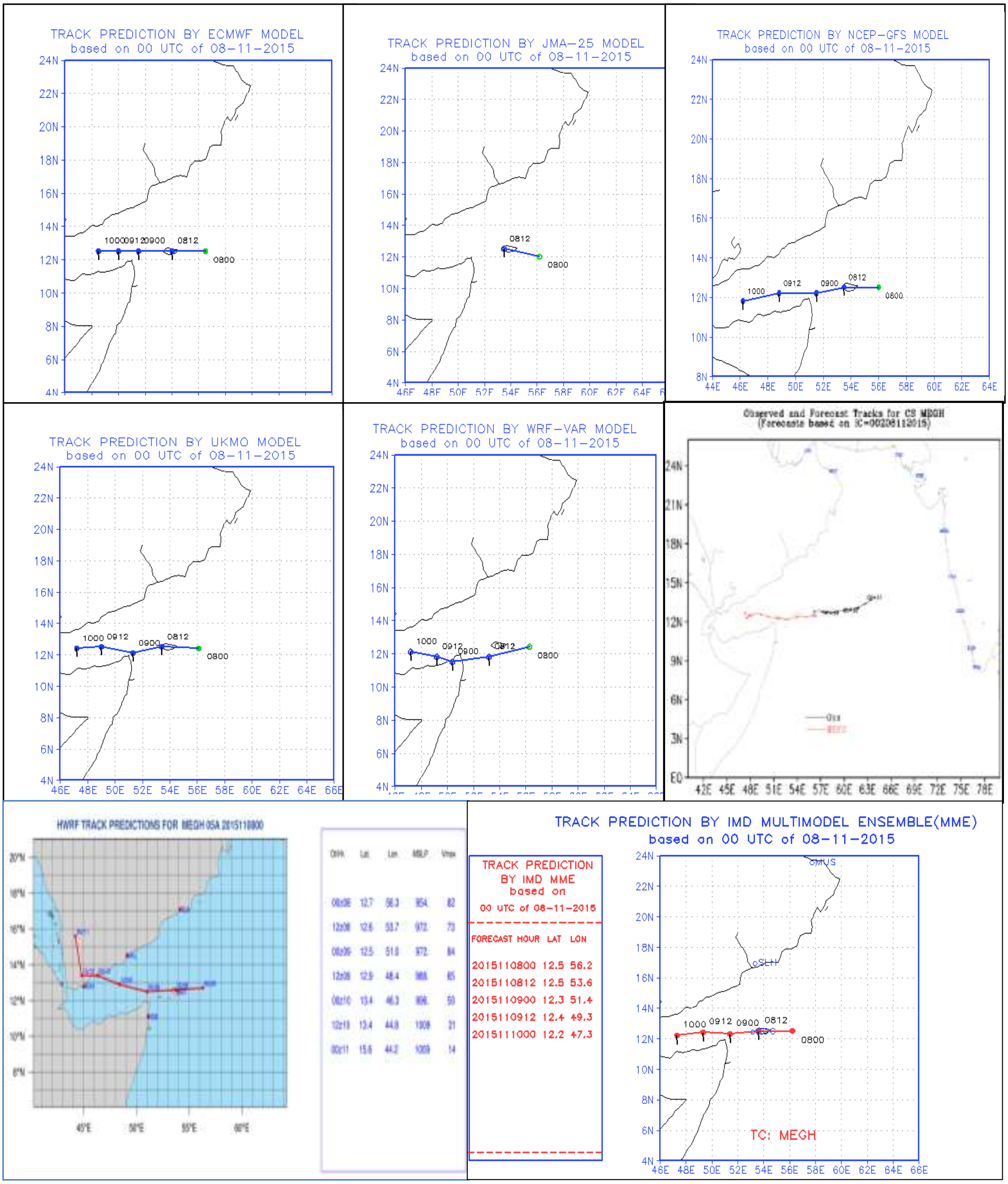


Fig.17 (g). Track prediction by NWP models based on 0000 UTC of 08.11.2015

Based on 1200 UTC of 8th November initial conditions, only HWRF was showing landfall over Yemen near 13.4^{0}N at 0000 UTC of 10th and northwestwards/ north-northwestwards recurvature of the system thereafter. All other models were showing weakening of the system over Gulf of Aden.

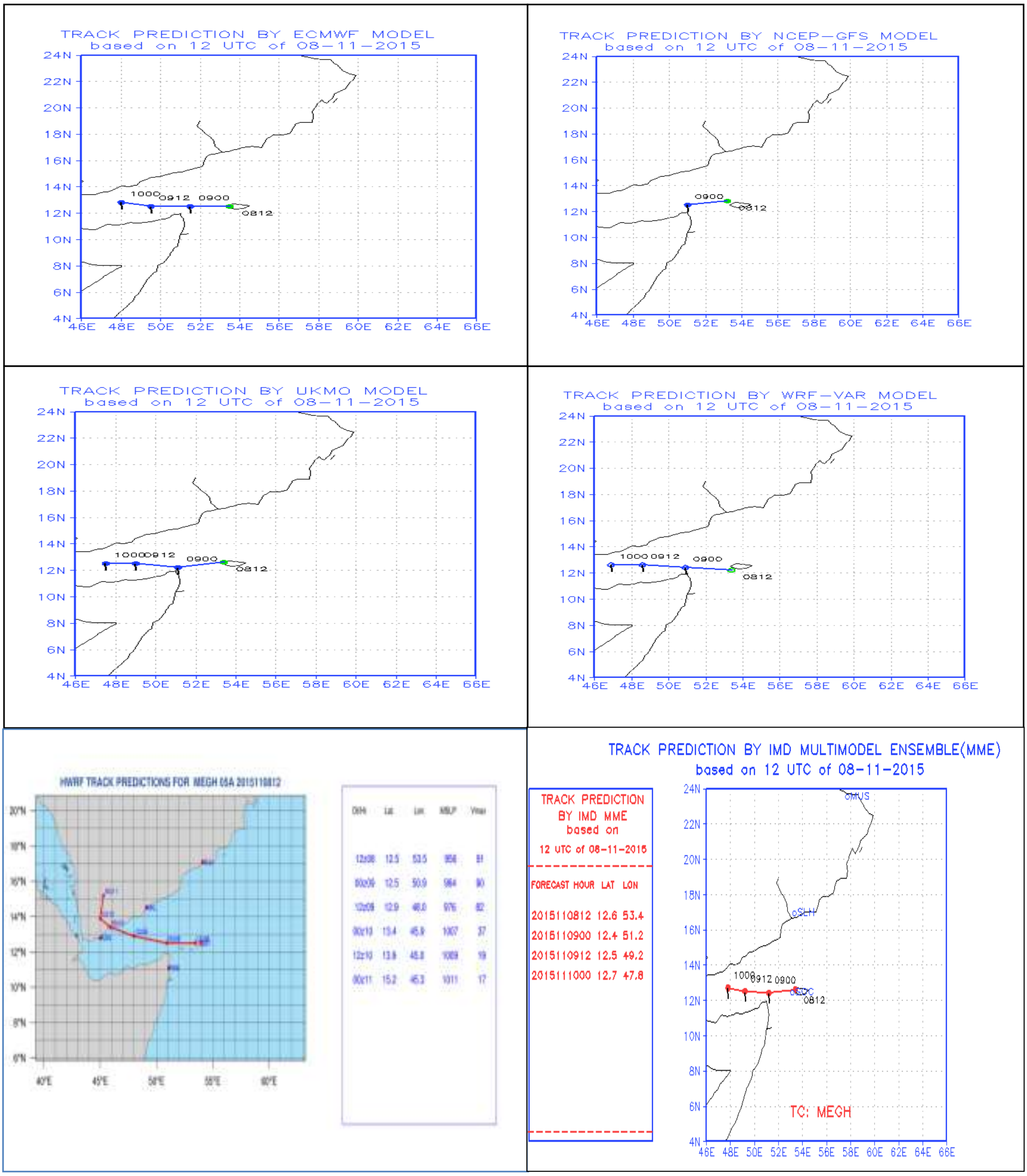


Fig.17 (h). Track prediction by NWP models based on 1200 UTC of 08.11.2015

HWRF model continued to predict landfall over Yemen coast near 13.4^{0}N between 0500 UTC to 1200 UTC of 10th based on initial conditions of 0000 UTC of 9th and 10th.

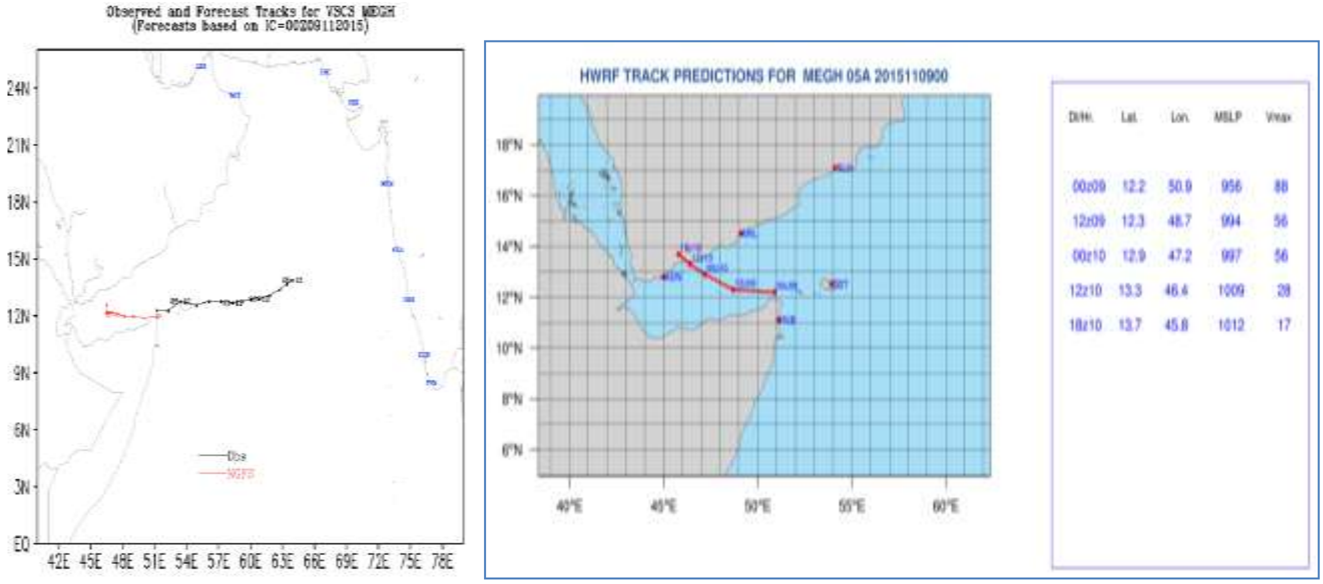


Fig.17 (i). Track prediction by NWP models based on 0000 UTC of 09.11.2015

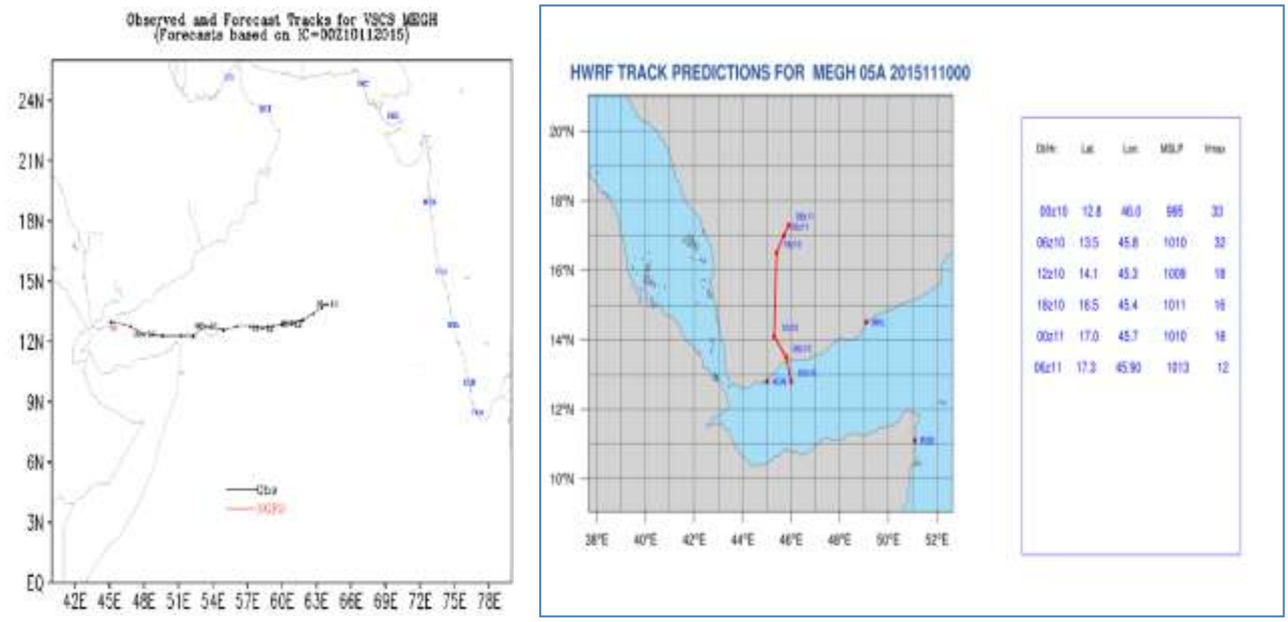


Fig. 17 (j). Track prediction by NWP models based on 0000 UTC of 10.11.2015

The Ensemble Prediction System (EPS) based track and strike probability with initial conditions of 1200 UTC of 7th to 9th November are presented in fig. 18 (a-c). All the members suggested westwrads to west-southwestwards movement. Most of the models suggested movement across Gulf of Aden with low probability of landfall over Yemen.

Hence to summarise, all models unanimously predicted the west-southwestwards movement towards Gulf of Aden. Only HWRF model consistently predicted the landfall of the system over Yemen from 1200 UTC of 5th itself near 13.5^{0}N between 0000 to 1200 UTC of 10th.

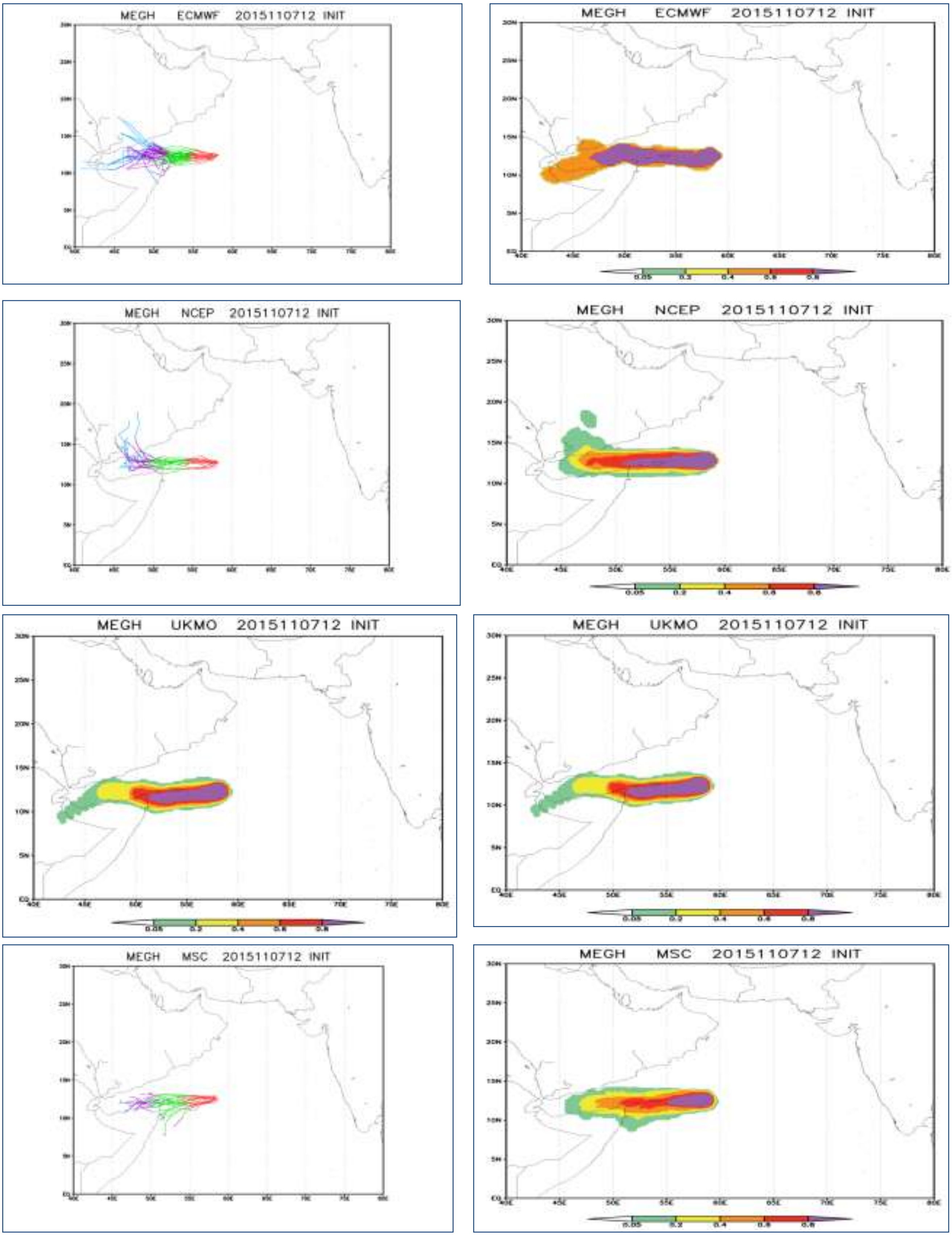


Fig. 18 (a). Track prediction and strike probability by EPS based on 1200 UTC of 7th November

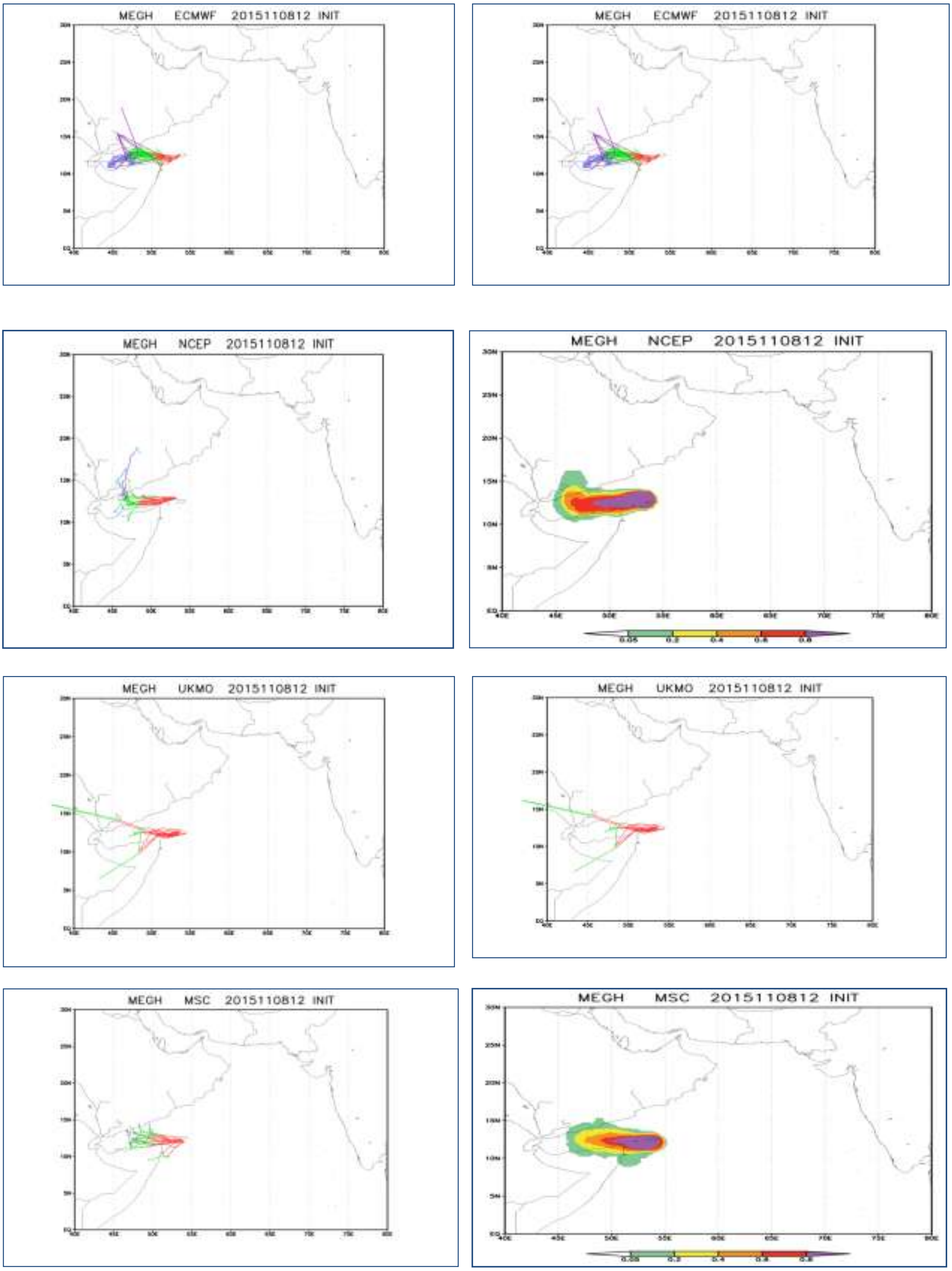


Fig. 18 (b). Track prediction and strike probability by EPS based on 1200 UTC of 8th November

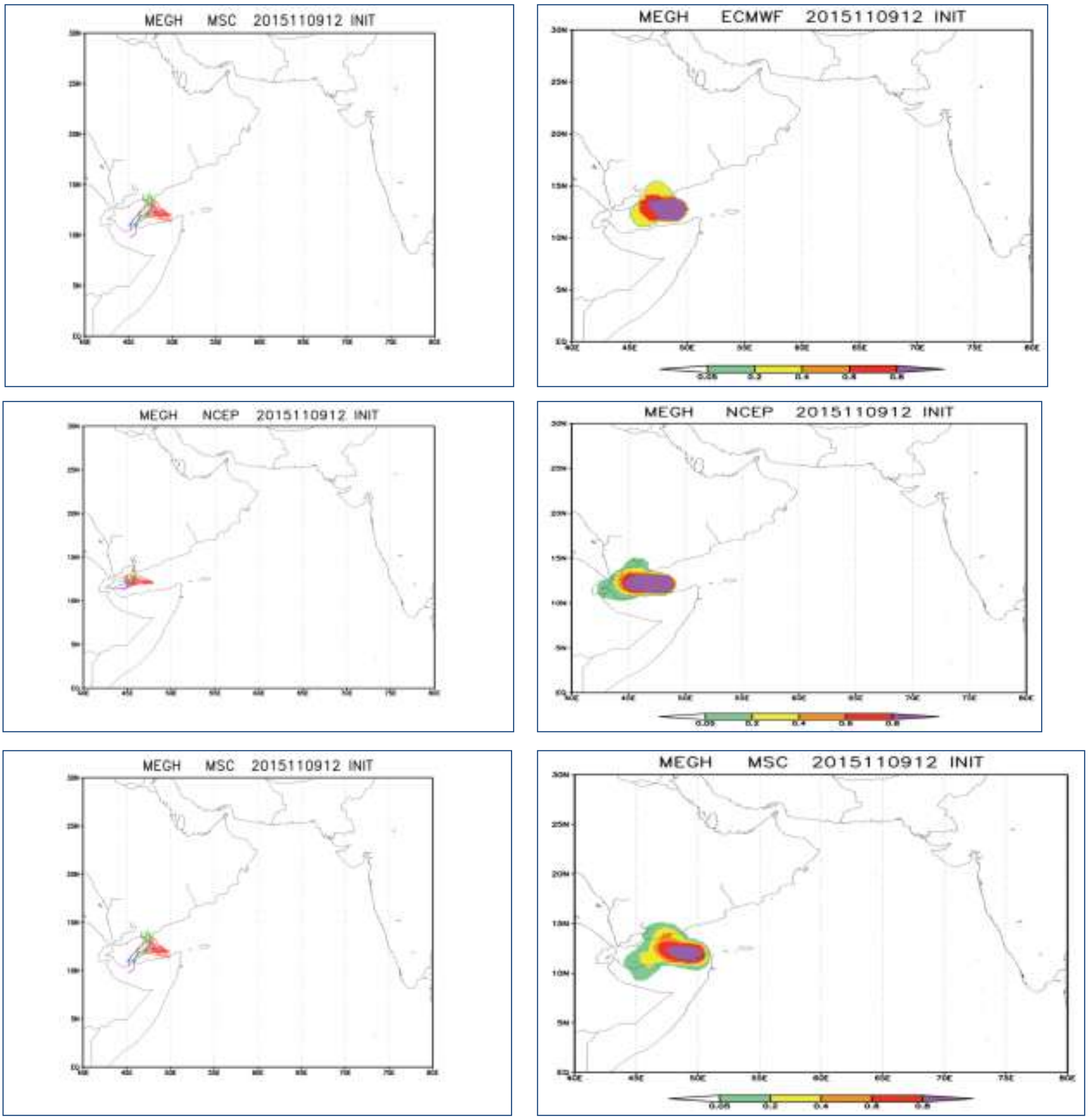


Fig. 18 (c). Track prediction and strike probability by EPS based on 1200 UTC of 9th November

The average track forecast errors (Direct Position Error) in km at different lead time (hr) of various models are given in Table2. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors were minimum for HWRF for 24 and 48 hours and UKMO for 72 hours laed period.

Table-2. Average track forecast errors (Direct Position Error) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	120hr
IMD-GFS	79(6)	88(5)	101(5)	185(5)	281(4)	349(4)	22(1)	59(1)	-	-
IMD-WRF	81(8)	132(8)	160(8)	215(7)	263(6)	304(5)	-	-	-	-
JMA	172(7)	165(6)	194(6)	205(5)	219(4)	343(4)	364(3)	-	-	-
NCEP	61(8)	80(7)	81(7)	81(7)	116(6)	118(3)	-	-	-	-
UKMO	45(8)	80(8)	103(8)	105(7)	84(6)	77(5)	105(3)	87(3)	143(2)	285(1)
ECMWF	44(8)	77(8)	128(8)	163(7)	205(6)	246(5)	336(3)	427(3)	511(2)	466(2)
IMD-MME	52(8)	69(8)	101(8)	92(7)	111(6)	139(5)	210(3)	297(3)	327(2)	358(2)
HWRF	36 (19)	47 (17)	57 (15)	65 (13)	77 (12)	109(10)	121(8)	130(6)	190(4)	229(3)
NGFS		89.3(4)		145.6 (3)		253.9 (2)		221.7 (1)		
NCUM		124.4 (4)		176.8 (3)		267.3 (2)		-		
NGEFS		76.9 (4)		154.6 (3)		260.9 (2)		282.3 (1)		

Figure given in parantheses is number of forecasts verified

- : No model forecast

10.3 Landfall forecast errors

As HWRF model only predicted landfall, the landfall forecast errors of HWRF model are presented in Table 3(a&b). It was less than 100km upto lead period of 84 hours and less than 200 km for 96-120 hours lead period. Landfall time error was less than 3 hours upto 72 hours lead period except 48 hours lead period.

Table 3a : Landfall Forecast Position Error (in km) of IMD-HWRF Model

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr	120 Hr
HWRF	33	55	46	38	74	95	99	112	145	181

Table 3b : Landfall Forecast Time Error (in hrs) of IMD-HWRF Model

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr	120 Hr
HWRF	-3.0	-3.0	3.0	-6.0	3.0	-3.0	-6.0	-9.0	-6.0	-6.0

10.4 Intensity forecast errors

The Average errors of intensity (wind) forecast by SCIP model and HWRF model are presented in Table 4. The verification of rapid intensification (RI) and rapid weakening (RW) predicted by HWRF model and RII model developed by IMD are presented in Table 5 (a&b). The average absolute errors (AAE) and Root Mean Square

Errors (RMSE) of HWRF model was significantly less than that of SCIP model. Considering the individual deterministic models, the performance of HWRF was the best upto 60 hours lead period and beyond that UKMO provided the best guidance.

ESCS Megh underwent Rapid Intensification from 0000 UTC of 7th November to 0000 UTC of 8th November. It can be seen from the table that RI index failed to predict RI. Comparing the forecast errors with the performance of dynamical statistical cyclone intensity prediction (SCIP) model and rapid intensification index (RI) model developed by IMD, it is observed that both these models failed to predict the rapid intensification of the system. It is worth mentioning that both these models consider external dynamical features/ environmental parameters and do not consider the internal dynamics of the system. Hence, this analysis confirms that intensity forecast can be improved significantly by considering both external and internal dynamics in the numerical weather prediction (NWP) models and dynamical statistical models. For this purpose, therefore there is need for observations from the core of the system for assimilation in numerical models.

Considering the individual deterministic models, the performance of Hurricane Weather Research Forecast (HWRF) model was better in predicting the intensification of the system. However, it could not be implemented operationally due to lack of confidence, as the model has been made operational with higher resolution and without ocean coupling for Indian region in 2015 only. Hence there is scope to improve intensity forecast by HWRF model with more data assimilation, high resolution and ocean atmosphere coupling.

Considering the individual deterministic models, the performance of high resolution Hurricane Weather Research Forecast (HWRF) model was better in predicting the intensification of the system.

Table-4 Average absolute errors (AAE) and Root Mean Square errors (RMSE) in knots of SCIP model and HWRF model

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	120hr
IMD-SCIP (AAE)	12.7 (6)	21.5 (6)	31.3 (6)	38.8 (6)	43.7 (6)	48.6 (5)	51.7 (3)	40.0 (3)	32.5 (2)	25.0 (1)
HWRF (AAE)	12 (19)	12 (17)	13 (15)	11 (13)	12 (12)	13 (10)	12 (8)	14 (6)	18 (4)	12 (3)
IMD-SCIP (RMSE)	14.2 (6)	23.3 (6)	34.5 (6)	42.4 (6)	46.3 (6)	50.7 (5)	52.4 (3)	42.5 (3)	34.5 (2)	25.0 (1)
HWRF (RMSE)	13.5 (19)	13.6 (17)	15 (15)	13.7 (13)	14.4 (12)	16.2 (10)	16 (8)	15.8 (6)	20.8 (4)	15 (3)

Figure given in parantheses is number of forecasts verified

Table-5(a) Verification of Rapid Intensification/Weakening by HWRF model

Date/ Time	HWRF Forecast						Actual 24 hr change in wind(kt)		
	Forecast 24 hr change in wind forecast (kt)			RI / RW Forecast					
	0-24	24-48	48-72	0-24	24-48	48-72	0-24	24-48	48-72
28 Oct./ 1200	28	32	18	**No RI**	**RI**	**No RI**	25	60	-10
29 Oct./ 0000	40	15	12	**RI**	**No RI**	**No RI**	55	20	-5
29 Oct./ 1200	26	21	3	No RI	**No RI**	**No RI**	60	-10	-5
30 Oct./ 0000	19	-3	-6	**No RI**	**No RI**	**No RI**	20	-5	-5
30 Oct./ 1200	-12	-3	-46	**No RI**	**No RI**	RW	-10	-5	-15
31 Oct./ 0000	0	3	-77	**No RI**	**No RI**	**RW**	-5	-5	-35
31 Oct./ 1200	10	-16	-78	**No RI**	**No RI**	**RW**	-5	-15	-45
01 Nov./ 0000	-3	-40	-49	**No RI**	**RW**	**RW**	-5	-35	-40
01 Nov./ 1200	-17	-51		**No RI**	**RW**		-15	-45	
02 Nov./ 0000	-40	-47		**RW**	**RW**		-35	-40	

RI: Rapid Intensification (Increase in wind speed by 30 kts in 24 hours)
RW: Rapid Weakening (decrease in wind speed by 30 kts in 24 hours)
Correct RI/RW and no RI/RW predictions are highlighted.

Table-5b Verification of Rapid Intensification/ Weakening by SCIP and RII model

Date/Time	Forecast 0-24 hr change in wind speed forecast (kt) by SCIP	Forecast RI Probability (%)	Actual 0-24 hr change in Wind speed (kt)
05 Nov./ 0000	**2**	5.2% (Very Low)	20
05 Nov./ 1200	**1**	9.4% (Very Low)	10
06 Nov./ 0000	**1**	9.4% (Very Low)	0
06 Nov./ 1200	-6	5.2% (Very Low)	15
07 Nov./ 0000	20	5.2% (Very Low)	40
07 Nov./ 1200	-7	9.4% (Very Low)	30
08 Nov./ 0000	-	-	
08 Nov./ 1200	-	-	

Correct RI predictions are highlighted.

11. Bulletins issued by IMD

11.1 Bulletins issued by Cyclone Warning Division, New Delhi

IMD continuously monitored, predicted and issued bulletins containing track & intensity forecast at +06, +12, +18, +24, +36, +48, +60, +72, +84, +96, +108 and +120 hrs or till the system weakened into a low pressure area. The above structured track and intensity forecasts were issued from the stage of deep depression onwards. The cone of uncertainty in the track forecast was also given for all cyclones. The radius of maximum wind and radius of ≥28 knots, ≥34 knots, ≥50 knots and ≥64 knots wind in four geographical quadrants of cyclone was also issued for every six hours. The graphical display of the observed and forecast track with cone of uncertainty and the wind forecast for different quadrants were uploaded in the RSMC, New Delhi website (http://rsmcnewdelhi.imd.gov.in/) regularly. The prognostics and diagnostics of the systems were described in the RSMC bulletins and tropical cyclone advisory bulletins. The TCAC bulletin was also sent to Aviation Disaster Risk Reduction (ADRR) centre of WMO at HongKong. Tropical cyclone vitals were prepared every six hourly from deep depression stage onwards and provided to various NWP modeling groups in India for cyclone vortex generation/ relocation. Bulletins issued by Cyclone Warning services of IMD in association with the system are given in Table 6 (a-b)

Table-6a: Bulletins issued by Cyclone Warning Division, New Delhi

S.No.	Bulletin	No. of Bulletins	Issued to
1	National Bulletin	18	1. RSMC, New Delhi website 2.a. 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, Dir. Indian Railways, Indian Navy, IAF, Chief Secretary- Kerala, Karnataka, Goa, Maharashtra, Gujarat & Administrator, Daman & Diu and Dadra Nagar Haveli 3. Email's to a. Modelling Groups- IIT-Delhi and Bhubaneswar, NCMRWF, INCOIS.
2	RSMC Bulletin	43	1. RSMC, New Delhi website 2. All WMO/ESCAP member countries and Yemen & Somalia through Global Telecommunication System (GTS) and E-mail. 3. Indian Navy, IAF, by E-mail
3	Tropical Cyclone Advisory Centre Bulletin (Text & Graphics)	21	1. Met Watch offices in Asia Pacific regions though GTS to issue Significant Meteorological information (SIGMET) for International Civil Aviation

			2. WMO's Aviation Risk Reduction (ADRR), HongKong through ftp 3. RSMC website
4	TC vitals	21	Modelling group-NCMRWF, IIT, INCOIS, IMD NWP through ftp and email for creation/relocation of synthetic vortex in NWP Models
5	Quadrant Wind radii	21	Modelling group- NCMRWF, IIT, INCOIS, IMD NWP by email
6	Press Release	3	RSMC, New Delhi website and Press & electronic media by e-mail.

Table-6b: Bulletins issued by ACWC Mumbai, CWC Ahmedabad

S.No.	Type of Bulletin Number	No. of Bulletins issued by ACWC Mumbai	No. of Bulletins issued CWC Ahmedabad
1.	Sea Area Bulletins	12	
2.	Coastal Weather Bulletins	12	05
3.	Fishermen Warnings issued	NIL	
4.	Port Warnings	09	03
5.	Heavy Rainfall Warning	NIL	
6.	Gale wind Warning	NIL	
7.	Storm Surge Warning	NIL	
8.	Information & Warning issued to State Government and other Agencies	02	

12. Operational Forecast Performance of IMD

Following are the salient features of the bulletins issued by IMD:

i. **4th November:** Forecast of formation of depression during next 24 hours. Depression formed over eastcentral AS at 0000 UTC of 5th November.

ii. **5th November/0000 UTC**: The system would move west-northwestwards and intensify into a DD during next 24 hours. No Indian coast would be affected by this system.

iii. **5th November/0600 UTC**: Intensification into CS during next 12 hours and thereafter it would move west-southwestwards towards Gulf of Aden. No Indian coast would be affected by the system. The system intensified into a CS at 1200 UTC of 5th.

iv. **5th November/1200 UTC:** Intensification into SCS during next 24 hours and movement towards Gulf of Aden. System intensified into SCS on 0900 UTC of 7th.

v. **6th November/0000 UTC:** Forecast of west-southwestwards movement and intensification into an SCS during next 24 hrs. It would continue to move west-southwestwards towards Gulf of Aden. System intensified into SCS at 0900 UTC of 7th.

vi. **7th November/ 0600 UTC:** The system would move west-northwestwards towards Gulf of Aden, reaching close to northern tip of Somalia around 0600 UTC of 9th November. The system would intensify further into a severe cyclonic storm during next 12 hours. It would maintain its intensity till 0000 UTC of 8th November and weaken gradually thereafter. It would cross Yemen coast near 13.4^{0}N/46.5^{0}E around 0600 UTC of 11th November as a depression. The system crossed Yemen coast near 13.4^{0}N/46.1^{0}E around 0900 UTC of 9th November.

vii. **7th November/ 0900 UTC:** Intensification into VSCS during next 12 hours. It would maintain its intensity till 0600 UTC of 8th November and weaken gradually thereafter. The system intensified into VSCS at 1500 UTC of 7th and started weakening from 1200 UTC of 8th November.

viii. **8th November/0000 UTC**: It would cross Yemen coast between latitude 13 and 14 degree north around 1200 UTCof 10th November.as a CS.

ix. **9th November/0300 UTC:** It would move west-southwestwards initially & then west-northwestwards across Gulf of Aden, weaken gradually and cross Yemen coast between latitude 13 & 14 degree north around 1200 UTC of 10th November as an **SCS**.

x. **10th November/0300 UTC:** It would cross Yemen coast near 13.2 degree north around 0600 UTC of 10th November.as a CS. The system crossed Yemen coast as a DD near 13.4 degree North/ 46.1 degree East at 0900 UTC of 10th November.

12.1 Genesis Forecast

i. **4th November:** Forecast of formation of depression during next 24 hours. Depression formed over eastcentral AS at 0000 UTC of 5th November.

ii. **5th November/0600 UTC**: Intensification into CS during next 12 hours and thereafter it would move west-southwestwards towards Gulf of Aden. The system intensified into a CS on 1200 UTC of 5th.

12.2. Operational landfall forecast error and skill

The operational landfall errors and skill are presented in Table 7. The landfall point error (LPE) has been about 78, 78 and 70 km against long period average (LPA) of 59, 86 and 109 km for 24, 48 and 72 hours lead period respectively. The LPE has been significantly lower than the LPA as for all lead periods beyond 24 hours. Upto 24 hours lead period, the LPE was slightly higher than the LPA. The landfall time error (LTE) has been 2.0, 3.0 and 3.0 hours against the LPA of 3.4, 4.4 and 1.8 hours for 24, 48 and 72 hours lead period respectively. The LTE had been slightly lower for 24 and 48 hours lead period and higher than LPA for 72 hours lead period. An example of forecast track along with cone of uncertainty issued at 0600 UTC of 7th November and observed track is presented in fig.19.

Table 7: Landfall Point and Time Error in association with ESCS Megh

Lead Period (hrs)	Base Time	Landfall Point (degrees)		Landfall Time (hours)		Operational Error		LPA error (2010-14)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	Absolute LTE (hours)
12	0918	13.2^0N/ 45.5^0E	13.4^0N/ 46.1^0E	10/0500	10/0900	44.0	-4.0	31.6	1.8
24	0906	13.3^0N/ 45.6^0E	13.4^0N/ 46.1^0E	10/0700	10/0900	77.8	-2.0	58.5	3.4
36	0818	13.5^0N/ 46.8^0E	13.4^0N/ 46.1^0E	10/0900	10/0900	11.0	0.0	81.6	5.0
48	0806	13.4^0N/ 46.2^0E	13.4^0N/ 46.1^0E	10/1200	10/0900	77.8	+3.0	85.7	4.4
60	0718	13.5^0N/ 46.8^0E	13.4^0N/ 46.1^0E	10/0900	10/0900	56.1	0.0	76.9	3.5
72	0706	13.4^0N/ 46.5^0E	13.4^0N/ 46.1^0E	10/1200	10/0900	69.6	+3.0	108.5	1.8

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

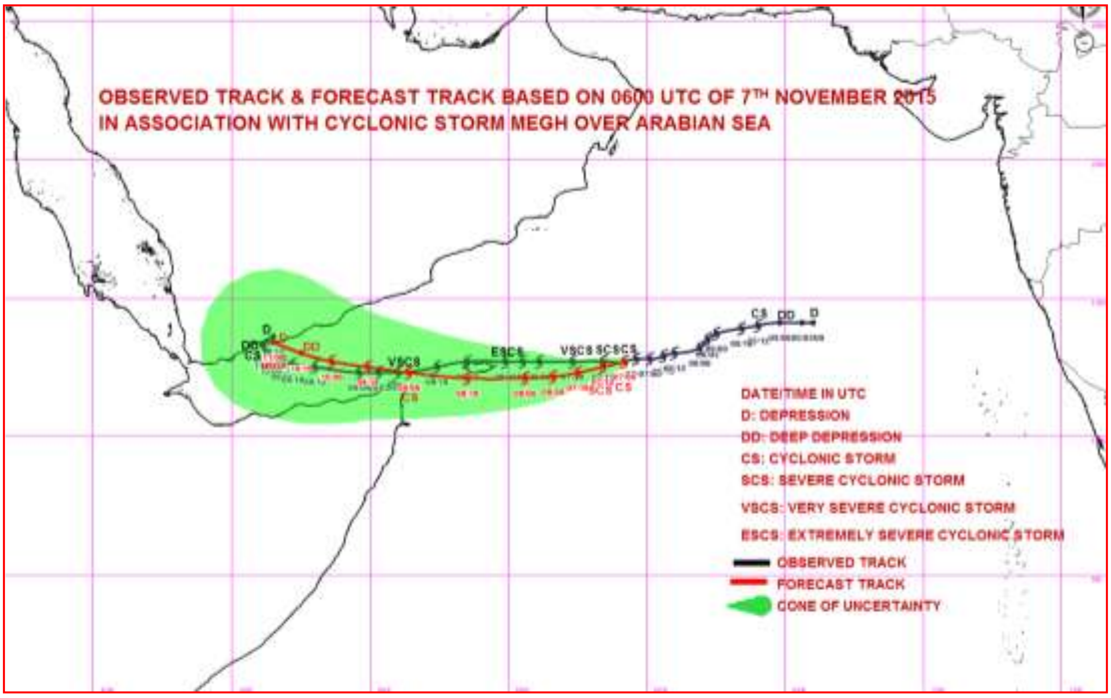


Fig.19. An example of forecast track along with cone of uncertainty issued at 0600 UTC of 7th November 2015 and observed track

12.3 Operational track forecast error and skill

The operational average track forecast errors and skills compared to climatology and persistence (CLIPER) forecasts are shown in Table 8. The track forecast errors for 24, 48 and 72 hours lead period have been 98, 133 and 169 km against the LPA of 107, 165 and 230 km respectively. The track forecast errors have been significantly lower than the LPA for 48 and 72 hours lead period and almost same as LPA for 24 hour forecast period.

Table 8: Track forecast errors and skill in association with ESCS Megh

Lead Period (hrs)	N	Track forecast error (km)		Skill (%)	LPA (2010-14)	
		Operational	CLIPER		Track forecast error (km)	Skill (%)
12	20	57.4	82.0	30.0	61.8	39.2
24	18	98.3	146.2	32.8	106.8	46.1
36	16	128.5	198.1	35.1	132.4	56.6
48	14	133.2	244.8	45.6	164.6	62.3
60	12	153.3	321.2	52.3	188.9	67.1
72	9	169.2	332.8	49.2	230.1	68.1
84	5	174.9	501.7	65.1	-	-
96	5	262.4	526.8	50.2	-	-
108	4	257.7	667.1	61.4	-	-
120	2	228.1	828.0	72.5	-	-

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

12.3 Operational Intensity forecast error and skill

The operational intensity (wind) forecast errors and skill compared to persistence forecast in terms of absolute error (AE) and root mean square error (RMSE) are presented in Table 9. The operational AE in intensity forecast has been about 17, 31 and 40 knots against LPA of 11, 16 and 18 knots for 24, 48 and 72 hours lead period. The forecast error has been higher than LPA for 24, 48 hours and 72 hours lead period. Similarly, operational RMSE in intensity forecast has been about 23, 38 and 42 knots against LPA of 15, 20 and 22 knots for 24, 48 and 72 hours lead period respectively. Higher errors in intensity forecast is mainly attributed to rapid intensification of the system on 07th November, which could not be predicted operationally as well as by the numerical models. The Rapid Intensification (RI) index developed by IMD could not predict the rapid intensification as seen from the table 5b.

Considering the variation of intensity error w.r.t. the lead periods, the AE gradually increased with increase in lead period from 12 hours (8 kts) to 96 hours (30 kts) lead period. It then decreased gradually with increase in lead period upto 120 hours (8 kts). Similarly, the RMSE increased from 12 hours (10 kts) to 96 hours (38 kts) and then decreased towards 120 hours (4 kts) lead period. This is mainly due to the fact that IMD could very well predict the trend in intensification and as well as the weakening of the system while moving towards Yemen coast. But the forecast for rapid intensification could not be predicted satisfactorily leading to higher errors in 48-96 hours lead period.

Skill in operational intensity forecast error in terms of AE has been 31, 46 and -03% against LPA of 40, 55 and 68% for 24, 48 and 72 hours lead period. In terms of

RMSE, it was 22, 48 and 18% against LPA of 45, 60 and 72% for 24, 48 and 72 hours lead period. As discussed in previous paragraph, the skill has been less than the LPA for all forecast times due to lower accuracy in prediction of rapid intensification of the system.

Operationally rapid intensification could not be predicted. However, rapid weakening could be predicted to a large extent w.r.t. time of commencement of weakening and the rate of weakening.

Table 9: Intensity forecast errors and skill in association with ESCS Megh

Lead Period (hrs)	N	Operational Error (kts)		LPA Error (kts) (2010-14)		Operational skill against Persistence (%)		LPA Skill against Persistence (2010-14) (%)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	20	8.0	10.3	7.2	10.1	13.1	15.2	26.7	34.6
24	18	17.2	22.7	11.1	14.6	30.6	22.1	40.2	45.2
36	16	25.1	32.1	14.3	18.5	14.0	35.6	49.3	53.1
48	14	31.1	38.1	15.8	20.3	45.6	47.5	55.4	60.4
60	12	35.9	38.1	16.2	19.5	31.7	47.5	63.5	69.1
72	9	40.1	41.7	17.7	21.9	-3.0	18.3	67.7	72.8
84	5	43.9	43.8	-	-	-9.9	0.8	-	-
96	5	30.4	32.4	-	-	50.2	52.0	-	-
108	4	16.8	20.8	-	-	84.5	81.5	-	-
120	2	3.2	4.0	-	-	97.6	96.9	-	-

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

12.4. Adverse weather forecast verification

No adverse weather like heavy rainfall, gale wind and storm surge was likely over the west coast of India, hence no warning was issued. No observations were available from Yemen to verify the gale winds forecast at the time of landfall. However, the forecast of gale winds issued by IMD is verified with the satellite T. No at the time of landfall and is given in Table -10

Table 10. Verification of Wind Forecast at the time of landfall

Date/ Time(IST)	Lead period	Wind at the time of landfall (kts)		Error (kts)
		Forecast	Actual	
0918	12	55	30	25
0906	24	60	30	30
0818	36	60	30	30
0806	48	55	30	25
0718	60	35	30	5
0706	72	35	30	5

13. Summary and Conclusion:

The ESCS Megh formed from a low pressure area over Lakshadweep and neighbourhood on 4th November and concentrated into a depression in the morning of 5th November. The system underwent rapid intensification reaching the peak intensity of Extremely Severe Cyclonic Storm at 0600 UTC of 8th. It moved west-southwestwards throughout its life cycle till landfall. It rapidly weakened over Gulf of Aden from 1800 UTC of 9th to 0600 UTC of 10th and crossed Yemen coast near latitude 13.4^{0}N/longitude 46.1^{0}E around 0900 UTC of 10th November as a deep depression.

IMD utilised all its resources to monitor and predict the genesis, track and intensification of ESCS Chapala. The forecast of its genesis (formation of Depression) on 5th November, its track, intensity, point & time of landfall, were predicted well with sufficient lead time. Its movement away from Indian coast was predicted from day-1 itself on 5th November.

For 24, 48 and 72 hrs lead period, the operational landfall point error was 78, 78 & 70 km, track forecast error was 98, 133 & 169 km and intensity forecast error based on absolute error was 17, 31 & 40 kts. Accuracy in track and landfall forecast errors was higher and errors were below long period average. However, intensity forecast errors were higher mainly due to instability to predict rapid intensification and rapid weakening.

Following lessons were learnt on the monitoring and prediction of the system:

- Due to lack of surface observations over Gulf of Aden and adjoining westcentral Arabian Sea, there were limitations in estimation of location and intensity of the system over the region. There were no observations along Yemen coast and northern tip of Somalia. Observations from Socotra Island were also not available. The forecast was mainly based on observations from various satellite products.
- No dynamical-statistical model could predict the rapid intensification and rapid weakening of the system. It may be mainly because of lack of observations and the fact that the deterministic models consider external dynamical features/ environmental parameters and do not consider the internal dynamics of the system.
- The HWRF model performance was better in predicting the intensification and weakening of the system including rapid intensification/weakening unlike other global models.

14. Acknowledgements:

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