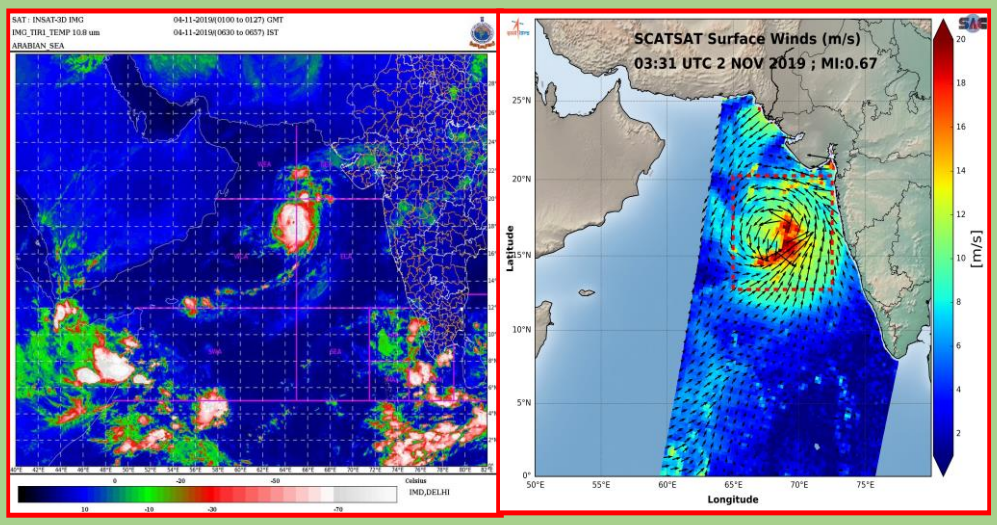
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Extremely Severe Cyclonic Storm "MAHA" over the Arabian Sea (30th October – 7th November, 2019): A Report



(a) INSAT 3D enhanced colored IR imagery based on 0100 UTC of 04th November and (b) SCAT SAT based sea surface winds at 0330 UTC of 2nd November

Cyclone Warning Division

India Meteorological Department

New Delhi

Extremely Severe Cyclonic Storm "MAHA" over the Arabian Sea (30th October-7th November, 2019)

1. Brief Life History:

- The Extremely Severe Cyclonic Storm (ESCS) 'MAHA' originated as a Low Pressure Area (LPA) over Equatorial Indian Ocean off south Sri Lanka coast in the forenoon (0600 UTC) of 28th October.
- It lay as a Well Marked Low pressure area (WML) over Comorin Area & adjoining Equatorial Indian Ocean in the early morning (0000 UTC) of 29th October.
- Moving west-northwestwards, under favourable environmental conditions, it concentrated into a Depression (D) over Maldives-Comorin Area in the early morning (0000 UTC) of 30th October. Moving northwestwards, it intensified into a Deep Depression (DD) over Lakshadweep and adjoining Southeast Arabian Sea & Maldives Area in the afternoon (0900 UTC) of 30th October.
- It moved further northwestwards, intensified into a Cyclonic Storm (CS) 'MAHA' in the evening (1200 UTC) of 30th October over Lakshadweep and adjoining Southeast Arabian Sea & Maldives Area and further into a Severe Cyclonic Storm (SCS) in the forenoon (0600 UTC) of 31st October over Lakshadweep and adjoining Southeast Arabian Sea. It moved across Lakshadweep Islands and emerged into eastcentral (EC) Arabian Sea in the same night (1500 UTC).
- Moving northwestwards and maintaining intensity of SCS for 75 hours, it further intensified into Very Severe Cyclonic Storm (VSCS) in the afternoon (0900 UTC) of 03rd November over eastcentral Arabian Sea (EC AS). Then it moved west-northwestwards and further intensified into an Extremely Severe Cyclonic Storm (ESCS) in the early morning (0000 UTC) of 04th November over EC & adjoining Westcentral (WC) AS.
- Maintaining intensity of ESCS for 27 hours, it entered into a COL region in which it moved nearly north-northwestwards. Subsequently, it came under the influence of colder Sea Surface Temperatures and increased vertical wind shear and weakened into a VSCS in the morning (0300 UTC) of 05th November over WC & adjoining EC AS.
- Under the influence of a mid-latitude westerly trough it started moving eastwards from the evening (1200 UTC) of 05th November. At this period, as it came under the influence of increased vertical wind shear, it weakened into a Severe Cyclonic Storm (SCS) in the early morning (0000 UTC) of 06th November over EC and adjoining Northeast (NE) AS.
- Continuing the eastward movement, it further weakened into a CS in the evening (1200 UTC) of 06th November over EC and adjoining NE AS and into a DD in the early morning (0000 UTC) of 07th November over EC and adjoining NE AS.
- Eastward movement continued as the system further weakened into a D in the forenoon (0600 UTC) of 07th November over EC and adjoining NE AS and into a WML over NE AS & adjoining coastal Saurashtra in the evening (1200 UTC) of 07th November.

- The observed track of the system during 30th October– 07th November is presented in **Fig.1a**. Best Track parameters associated with the system are presented in **Table1**.
- ESCS MAHA co-existed with SuCS KYARR during 30th October – 2nd November and with VSCS BUL BUL over the Bay of Bengal during 5th – 7th November. The observed track of MAHA with KYARR and BULBUL are presented in **Fig.1(b-c)**.

2. Salient Features:

The salient features of the system were as follows:

i. It was the fourth Cyclonic Storm and also the fourth in severe category after the Super Cyclonic Storm 'KYARR' and Very Severe Cyclonic Storms 'VAYU' & 'HIKAA' developing over the Arabian Sea during the year 2019 against the normal (1891-2018) of 1 per year.

ii. Over EC AS, it followed the track of SuCS KYARR and intensified over this region, owing to favourable vertical wind shear and moderately favourable Tropical Cyclone Heat Potential (of the order of 100 - 120 KJ / cm^2) succeeding the passage of KYARR.

iii. A total of 19 Depressions formed over Southeast Arabian Sea & Maldives-Comorin Area (64°E-81°E & 05°N-12°N) **[Fig.2 (a)]** in the month of October during 1891-2018, out of which only 7 intensified into Cyclonic Storms and 6 into Severe Cyclonic Storms **[Fig.2 (b)]**, remaining 6 could not intensify above Depression stage

iv. Out of total 13 CS/SCS having genesis over the above area, 2 Cyclonic Storms made Landfall over Gujarat Coast, 1 Severe Cyclonic Storm over Maharashtra Coast, 1 CS over Somalia and 3 CS/SCS over Yemen-Oman coast. Rest 6 CS & SCS dissipated over Sea during 1891-2018.

v. It had northwestward track upto ESCS stage, followed by a north-northwestward and then eastward track prior to weakening over the Sea with total length of 2910 km. It was mainly steered by the winds at the periphery of an anticyclone in middle & upper tropospheric levels to the northeast of the system centre prior to re-curvature and by the southern periphery winds of a mid-latitude westerly trough, after the re-curvature.

vi. The system rapidly intensified from depression to cyclonic storm within 12 hours of it's formation on 30th October, under favourable environmental conditions. It also exhibited rapid intensification during 3rd evening (1200 UTC) to 4th early morning (0000 UTC) registering an increase of 30 kts in maximum sustained wind (MSW) in 24 hours. This rapid intensification is mainly attributed to low vertical wind shear (5-10 kt) over EC AS during that period and increased low level vorticity ($200X10^{-5}$ sec^{-1}) near system centre. It also exhibited rapid weakening from 5th evening onwards (1200 UTC) till 7th November. From 5th early morning, the system entered into unfavourable environment having moderate vertical wind shear (15-20 kt) and lower sea surface temperature (24-26^{0}C) & ocean thermal energy (20-40 KJ/cm^2).

vii. The peak MSW of the cyclone was 175-185 kmph (100 knots) gusting to 205 kmph during 1200 UTC to 2100 UTC of 04th November over the Westcentral and adjoining Eastcentral Arabian Sea. The lowest estimated central pressure was 956 hPa during 1200 UTC to 2100 UTC of 04th November**.**

viii. A slight weakening (by 5 knots) for a brief period was noticed during 1200 UTC of 01st November to 0900 UTC of 02nd November probably owing to the interaction with the remnant vortex associated with KYARR.

ix. 'MAHA' weakened into a Depression over the EC and adjoining NE AS at 0600 UTC of 07th November owing to increased vertical wind shear and colder SSTs.

x. The system maintained the Severe Cyclonic Storm intensity for 75 hours (0600 UTC of 31st October to 0900 UTC of 03rd November) whereas it maintained intensities of ESCS, VSCS and CS for only 27,15 and 18 hours respectively.

xi. The life period (D to D) of the system was 198 hours (08 days & 12 hours) against long period average (LPA) (1990-2013) of 107 hours for VSCS category over the AS during post monsoon season.

xii. It moved with normal speed as 12 hour average translational speed was about 14.0 kmph against LPA (1990-2013) of 14.3 kmph for VSCS category over north Indian Ocean.

xiii. The Velocity Flux, Accumulated Cyclone Energy (a measure of damage potential) and Power Dissipation Index (a measure of loss) were 18.20x10^2 knots, 12.3X10^4knots^2 and 8.95X10^6 knots^3 respectively against long period average during 1990-2013 of 2.12 X10^2 knots, 1.4 X 10^4 knots^2 and 1.0 X10^6 knots^3 respectively over the Arabian Sea.

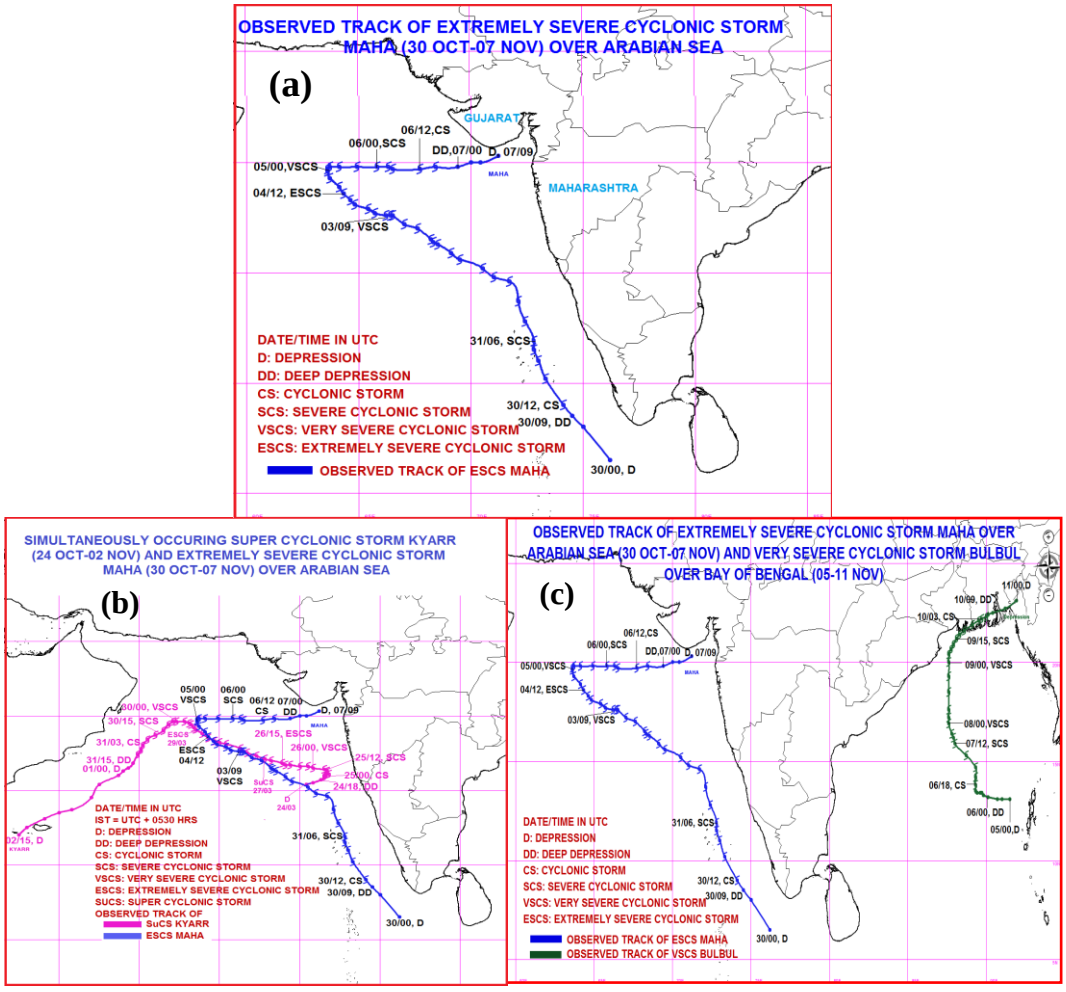


Fig.1: (a) Observed track of ESCS 'MAHA' over the Arabian Sea (30th October–07th November, 2019); (b) its track along with SuCS KYARR (24th October – 2nd November & (c) along with VSCS Bulbul (05th-11th November)

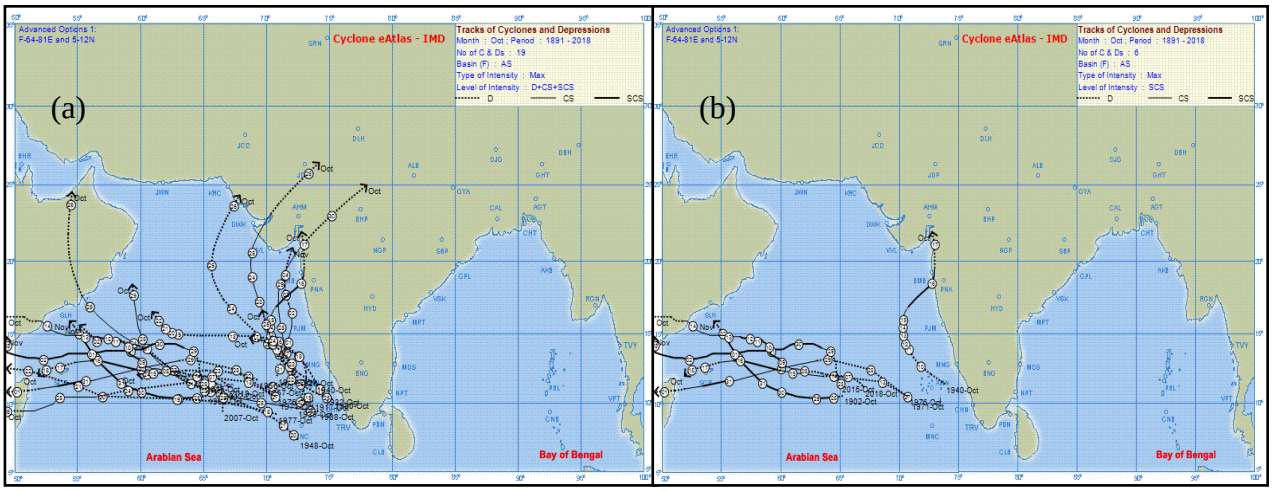


Fig.2: Tracks (during 1891-2018) of (a) cyclonic disturbances having genesis over the southeast AS & Comorin-Maldives Area (64°E-81°E & 05°N-12°N) and (b) severe cyclonic storms in the month of October.

Table 1: Best track positions and other parameters of the Extremely Severe Cyclonic Storm, 'MAHA' over the Arabian Sea during 30th Oct-07th Nov, 2019

Date	Time (UTC)	Centre		C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
		Lat. 0 N	Long. 0 E					
30/10/2019	0000	6.5	76.2	1.5	1003	25	03	**D**
	0300	8.0	75.0	1.5	1003	25	03	D
	0600	8.0	75.0	1.5	1002	25	04	D
	0900	8.5	74.5	2.0	1001	30	05	**DD**
	1200	9.0	74.1	2.5	1000	35	06	**CS**
	1500	9.6	73.8	2.5	998	40	08	CS
	1800	10.2	73.3	2.5	998	40	08	CS
	2100	10.6	73.1	2.5	998	40	08	CS
31/10/2019	0000	11.0	73.0	3.0	996	45	10	CS
	0300	11.5	72.8	3.0	996	45	10	CS
	0600	11.9	72.8	3.0	994	50	12	**SCS**
	0900	12.3	72.8	3.0	994	50	12	SCS
	1200	12.8	72.4	3.0	992	50	14	SCS
	1500	13.3	72.2	3.5	990	55	16	SCS
	1800	13.7	72.1	3.5	990	55	16	SCS
	2100	13.9	72.0	3.5	990	55	16	SCS
01/11/2019	0000	14.6	71.7	3.5	990	55	16	SCS
	0300	14.8	71.0	3.5	990	55	16	SCS
	0600	15.2	70.5	3.5	990	55	16	SCS
	0900	15.4	70.0	3.5	990	55	16	SCS
	1200	15.6	69.5	3.0	992	50	14	SCS
	1500	15.7	69.2	3.0	992	50	14	SCS
	1800	15.9	69.1	3.0	992	50	14	SCS
	2100	16.2	68.8	3.0	992	50	14	SCS
02/11/2019	0000	16.3	68.5	3.0	992	50	14	SCS
	0300	16.4	68.3	3.0	992	50	14	SCS

	0600	16.5	68.2	3.0	992	50	14	SCS
	0900	16.8	67.9	3.0	992	50	14	SCS
	1200	17.0	67.6	3.5	990	55	16	SCS
	1500	17.1	67.3	3.5	990	55	16	SCS
	1800	17.2	67.0	3.5	988	60	18	SCS
	2100	17.5	66.8	3.5	988	60	18	SCS
03/11/2019	0000	17.6	66.5	3.5	988	60	18	SCS
	0300	17.6	66.4	3.5	988	60	18	SCS
	0600	17.6	66.2	3.5	988	60	18	SCS
	0900	17.6	65.9	4.0	984	65	22	**VSCS**
	1200	17.7	65.7	4.0	982	70	24	VSCS
	1500	17.8	65.6	4.5	978	75	28	VSCS
	1800	17.9	65.4	4.5	974	80	32	VSCS
	2100	18.0	65.0	4.5	970	85	36	VSCS
04/11/2019	0000	18.1	64.8	5.0	966	90	40	**ESCS**
	0300	18.3	64.6	5.0	966	90	40	ESCS
	0600	18.6	64.3	5.0	966	90	40	ESCS
	0900	18.7	64.2	5.0	962	95	44	ESCS
	1200	18.9	64.1	5.5	956	100	50	ESCS
	1500	19.2	63.9	5.5	956	100	50	ESCS
	1800	19.3	63.7	5.5	956	100	50	ESCS
	2100	19.5	63.6	5.5	956	100	50	ESCS
05/11/2019	0000	19.6	63.6	5.0	966	90	40	ESCS
	0300	19.7	63.6	4.5	970	85	36	**VSCS**
	0600	19.8	63.7	4.5	974	80	32	VSCS
	0900	19.8	63.8	4.5	974	80	32	VSCS
	1200	19.8	64.1	4.0	982	70	24	VSCS
	1500	19.8	64.3	4.0	982	70	24	VSCS
	1800	19.8	64.9	4.0	982	70	24	VSCS
	2100	19.8	65.5	4.0	982	70	24	VSCS
06/11/2019	0000	19.8	65.8	3.5	988	60	18	**SCS**
	0300	19.8	66.3	3.5	990	55	16	SCS
	0600	19.7	66.5	3.0	994	50	12	SCS
	0900	19.6	67.1	3.0	994	50	12	SCS
	1200	19.7	67.7	3.0	996	45	10	**CS**
	1500	19.8	68.3	2.5	998	40	08	CS
	1800	19.8	68.4	2.5	998	40	08	CS
	2100	19.8	68.9	2.5	1000	35	07	CS
07/11/2019	0000	19.8	69.4	2.0	1003	30	05	**DD**
	0300	20.0	70.0	2.0	1003	30	05	DD
	0600	20.0	70.4	1.5	1005	25	03	**D**
	0900	20.2	70.6	1.5	1005	20	03	D
	1200	Well-Marked Low Pressure Area over northeast Arabian Sea and adjoining south Gujarat coast						

3. Brief life history

3.1. Genesis

It originated from an LPA over EIO off south Sri Lanka coast in the forenoon (0600 UTC) of 28th October. It lay as a WML over Comorin Area & adjoining EIO in the early morning (0000 UTC) of 29th October.

3.2. Intensification and movement

At 0000 UTC of 30th November, the Madden Julian Oscillation (MJO) index lay in phase 3 with amplitude less than 1. The sea surface temperature (SST) was around 29 - 30°C over the system area and was decreasing along the forecast track. Tropical cyclone heat potential (TCHP) was around 100-120 KJ/cm^2 over the system area. The low level relative vorticity was about 100 x10^{-5} sec^{-1} over the system centre. Positive vorticity field was extending upto 500 hPa level. The ridge over the system area ran roughly along 15^0 N. The lower level convergence was about 20 x10^{-5} sec^{-1} over the system centre and the upper level divergence was about 20 x10^{-5} sec^{-1} over the system centre. The vertical wind shear was moderate to high (20-25 Knots) over the system area. Under these favourable conditions, the system intensified into a depression over Maldives-Comorin area near latitude 6.5°N and longitude 76.2°E.

At 0900 UTC of 30th October, similar MJO and sea conditions prevailed. The low level relative vorticity further increased and was about 150 x10^{-5} sec^{-1} over the system centre. Positive vorticity field was extending upto 500 hPa level. The ridge over the system area ran roughly along 15^0 N. The lower level convergence was about 20 x10^{-5} sec^{-1} over the system centre and the upper level divergence increased and was about 30 x10^{-5} sec^{-1} over the system centre. The vertical wind shear was moderate to high (20-25 knots) over the system area. Under these favourable environment conditions, the system intensified into a deep depression over Lakshadweep & adjoining Maldives area and southeast Arabian Sea near latitude 8.5°N and longitude 74.5°E.

At 1200 UTC of 30th, similar MJO and sea conditions continued. The low level relative vorticity was about 150 x10^{-5} sec^{-1} over the system centre. Positive vorticity field extended upto 500 hPa level. The ridge over the system area ran roughly along 15^{0}N. The lower level convergence was about 20 x10^{-5} sec^{-1} over the system centre and the upper level divergence was about 30 x10^{-5} sec^{-1} over the system centre. The vertical wind shear was moderate to high (20-25 knots) over the system area. Under these favourable conditions, the system intensified into a CS over Lakshadweep & adjoining Maldives area and southeast Arabian Sea near latitude 9.6°N and longitude 73.8°E.

At 0600 UTC of 31st October, similar MJO and SST conditions prevailed. However, the TCHP decreased over the system area and was around 70-90 KJ/cm^2. The low level relative vorticity increased and was about 200 x10^{-5} sec^{-1} to the south of the system centre. Positive vorticity field extended upto 500 hPa level. The ridge over the system area ran roughly along 18^{0}N. The lower level convergence was about 20 x10^{-5}sec^{-1} to the northeast of the system centre and the upper level divergence was about 30 x10^{-5} sec^{-1} around the system centre. The vertical wind shear was low to moderate (10-20 knots) over the system area. Under these favourable conditions, the system intensified into an SCS over eastcentral Arabian Sea near latitude 11.9°N and longitude 72.8°E.

Similar features continued and the system maintained it's intensity of SCS till 0600 UTC of 3rd November over eastcentral Arabian Sea.

At 0900 UTC of 3rd November, the low level relative vorticity was about 200 x10^{-5} sec^{-1} to the south of the system centre. The ridge over the system area ran roughly along 18^{0}N. The lower level convergence was about 20 x10^{-5} sec^{-1} to the southwest of the system centre and the upper level divergence was about 20 x10^{-5} sec^{-1} over the system area. The vertical wind shear was low (05-10 knots) over the system area and along the forecast track. SST was around 26-28°C and TCHP was around 20-40 KJ/cm^2 around the system center. At this time there was an anticyclone located to the northeast of the system and the system was being steered in west-northwest direction by the southern

periphery winds. Under these conditions, the system further intensified into a VSCS over eastcentral Arabian Sea near latitude 17.6°N and longitude 65.9°E.

At 0000 UTC of the 04th November, similar sea conditions prevailed. The low level relative vorticity was about 200 $x10^{-5}$ sec^{-1} around the system centre. The ridge over the system area ran roughly along 18^0N. The lower level convergence was about 20 $x10^{-5}$ sec^{-1} around the system centre and the upper level divergence was about 30 $x10^{-5}$ sec^{-1} around the system center. The vertical wind shear was low (05-10 knots) over the system area and along the forecast track. SST was around 26-28°C and TCHP was 20-40 KJ/cm^2 around the system center. As the system lay in the southern periphery of anticyclone located to the northeast of the system centre, it continued to move west-northwestwards. Under these conditions, the system further intensified into an ESCS over EC and adjoining WC Arabian Sea near latitude 18.1°N and longitude 64.8°E.

At 0300 UTC of 05th, the system entered an area of lower SST (24-26°C) and lower TCHP (20-40 KJ/cm^2) around the system center. The low level relative vorticity was about 150 $x10^{-5}$ sec^{-1} to the south of the system centre. The ridge roughly ran along 19^0N. The lower level convergence was about 20 $x10^{-5}$ sec^{-1} around the system centre and the upper level divergence was about 20 $x10^{-5}$ sec^{-1} to southeast of the system center. The vertical wind shear was 15-20 knots over the system area and 20-25 knots along the forecast track. The system was situated north of the col region. Under these conditions, the system moved northwards and weakened into a VSCS over EC & adjoining WC Arabian Sea near latitude 19.7°N and longitude 63.6°E.

At 0000 UTC of 06th November, similar Sea conditions prevailed. The low level relative vorticity was about 150 $x10^{-5}$ sec^{-1} to the south of system centre. The ridge roughly ran along 19°N over the system area. The lower level convergence was about 10 $x10^{-5}$ sec^{-1} around the system centre and the upper level divergence was about 20 $x10^{-5}$ sec^{-1} around the system center. The vertical wind shear was 20- 25 knots over the system area and 25-30 knots along the forecast track. Mid-latitude westerlies steered the system east-northeastwards. Under these conditions, the system weakened into a severe cyclonic storm over EC and adjoining northeast Arabian Sea near latitude 19.8°N and longitude 65.8°E.

At 1200 UTC of 06th, the unfavourable environment continued. The low level relative vorticity was about 150 $x10^{-5}$ sec^{-1} to the south of system centre. The ridge roughly ran along 19°N runs over the system area. The lower level convergence was about 30 $x10^{-5}$ sec^{-1} in south west sector and the upper level divergence was about 30 $x10^{-5}$ sec^{-1} around the system center. The vertical wind shear was 25-30 knots over the system area and 25-30 knots along the forecast track. SST was between 24-26°C to the southwest of the system center and TCHP was about 20-40 KJ/cm^2 around the system center. The system was steered in east-northeastward direction under the influence of mid-latitude westerlies. Under these conditions, the system weakened into a CS over EC & adjoining northeast Arabian Sea near latitude 19.7°N and longitude 67.7°E.

At 0000 UTC of 7th, the unfavourable environment continued and the system weakened into a DD near EC & adjoining northeast Arabian Sea near latitude 19.8°N and longitude 69.4°E. At 0600 UTC of 07th, the system weakened into a depression over EC & adjoining northeast Arabian sea near latitude 20.0°N and longitude 70.4°E. The low level relative vorticity was about 50-100 $x10^{-5}$ sec^{-1} to the south of system centre. The upper tropospheric ridge roughly ran along 19°N. The lower level convergence was about 05 $x10^{-5}$ sec^{-1} in the southwest sector. The vertical wind shear was 30-35 knots over the system area and along the forecast track. SST was between 28-29°C to the southwest of

the system center and TCHP was 20-40 KJ/cm^2 around the system center. The system moved eastwards under the influence of mid-latitude westerlies.

Typical TPW imageries during 30th October- 7th November, 2019 are presented in **Fig.3**. TPW imageries indicated warm air intrusion into the core till 2nd November.

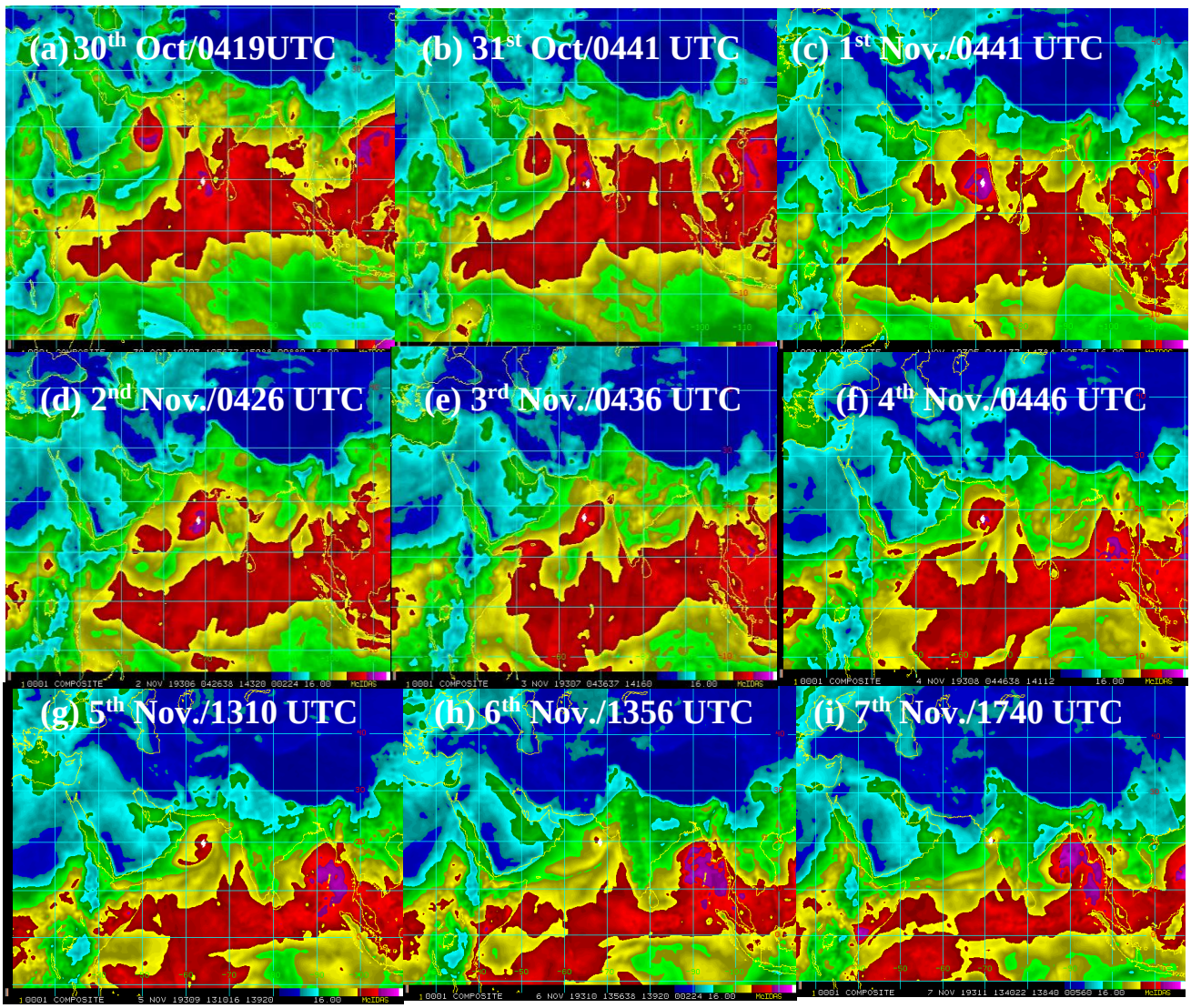


Fig. 3: Total Precipitable Water (TPW) imageries during ESCS MAHA (30th October- 7th November, 2019)

The mean vertical wind shear (VWS) speed & direction in the layer 200 to 850 hPa and 500 to 850 hPa is presented in **Fig.4**. The mean wind shear speed for the layer 200 to 850 hPa was low to moderate till 5th Nov., becoming high thereafter. The direction of mean VWS in the layer 200 to 850 hPa wind was westerly till 2nd becoming southwesterly thereafter till 5th and northeasterly thereafter. It caused the convective cloud mass to be sheared to the east of the system centre till 2nd, to northeast of system centre thereafter till 5th and southeast of system centre thereafter.

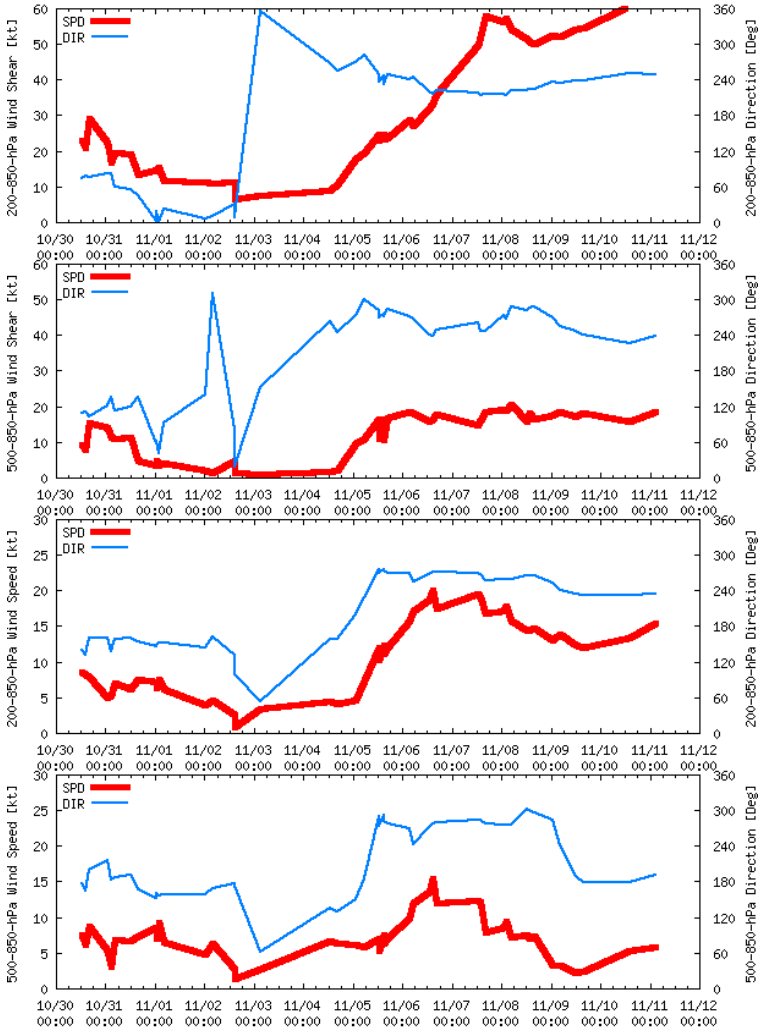


Fig.4 Wind shear and wind speed in the layers between 200 to 850 hPa and 500 to 850 hPa around the ESCS MAHA (30th Oct.-7th Nov., 2019)

From **Fig.4**, it is seen that the mean wind speed in the layers 200 to 850 hPa and 500 to 850 hPa was about 7 kts. The twelve hourly movement of VSCS Bulbul is presented in **Fig.5a**. The 12 hourly average translational speed of the cyclone was about 14.5 kmph and hence the cyclone was moving with the normal speed of 14.3 kmph (1990-2013).

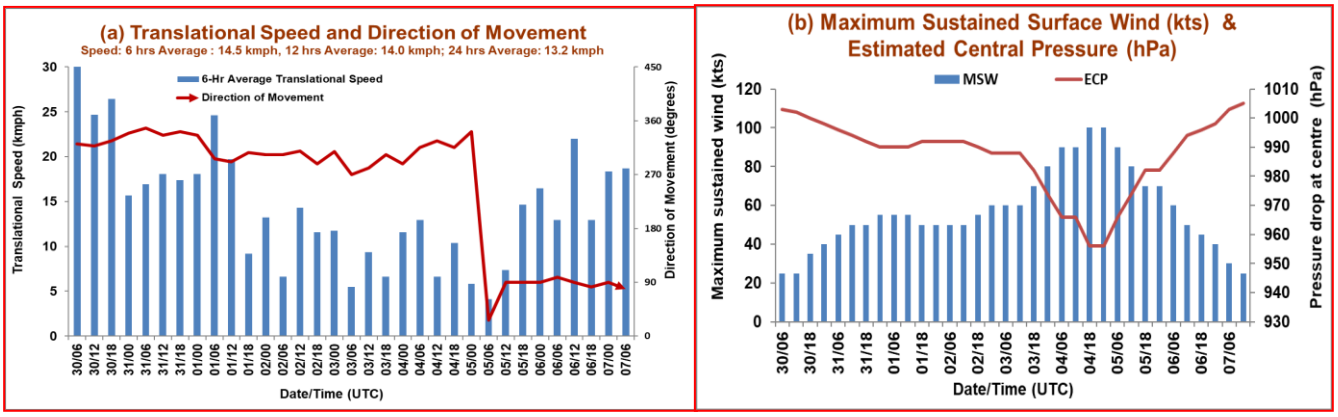


Fig.5: (a) Translational speed & direction of movement and (b) maximum sustained wind speed during life cycle of Maha (30th October-7th November)

3.3 Maximum Sustained Surface Wind speed and estimated central pressure

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig.5b**. The lowest estimated central pressure had been 956 hPa during 4th/1200-4th/1800 UTC. The estimated maximum sustained surface wind speed (MSW) was 100 knots during the same period with pressure drop of 50 hPa.

4. Monitoring of ESCS, 'MAHA'

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the cyclone was monitored since 28th October when low pressure area formed over equatorial Indian Ocean off south Sri Lanka coast. The cyclone was monitored mainly with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites and available ships & buoy observations in the region and the Doppler weather radars of IMD along the west coast namely DWR Kochi & Goa. Various numerical weather prediction models run by Ministry of Earth Sciences (MoES) institutions and dynamical-statistical models were utilized to predict the genesis, track, landfall and intensity of the cyclone. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning product generation.

4.1. Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D and 3DR imageries. Satellite imageries of international geostationary satellites Meteosat-8 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 temperature imageries are presented in **Fig.6**. Typical satellite features associated with the system are discussed in this section.

At 1200 UTC of 30th October, the intensity of the system was T 2.5. Associated scattered low to medium clouds with embedded intense to very intense convection lay over Comorin and adjoining areas between latitude 6.5^0N to 11.5^0N and longitude 70.5^0E to 74.5^0E. The minimum CTT was -93^0C.

At 0600 UTC of 31st October, the current intensity of the system was T 3.0. Associated scattered low to medium clouds with embedded intense to very intense convection lies over Comorin and adjoining areas between latitude 9.5^0N to 15.0^0N and longitude 68.0^0E to 74.5^0E. The minimum CTT is -93^0C.

At 0000 UTC of 1st November, the current intensity of the system was T 3.5. Associated scattered low to medium clouds with embedded intense to very intense convection lay over eastcentral AS between latitude 13.5^0N to 17.0^0N and longitude 65.0^0E to 70.5^0E. The minimum CTT is -93^0C.

At 0000 UTC of 1st November, the current intensity of the system was T 3.5. Associated scattered low to medium clouds with embedded intense to very intense convection lay over southeast and adjoining eastcentral AS between latitude 12.0^0N to 15.5^0N and longitude 67.5^0E to 72.0^0E. The minimum CTT is -93^0C.

At 0000 UTC of 2nd November, the current intensity of the system was T 3.5. Associated scattered low to medium clouds with embedded intense to very intense convection lay over eastcentral AS between latitude 13.5^0N to 17.0^0N and longitude 65.0^0E to 70.5^0E. The minimum CTT is -93^0C.

At 0900 UTC of 03rd November, the current intensity of the system was T 4.0. Associated broken low to medium clouds with embedded intense to very intense convection lay over eastcentral AS between latitude 15.8^{0}N to 21.0^{0}N and longitude 64.5^0 E to 68.0 ^{0} E. The minimum CTT is -93^{0}C.

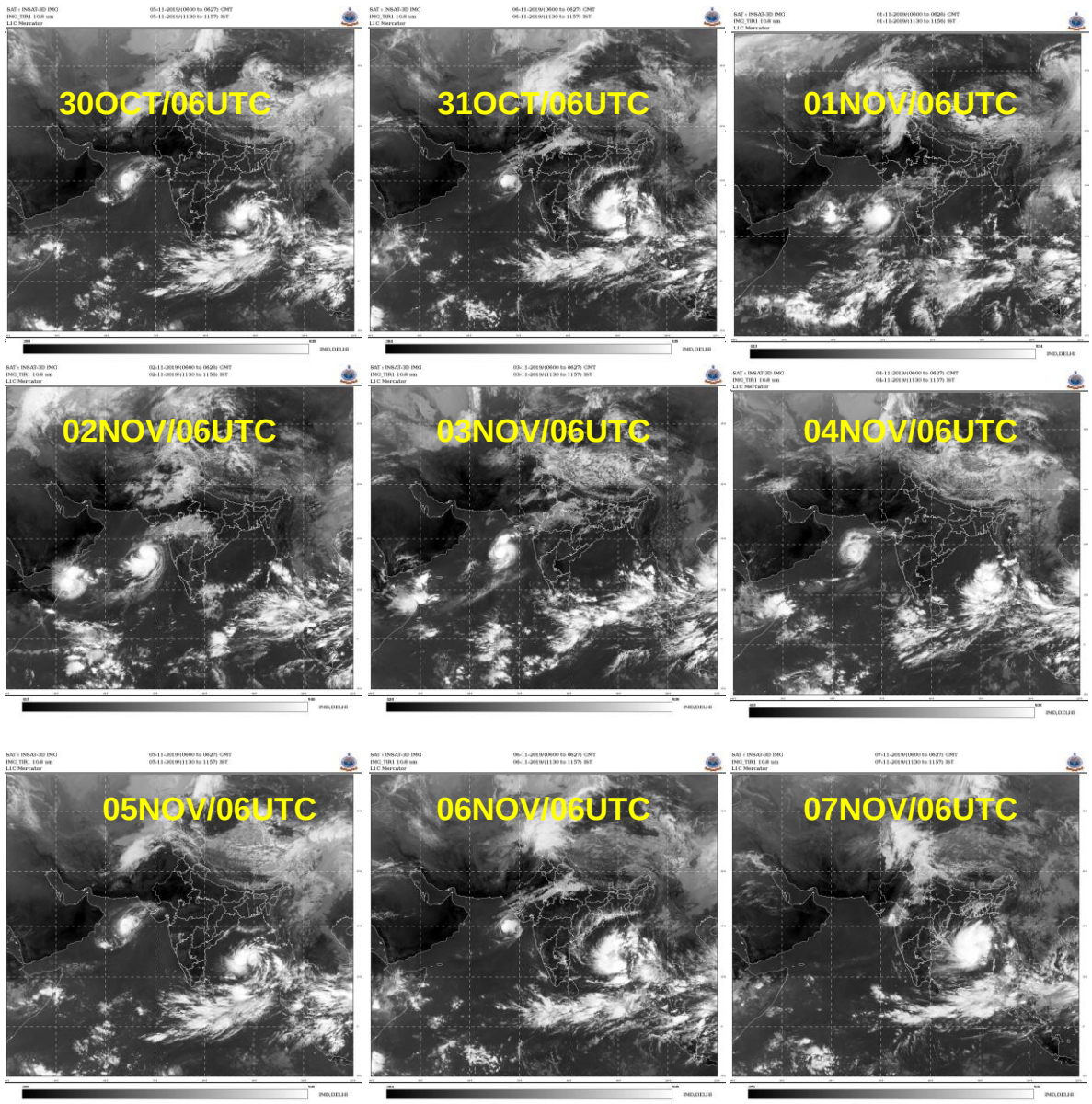


Fig. 6a: INSAT-3D IR imageries during life cycle of ESCS MAHA (30 Oct-7th November, 2019)

At 0000 UTC of 04th November, the current intensity of the system was T 5.0. System showed eye pattern with diameter of 15km. Eye temperature was -4.7^{0}c. Associated broken low to medium clouds with embedded intense to very intense convection lay over eastcentral AS between latitude 16.0 ^{0}N to 19.5^{0}N and longitude 63.5^0 E to 66.5^0 E. The minimum CTT was -93^{0}C.

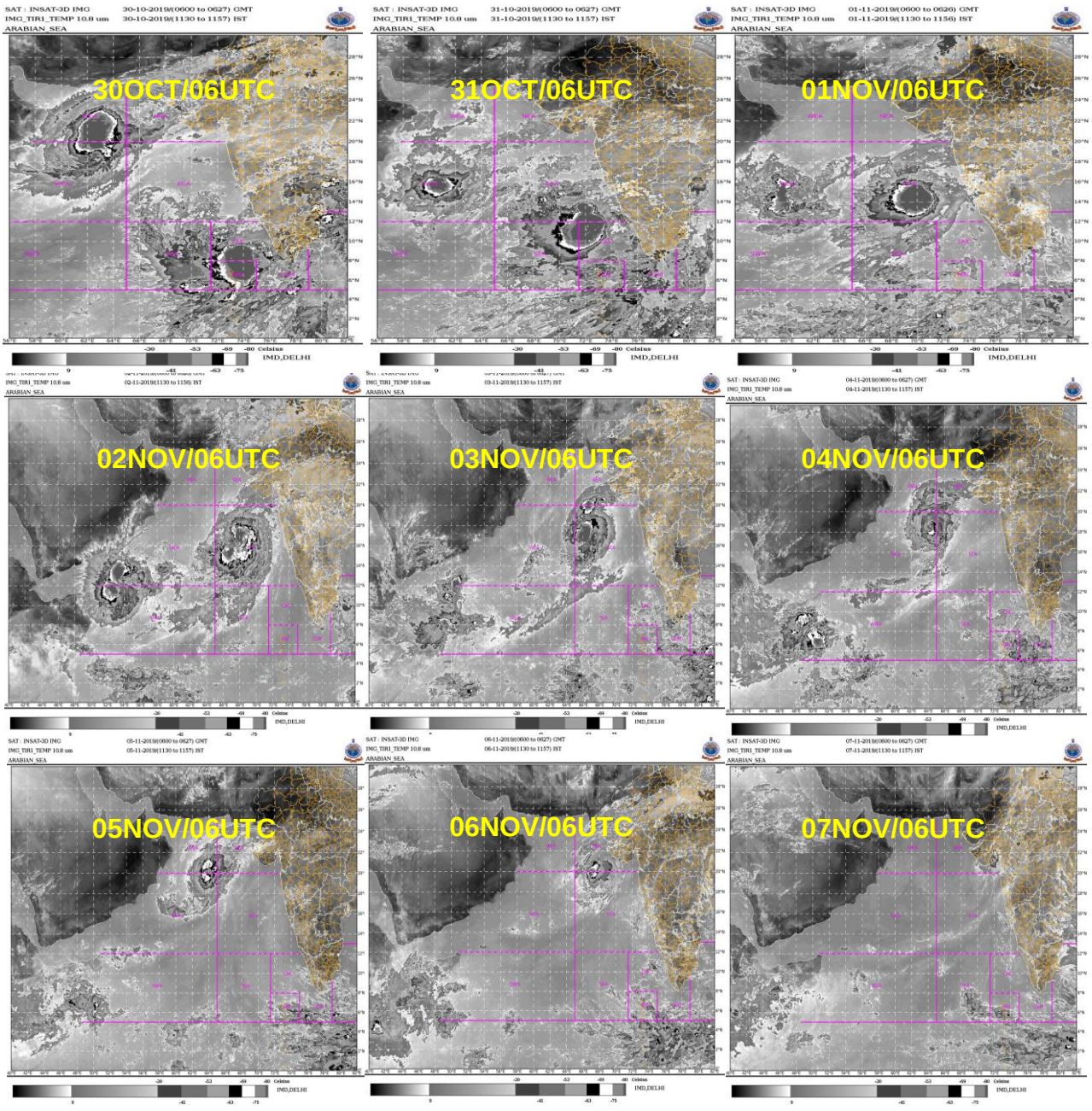


Fig. 6b: INSAT-3D BD imageries during life cycle of ESCS MAHA (30 Oct-7th November, 2019)

At 0300 UTC of 05th November, the current intensity of the system was T 4.5/C.I. 5.5. Associated broken low to medium clouds with embedded intense to very intense convection lay over eastcentral & adjoining westcentral and north AS between latitude 18.5 ^{0}N to 21.5^{0}N and longitude 62.2^{0}E to 65.5^{0}E. The minimum CTT was - 81^{0}C.

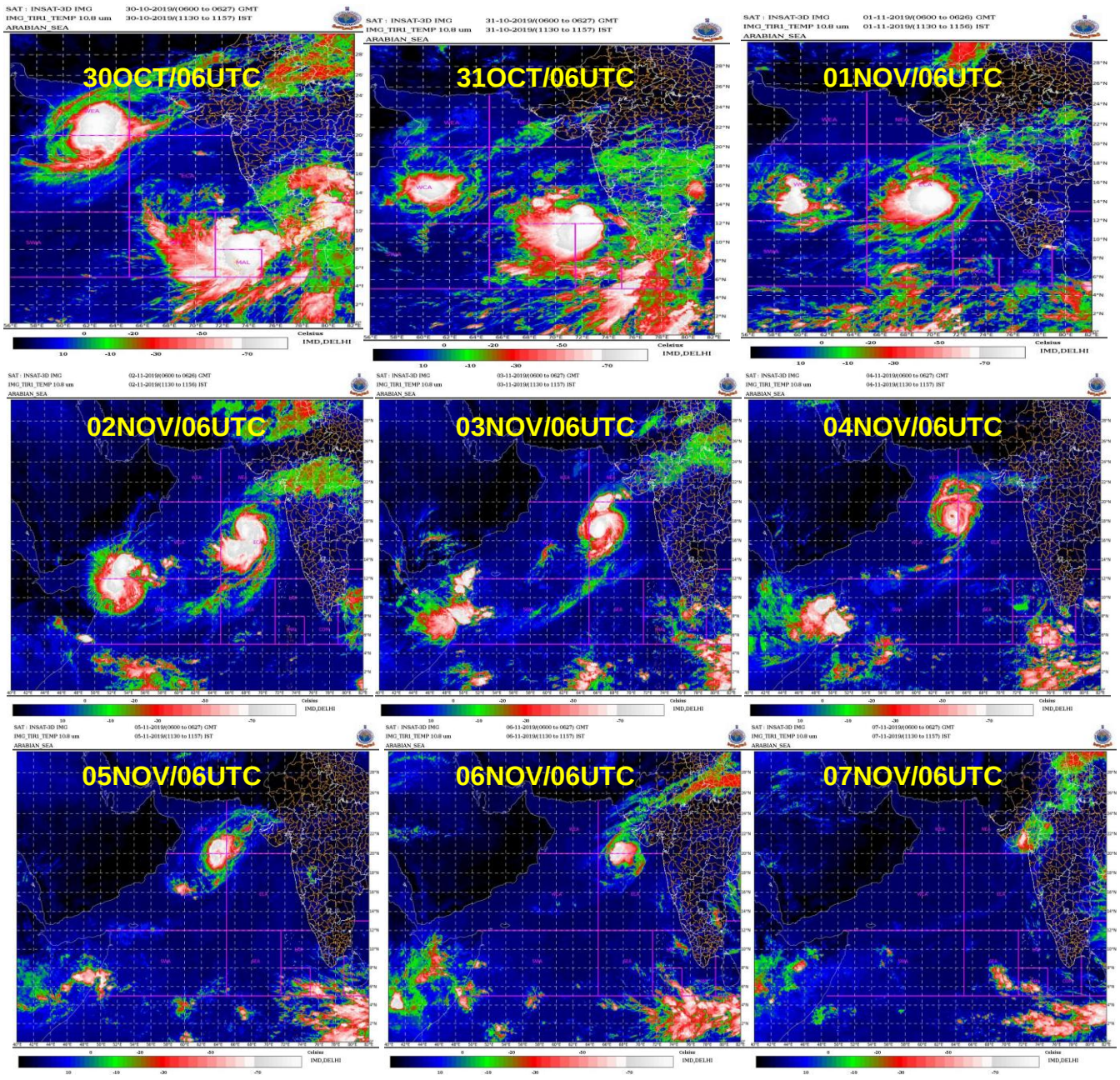


Fig. 6c: INSAT-3D enhanced colour imageries during life cycle of ESCS MAHA (30 Oct-7th November, 2019)

At 0000 UTC of 06th November, the current intensity of the system was T 3.5/C.I.4.0. Associated broken low to medium clouds with embedded intense to very intense convection lay over westcentral & adjoining eastcentral and north AS between latitude 18.0 °N to 21.0°N and longitude 64.5°E to 67.5°E. The convection associated with the system reduced significantly. The minimum CTT was -67°C.

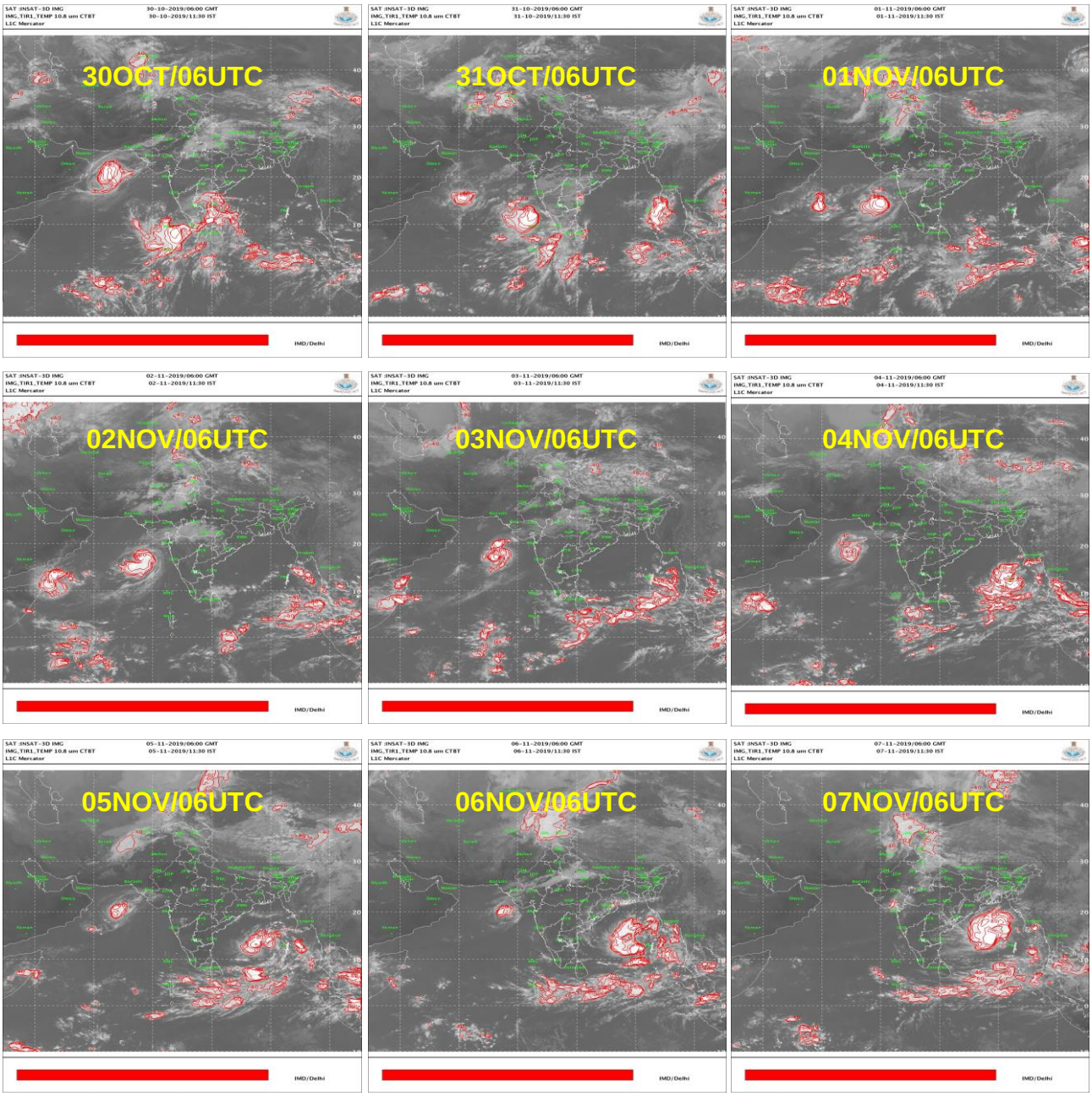


Fig. 6d: INSAT-3D Cloud Top brightness imageries during life cycle of ESCS MAHA (30 Oct-7th November, 2019)

At 1200 UTC of 06th November, the current intensity of the system was T 2.5/C.I.3.0. Associated broken low to medium clouds with embedded intense to very intense convection lay over eastcentral & adjoining north AS between latitude 18.8°N to 22.0°N and longitude 66.5°E to 69.7°E. The minimum CTT was -93°C.

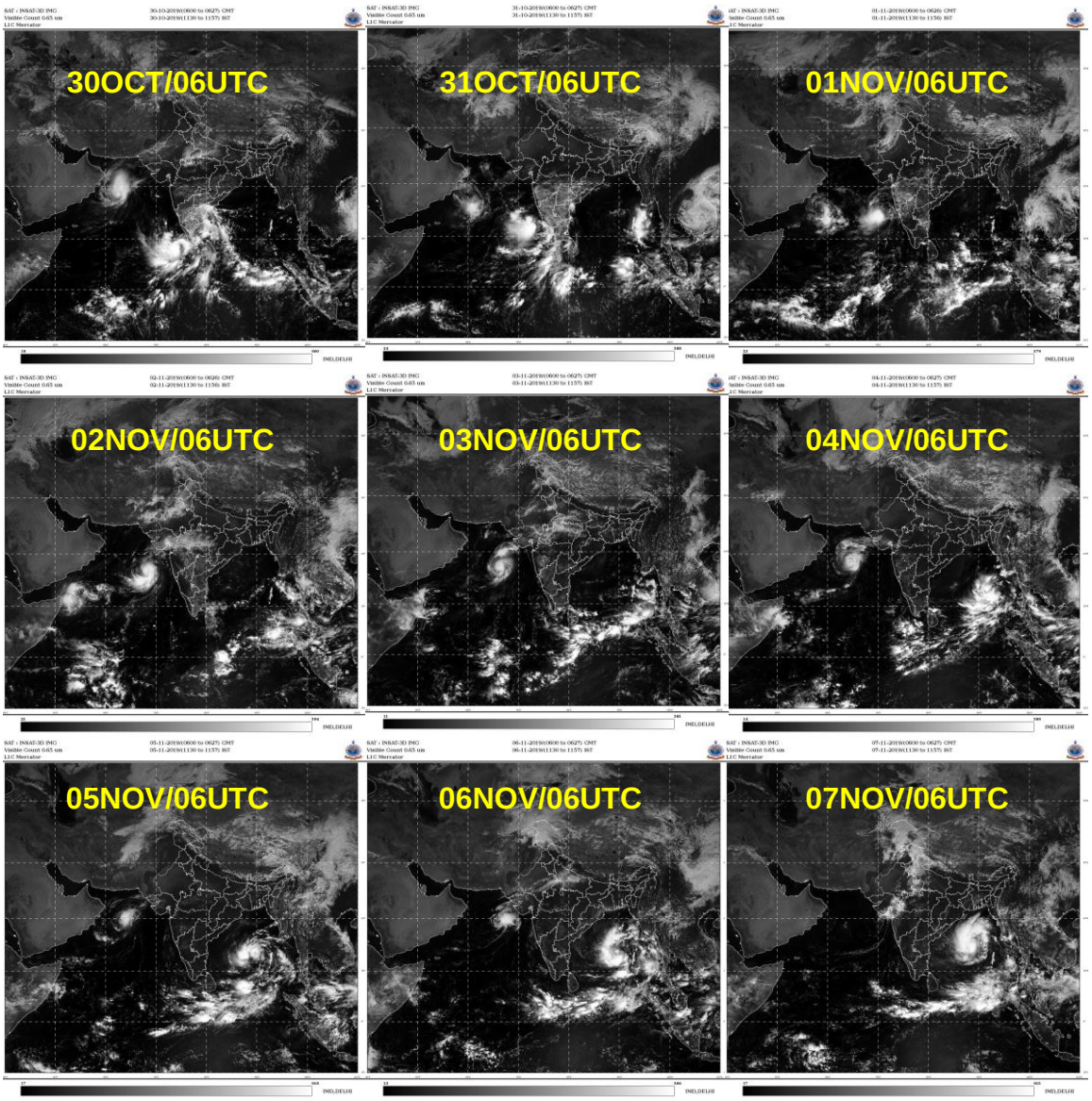


Fig. 6e: INSAT-3D Visible imageries during life cycle of ESCS MAHA (30 Oct-7th November, 2019)

At 0600 UTC of 07th November, the current intensity of the system was T 1.0/C.I.2.0. Associated broken low to medium clouds with embedded moderate to intense convection lay over northeast AS, Gulf of Cambay & adjoining south Gujarat between latitude 21.0°N to 23.0°N and longitude 71.5°E to 72.5°E.

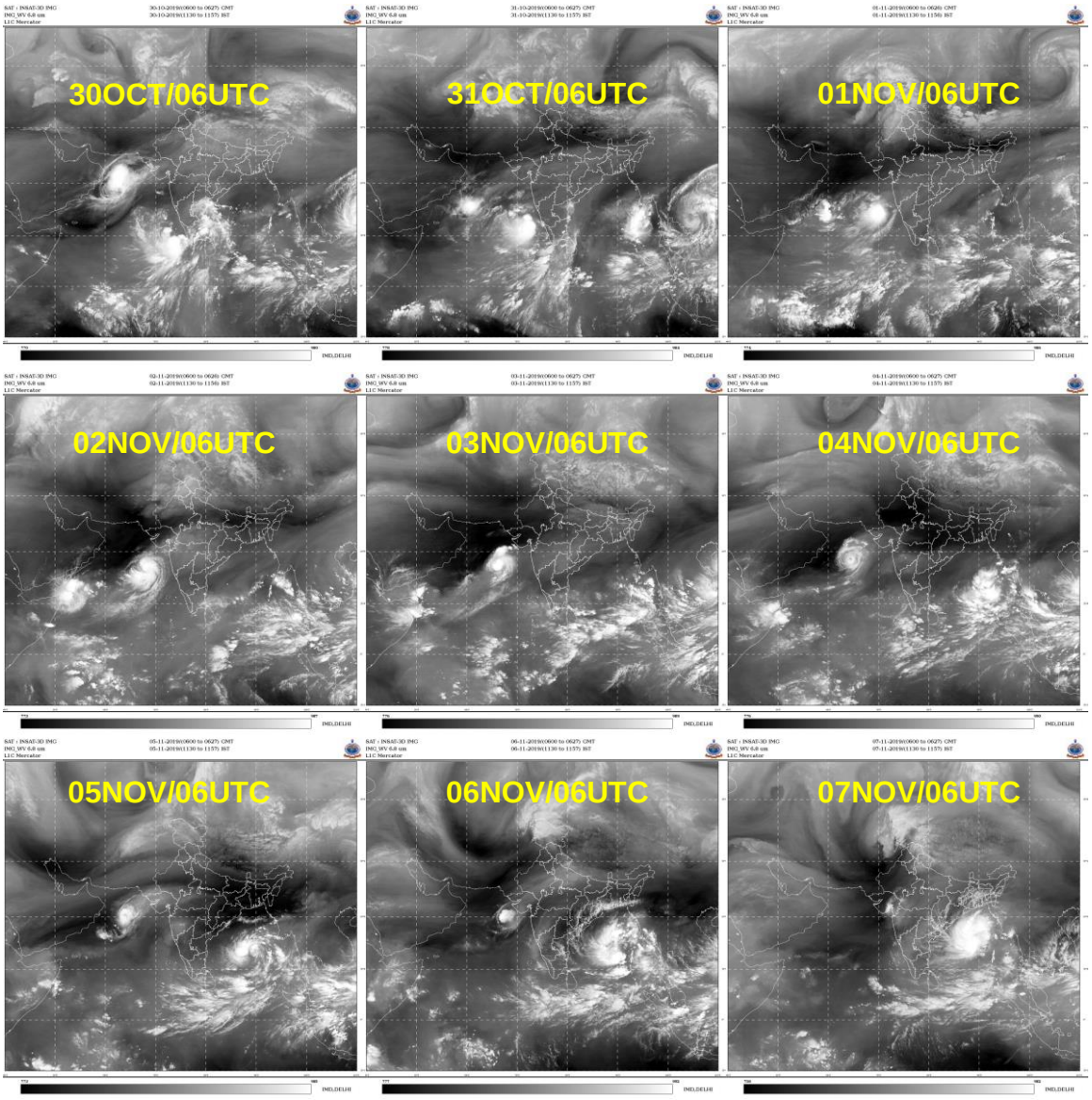


Fig. 6f: INSAT-3D Water Vapour imageries during life cycle of ESCS MAHA (30 Oct-7th November, 2019

ASCAT imageries during 30th Oct.-8th November are presented in Fig. 6h. Circulation centre was correctly picked up on 31st Oct. and 1st Nov., however ASCAT has limitations wrt estimation of intensity beyond 50 kts.

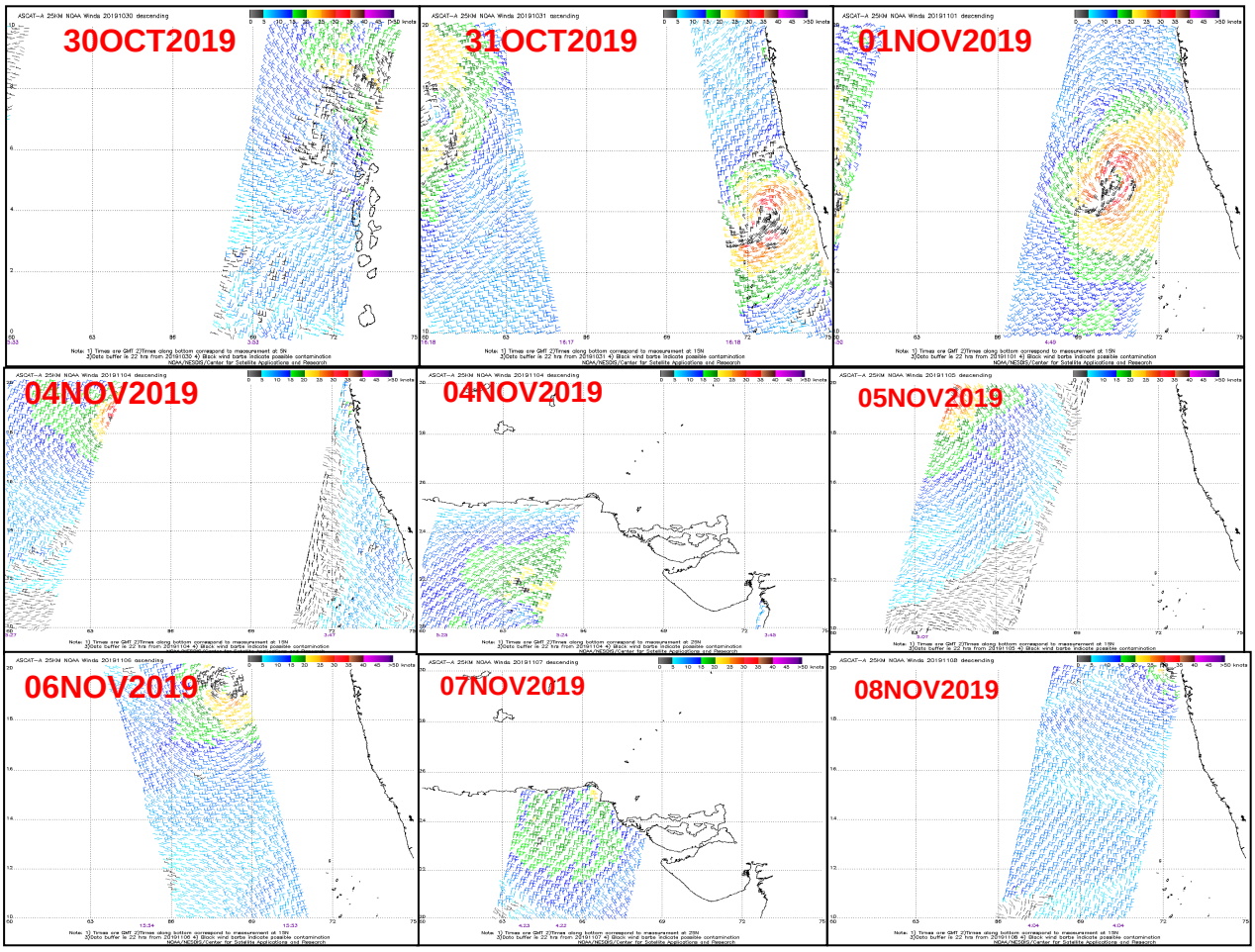


Fig. 6g: Typical ASCAT imageries in association with ESCS MAHA

Typical microwave imageries from polar orbiting satellites F-17, GCOM W1, F-18, WindSat and F-15 satellites are presented in Fig. 6h. During 3rd – 5th eye could be seen clearly.

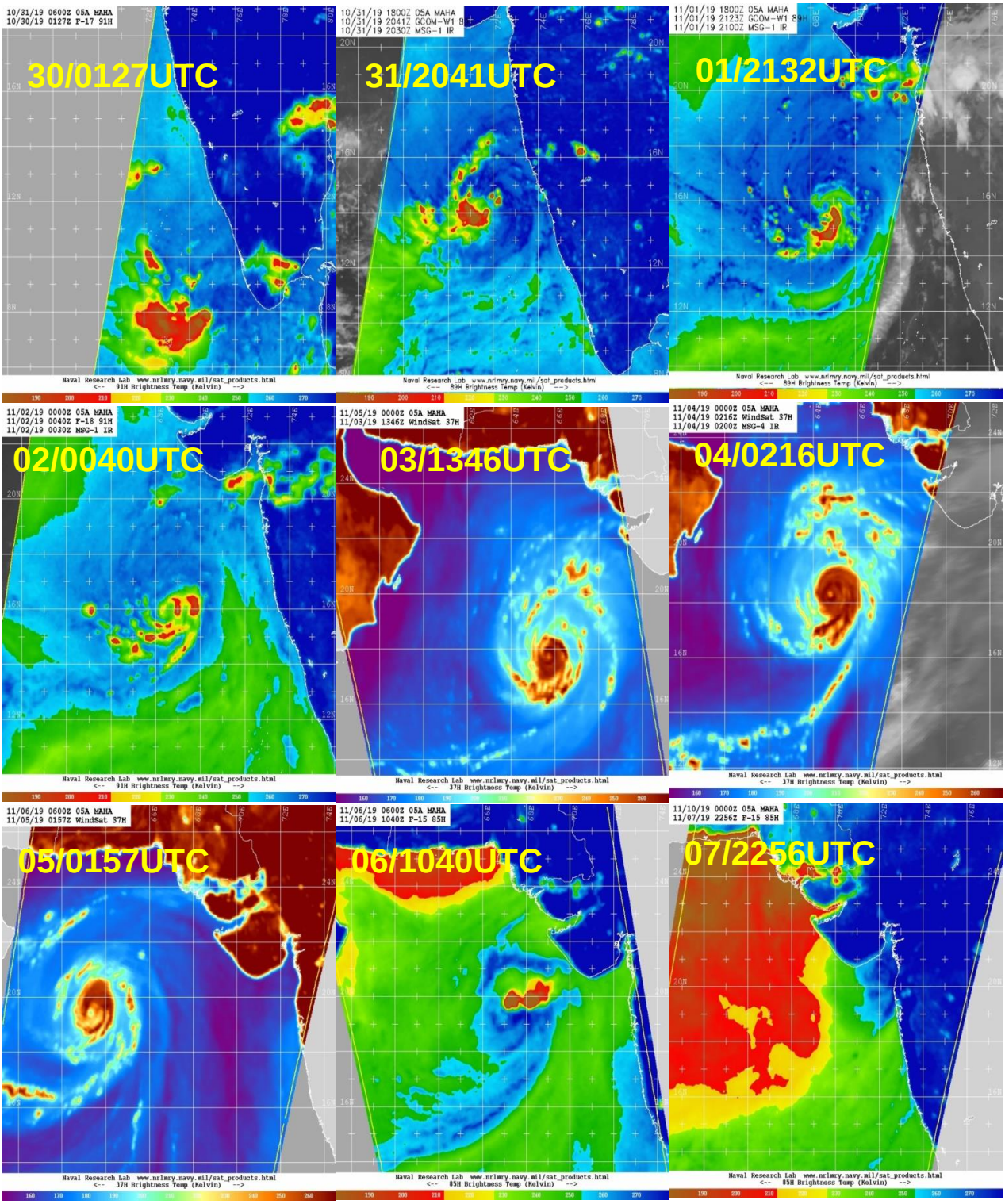


Fig. 6h: Typical microwave imageries during 30thOctober - 7th November in association with ESCS MAHA

5. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa level during 19th-21st September are presented in Fig.7. GFS (T1534) analysis based on 0000 UTC of 30th October, indicated a depression over Maldives-Comorin area. Actually cyclogenesis occurred at 0000 UTC of 30th over Maldives-Comorin area.

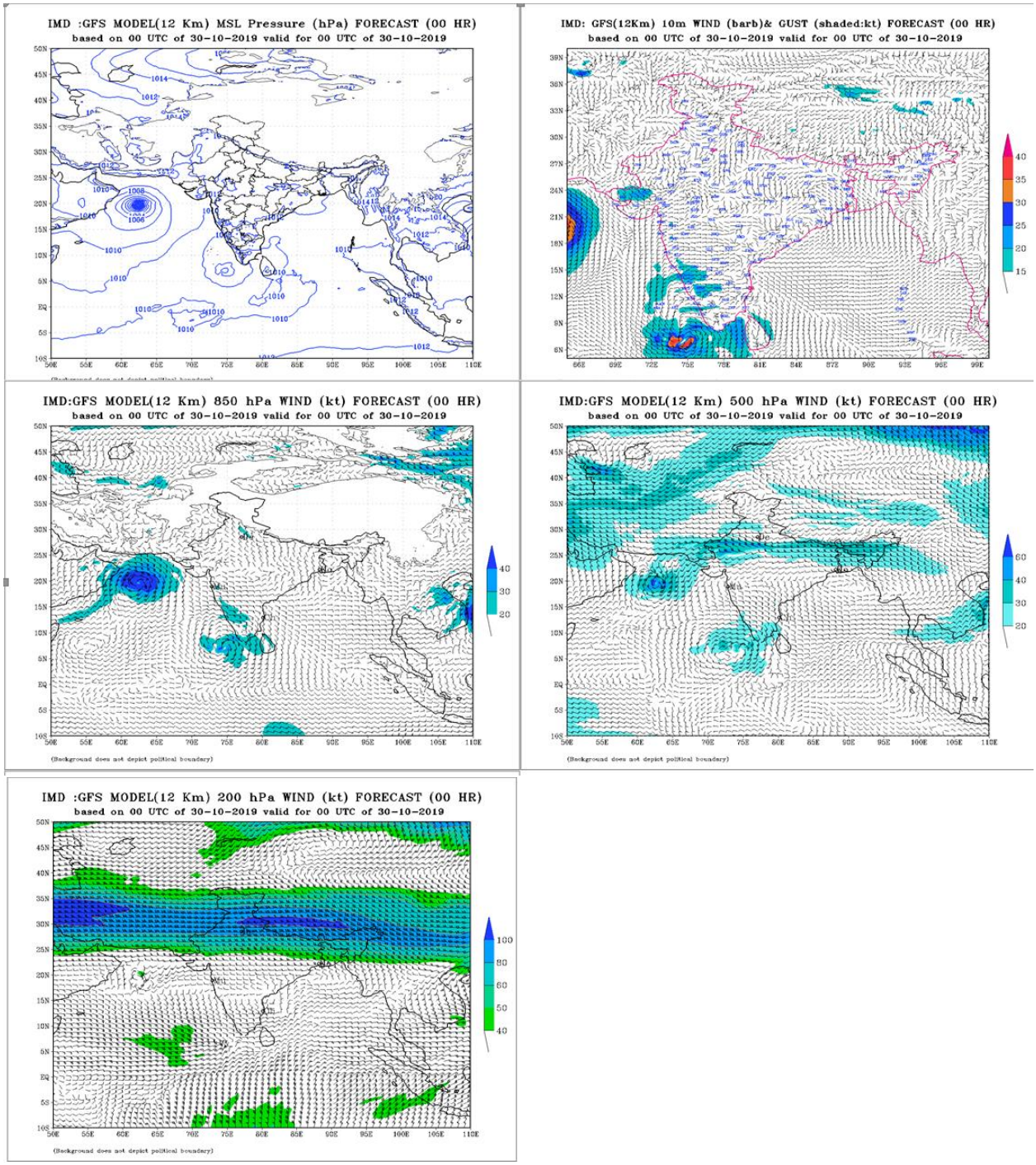


Fig.7a: IMD GFS analysis of MSLP, 10 m wind and winds at 850, 500 & 200 hPa levels based on 0000 30th October

IMD GFS analysis field based on 0000 UTC of 31st October, indicated intensification of system into a cyclonic storm over southeast Arabian Sea. Synoptically also at that time system lay as a CS over southeast AS.

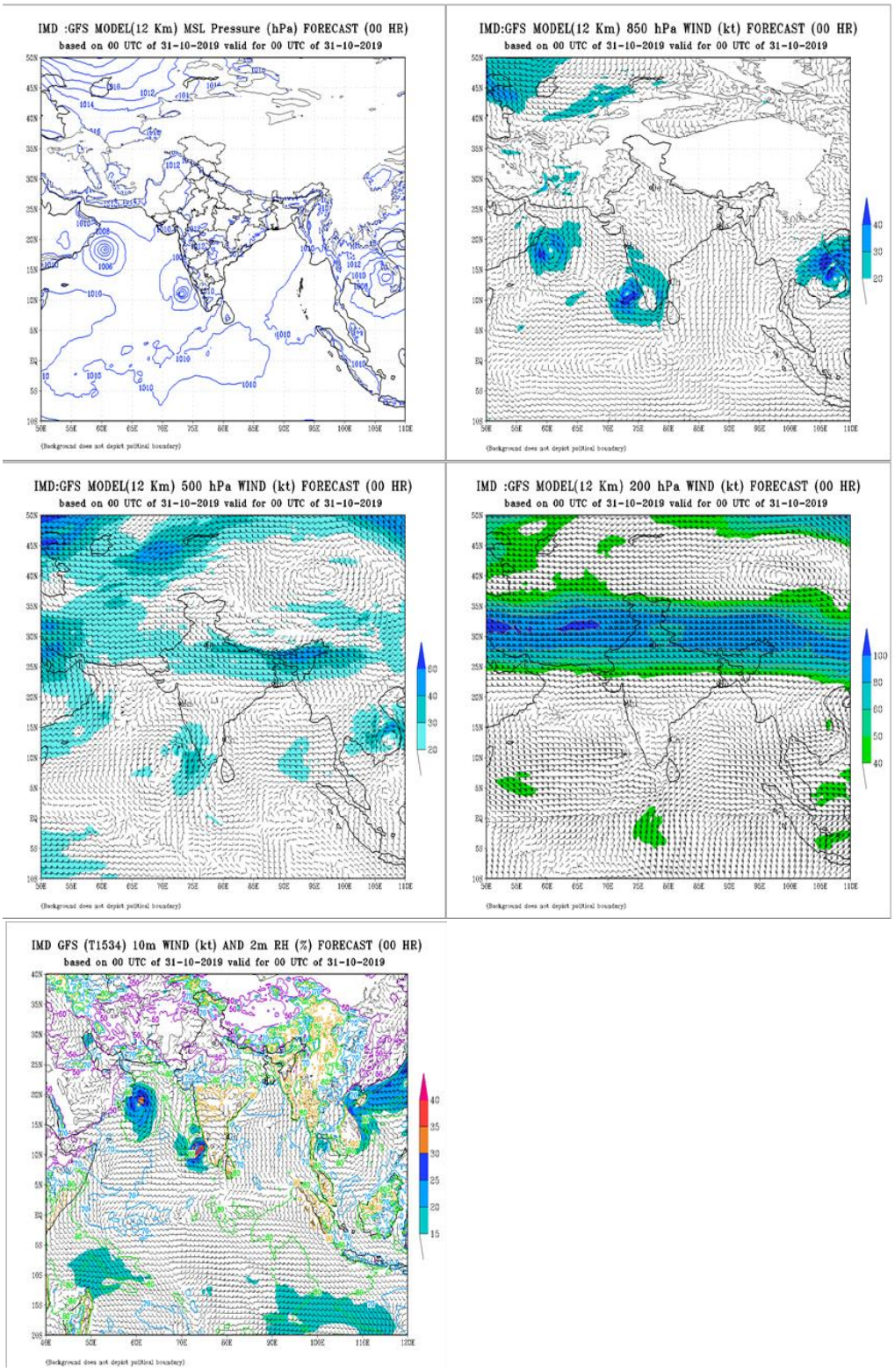


Fig.7b: IMD GFS analysis of MSLP, 10 m wind and winds at 850, 500 & 200 hPa levels based on 0000 31st October

IMD GFS analysis field based on 0000 UTC of 1st November, indicated further intensification of system into an SCS over southeast Arabian Sea. Synoptically also at that time system lay as an SCS over southeast AS.

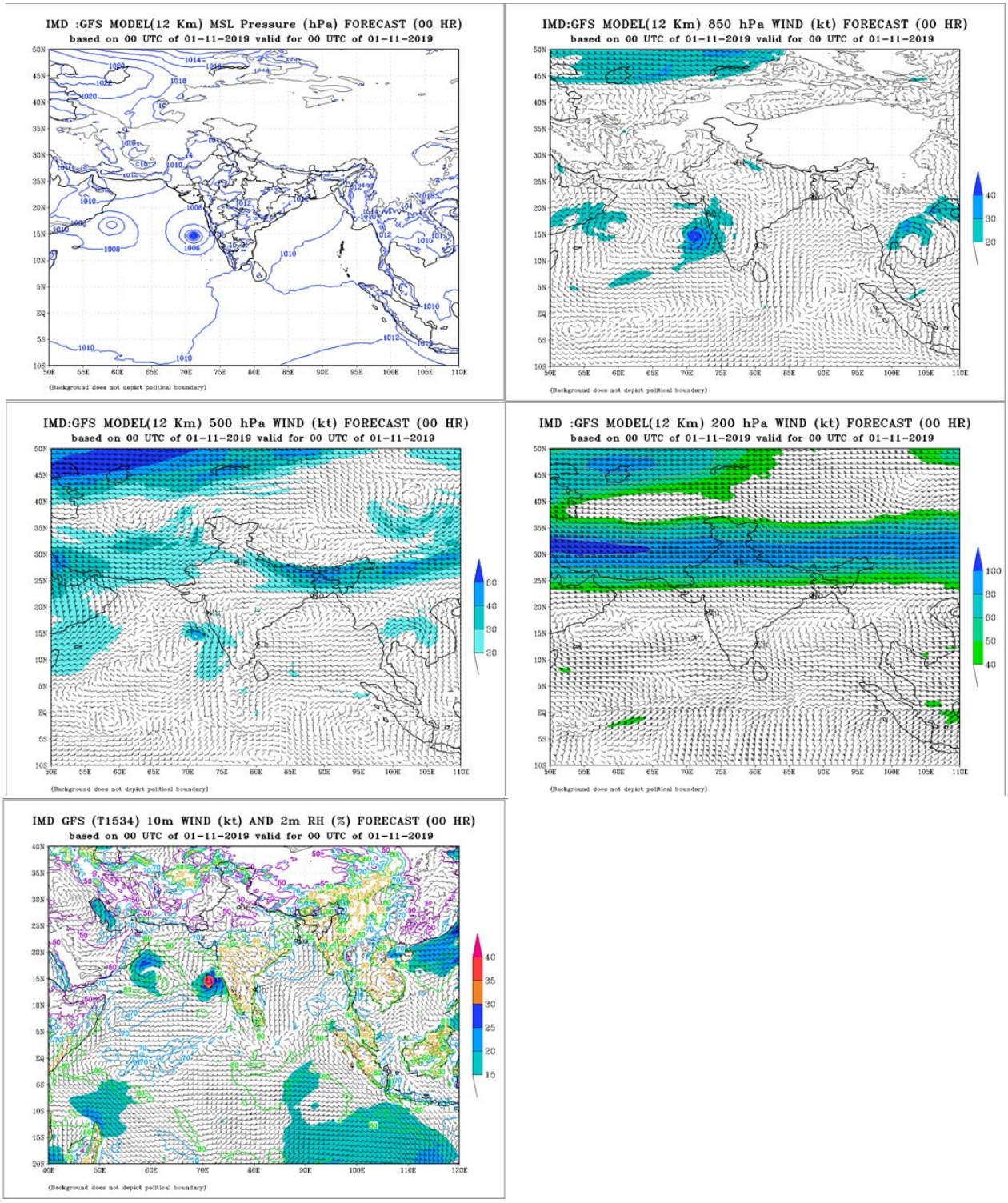


Fig.7c: IMD GFS analysis of MSLP, 10 m wind and winds at 850, 500 & 200 hPa levels based on 0000 1st November

IMD GFS analysis field based on 0000 UTC of 2nd November, indicated an SCS over eastcentral AS near 16.0N/68.0E. Synoptically also at that time system lay as an SCS over eastcentral AS near 16.3N/68.5E.

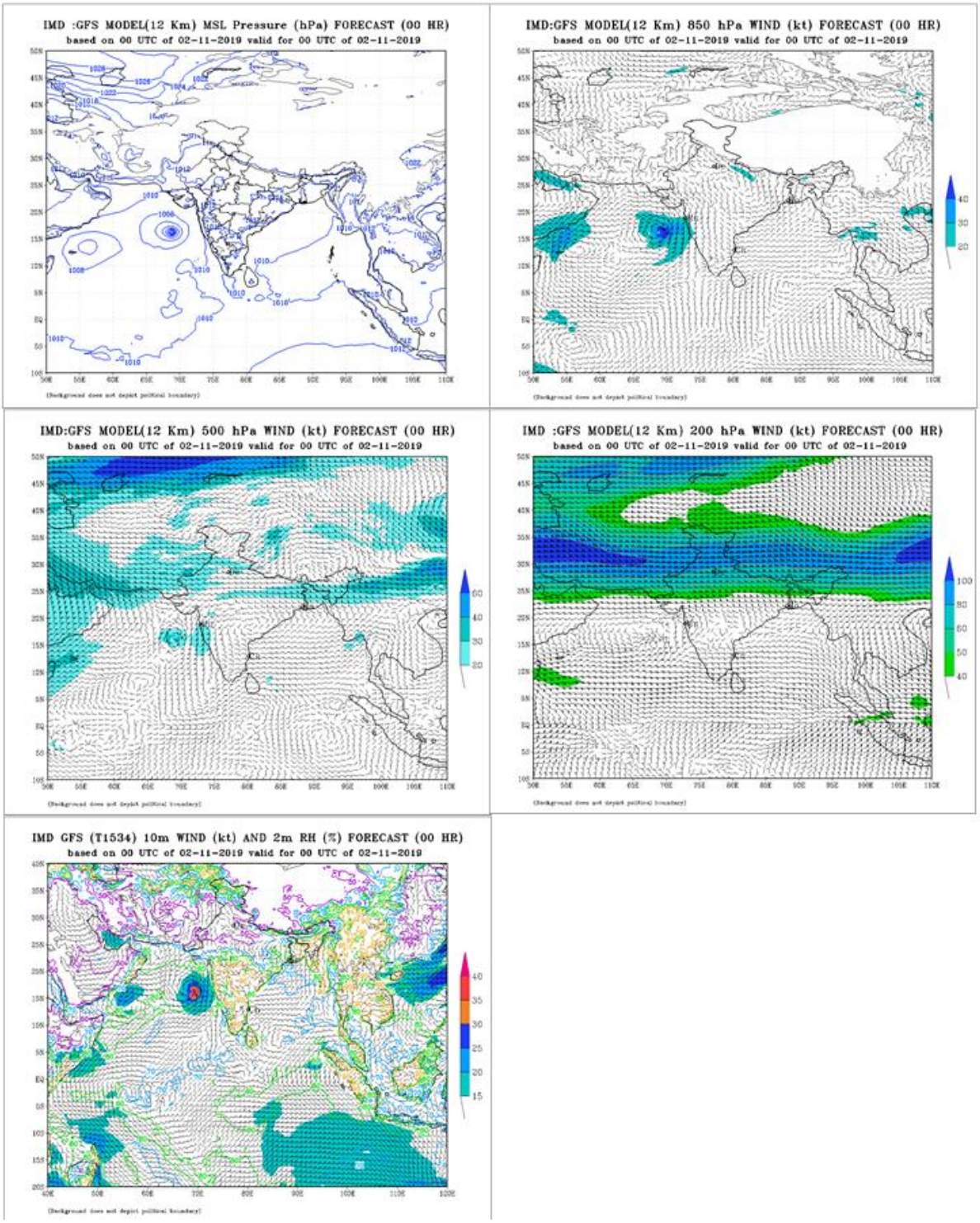


Fig.7d: IMD GFS analysis of MSLP, 10 m wind and winds at 850, 500 & 200 hPa levels based on 0000 of 2nd November

IMD GFS analysis field based on 0000 UTC of 3rd November, indicated further intensification of system over eastcentral Arabian Sea near 17.5N/66.5E. Synoptically also at that time system lay as an SCS over eastcentral AS near 17.6N/66.5E.

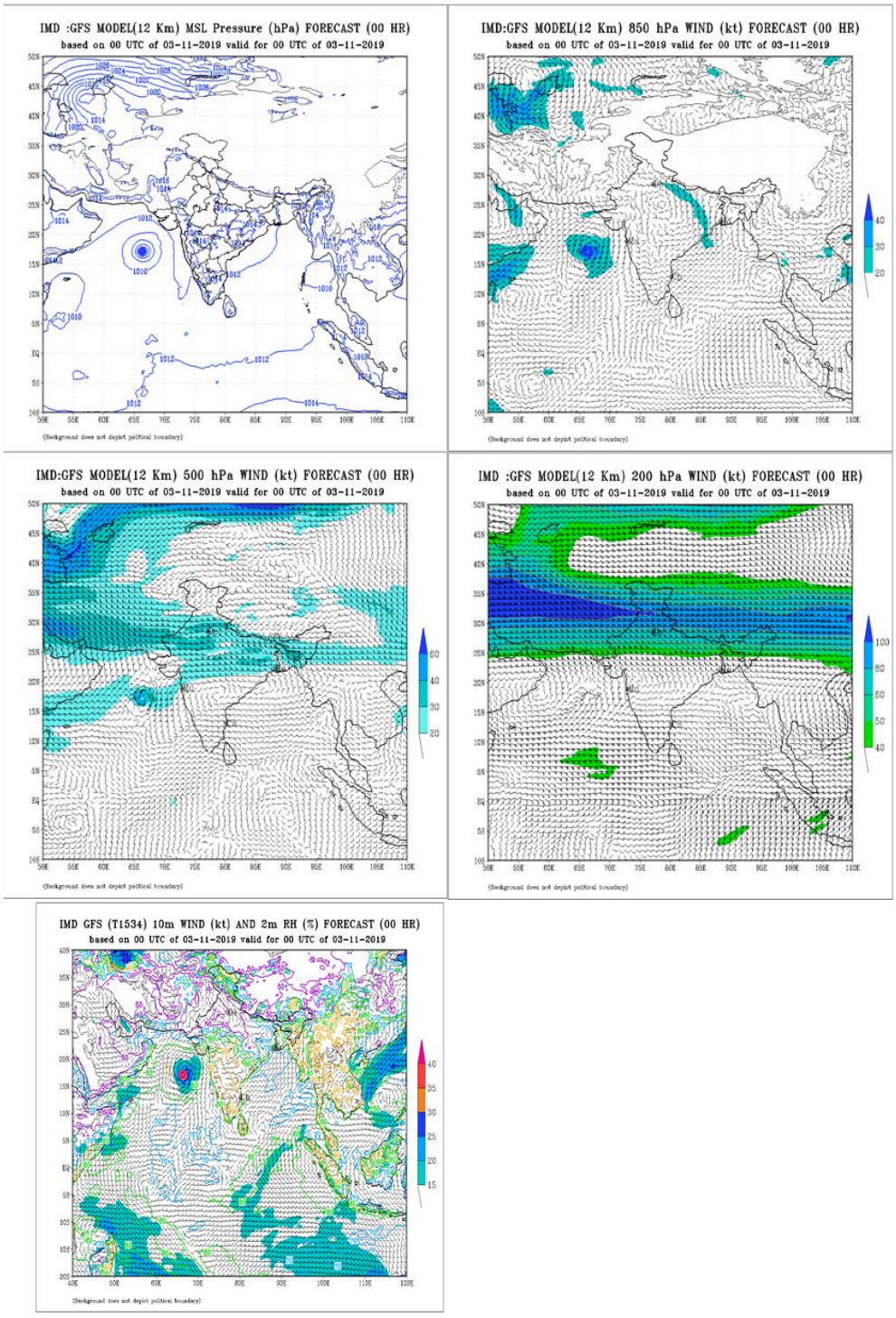


Fig.7d: IMD GFS analysis of MSLP, 10 m wind and winds at 850, 500 & 200 hPa levels based on 0000 3rd November

IMD GFS analysis field based on 0000 UTC of 4th November, indicated further intensification of system over westcentral Arabian Sea near 17.5N/65.0E. Synoptically also at that time system lay as an ESCS over westcentral AS near 18.1N/64.8E.

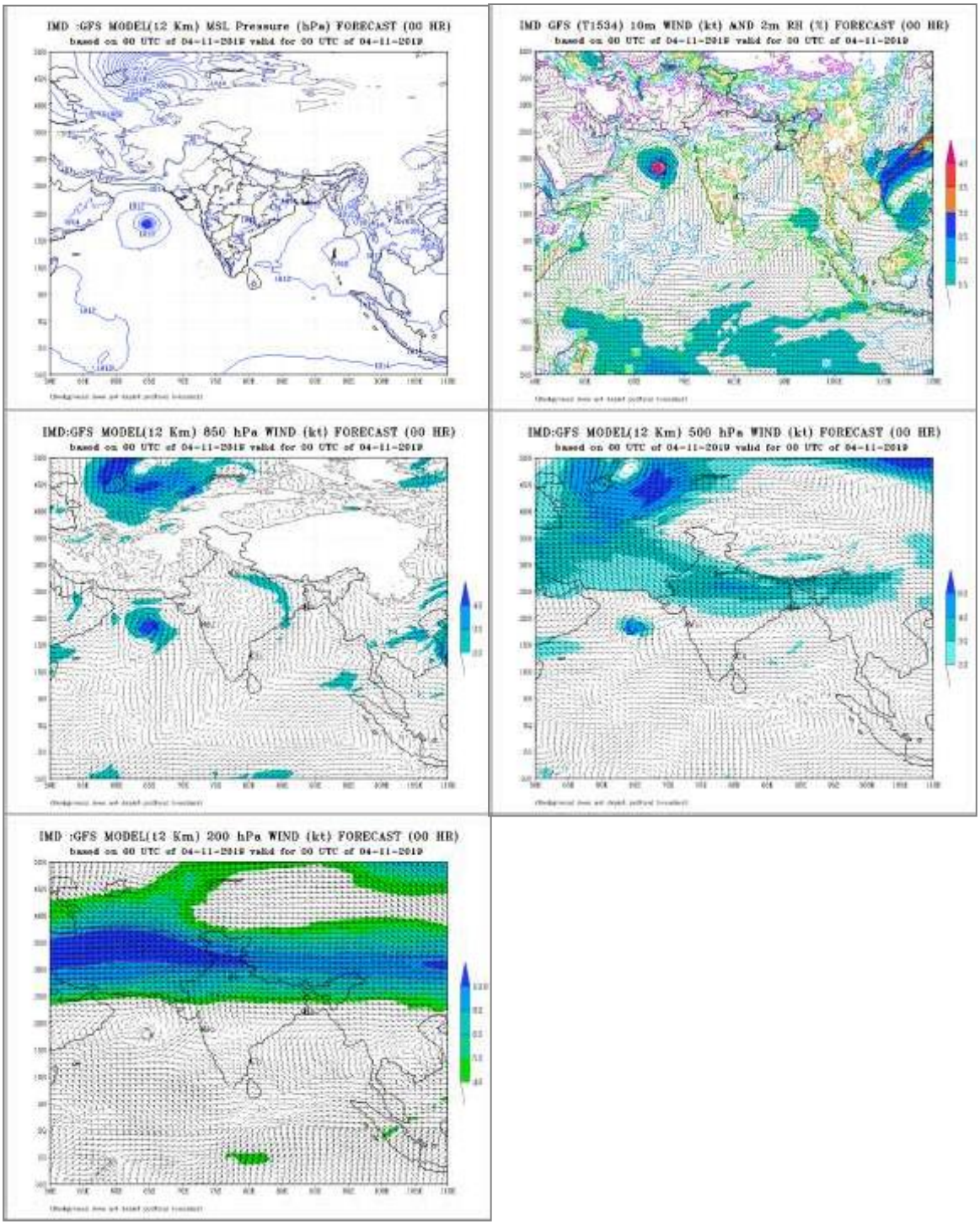


Fig.7e: IMD GFS analysis of MSLP, 10 m wind and winds at 850, 500 & 200 hPa levels based on 0000 of 4th November

IMD GFS analysis field based on 0000 UTC of 5th November, indicated further intensification of system over westcentral Arabian Sea near 20.0N/64.0E. Synoptically at that time system lay as an ESCS over westcentral AS near 19.6N/63.6E.

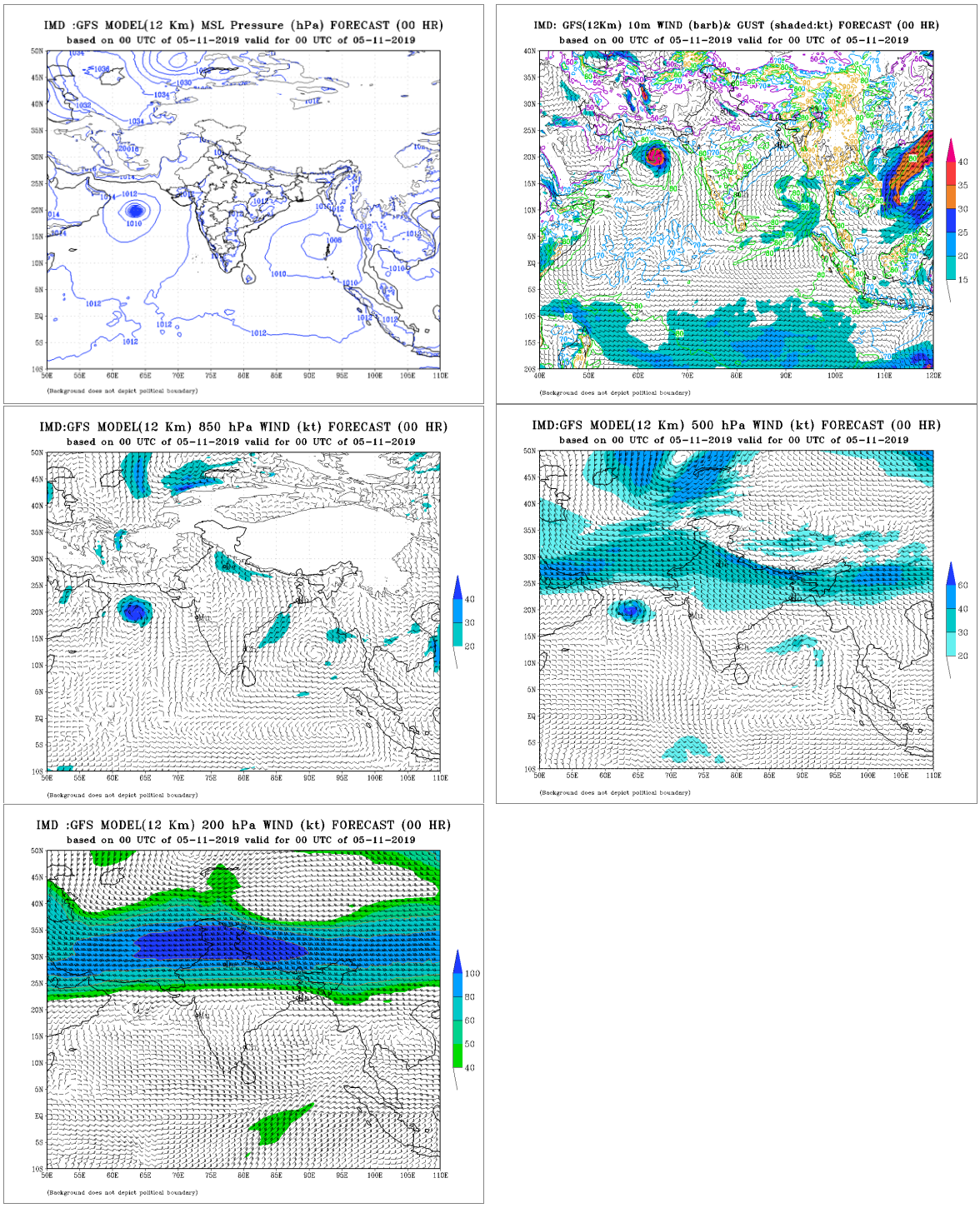


Fig.7f: IMD GFS analysis of MSLP, 10 m wind and winds t 850, 500 & 200 hPa levels based on 0000 of 5th November

IMD GFS analysis field based on 0000 UTC of 6th November, indicated weakening of system over eastcentral and adjoining westcentral Arabian Sea near 20.0N/65.5E. Synoptically at that time system lay as an SCS over eastcentral AS near 19.8N/65.8E.

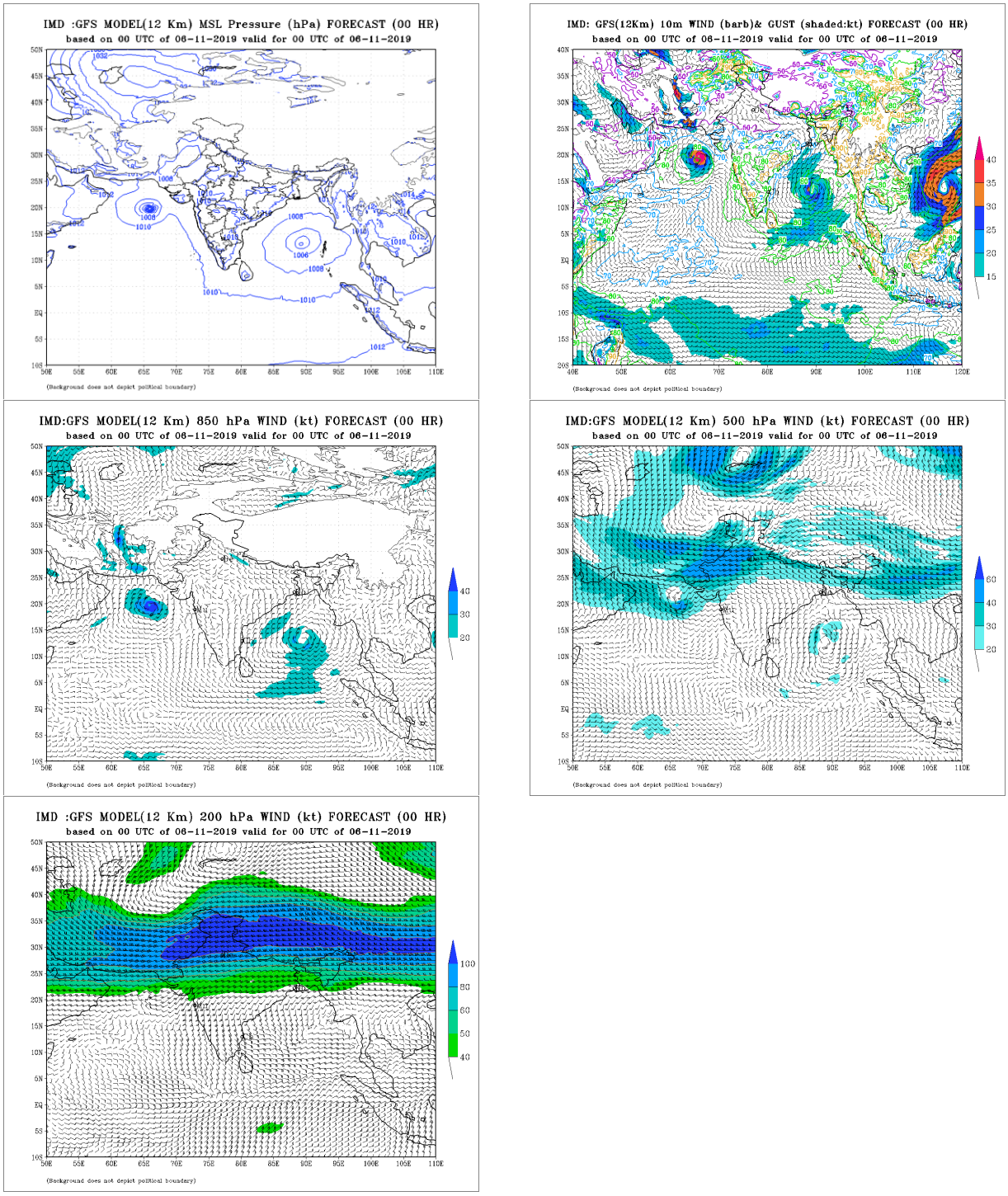


Fig.7g: IMD GFS analysis of MSLP, 10 m wind and winds t 850, 500 & 200 hPa levels based on 0000 of 6th November

IMD GFS analysis field based on 0000 UTC of 7th November, indicated weakening of system into an LPA over eastcentral Arabian Sea near 19.5N/69.5E. Synoptically at that time system lay as a DD over eastcentral AS near 19.8N/69.4E.

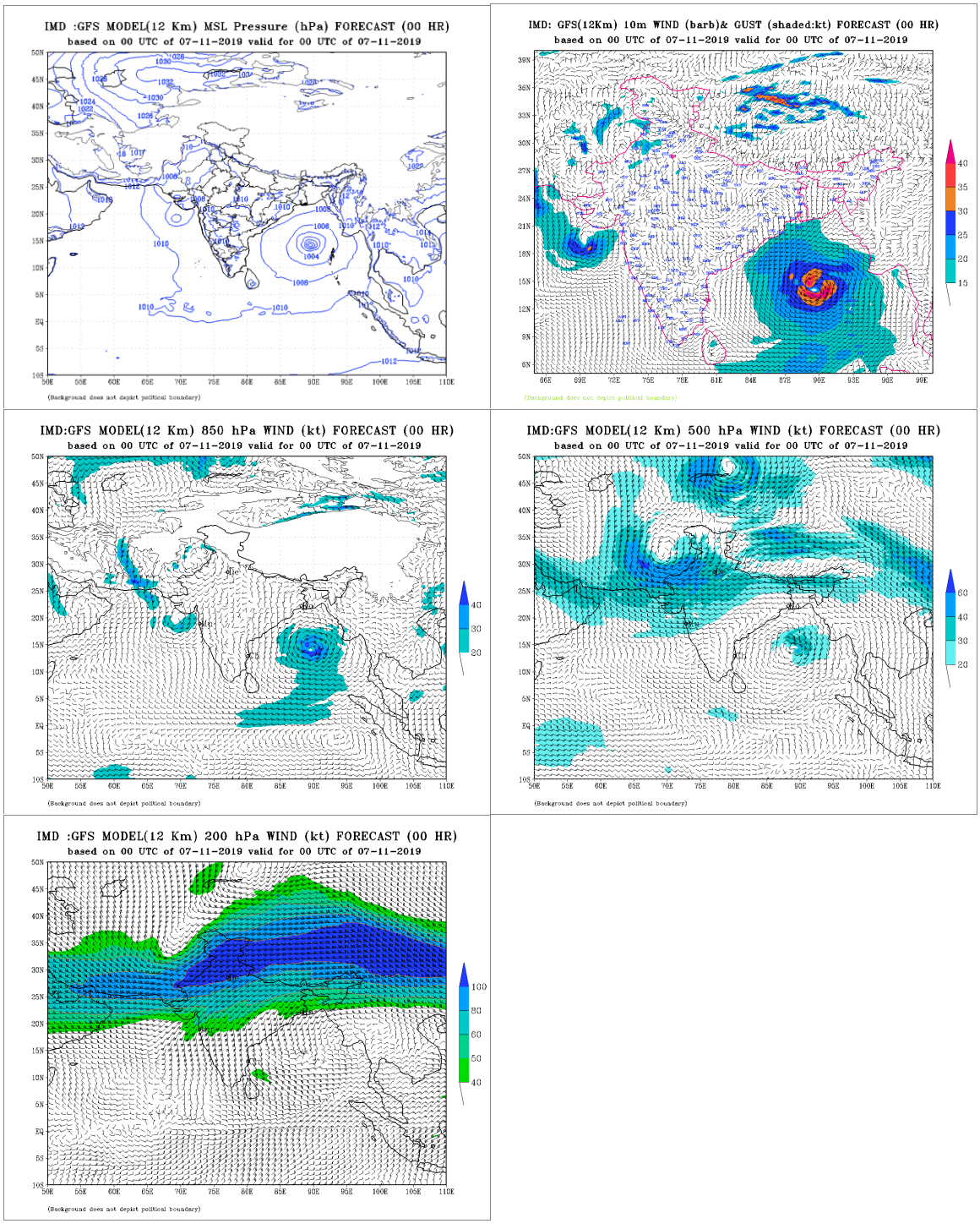


Fig.7h: IMD GFS analysis of MSLP, 10 m wind and winds t 850, 500 & 200 hPa levels based on 0000 of 7th November

Thus, IMD GFS could well capture genesis, intensification and movement of the system. However, weakening was over estimated.

6. Realized Weather:

6.1. Rainfall

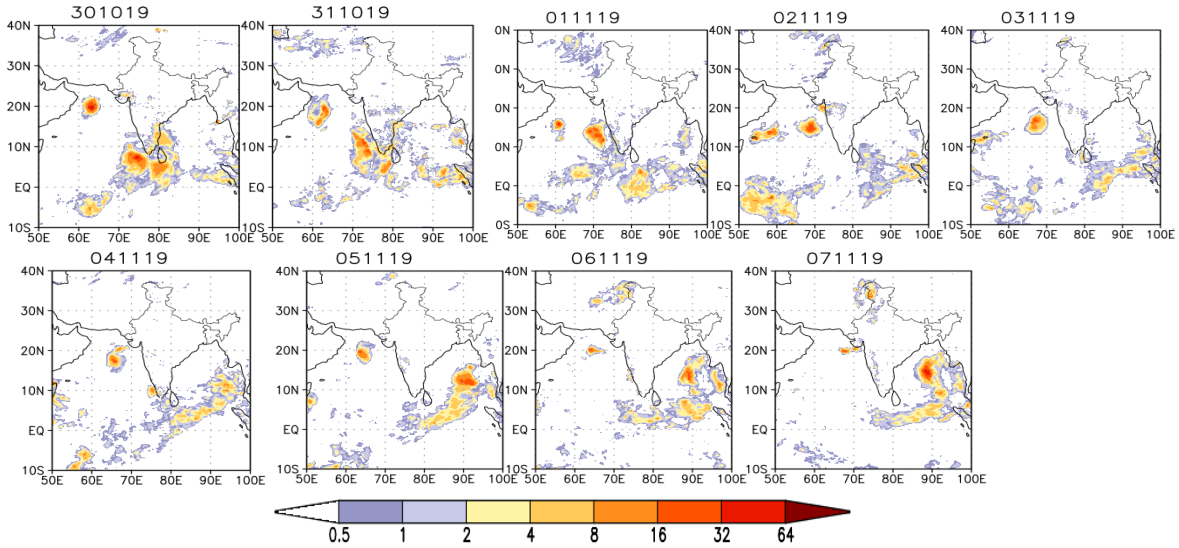


Fig.8: IMD-NCMRWF GPM merged gauge 24 hr cumulative rainfall (cm) ending at 0300 UTC of date during 30th October – 7th November

Rainfall associated with ESCS Maha based on IMD-NCMRWF GPM merged gauge 24 hours cumulative rainfall ending at 0300 UTC of date is depicted in **Fig 8**. It didn't cause any significant rainfall over the states along the west coast of India throughout it's life period. However, on 30th October, it caused heavy to very rainfall at most places with extremely heavy falls at few places over Maldives and heavy rainfall at most places over Comorin area. On 31st October, it caused heavy to very rainfall at few places over Maldives and heavy rainfall at few places over Comorin area. On 7th November, it caused heavy rainfall at isolated places over eastcentral Arabian Sea off south Gujarat coast.

Lakshadweep Islands reported light to moderate rainfall at most places with isolated heavy to very heavy and extremely heavy falls at isolated places on 30th & 31st October 2019. As the system moved over to eastcentral AS, coastal areas and windward side of the western Ghats of Maharashtra also received fairly widespread to widespread rainfall with heavy to very heavy falls at isolated places on 2nd November.
Rainfall amounts exceeding 07 cm recorded during the past 24 hours ending at 0300 UTC of date are given below:

30th October: Minicoy – 8
31st October: Amini – 30, Agatti – 14, Minicoy – 12
02nd November: Nandgaon – 15, Girnadam -12, Alibag – 9, Chandwad - 8

6.2. Wind:

On 31st October, Aminidivi reported MSW of 83 kmph at 1130 hrs IST (0600 UTC), 72 kmph at 1430 hrs IST (0900 UTC), 59 kmph at 1730 hrs IST (1200 UTC) & 45 kmph and 35 kmph at 1500 & 1800 UTC respectively.

Apart from the above, no adverse weather was reported from any of the states along west coast of India in association with this system.

7. Damage due to ESCS MAHA from Lakshadweep

THE PRELIMINARY DAMAGE ASSESSMENT REPORT

[As on 02.11.2019 at 10.30 hrs] 1673 556.7

Name of the UT: Lakshadweep

Sr. No.	Particulars	Damage during 'MAHA' Cyclone period
i.	Rainfall received	666.4 mm (within 3 days)
ii.	No. of District Affected with Name	1 (UT of Lakshadweep)
iii.	No. of Islands affected	10
iv.	Population affected	Entire population
v.	Human lives lost (district wise with cause of death)	Nil
vi.	No. of missing	Nil
vii.	No. of injured	Nil
viii.	Houses damaged	Fully - Nil Partially - 5 (aprox.)
ix.	Animal deaths	No report received
x.	No. of persons evacuated	786
xi.	No. of relief camp opened	32
xii.	Inmates in the relief camps	786
xiii.	Relief material distributed	Yes
xiv.	Total crop area affected (in hectares)	Coconut tree- 103 (aprox.) Other trees- 123(aprox.)
xv.	Infrastructure Damage (Status of Air, Rail, Road, Telephone, Power etc.	Nil

Assistance provided by Government of India:

i..	NDRF	Nil
ii.	Air Force, Navy & Army	YES
iii.	Other Central Government Ministry / Department	YES

Deployment of State Forces:

i.	SDRF	YES
ii.	State Police / Fire	YES
iii.	Boats	Nil

8. Performance of operational NWP models

IMD operationally runs a regional model, WRF for short-range prediction and one Global model T1534 for medium range prediction (10 days). The WRF-VAR model is run at the horizontal resolution of 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 12 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. 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 (e) 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 for ESCS Maha are presented and discussed.

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

Predicted zone of cyclogenesis based on 0000 UTC of 25th to 30th October for 30th October is presented in Fig.9. The model could predict cyclogenesis zone correctly about 72 hrs in advance.

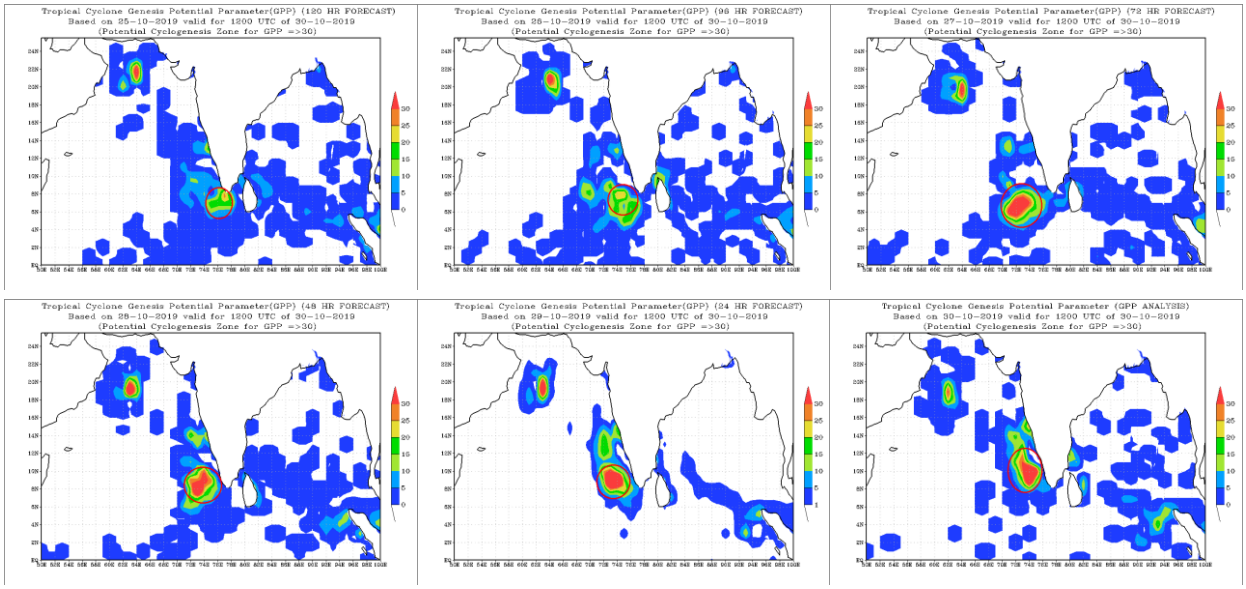


Fig.9 (a-f): Predicted zone of Cyclogenesis based on 0000 UTC from 25th-30th October 2019 for 30th October (120-00 hrs lead period)

9.2 Track prediction by IMD HWRF model

Track prediction by IMD HWRF model is presented in **Fig.10**. IMD HWRF could capture the movement correctly, however from 4th onwards it was predicting landfall over south Gujarat coast. Actually the system weakened over the Sea.

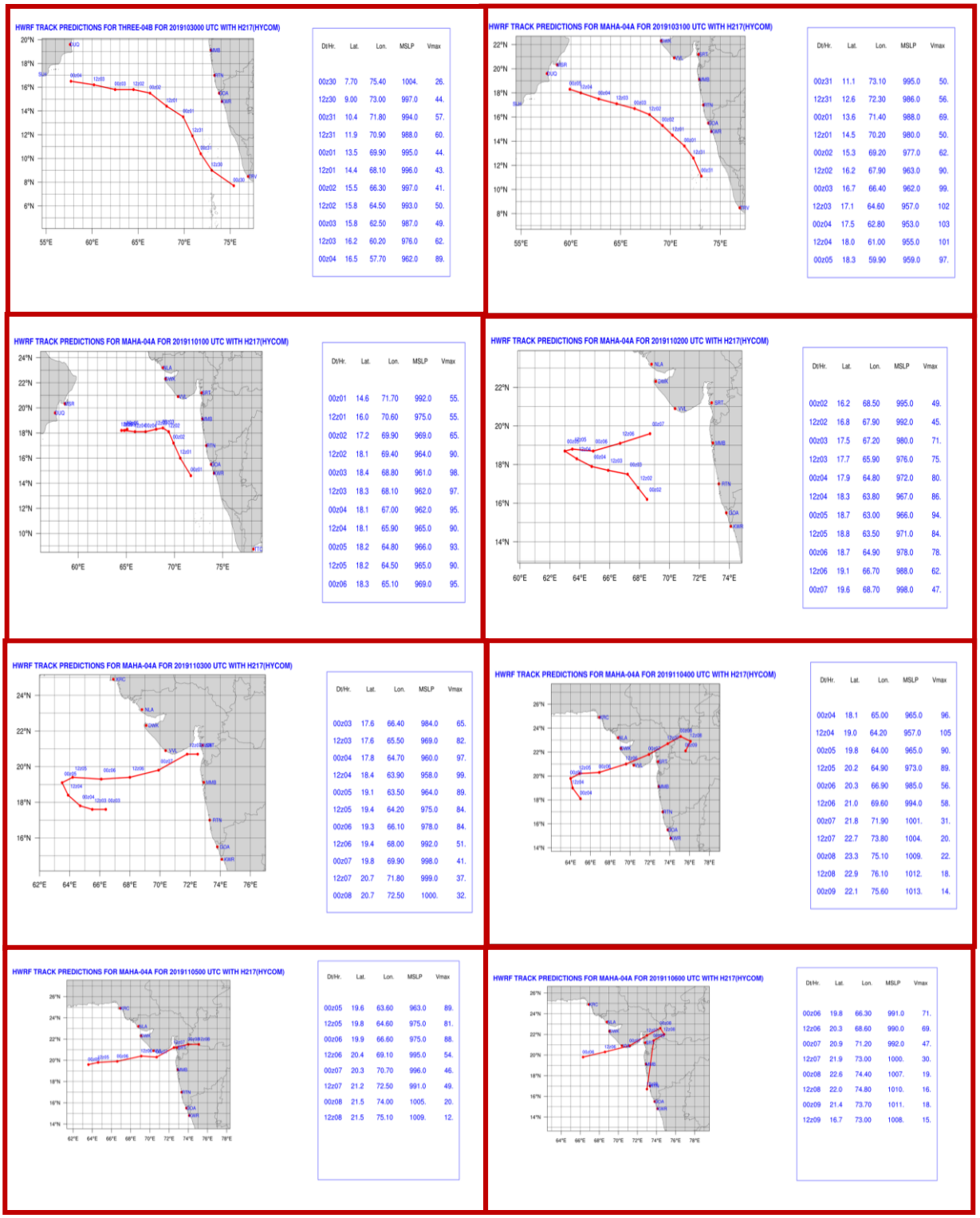


Fig. 10: Track prediction by IMD HWRF based on 0000 UTC during 30th October to 6th November, 2019.

9.3 Track 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 2(a)**. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of MME was the least minimum for all lead periods followed by NCEP GFS and IMD GFS.

Table-2 (a). Average track forecast errors (Direct Position Error (DPE)) in km (Number of forecasts verified is given in the parentheses)

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108 H	120H
IMD-MME*	31(16)	32(15)	53(14)	75(13)	83(12)	99(11)	104(10)	128(9)	137(8)	125(7)
ECMWF	60	72	96	123	131	165	186	223	294	328
NCEP-GFS	36	32	51	66	88	131	169	208	199	188
UKMO	43	73	106	139	149	166	202	269	280	246
JMA	91	110	134	155	173	187	197	--	--	--
IMD-GFS	44	61	85	110	113	119	124	132	116	100
IMD-WRF	73	135	174	202	271	375	--	--	--	--
IMD-HWRF	49(32)	81 (30)	110(28)	122(26)	137(24)	143(22)	175(20)	241(18)	332(16)	425(14)
NCUM	---	92(16)	---	125(17)	---	141(15)	---	187(13)	---	252(11)
NEPS	---	88(16)	---	125(14)	---	140(12)	---	251(10)	---	339(8)
UM REG	---	96(17)	---	101(17)	---	179(13)	---	---	---	---

The along track and cross track errors by IMD HWRF are presented in Fig. 2 (b-c). along track errors were less as compared to cross track errors

Table-2(b): Along the Track (AT) Forecast Error in km of IMD-HWRF Model

(Number of forecasts verified is given in the parentheses)

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr	120 Hr
HWRF	29(32)	54 (30)	81(28)	87(26)	103(24)	114(22)	135(20)	158(18)	237(16)	302(14)

Table-2(c): Cross the Track (CT) Forecast Error in km of IMD-HWRF Model

(Number of forecasts verified is given in the parentheses)

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr	120 Hr
HWRF	78(32)	81 (30)	83(28)	106(26)	118(24)	138(22)	158(20)	170(18)	186(16)	198(14)

9.4 Intensity forecast errors by various NWP Models

The intensity forecast errors of IMD HWRF model are shown in Table **3.**

Table-3: Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of HWRF model (Number of forecasts verified is given in the parentheses)

Lead time →	**12H**	**24H**	**36H**	**48H**	**60H**	**72H**	**84H**	**96H**	**108H**	**120H**
HWRF (AAE)	9.5(32)	11.4(30)	12.3(28)	13.8(26)	15.3(24)	13.9(22)	12.8(20)	13.0(18)	12.2(16)	18.2(14)
HWRF (RMSE)	13.5(32)	14.1(30)	16.3(28)	16.3(26)	19.2(24)	18.0(22)	15.6(20)	15.9(18)	14.9(16)	21.2(14)

10. Operational Forecast Performance

10.1. Genesis Forecast

- First information about formation of LPA over equatorial Indian Ocean off south Sri Lanka was provided in the Press Release issued at 1330 hrs IST (0800 UTC) of 28th October. It was also indicated that the system would concentrate into a depression over southeast Arabian Sea and adjoining Lakshadweep & Maldives area around 30th October. Depression formed over Maldives-Comorin area in the early morning (0000 UTC) of 30th October. Thus, genesis was predicted around 40 hours in advance.

- Pre Cyclone Watch was issued for Lakshadweep Islands at 1500 hrs IST (0930 UTC) of 30th when the system was a depression at 1130 hrs IST (0600 UTC) of 30th over Maldives-Comorin area.
- Cyclone Alert for Lakshadweep Islands was issued at 1750 hrs IST of 30th, when it lay as a deep depression at 1430 hrs IST (0900 UTC) of 30th over Lakshadweep and adjoining southeast Arabian Sea & adjoining Maldives area.
- Cyclone Warning for Lakshadweep Islands was issued at 2000 hrs IST of 30th, when it lay as a cyclonic storm at 1730 hrs IST (1200 UTC) of 30th over Lakshadweep and adjoining southeast Arabian Sea and adjoining Maldives area.
- Dewarning message for Lakshadweep Islands was issued at 0900 hrs IST of 1st November when the system lay over eastcentral Arabian Sea at 0530 hrs IST (0000 UTC) of 1st November as a severe cyclonic storm, after it has moved away from Lakshadweep Islands.

10.2 Track, Intensity and Landfall Forecast

- In the first bulletin issued at 1230 hrs IST (around 0700 UTC) of 30th October, it was indicated that the system would move initially north-northwestwards and then re-curve west-northwestwards from 1st early morning (0000 UTC). Actually, system started recurring west-northwestwards from 1st early morning (0000 UTC). Thus, first re-curvature of the system could be correctly predicted around 2 days (45 hours) in advance.
- In the subsequent bulletin issued at 1750 hrs IST (around 1200 UTC) of 30th October, it was predicted that the system would move across Lakshadweep till 31st evening (1200 UTC). Actually, the system lay over eastcentral AS and adjoining

Lakshadweep area in the noon (0600 UTC) of 31st and over eastcentral AS in the early morning (0000 UTC) of 1st November. Thus, movement across Lakshadweep area was well predicted.

- In the bulletin issued at 1130 hrs IST (0600 UTC) of 1st November, second re-curvature of the system was predicted (around 4 days in advance). The bulletin indicated that the system would re-curve northeastwards from 5th evening. Actually, from 5th early hours (0030 hrs IST/ around 2100 UTC), it moved northwards for some time and then gradually re-curved northeastwards from noon (around 0600 UTC) of 5th November. Thus, the track was well predicted despite multiple re-curvatures.
- In the first bulletin issued at 1230 hrs IST (around 0700 UTC) of 30th October, it was indicated that the system would intensify into a CS around 1st evening. However, the system intensified into a CS in the evening (1200 UTC) of 30th.
- In the bulletin issued at 1750 hrs IST (around 1200 UTC) of 30th, it was indicated that the system would intensify upto VSCS stage.
- In the bulletin issued at 0530 hrs IST (0000 UTC) of 2nd November, it was predicted that the system would move towards south Gujarat and adjoining north Maharashtra coasts and while moving east-northeastwards, the system would gradually weaken. However, cyclone watch for Gujarat coast was issued at 0900 hrs IST of 3rd November as it was predicted that the system would cross south Gujarat coast as an SCS around 7th early morning. Cyclone Alert for Gujarat coast was issued at 1040 hrs IST of 4th November as landfall as SCS was predicted.
- However, in the bulletin issued at 1210 hrs IST (around 0700 UTC) of 6th November, it was predicted that the system would instead skirt Saurashtra coast as a deep depression/depression and weaken gradually. Actually, it weakened into a well marked low pressure area over northeast Arabian Sea and adjoining south Gujarat coast in the evening (1200 UTC) of 7th November.
- Typical observed and forecast track along with cone of uncertainty and wind distribution indicating accuracy in track prediction is presented in **Fig. 11**.

Thus the genesis, track, intensification and weakening of the system were well predicted by IMD. Adverse weather like heavy rainfall and strong wind associated with the system were also well predicted by IMD both for Lakshadweep Islands and the states of Gujarat & Maharashtra. However, there was slight over warning w.r.t. landfall over Gujarat during east-northeastwards movement of system. Since the first bulletin, state of Sea and warnings for fishermen in deep Seas of south, central and northern parts of Arabian Sea, Lakshadweep, Maldives & Comorin areas and along & off Gujarat, Maharashtra coasts were issued both in textual and graphical form.

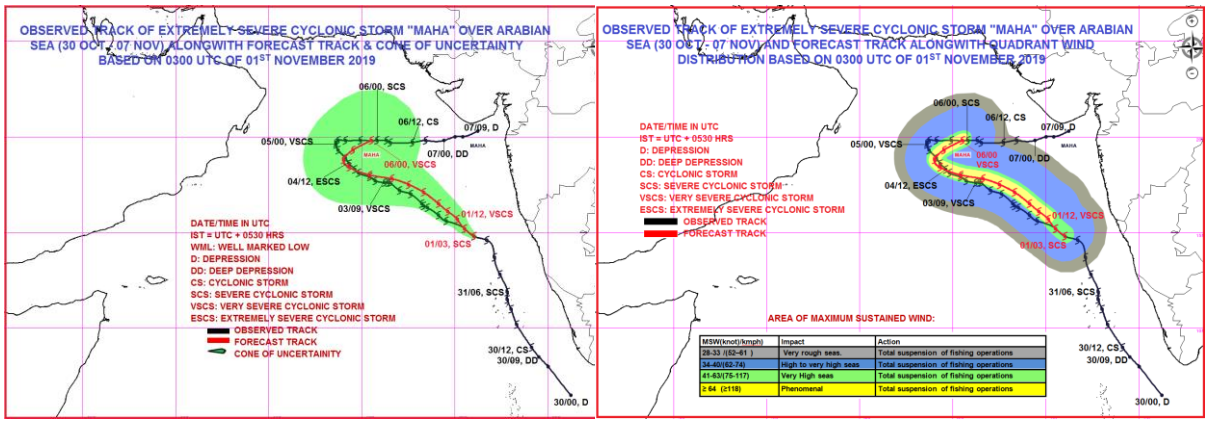


Fig.11: Observed and forecast track of ESCS 'MAHA' along with (a) cone of uncertainty and (b) wind distribution indicating accuracy in track and intensity predictions during life cycle of MAHA.

10.3. Track Forecast Errors:

- The track forecast errors for 24, 48 and 72 hrs lead period were 72, 92, and 122 km respectively against the average track forecast errors of 86, 132 and 178 km during last five years (2014-18) respectively (**Fig.12a)**.
- The track forecast skill was about 71%, 89%, and 83% against the long period average (LPA) of 58%, 70%, and 74% during 2014-18 for 24, 48 and 72 hrs lead period respectively (**Fig.12b)**.
- Fig. 12 (a&b) indicate that for all lead periods the track forecast errors and skill were better than long period average during 2014-18.

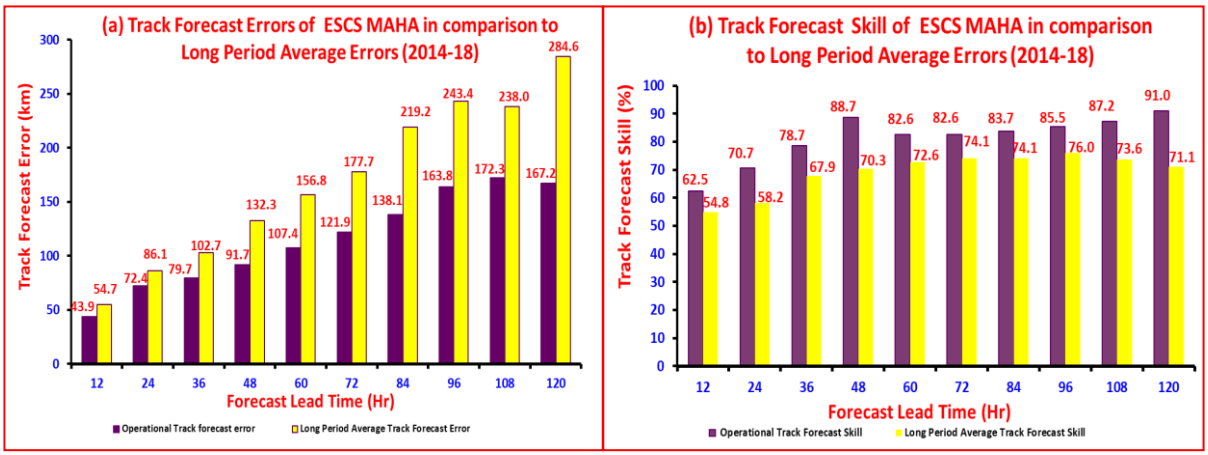


Fig. 12: Track forecast (a) Errors and (b) skill of ESCS 'MAHA' as compared to long period average (2014-18)

10.5. Intensity Forecast Errors:

- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 09, 12 and 10 knots against the LPA of 10, 14 and 14 knots respectively **(Fig. 13a).**
- The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 11, 13 and 12 knots against the LPA of 13, 19 and 19 knots respectively **(Fig. 13b).**
- For all lead periods except 120 hrs, the intensity forecast errors were significantly less than the long period average errors of 2014-18.

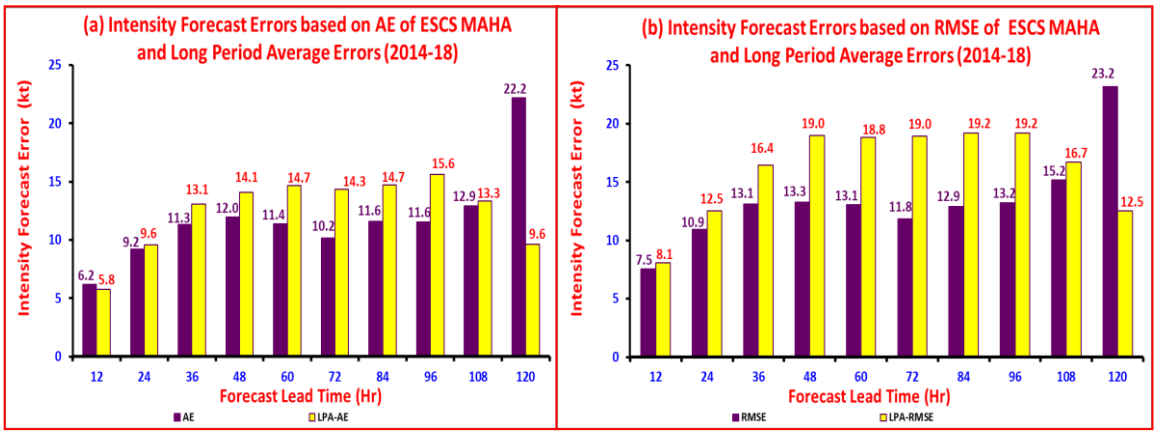


Fig. 13: (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) in intensity forecast (winds in knots) in association with ESCS 'MAHA' as compared to long period average (2014-18)

- The skill in intensity forecast based on AE for 24, 48 and 72 hrs lead period was 44, 70 and 82 % against the LPA of 43, 68 and 72 % respectively **(Fig. 14 a).**
- The skill in intensity forecast based on RMSE for 24, 48 and 72 hrs lead period was 47, 74 and 84 % against the LPA of 49, 59 and 69 % respectively **(Fig. 14 b).**
- For all lead periods except 12 and 120 hours, the skill in intensity forecast was comparable/more than the long period average of 2014-18.

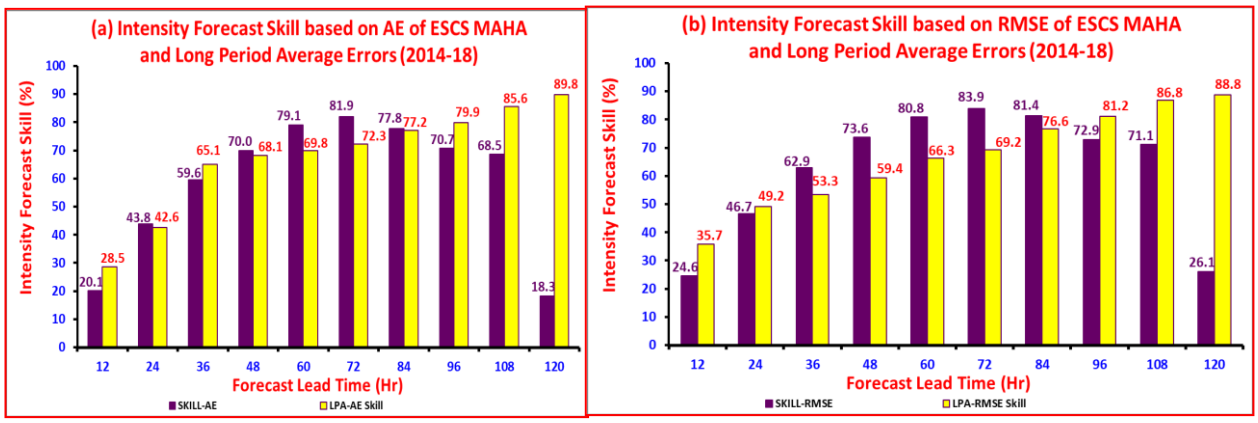


Fig. 14: Skill in intensity forecast (%) based on (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) in association with ESCS 'MAHA' as compared to long period average (2014-18)

11. Warning Services

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 for +06, +12, +18, +24, +36 and +48… +120 hrs lead period till the system weakened into a low pressure area. The above forecasts were issued from the stage of depression onwards along with the cone of uncertainty in the track forecast five times a day and every three hours during the cyclone period. Typical graphical product is presented in **Fig. 11(a)**.

- **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 and +120 hrs lead period. Typical graphical product is presented in **Fig. 11(b)**.
- **Adverse weather warning bulletins:** The tropical cyclone forecasts along with expected adverse weather like heavy rain and gale wind was issued with every three hourly update to central, state and district level disaster management agencies including MHA NDRF, NDMA for all concerned states along the east coast of India including Kerala, Karnataka, Goa, Maharashtra, Gujarat and Lakshadweep. The bulletins also contained the suggested action for disaster managers and general public in particular for fishermen. These bulletins were also issued to Defense including Indian Navy & Indian Air Force.
- **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. The adverse weather warnings related to gale/squally winds were also presented in graphics in the website.
- **Warning and advisory through social media:** Daily updates (every six hourly or whenever there was any significant change in intensity/track/landfall) were uploaded on face book and twitter regularly during the life period of the system. Bulletins were also issued to state level disaster managers through whatsapp.
- **Press release and press briefing:** Press and electronic media were given daily updates since inception of system through press release, e-mail, website and SMS.
- **Warning and advisory for marine community:** The three/six hourly Global Maritime Distress Safety System (GMDSS) bulletins were issued by the Marine Weather Services division at New Delhi and bulletins for maritime interest were issued by Area Cyclone Warning Centres of IMD at Chennai & Mumbai, Cyclone Warning Centres at Thiruvananthapuram & Ahmadabad and Meteorological Centres at Bangaluru & Goa, to ports, fishermen, coastal and high Sea shipping community.
- **Fishermen Warning:** Regular warnings for fishermen were issued for deep Sea of southeast AS, central AS and northeast AS during the life period of the system.
- **Advisory for international Civil Aviation:** The Tropical Cyclone Advisory Centre (TCAC) bulletin for International Civil Aviation were issued every six hours 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.
- **Diagnostic and prognostic features of cyclone:** The prognosis and diagnosis of the systems were described in the RSMC bulletins.
- Bulletins issued by RSMC New Delhi, IMD and those by ACWC Mumbai and CWCs Thiruvananthapuram & Ahmadabad are presented in **Table 4 and Table 5** respectively.

Table 4: Bulletins issued by RSMC New Delhi

S.N	Bulletin	No. of Bulletins	Issued to
1	National Bulletin	83	1. IMD's website, RSMC New Delhi website 2. FAX and e-mail to Control Room Ministry of Home Affairs & National Disaster Management Authority, Cabinet Secretariat, Minister of Science & Technology, Headquarter Integrated Defense Staff, Director General Doordarshan, All India Radio, National Disaster Response Force, Chief Secretary- Kerala, Karnataka, Goa, Gujarat and Maharashtra, Administrator- Lakshadweep Islands, Union Territory of Daman and Diu, Union Territory of Dadar and Nagar Haveli.
2.	Bulletin from DGM, IMD	5	Cabinet Secretary, Principal Secretary to PM, Secretary, Ministry of Home Affairs, Ministry of Agriculture, Ministry of I & B, MoES, Secretary, DST, Control Room, NDM, Ministry of Home Affairs, Director of Punctuality, Indian Railways, Director General, Doordarshan, Director General, AIR, Secretary, NDMA, Director General, NDRF, Chief Secretary Kerala, Karnataka, Goa, Gujarat and Maharashtra, Administrator- Lakshadweep Islands, Union Territory of Daman and Diu, Union Territory of Dadar and Nagar Haveli.
2	RSMC Bulletin	83	1. IMD's website 2. WMO/ESCAP member countries and WMO through GTS and E-mail.
3	GMDSS Bulletins	7	1. IMD website, RSMC New Delhi website 2. Transmitted through WMO Information System (WIS) to Joint WMO/IOC Technical Commission for Ocean and Marine Meteorology (JCOMM)
4	Tropical Cyclone Advisory Centre Bulletin (Text & Graphics)	32	1. Met Watch offices in Asia Pacific regions and middle east through 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
5	Tropical Cyclone Vital Statistics	32	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
6	Warnings through SMS	Daily four times and when intensity changed	SMS to disaster managers at national level and concerned states (every time when there was change in intensity)-2305 To general public to users registered with RSMC website from the states of Kerala, Karnataka, Goa, Gujarat and Maharashtra and National level disaster managers - 376535

			Through INCOIS on Ocean State Forecast-6,01,552 To farmers of Gujarat & Maharashtra through Kisaan Portal-5,52,669
6.	Warnings through Social Media	Daily four times and when intensity changed	Cyclone Warnings were uploaded on Social networking sites (Face book, Twitter and Whatsapp) since inception to weakening of system (every time when there was change in track, intensity and landfall characteristics)
7.	Press Release	8 (once a day)	Disaster Managers, Media persons by email and uploaded on website
8.	Press Briefings	Frequently	Regular briefing daily

Table 5: Bulletins issued by ACWCs & CWCs

S. No.	Type of Bulletin	Number of Bulletins issued by		
		CWC Thiruvananthapuram	CWC Ahmadabad	ACWC Mumbai
1.	Sea Area Bulletins	00	32	42
2.	Coastal Weather Bulletins	25	64	20
3.	Fishermen Warnings issued	36	32	40
4.	Port Warnings	06	32	46
5.	Heavy Rainfall Warning	24	32	04
6.	Gale Wind Warning	26	32	0
7.	Information & Warning issued to State Government and other Agencies	75	32	10
8	Special Weather Bulletins	02	32	-
9.	SMS / Social Media messages	42	2442	19825

12. Summary:

The ESCS 'MAHA' originated as an LPA over Equatorial Indian Ocean off south Sri Lanka coast in the forenoon of 28th October. Under favourable environmental conditions, it concentrated into a Depression (D) over Maldives-Comorin Area in the early morning (0000 UTC) of 30th October and into an ESCS in the early morning (0000 UTC) of 04th November over eastcentral & adjoining westcentral AS. It weakened into a WML over northeast AS & adjoining coastal Saurashtra in the evening (1200 UTC) of 07th November. The system was monitored since it's inception as a low pressure area on 28th October. It caused adverse weather over Lakshadweep Islands. The track and intensity of the system were well predicted. The track forecast errors for 24, 48 and 72 hrs lead period were 72, 92, and 122 km respectively against the average track forecast errors of 86, 132 and 178 km during last five years (2014-18) respectively. For all lead periods the track forecast errors and skill were better than long period average during 2014-18. The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 09, 12 and 10 knots against the LPA of 10, 14 and 14 knots respectively. For all lead periods except 120 hrs, the intensity forecast errors were significantly less than the long period average errors of 2014-18.

13. Acknowledgement:

IMD and RSMC New Delhi duly acknowledge the contribution from all the stake holders and disaster management agencies who contributed to the successful monitoring, prediction and early warning service of ESCS 'MAHA'. We acknowledge the contribution of all sister organisations of Ministry of Earth Sciences including National Centre for Medium Range Weather Forecasting Centre (NCMRWF), Indian National Centre for Ocean Information Services (INCOIS), National Institute of Ocean Technology (NIOT), Indian Institute of Tropical Meteorology (IITM) Pune, research institutes including IIT Bhubaneswar, IIT Delhi and Space Application Centre, Indian Space Research Organisation (SAC-ISRO) for their valuable support. The support from various Divisions/Sections of IMD including Area Cyclone Warning Centre (ACWC) Chennai & Mumbai, Cyclone Warning Centre (CWC) Thiruvananthapuram & Ahmedabad, Meteorological Office Goa, Bengaluru, Office of Cyclone Detection Radar Kochi & Goa and coastal observatories along the west coast of India. The contribution from Numerical Weather Prediction Division, Satellite and Radar Division, Agromet Advisory Division, Surface & Upper air instruments Divisions, New Delhi and Information System and Services Division at IMD is also duly acknowledged.
