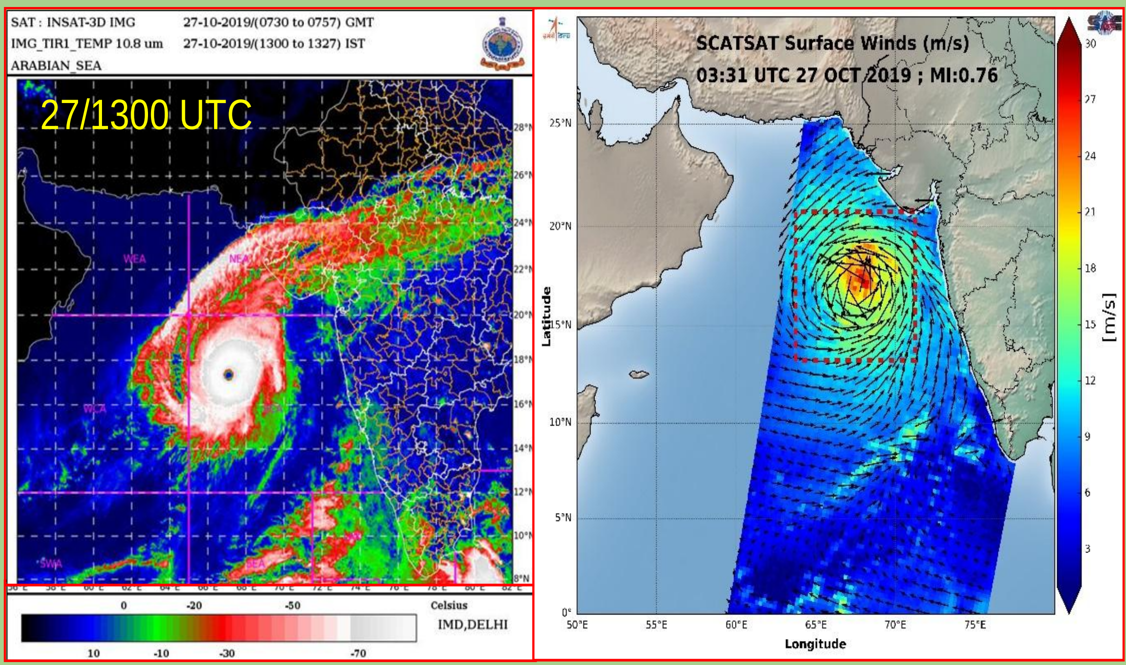
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Super Cyclonic Storm, ‘KYARR’ over the Arabian Sea (24 October – 02 November 2019): A Report



INSAT-3D enhanced colored IR imagery & SCATSAT Surface Winds for SuCS KYARR over Arabian Sea

Cyclone Warning Division

India Meteorological Department

New Delhi

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Super Cyclonic Storm, ‘KYARR’ over the Arabian Sea
(24th October – 02nd November 2019)

1. Introduction

The Super Cyclonic Storm (SuCS) ‘KYARR’ originated from a Low Pressure Area (LPA) over southeast Arabian Sea (AS) and adjoining Lakshadweep area on 17th October. It lay as a Well Marked Low pressure area (WML) over central parts of AS on 22nd October. Under favourable environmental conditions, it concentrated into a Depression (D) over east-central Arabian Sea in the morning (0300 UTC) of 24th October, 2019. Moving east-northeastwards, it intensified into a Deep Depression (DD) over east-central AS in the evening (1200 UTC) of 24th October. Continuing to move further east-northeastwards, it intensified into a Cyclonic Storm (CS) ‘KYARR’ in the early morning (0000 UTC) of 25th October over the same region and further into a Severe Cyclonic Storm (SCS) in the evening (1200 UTC) of 25th October over the same region. Thereafter, it recurved west-northwestwards and intensified into a very severe cyclonic storm (VSCS) over east-central AS in the early morning (0000 UTC) of 26th. Continuing to move west-northwestwards, it intensified into an Extremely Severe Cyclonic Storm (ESCS) in the night (1500 UTC) of 26th October over the same region. Moving west-northwestwards, it intensified into a **Super Cyclonic Storm** (SuCS) in the early morning (0000 UTC) of 27th October over east-central AS.

It maintained the intensity of SuCS for 51 hours and thereafter under unfavourable environmental conditions (mainly reduction in tropical cyclone heat potential to less than 50 KJ/cm^2, equatorward outflow in upper troposphere and decrease in warm & moist air in the core of system), it weakened into an ESCS in the morning (0300 UTC) of 29th October over west-central AS. It started moving westwards from the midnight (1800 UTC) of 29th October and weakened into a VSCS in the early morning (0000 UTC) of 30th.

Thereafter, it re-curved west-southwestwards from noon (0600 UTC) of 30th under the influence of anticyclone over Arabian Peninsula located to the northwest of system and weakened into an SCS in the night (1500 UTC) of 30th.

Thereafter, due to unfavourable conditions like lower Sea surface temperatures, lower ocean thermal energy, cold & dry air entrainment into the core of system & increased vertical wind shear over the west-central AS, the system continued to lose it’s strength and weakened into a CS in the morning (0300 UTC) of 31st, a DD in the night (1500 UTC) of 31st October and D in the early morning of 1st November.

It maintained the intensity of depression for next 42 hours and weakened into a well marked low pressure area near Somalia in the midnight of 2nd November.

The observed track of the system during 24th October– 02nd November is presented in **Fig.1(a)** and the tracks of both SuCS Kyarr & ESCS Maha, which co-existed over the AS during 30th Oct. to 2nd November is shown in **Fig.1(b)**. Best Track parameters associated with the system are presented in **Table1**.

2. Salient Features:

The salient features of the system were as follows:

1. Kyarr was the first cyclone of post monsoon season over the north Indian Ocean in 2019. It was the 3rd cyclonic storm and also the 3rd in severe category over the Arabian Sea during the year 2019. The normal frequency is one cyclonic storm over the Arabian Sea per year.
2. Climatologically, Kyarr was the 7th Super Cyclonic Storm over north Indian Ocean during the period 1965-2019.
3. It was the 2nd Super Cyclonic Storm over the Arabian Sea during the period 1965-2019 after SuCS Gonu in June, 2007. However, Gonu crossed Oman coast as a VSCS with maximum sustained wind speed of 77 KTS while Kyarr weakened over Sea.
4. It was the 1st SuCS over the Arabian Sea in the post monsoon season during the period 1965-2019.
5. It co-existed with ESCS Maha, for a brief period over the AS. Climatologically, no such simultaneous occurrence of two cyclonic storms over Arabian Sea has been observed so far during the period 1961-2018. However, simultaneous occurrence of cyclonic storms over Arabian Sea and Bay of Bengal was last observed in 2018 (VSCS Luban over Arabian Sea and VSCS Titli over Bay of Bengal).
6. A total of 6 cyclonic storms formed over southeast Arabian Sea (65°E-73°E & 13°N-18°N) in the month of October during 1891-2018 **[Fig.2 (a)],** out of which only 2 intensified into severe cyclones. Out of the six cyclonic storms, 2 crossed Gujarat coast, one as a cyclonic storm and the other as a severe cyclonic storm **[Fig.2 (b)]**. Remaining four weakened over Sea. Also, out of six cyclonic storms, four moved towards west and only two moved towards Indian coast (Gujarat).
7. It exhibited multiple re-curvatures. It moved east-northeastwards initially till 25th noon, thereafter west-northwestwards till 29th night, followed by westward movement till 30th morning and west-southwestward movement thereafter. The system had a track length of 2731 km.
8. It exhibited rapid intensification during 26th midnight (1800 UTC) to 27th early morning (0000 UTC) registering an increase in maximum sustained wind (MSW) 30-35 KT in 24 hours.
9. The peak MSW of the cyclone was 235-245 kmph (130 KT) gusting to 260 kmph during 0900 UTC to 1800 UTC of 27th October over the east-central AS. The lowest estimated central pressure was 922 hPa during 0900 UTC to 1800 UTC of 27th October **[Fig.3 (a)]**.
10. The life period (D to D) of the system was 231 hours (09 days & 15 hours) against long period average (LPA) (1990-2013) of 107 hours for VSCS category over the AS during post monsoon season.
11. It moved with a slow speed as 12hour average translational speed was about 11.7 kmph against LPA (1990-2013) of 14.3 kmph for VSCS category over north Indian Ocean **[Fig.3 (b)]**.
12. The Velocity Flux, Accumulated Cyclone Energy (a measure of damage potential) and Power Dissipation Index (a measure of loss) were 23.55x102 knots, 23.45X104 knots^2 and 25.43X106 knots^3 respectively.

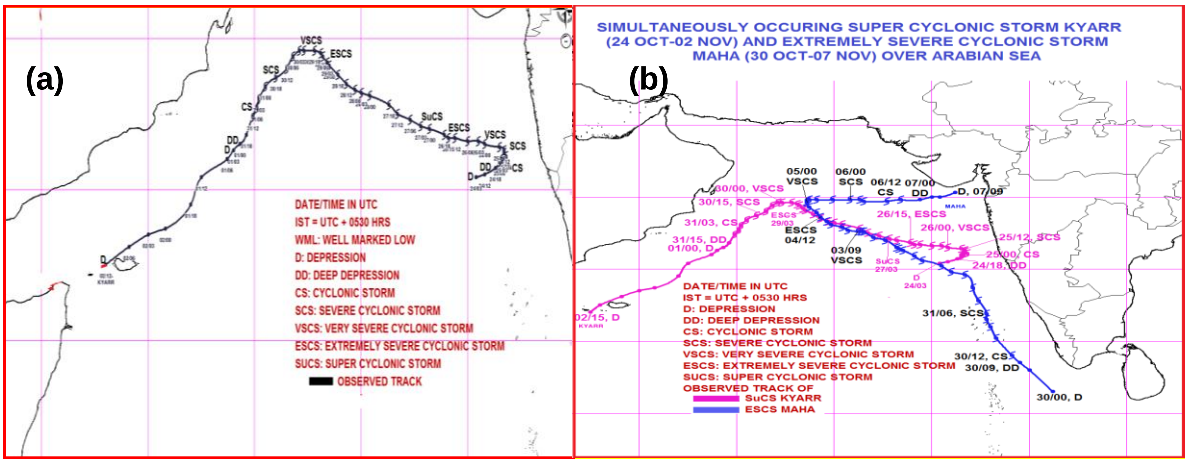

Fig.1: (a) Observed track of SuCS 'KYARR' over the Arabian Sea (24th October–02nd November, 2019) and (b) observed track of simultaneously occurring cyclones Kyarr and Maha

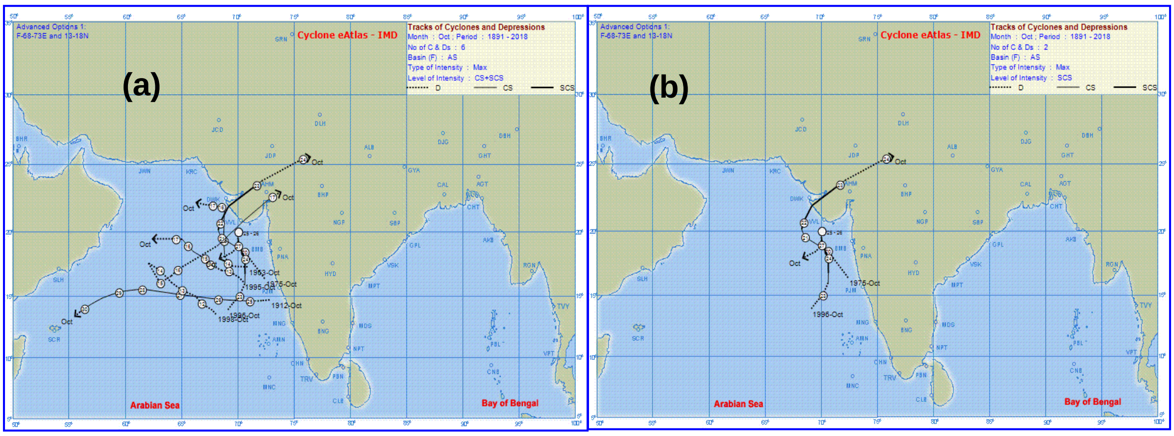

Fig.2: Tracks of (a) cyclonic storms over southeast Arabian Sea in the month of October during 1891-2018 and (b) severe cyclonic storms having genesis in a grid ± 2.5⁰ of area of formation of Kyarr (68°E-73°E & 13°N-18°N) in the month of October during 1891-2018

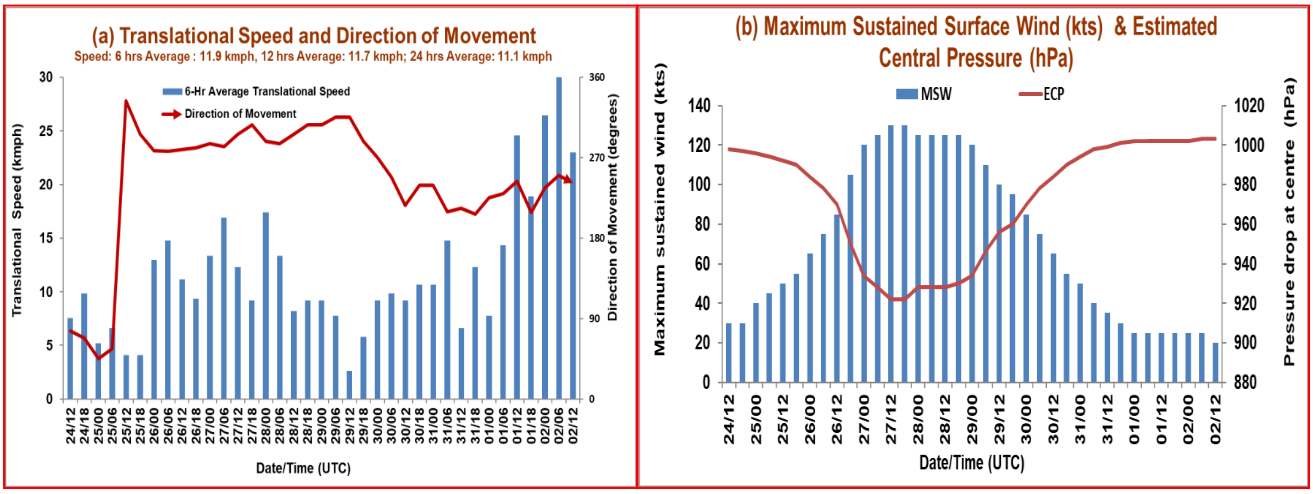

Fig. 3: (a) Translational speed & direction of movement and (b) Maximum sustained surface winds (Knots) & Estimated Central Pressure (hPa) during life cycle of SuCS Kyarr.

3. Monitoring of SuCS, 'KYARR'

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the genesis was monitored since 15th October even before the formation of low pressure area over Arabian Sea. In the extended range outlook issued on 17th October, genesis over east-central Arabian Sea was predicted. In the extended range outlook issued on 24th, the initial northeastward movement and west-southwestwards re-curvature of system towards west-central Arabian Sea with high confidence (>75% probability) was predicted. 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. Doppler weather radars along the west coast (DWRs at Kochi, Goa and Mumbai) were also utilised for monitoring the system, when it was under the respective RADAR range. Various numerical weather prediction models run by the 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. Typical satellite imagery and SCATSAT based Sea surface wind are presented in **Fig. 4 (a & b)** respectively.

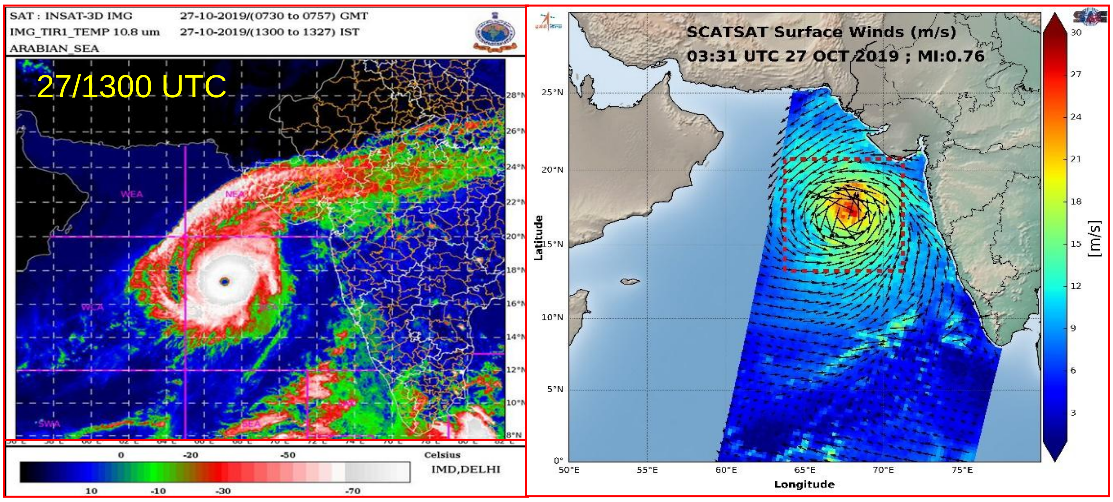

Fig.4: Typical satellite imageries from (a) INSAT 3D imagery at 1300 UTC of 27th October and (b) SCAT SAT based Sea surface winds at 0330 UTC of 27th October in association with SuCS Kyarr over the Arabian Sea.

Table 1: Best track positions and other parameters of the Super Cyclonic Storm, 'KYARR' over the Arabian Sea during 24th Oct-02nd Nov, 2019

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E		C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (KT)	Estimated Pressure drop at the Centre (hPa)	Grade
24/10/2019	0300	15.4	70.4	1.5	1000	25	03	**D**
	0600	15.4	70.4	1.5	1000	25	03	D

	1200	15.5	70.8	1.5	998	30	05	**DD**
	1800	15.7	71.3	2.0	997	30	06	DD
25/10/2019	0000	15.9	71.5	2.5	996	40	08	**CS**
	0300	16.0	71.6	2.5	996	40	08	CS
	0600	16.1	71.8	3.0	994	45	10	CS
	0900	16.2	71.7	3.0	994	45	10	CS
	1200	16.3	71.7	3.0	992	50	12	**SCS**
	1500	16.3	71.7	3.5	991	55	15	SCS
	1800	16.4	71.5	3.5	990	55	16	SCS
	2100	16.5	71.2	3.5	988	60	18	SCS
26/10/2019	0000	16.5	70.8	4.0	984	65	22	**VSCS**
	0300	16.6	70.5	4.0	984	65	22	VSCS
	0600	16.6	70.0	4.5	978	75	28	VSCS
	0900	16.6	69.8	4.5	974	80	32	VSCS
	1200	16.7	69.4	4.5	970	85	36	VSCS
	1500	16.7	69.1	5.0	966	90	40	**ESCS**
	1800	16.8	68.9	5.5	950	105	56	ESCS
	2100	16.9	68.5	6.0	946	110	60	ESCS
27/10/2019	0000	17.0	68.2	6.0	934	120	72	**SuCS**
	0300	17.1	67.8	6.5	928	125	78	SuCS
	0600	17.2	67.3	6.5	928	125	78	SuCS
	0900	17.4	67.0	6.5	922	130	84	SuCS
	1200	17.5	66.7	6.5	922	130	84	SuCS
	1500	17.5	66.5	6.5	922	130	84	SuCS
	1800	17.8	66.3	6.5	922	130	84	SuCS
	2100	18.0	65.7	6.5	926	125	80	SuCS
28/10/2019	0000	18.1	65.4	6.5	928	125	78	SuCS
	0300	18.2	65.0	6.5	928	125	78	SuCS
	0600	18.3	64.7	6.5	928	125	78	SuCS
	0900	18.4	64.5	6.5	928	125	78	SuCS
	1200	18.5	64.3	6.5	928	125	78	SuCS
	1500	18.7	64.1	6.5	928	125	78	SuCS
	1800	18.8	63.9	6.5	930	125	76	SuCS
	2100	18.9	63.8	6.5	930	125	76	SuCS
29/10/2019	0000	19.1	63.5	6.0	934	120	72	SuCS
	0300	19.2	63.4	6.0	940	115	66	**ESCS**
	0600	19.4	63.2	6.0	946	110	60	ESCS
	0900	19.4	63.1	6.0	950	105	56	ESCS
	1200	19.5	63.1	5.5	956	100	50	ESCS
	1500	19.5	62.9	5.5	956	100	50	ESCS
	1800	19.6	62.8	5.5	960	95	46	ESCS
	2100	19.6	62.6	5.0	966	90	40	ESCS
30/10/2019	0000	19.6	62.3	4.5	970	85	36	**VSCS**
	0300	19.6	62.1	4.5	974	80	32	VSCS
	0600	19.4	61.8	4.5	978	75	28	VSCS
	0900	19.3	61.7	4.0	982	70	24	VSCS
	1200	19.0	61.5	4.0	984	65	22	VSCS
	1500	18.9	61.2	3.5	988	60	18	**SCS**
	1800	18.7	61.0	3.5	990	55	16	SCS
	2100	18.5	60.7	3.5	991	55	15	SCS

31/10/2019	0000	18.4	60.5	3.0	994	50	12	SCS
	0300	18.0	60.2	3.0	996	45	10	**CS**
	0600	17.7	60.1	2.5	998	40	08	CS
	0900	17.5	60.0	2.5	998	40	08	CS
	1200	17.4	59.9	2.5	999	35	07	CS
	1500	17.2	59.6	2.0	1001	30	05	**DD**
	1800	16.8	59.6	2.0	1001	30	05	DD
	2100	16.7	59.5	2.0	1001	30	05	DD
01/11/2019	0000	16.5	59.3	1.5	1002	25	04	**D**
	0300	16.3	59.0	1.5	1002	25	04	D
	0600	16.0	58.7	1.5	1002	25	04	D
	0900	15.8	58.4	1.5	1002	25	04	D
	1200	15.4	57.5	1.5	1002	25	04	D
	1500	15.0	57.4	1.5	1002	25	04	D
	1800	14.5	57.0	1.5	1002	25	04	D
	2100	14.0	56.4	1.5	1002	25	04	D
02/11/2019	0000	13.7	55.8	1.5	1002	25	04	D
	0300	13.5	55.0	1.5	1003	25	03	D
	0600	13.1	54.1	1.5	1003	25	03	D
	0900	12.5	53.8	1.5	1003	25	03	D
	1200	12.5	53.0	1.5	1003	20	03	D
	1500	12.0	52.5	1.5	1003	20	03	D
	1800	Well marked low pressure area over west-central & adjoining southwest Arabian Sea off North Somalia coast.						

4 Brief life history

4.1. Genesis

- First information about possible cyclogenesis over east-central Arabian Sea was given in in the extended range outlook issued on 17th October. In the extended range outlook issued on 24th, when the system lay as a depression over east--central Arabian Sea, the initial northeastward movement and west-southwestwards re-curvature of system towards west-central Arabian Sea was predicted with high confidence (>75% probability).

- First information about formation of an LPA over Lakshadweep area & neighbourhood during next 48 hours was issued at 0000 UTC of 17th. The LPA formed over southeast Arabian Sea & adjoining Lakshadweep area at 0300 UTC of 17th.

- At 1200 UTC of 20th, it was indicated that the system would intensify into a WML by 22nd. It was also indicated that it would further intensify into Depression by 24th. It was also indicated that the system would initially move north northeastwards over east-central Arabian Sea till 24th October and then recurve west northwestwards towards Oman - Yemen coasts with gradual intensification. A WML formed in the afternoon (0900 UTC) of 22nd and Depression formed in the morning (0300 UTC) of 24th.

4.2. Intensification and movement

At 0600 UTC of 24th, the convectively active phase of Madden Julian oscillation (MJO) lay in Phase 2 (west Indian Ocean) with amplitude greater than 1. Total precipitable water vapour (TPW) imageries indicated warm air advection to the system centre. The low level cyclonic vorticity increased in past 24 hours and became 150 $x10^{-6}S^{-1}$ around the system centre. Positive vorticity extended upto 200 hPa level. The lower level convergence was about 20 $x10^{-5}s^{-1}$ south of the system center. The upper level divergence was about 30 $x10^{-5}s^{-1}$ to the southwest of the system center. The vertical wind shear was moderate (15-20 Knots) over the system. The upper tropospheric ridge extended along 18°N. Sea surface temperature over most parts of eastcentral Arabian Sea was 29-30°C and tropical cyclone heat potential was 80 KJ/cm^2 over the region thereby favoring further intensification. As the system lay to the south of upper tropospheric ridge and was being steered by middle and upper tropospheric winds, it was expected to move east-northeastwards till 25th evening. Under these circumstances, the system concentrated into a D over east-central Arabian Sea near 15.4°N/70.4°E.

At 1200 UTC of 24th, the MJO continued to be in phase 2 with amplitude greater than 1. TPW imageries indicated warm air advection to the system centre. The low level relative vorticity was 200 $x10^{-6}s^{-1}$ around the system centre. Positive vorticity extended upto 200 hPa level. The lower level convergence is about 10 $x10^{-5}\ s^{-1}$ south of the system center. The upper level divergence is about 20 $x10^{-5}s^{-1}$ to the south of the system center. The vertical wind shear was moderate (15-25 Knots) over the system. The upper tropospheric ridge extended along 16°N. Sea surface temperature (SST) over most parts of eastcentral Arabian Sea was 29-30°C and tropical cyclone heat potential (TCHP) 80 KJ/cm2 over the region thereby favoring further intensification. Under these circumstances, the D intensified into a DD over east-central Arabian Sea near 15.5°N/70.8°E.

At 0000 UTC of 25th, the MJO was in phase 2 with amplitude greater than 1. TPW imageries indicated warm air advection to the system centre. The low level relative vorticity was 200 $x10^{-6}s^{-1}$ around the system centre. Positive vorticity extended upto 200 hPa level. The lower level convergence was about 10 $x10^{-5}$ s-1 to the southeast of the system center. The upper level divergence was about 20 $x10^{-5}$s-1 to the south of the system center. The vertical wind shear was low to moderate (05-10 Knots) over the system. The upper tropospheric ridge extended along 17°N. SST over most parts of east-central Arabian Sea was 29-30°C and TCHP 80 KJ/cm2 over the region. All these dynamical & environmental features favoured further intensification of the system. Under these circumstances, the DD intensified into a CS over east-central Arabian Sea near 16.0°N/71.3°E.

At 1200 UTC of 25th, the MJO lay in phase 2 with amplitude greater than 1. TPW imageries indicated warm air advection to the system centre. The low level relative vorticity was 200 $x10^{-6}\ s^{-1}$ to the south of the system centre. The lower level convergence was about 20 $x10^{-5}\ s^{-1}$ around the system center. The upper level divergence was about 20 $x10^{-5}s^{-1}$ around the system center. The vertical wind shear was moderate (10-15 Knots) over the system center. SST over most parts of eastcentral Arabian Sea continued to be 29-30°C and TCHP 80 KJ/cm2 over the region. The system was expected to move over to a region with still lower wind shear as well. Under these circumstances, the CS intensified into an SCS over east-central Arabian Sea near 16.3°N/71.7°E.

At 0000 UTC of 26th, the MJO continued in the phase 2 with amplitude greater than 1. TPW imageries indicated continued warm air advection to the system centre. The low level relative vorticity was 200 $x10^{-6}s^{-1}$ to the south of the system centre. The lower level convergence was about 40 $x10^{-5}$ s^{-1} to the west of the system center. The upper level divergence was about 20 $x10^{-5}s^{-1}$ around the system center. The vertical wind shear has been low (5-10 knots) around the system center. SST over most parts of east-central Arabian Sea was 29-30°C and TCHP 80 KJ/cm2. Under these circumstances, the SCS intensified into a VSCS over east-central Arabian Sea near 16.5°N/70.8°E.

At 1500 UTC of 26th, the MJO continued to be in phase 2 with amplitude greater than 1. TPW imageries indicated warm air advection to the system centre. The low level relative vorticity increased and became 300 $x10^{-6}s^{-1}$ over the system centre. The lower level convergence also increased and was about 20 $x10^{-5}s^{-1}$ to the southeast of the system centre. The upper level divergence decreased to about 20 $x10^{-5}s^{-1}$ to the northeast of system centre. The vertical wind shear continued to be low (5-10 knots) around the system center. SST over most parts of east-central Arabian Sea was 29-30°C and TCHP is 80 KJ/cm2 over the region thereby favoring further intensification. Both poleward and equatorward outflow has been taking place in the upper tropospheric levels. All these dynamic and thermodynamic conditions favoured further rapid intensification. Under these circumstances, the VSCS intensified into an ESCS over east-central Arabian Sea near 16.7°N/69.1°E.

At 0000 UTC of 27th, the MJO continued in the phase 2 with amplitude greater than 1. TPW imageries indicated warm air advection to the system centre. The low level relative vorticity was 300 $x10^{-6}s^{-1}$ to the south of the system centre. The lower level convergence was about 30 $x10^{-5}s^{-1}$ to the south of the system centre. The upper level divergence was about 20 $x10^{-5}s^{-1}$ around the system centre. The vertical wind shear was low (5-10 knots) around the system center. SST over most parts of eastcentral Arabian Sea was 29-30°C and TCHP was 80 KJ/cm2 over the region. Both poleward and equatorward outflow was taking place in the upper tropospheric levels. All these dynamic and thermodynamic conditions favoured further intensification. Under these circumstances, the VSCS intensified into an SuCS over east-central Arabian Sea near 17.0°N/68.2°E.

At 0300 UTC of 29th, the MJO transited into phase 3 with amplitude less than 1 The low level relative vorticity was about 300 $x10^{-6}$ s^{-1} to the southeast of the system centre. The lower level convergence was about 40 $x10^{-5}s^{-1}$ to the south of the system centre and the upper level divergence was about 20 $x10^{-5}s^{-1}$ over the system centre. The vertical wind shear was moderate (20 kt) around the system center. SST to the southwest of the system center and over most parts of west central Arabian Sea was around 27-28°C while to the north of the system centre, it was warmer (29-30°C). TCHP to the west of the system center over west-central Arabian Sea has been 40-50 KJ/cm^2 while to the east of the system center over east-central Arabian Sea, it was 50-70 KJ/cm^2. Under these unfavourable circumstances, the SuCS weakened into an ESCS over west-central and adjoining eastcentral and north Arabian Sea near 19.2°N/63.4°E.

At 0000 UTC of 30th, the MJO continued to be in phase 3 with amplitude less than 1. The low level relative vorticity was about 230 $x10^{-6}$ s^{-1} to the southeast of the system centre. The lower level convergence was about 20 $x10^{-5}s^{-1}$ to the southwest of the system centre and the upper level divergence was about 20 $x10^{-5}s^{-1}$ to the southeast of the system centre. The vertical wind shear has been moderate (5-10 knots) around the system center. SST to the southwest of the system center over most parts of west central Arabian Sea was around 27-28°C while to the north of the system centre, it was warmer (29-30°C). TCHP to the west of the system center over west-central Arabian Sea was 20-

40 KJ/cm^2 while to the east of the system center over east-central Arabian Sea; it was 50-80 KJ/cm^2. Under these circumstances, the ESCS further weakened into a VSCS over west-central and north Arabian Sea near 19.6°N/62.3°E.

At 1500 UTC of 30th, the MJO had moved into phase 4 with amplitude less than 1. The low level relative vorticity was about 250 x10^{-6} s^{-1} to the south of the system centre. The lower level convergence was about 10 x10^{-5}s^{-1} to the south of the system centre and the upper level divergence about 20 x10^{-5}s^{-1} around the system centre. The vertical wind shear became moderate (10-15 knots) over the system area. SST has been around 27-28°C over the system area while it was warmer (29-30°C) towards north. TCHP around the system center over west-central Arabian Sea was 20-40 KJ/cm^2. Under these circumstances, the VSCS further weakened into an SCS over west-central & adjoining northwest Arabian Sea near 18.9°N/61.2°E.

At 0300 UTC of 31st October, the MJO continued to be in phase 4 with amplitude less than 1. The low level relative vorticity was about 200 x10^{-6} s^{-1} around the system centre. The lower level convergence was about 10 x10^{-5}s^{-1} around the system centre and the upper level divergence about 10 x10^{-5}s^{-1} to the southwest of the system centre. The vertical wind shear has been low (05-15 knots) over the system area. SST was around 26-28°C over the system area. TCHP around the system center over west-central Arabian Sea was 20-40 KJ/cm^2. Under colder SST & lower TCHP, the SCS further weakened into a CS over west-central Arabian Sea near 18.0°N/60.2°E.

At 1500 UTC of 31st October, the MJO continued to be in phase 4 with amplitude less than 1. The low level relative vorticity further reduced and was about 100 x10^{-6} s^{-1} around the system centre. The lower level convergence was about 10 x10^{-5}s^{-1} to the southeast of the system centre and the upper level divergence about 10 x10^{-5}s^{-1} to the south of the system centre. The vertical wind shear was low (05-10 kt) over the system area. SST was around 26-28°C over the system area. TCHP around the system center over west-central Arabian Sea was 20-40 KJ/cm^2. Under these circumstances, the CS further weakened into a DD over west-central Arabian Sea near 17.2°N/59.6°E.

At 0000 UTC of 1st November, the MJO had moved over to phase 5 with amplitude close to 1. The low level relative vorticity further reduced and was about 100 x10^{-6} s^{-1} around the system centre. The lower level convergence was about 10 x10^{-5}s^{-1} over system centre and the upper level divergence was about 10 x10^{-5}s^{-1} to the southwest of the system centre. The vertical wind shear has been low (05-10 knots) over the system area. SST was around 26-28°C over the system area. TCHP around the system center over west-central Arabian Sea was 20-40 KJ/cm^2. Under these circumstances, the DD further weakened into a D over west-central Arabian Sea near 16.4°N/59.5°E.

At 1800 UTC of 2nd November, the D weakened into a WML over west-central & adjoining southwest Arabian Sea off North Somalia coast.

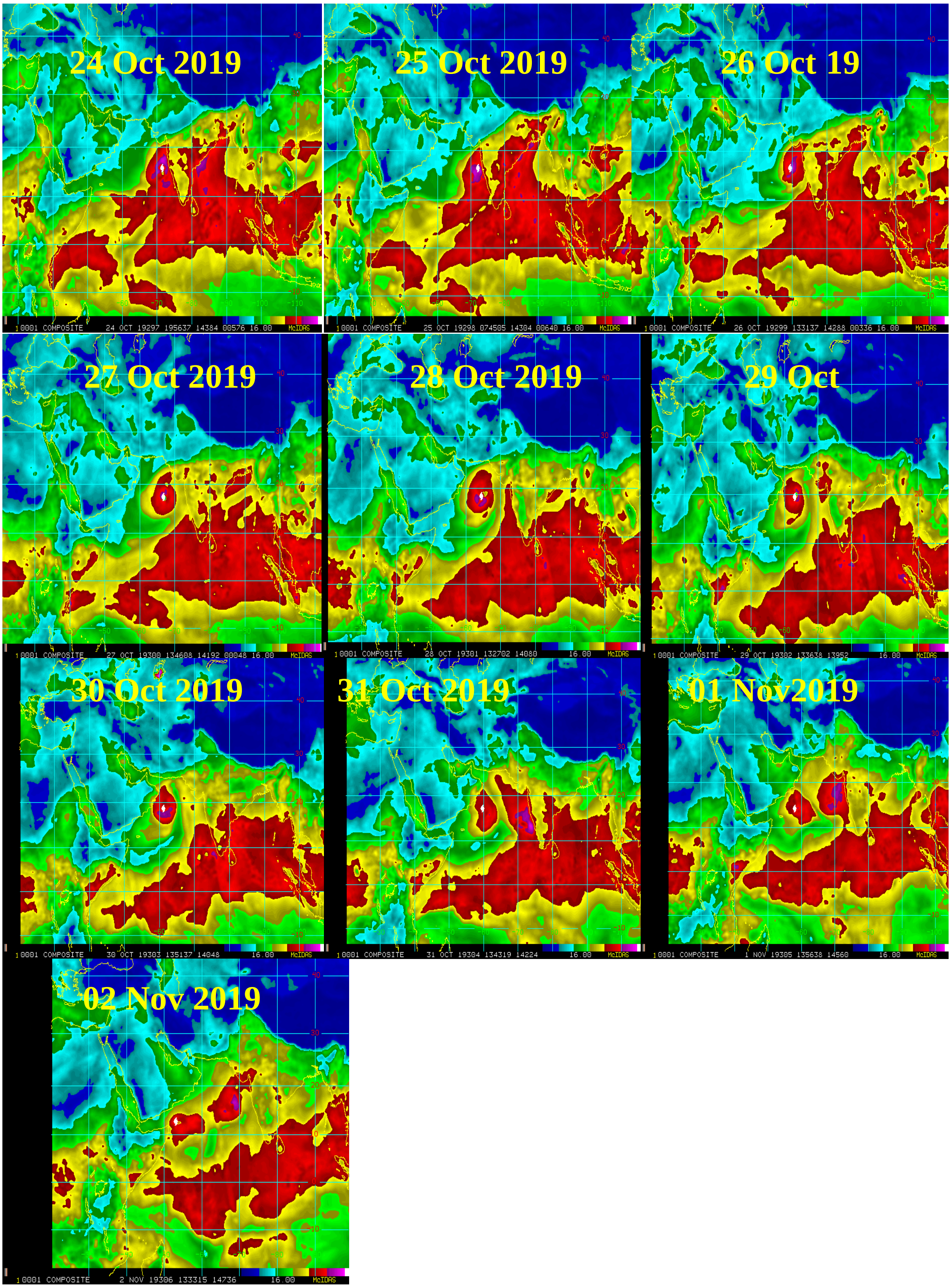

Fig.5: Total Precipitable Water vapour (TPW) imageries during SuCS KYARR (24th October – 2nd November 2019)

The wind speed in middle and deep layer around the system centre is presented in **Fig.6**. The wind shear around the system between 200 & 850 hPa levels remained Low to moderate (05-15 knots) till 0000 UTC of 01st November. Thereafter, it increased becoming moderate (15-20 knots) till dissipation as the system came under the combined influence of anticyclone over Arabian Peninsula to the northwest of system centre. The direction of 200-850 hPa wind shear was southeasterly during the formative as well as the dissipation Phase and southerly during the mature Phase. It caused the convective cloud mass to be sheared to the northeast of the system centre.

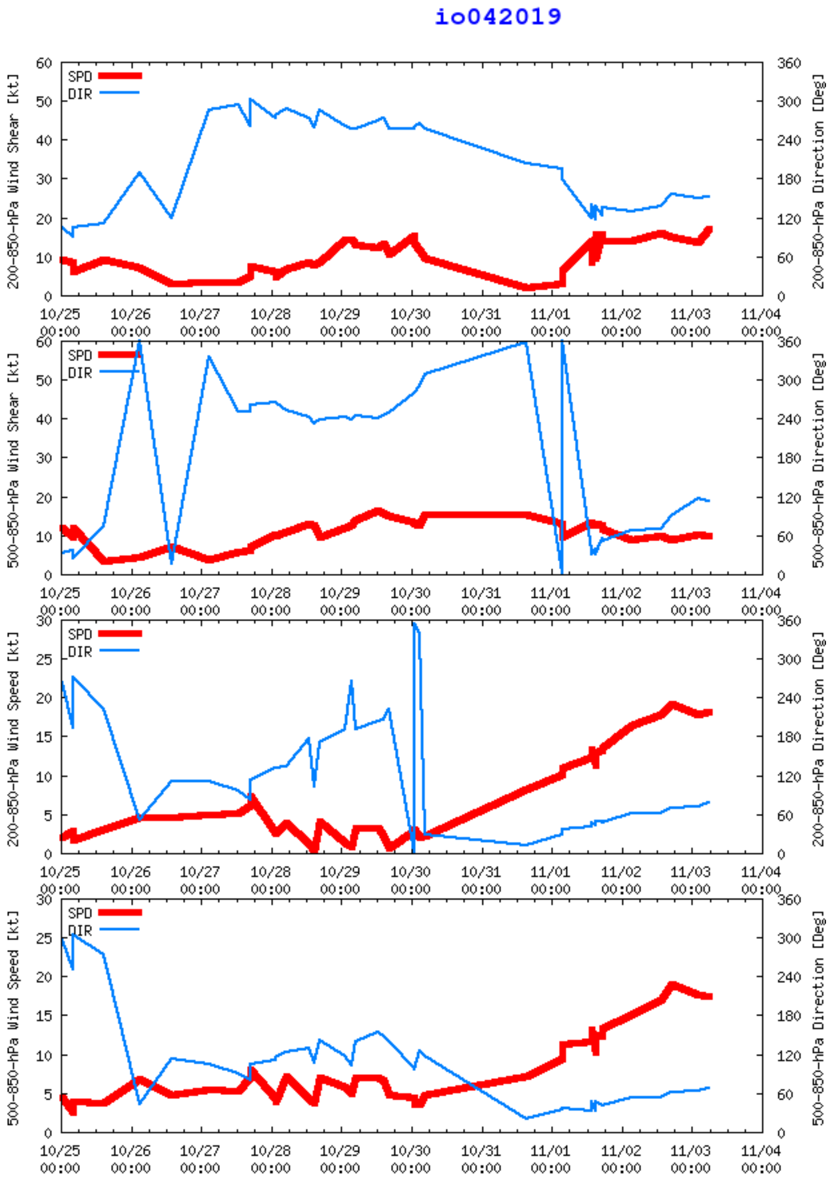

Fig.6: Wind shear and wind speed in the middle and deep layer around the system during SuCS KYARR (24 October-02 November), 2019

From Fig.6, it may also be noted that from the genesis stage, the mean deep layer winds between 200-850 hPa levels steered the system initially northeastwards till 06 UTC of 25th October, then northwestwards till 06 UTC of 30th October, nearly westwards for a brief while and southwestwards thereafter towards Somalia coast. The six hourly movement of SuCS KYARR is presented in **Fig.7**. The 6 hourly average translational speed of the cyclone was about 11.9 kmph and hence the cyclone was moving slower against the normal speed of 14.7 kmph.

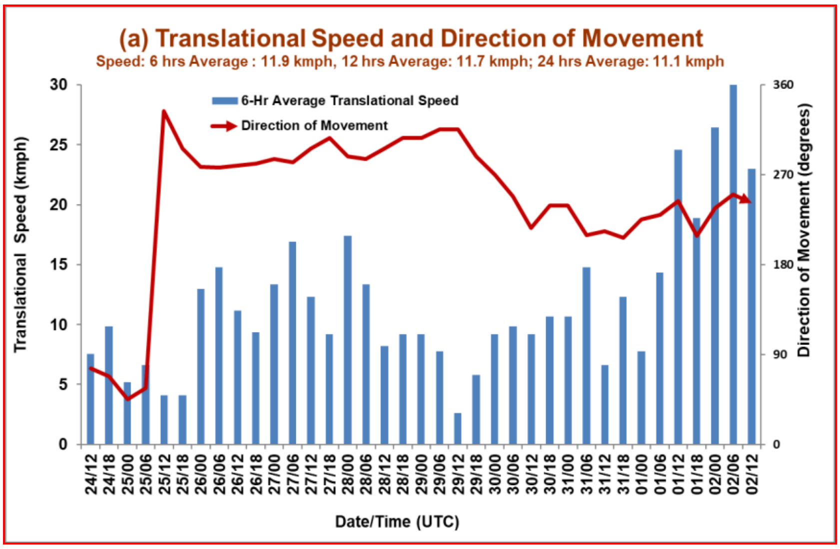

Fig.7 Six hourly average translational speed (kmph) and direction of movement in association with SuCS KYARR (24 October-02 November), 2019

4.3 Maximum Sustained Surface Wind speed and estimated central pressure

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig.8**. The lowest estimated central pressure had been 922 hPa during 0900-1800 UTC of 27th Oct. The estimated maximum sustained surface wind speed (MSW) was 130 knots during the same period with pressure drop of 84 hPa.

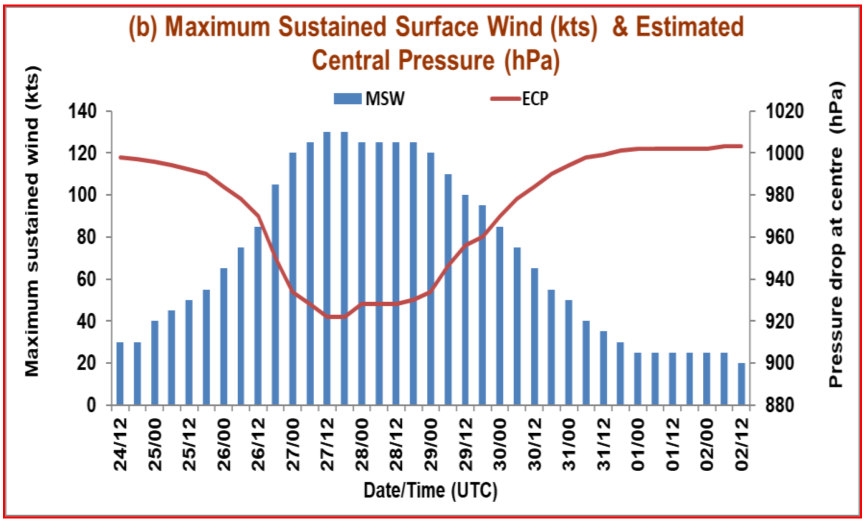

Fig.8. Lowest estimated central pressure and the maximum sustained wind speed associated with SuCS KYARR (24th October – 2nd November 2019)

5. Monitoring

5. 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.9**. The system showed curved band pattern during genesis and growth stage upto the intensity of CS. It had central dense overcast (CDO) pattern during SCS stage and “EYE” pattern during VSCS, ESCS & SuCS stages. It showed sheared pattern during the weakening phase.

At 0600 UTC of 24th, the intensity of the system was T1.5. The cloud organization was shear pattern and the convective clouds were oriented from southwest to northeast direction. Associated broken low to medium clouds with embedded intense to very intense convection lay over east central and adjoining southeast Arabian Sea between lat 11.0^{0}N to 18.0^{0}N long 66.5^{0}E to 74.0^{0}E. Minimum cloud top temperature (CTT) was minus 93^{0}C.

At 1200 UTC of 24th, Satellite images indicates further organisation of clouds around the system centre during past six hours having CDO pattern. The current intensity of the system was T1.5. Associated broken low to medium clouds with embedded intense to very intense convection lay over east central and adjoining southeast Arabian Sea between lat 11.0^{0}N to 18.0^{0}N long 66.5^{0}E to 73.0^{0}E. The minimum CTT was minus 93^{0}C.

At 0000 UTC of 25th, Satellite images indicated further organisation of clouds around the system centre during past six hours having CDO pattern. The current intensity of the system was T2.5. Associated broken low to medium clouds with embedded intense to very intense convection lay over east central Arabian Sea between lat 14.0^{0}N to 18.5^{0}N long 69.5^{0}E to 73.5^{0}E. The minimum CTT was minus 93^{0}C.

At 1200 UTC of 25th, Satellite images indicated further organisation and steadily increasing convection around the system centre during past six hours having CDO pattern. The current intensity of the system was T3.0. Associated broken low to medium clouds with embedded intense to very intense convection lay over east central Arabian Sea between lat 14.5^{0}N to 17.5^{0}N east of long 70.0^{0}E to 73.0^{0}E. The minimum CTT was minus 93^{0}C.

At 0000 UTC of 26th, Satellite images indicated CDO pattern. The current intensity of the system was T4.0. Associated broken low to medium clouds with embedded intense to very intense convection lay over east central Arabian Sea between lat 14.0^{0}N to 18.0^{0}N east of long 68.5^{0}E to 73.5^{0}E. The minimum CTT was minus 93^{0}C.

At 1500 UTC of 26th, Satellite images indicated banding eye pattern with tightly wrapped curved bands visible. Centre clearly exposed in microwave imagery. The current intensity of the system was T5.0. Associated broken low to medium clouds with embedded intense to very intense convection lay over east central Arabian Sea between lat 14.5^{0}N to 18.0^{0}N and long 67.5^{0}E to 71.5^{0}E. The minimum CTT was minus 93^{0}C.

At 0000 UTC of 27th, Satellite images indicated eye pattern with eye temperature +9.4^{0}C and eye diameter about 40 km. The current intensity of the system was T6.0. Associated broken low to medium clouds with embedded intense to very intense convection lay over east central Arabian Sea between lat 14.5^{0}N to 18.5^{0}N and long 66.5^{0}E to 70.5^{0}E. The minimum CTT was minus 93^{0}C.

At 0300 UTC of 29th, Satellite images indicated eye pattern with ragged eye in IR imagery. Eye temperature was minus 34.6^{0}C. The current intensity of the system was T5.5/6.5. Associated broken low to medium clouds with embedded intense to very intense convection lay over west-central and adjoining east central Arabian Sea between lat 17.5^{0}N to 21.5^{0}N and long 61.5^{0}E to 65.5^{0}E. The minimum CTT is minus 93^{0}C.

At 0000 UTC of 30th, the current intensity of the system was T4.5/CI5.5. Associated broken low to medium clouds with embedded intense to very intense convection lay over west-central and adjoining east central Arabian Sea between lat 17.0^{0}N to 22.0^{0}N and long 60.0^{0}E to 64.^{0}E. The minimum CTT was minus 93^{0}C.

At 1500 UTC of 30th, the current intensity of the system was T3.5/CI4.5. Associated broken low to medium clouds with embedded intense to very intense convection lay over west-central and adjoining east central Arabian Sea between lat 18.50^{0}N to 23.0^{0}N and long 61.0^{0}E to 64.0^{0}E. The minimum CTT was minus 93^{0}C.

At 0300 UTC of 31st October, the current intensity of the system was T 2.5/3.0. Associated broken low to medium clouds with embedded intense to very intense convection lay over west-central and adjoining east central Arabian Sea between lat 15.0^{0}N to 17.5^{0}N and long 60.0^{0}E to 62.5^{0}E. The minimum CTT was minus 93^{0}C.

At 1500 UTC of 31st October, the current intensity of the system was T2.0/2.5. Associated broken low to medium clouds with embedded intense to very intense convection lay over west-central Arabian Sea between lat 15.5^{0}N to 16.5^{0}N and long 60.5^{0}E to 61.5^{0}E. The minimum CTT was minus 93^{0}C.

At 0000 UTC of 1st November, the current intensity of the system was T1.5/2.0. Associated broken low to medium clouds with embedded intense to very intense convection lay over west-central Arabian Sea between lat 14.5^{0}N to 17.0^{0}N and long 59.5^{0}E to 61.0^{0}E. The minimum CTT was minus 93^{0}C.

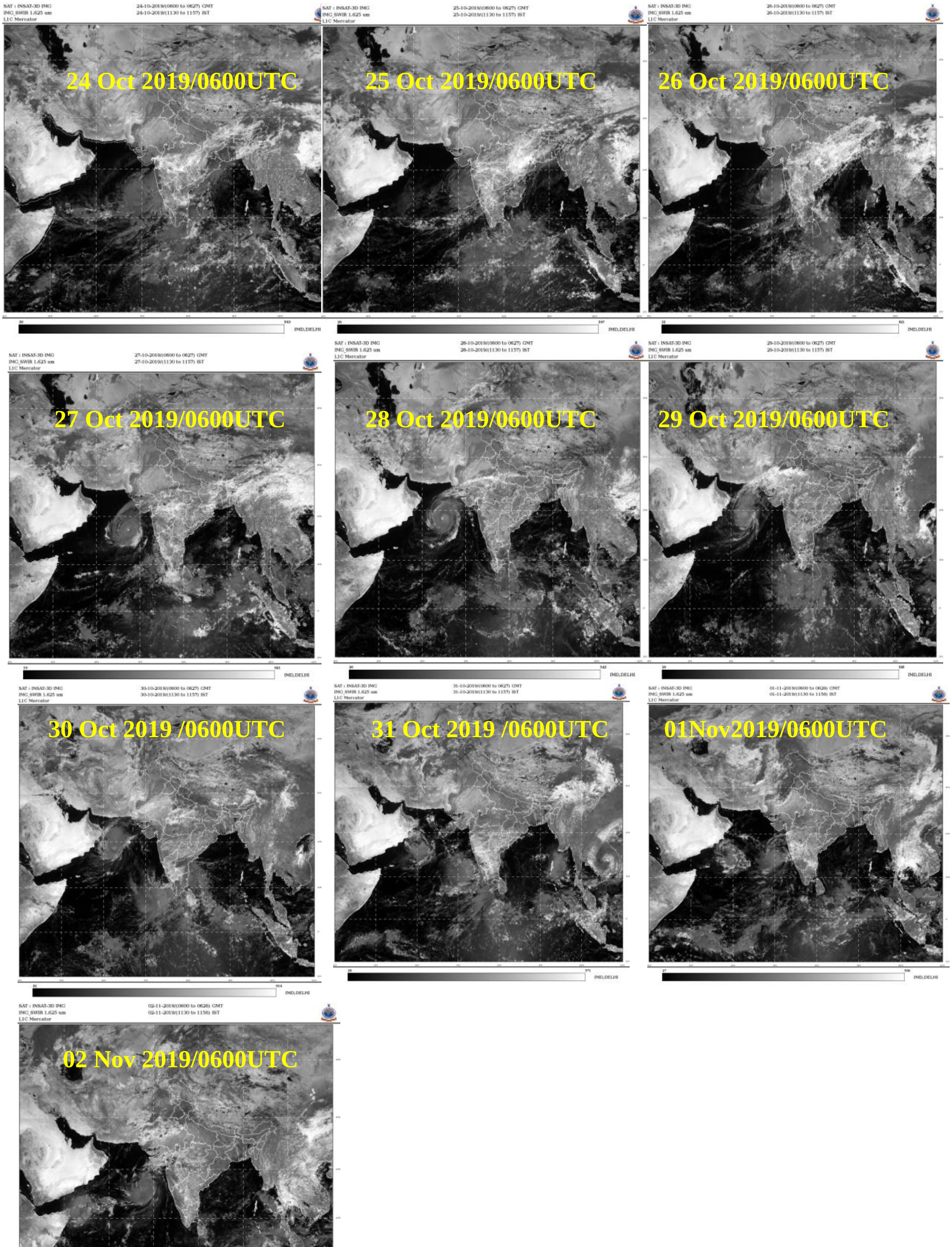

Fig. 9a: INSAT-3D SWIR imageries during life cycle of SuCS KYARR (24 October-02 November), 2019

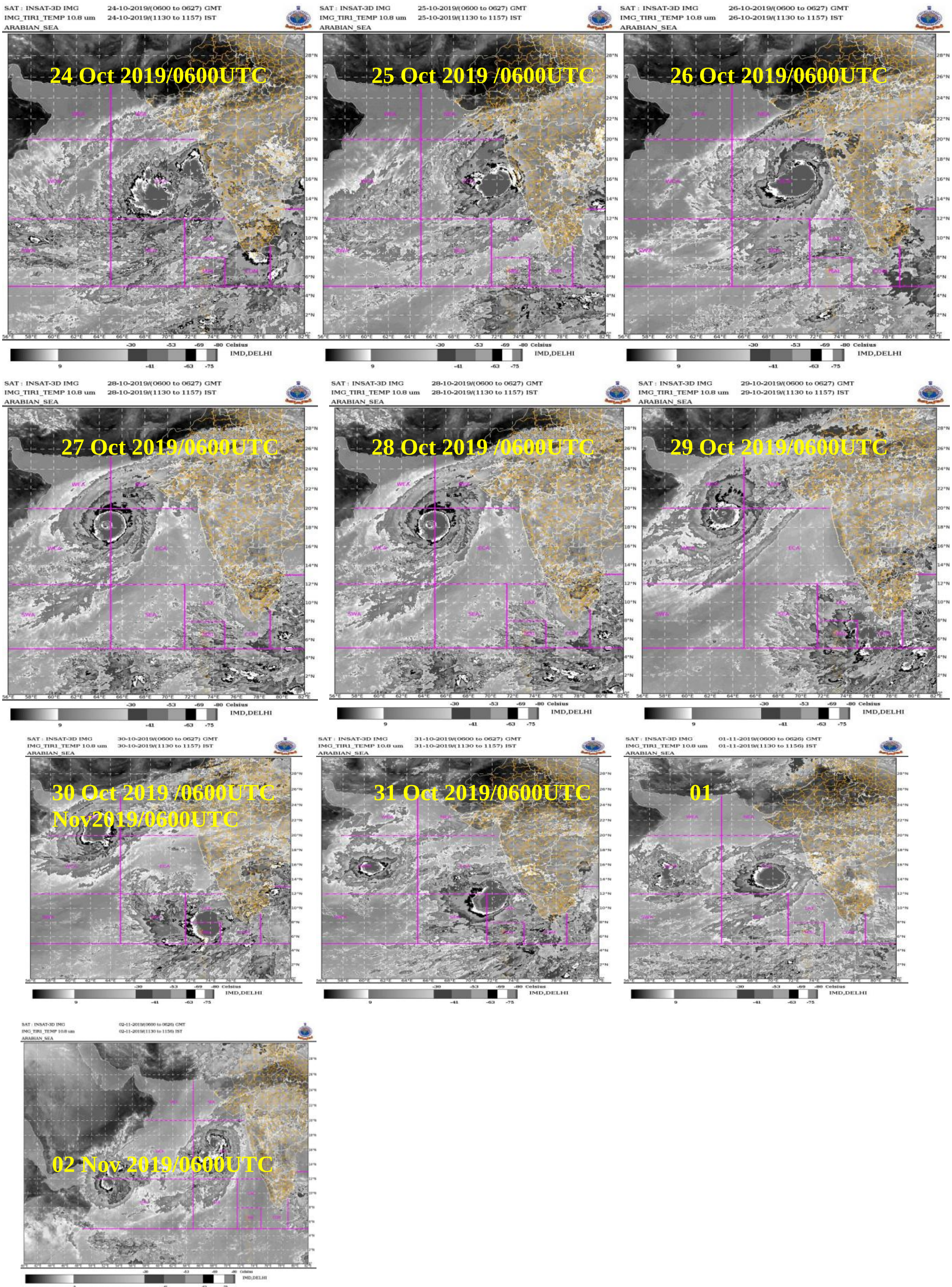

Fig. 9b: INSAT-3D Clod top Brightness imageries during life cycle of SuCS KYARR (24 October-02 November), 2019

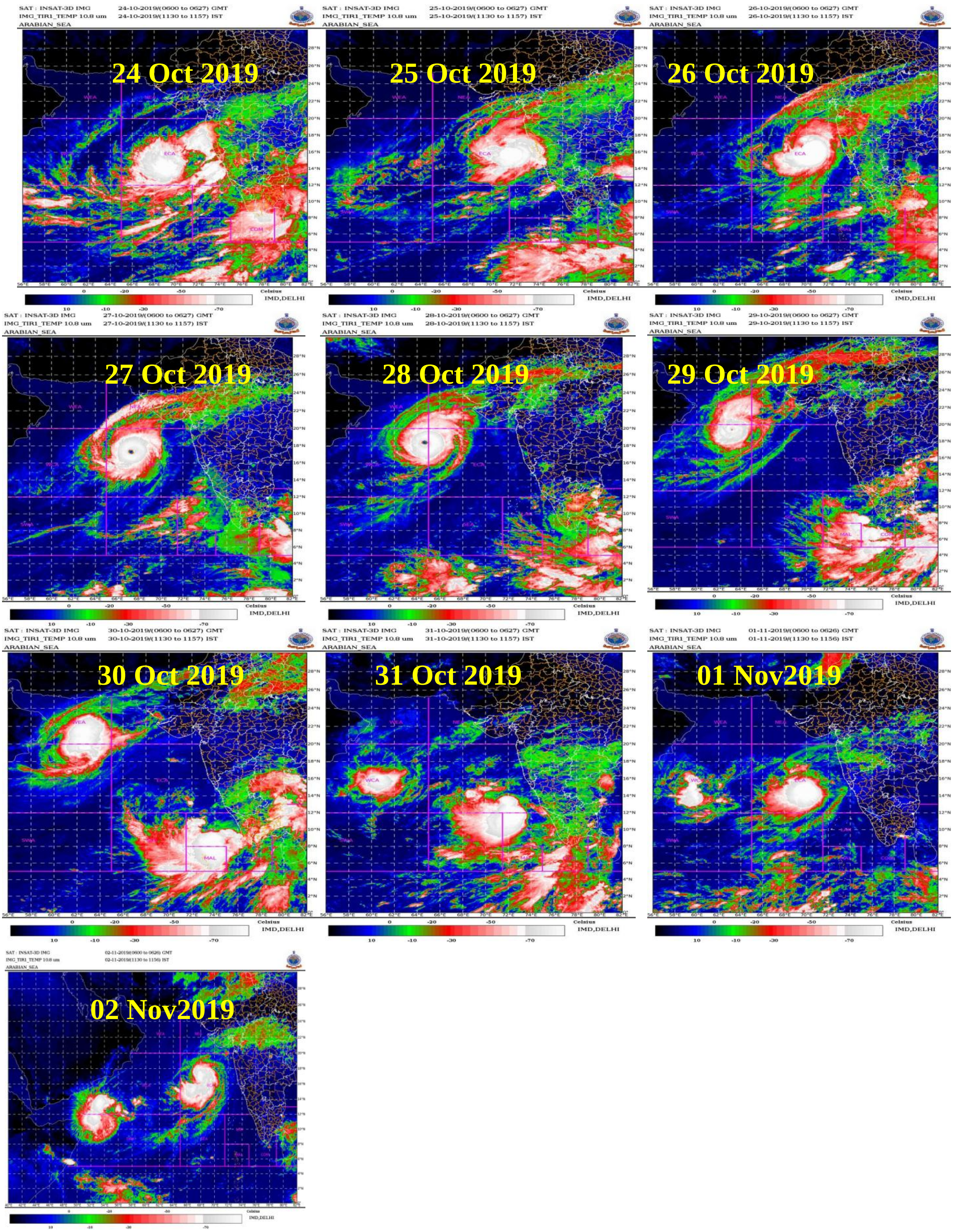

Fig. 9c: INSAT-3D enhanced colored imageries during life cycle of SuCS KYARR (24 October-02 November), 2019

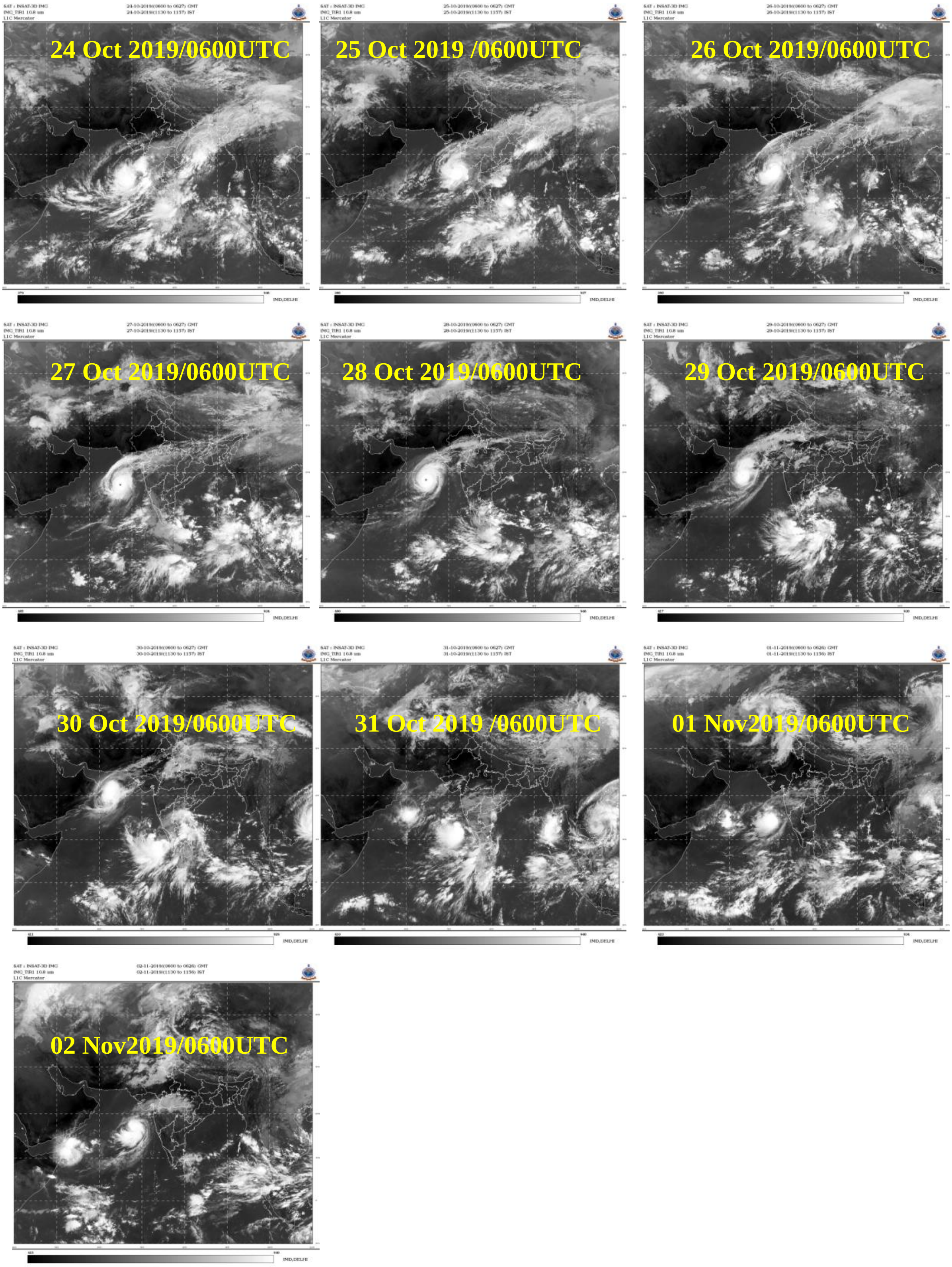

Fig. 9d: INSAT-3D IR1 imageries during life cycle of SuCS KYARR (24 October-02 November), 2019

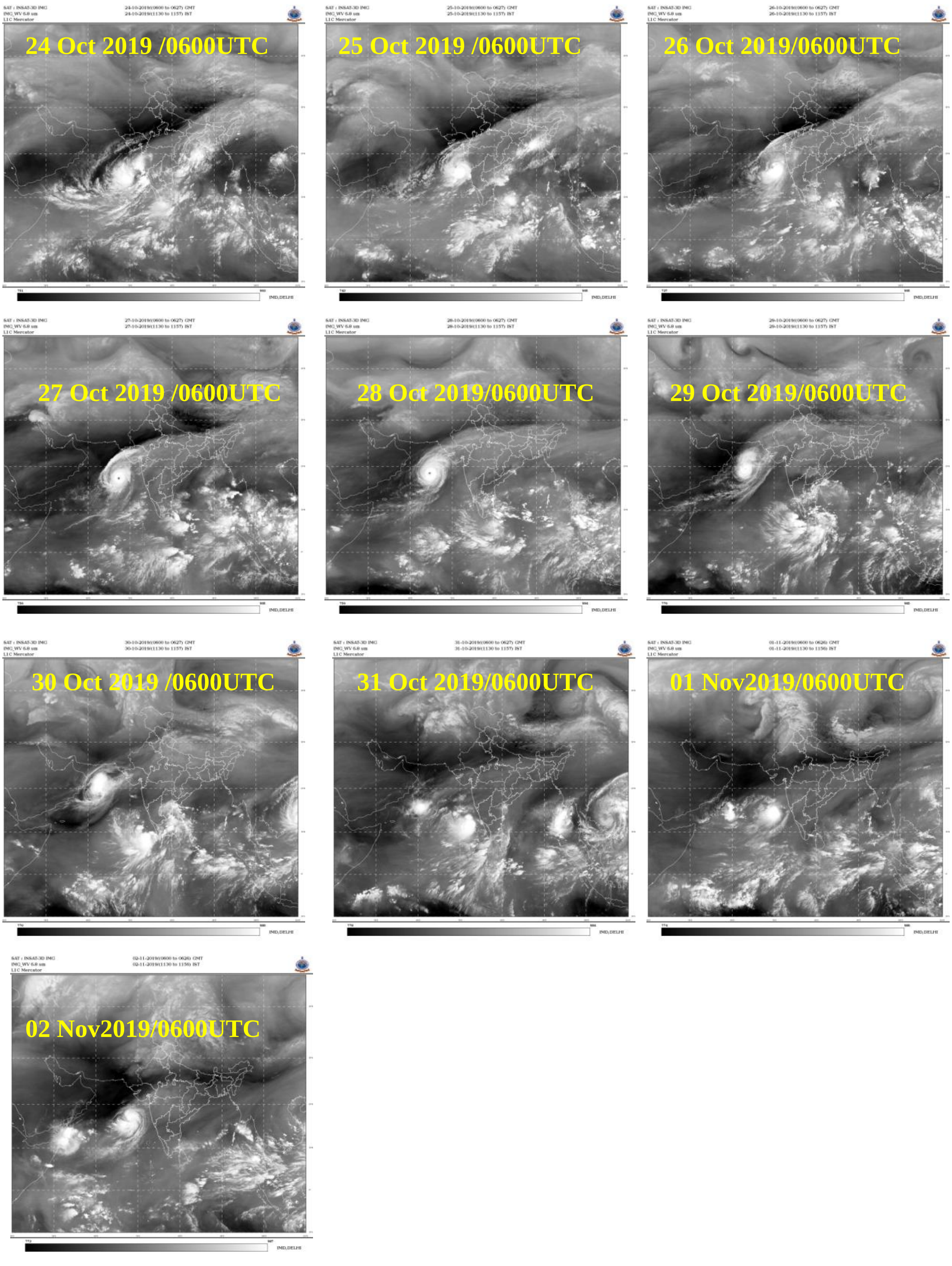

Fig. 9e: INSAT-3D Water Vapor imageries during life cycle of SuCS KYARR (24 October-02 November), 2019

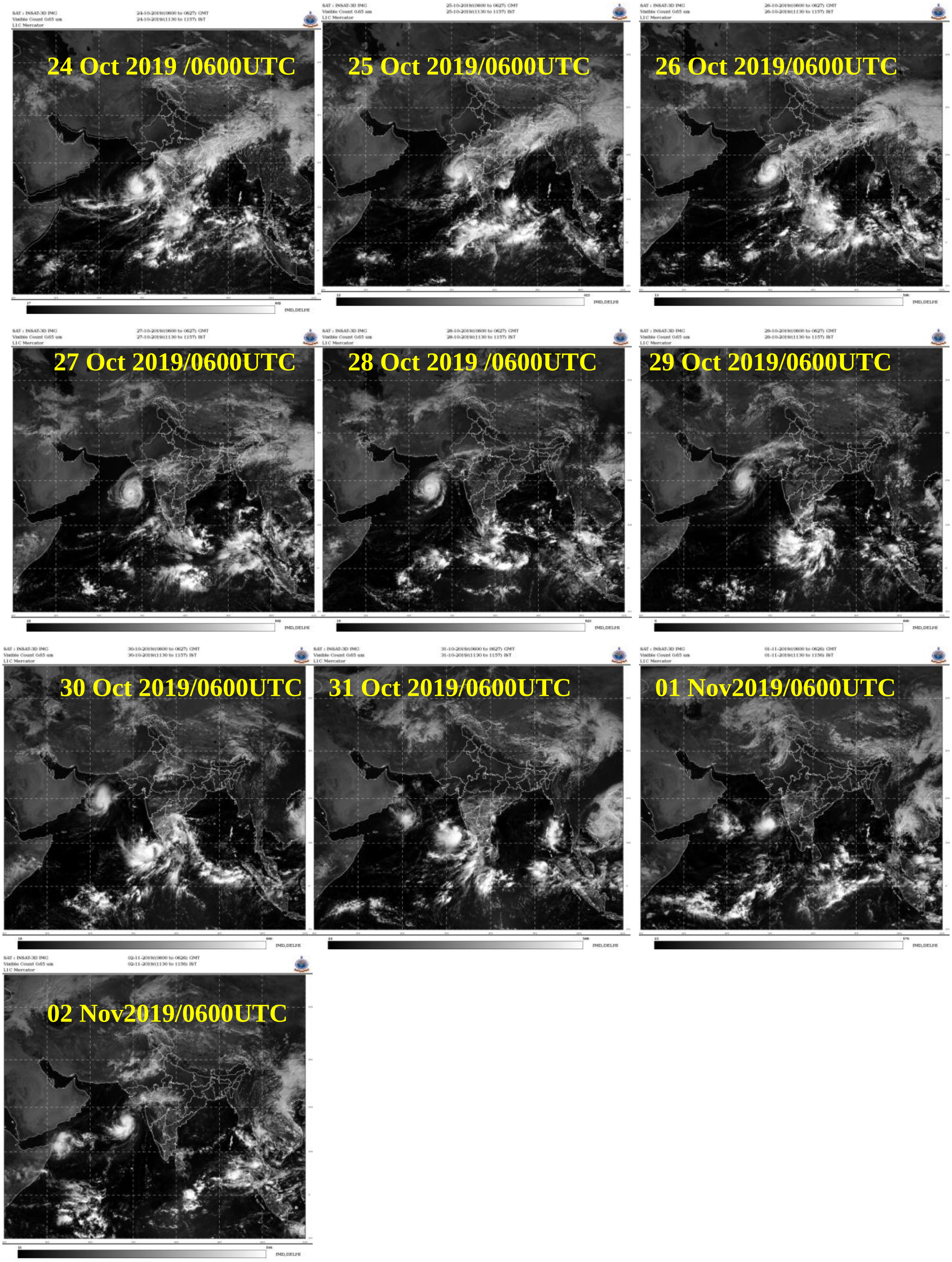

Fig. 9f: INSAT-3D Visible imageries during life cycle of SuCS KYARR (24 October - 02 November), 2019

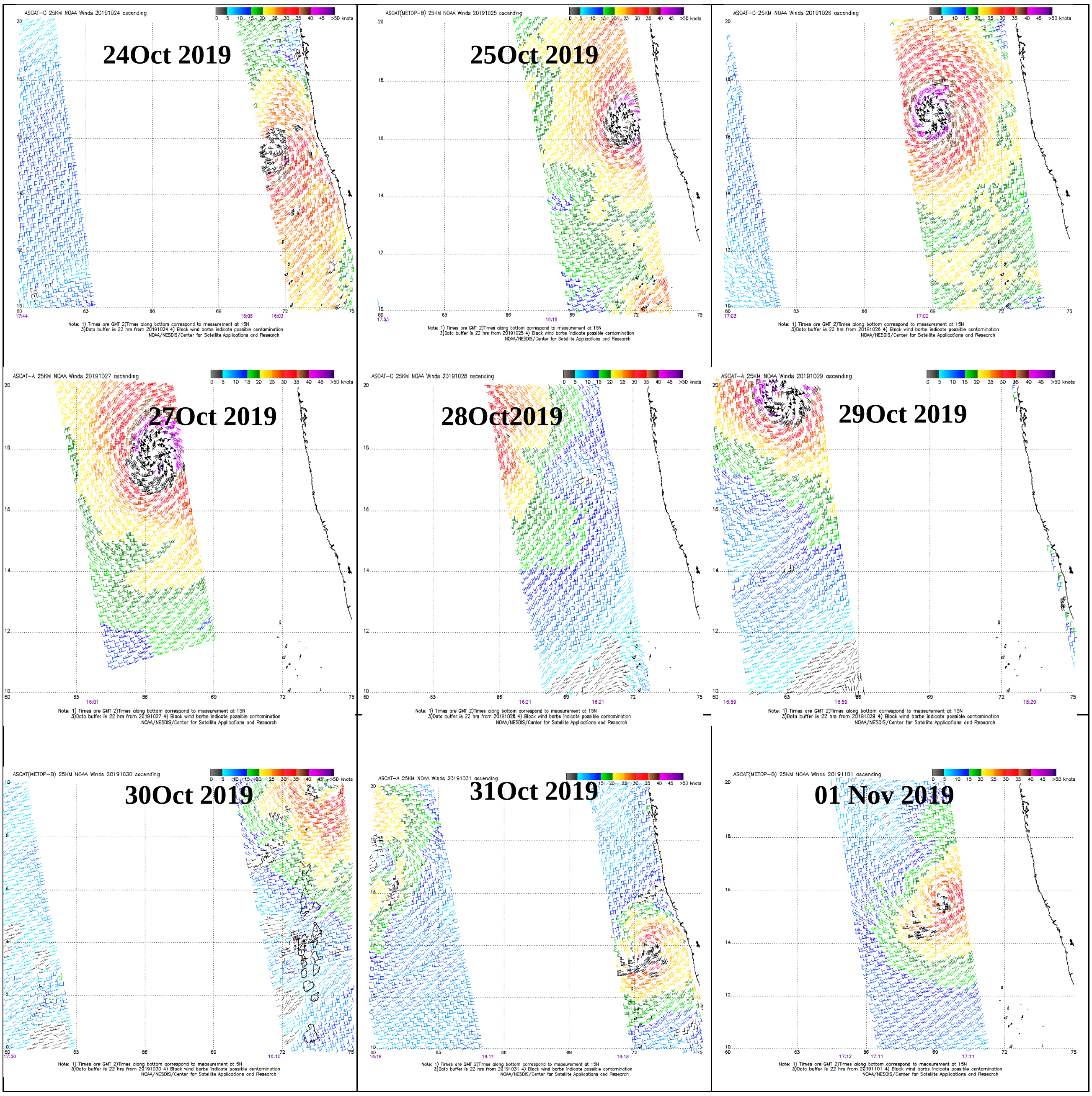

Fig. 9g: ASCAT derived surface winds during life cycle of SuCS KYARR (24 October -02 November), 2019

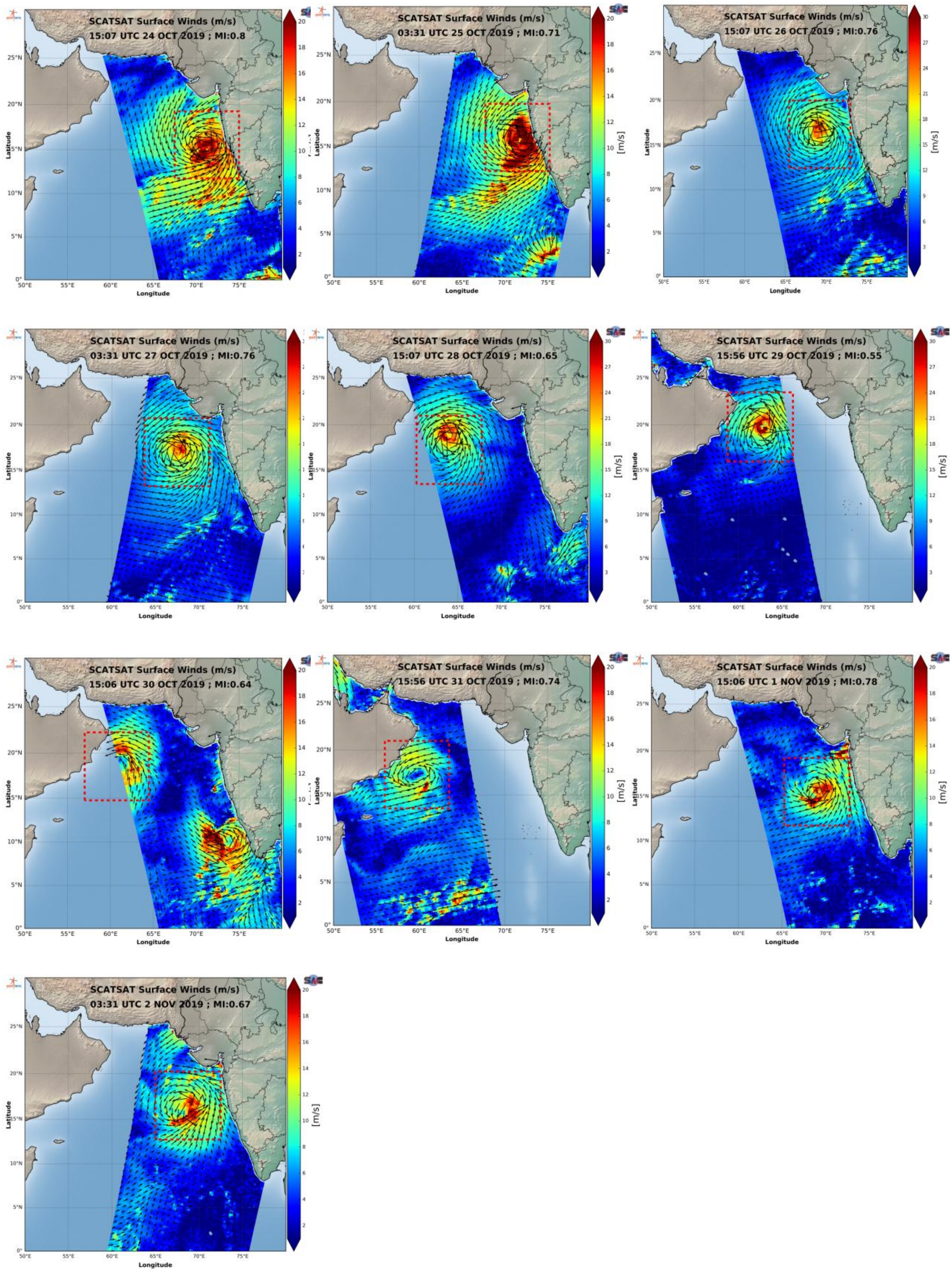

Fig. 9h: SCATSAT derived surface winds during life cycle of SuCS KYARR (24 Oct - 02 Nov), 2019

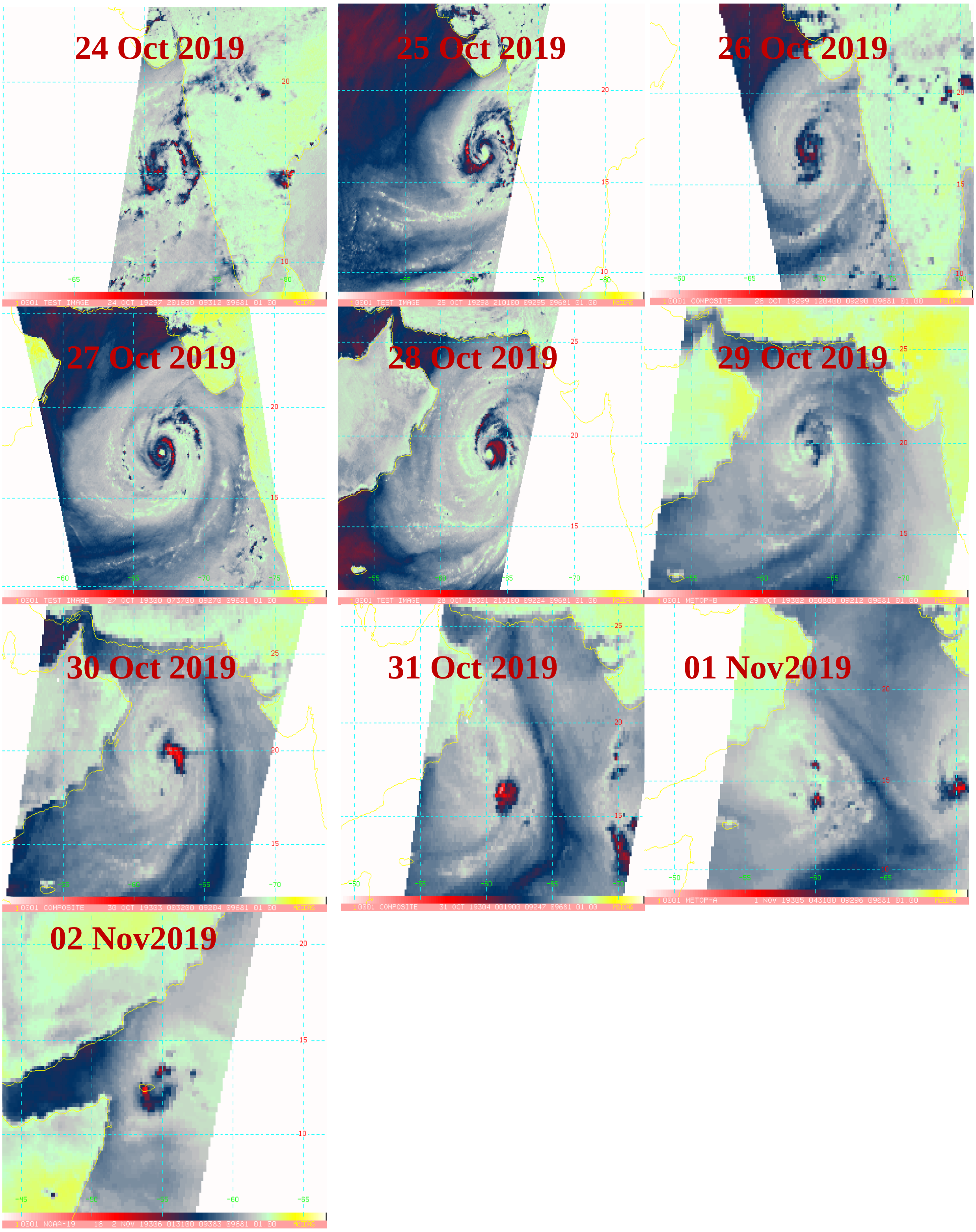

Fig. 9i: Microwave imageries during life cycle of SuCS KYARR (24 Oct -02 Nov), 2019

5.2 Features observed through Radar

The system, in its initial period of genesis and northeastward movement gave some signature in the Doppler Weather RADARs (DWR) viz., Mumbai & Goa along the west coast of India. As it moved away from the Indian coast line, no further monitoring could be done via RADARs. Typical imageries from DWRs Mumbai & Goa are presented in **Fig.10**.

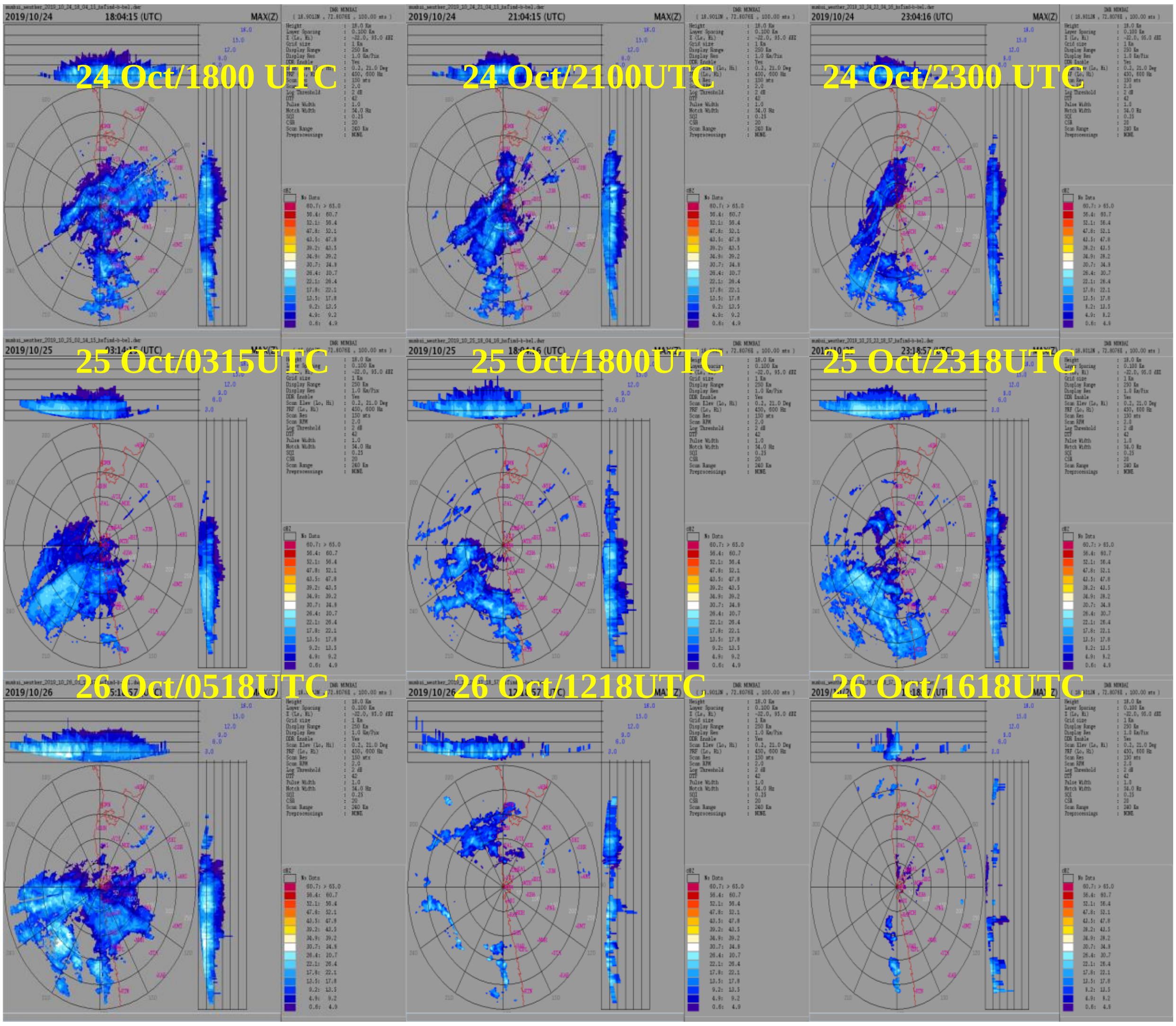

Fig. 10(a): Typical Radar imagery MAX-Z from DWR Mumbai From 24 Oct – 26 Oct

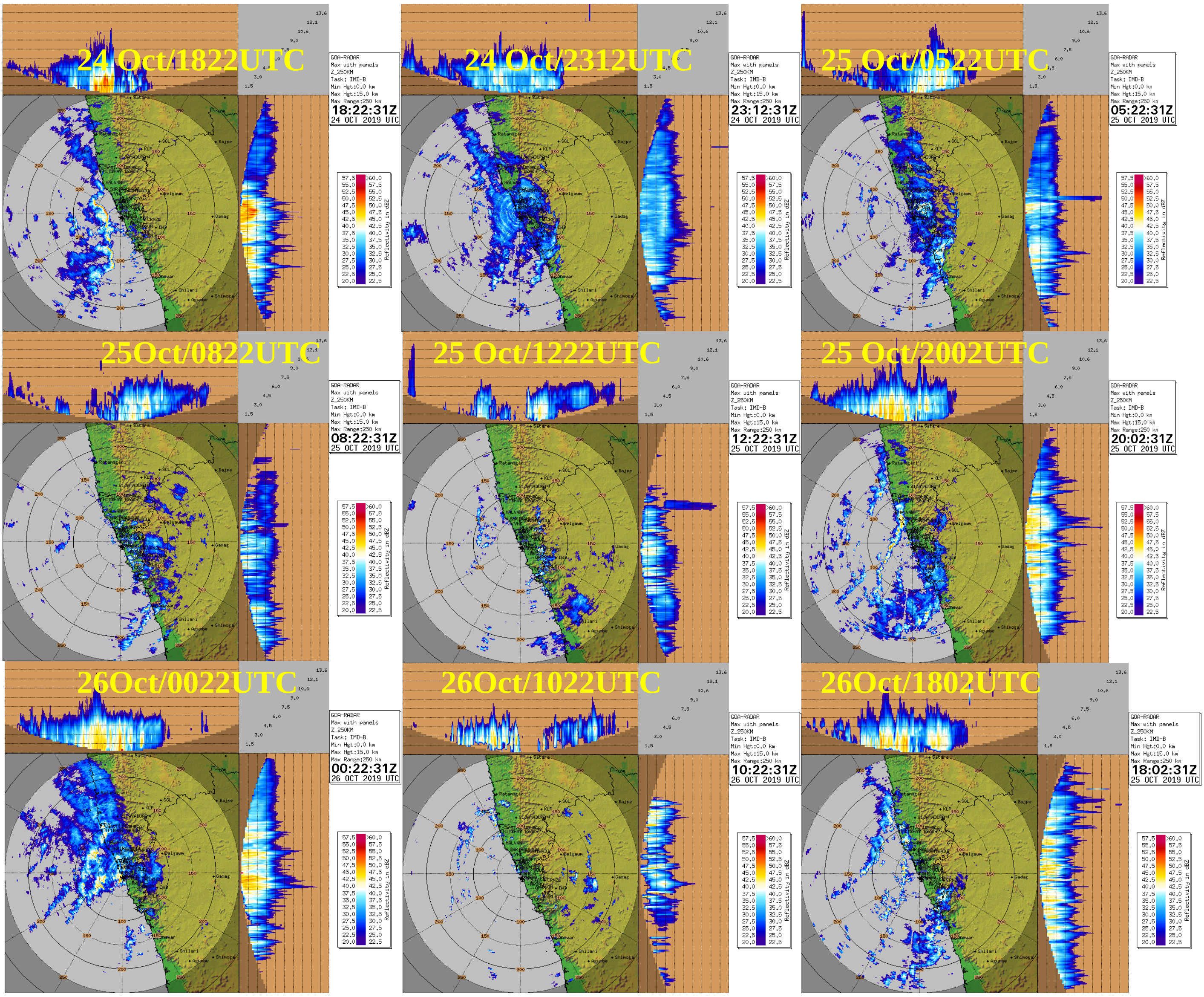

Fig.10 (b): Typical Radar imagery MAX-Z from DWR Goa From 24 Oct – 26 Oct

6. **Dynamical features**

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 24th October – 02nd November 2019 are presented in **Fig.11**.

IMD GFS (T1534) Analysis based on 0000 UTC of 24th October 2019 indicates that the model though simulated the vortex over east central AS, the intensity was over predicted.

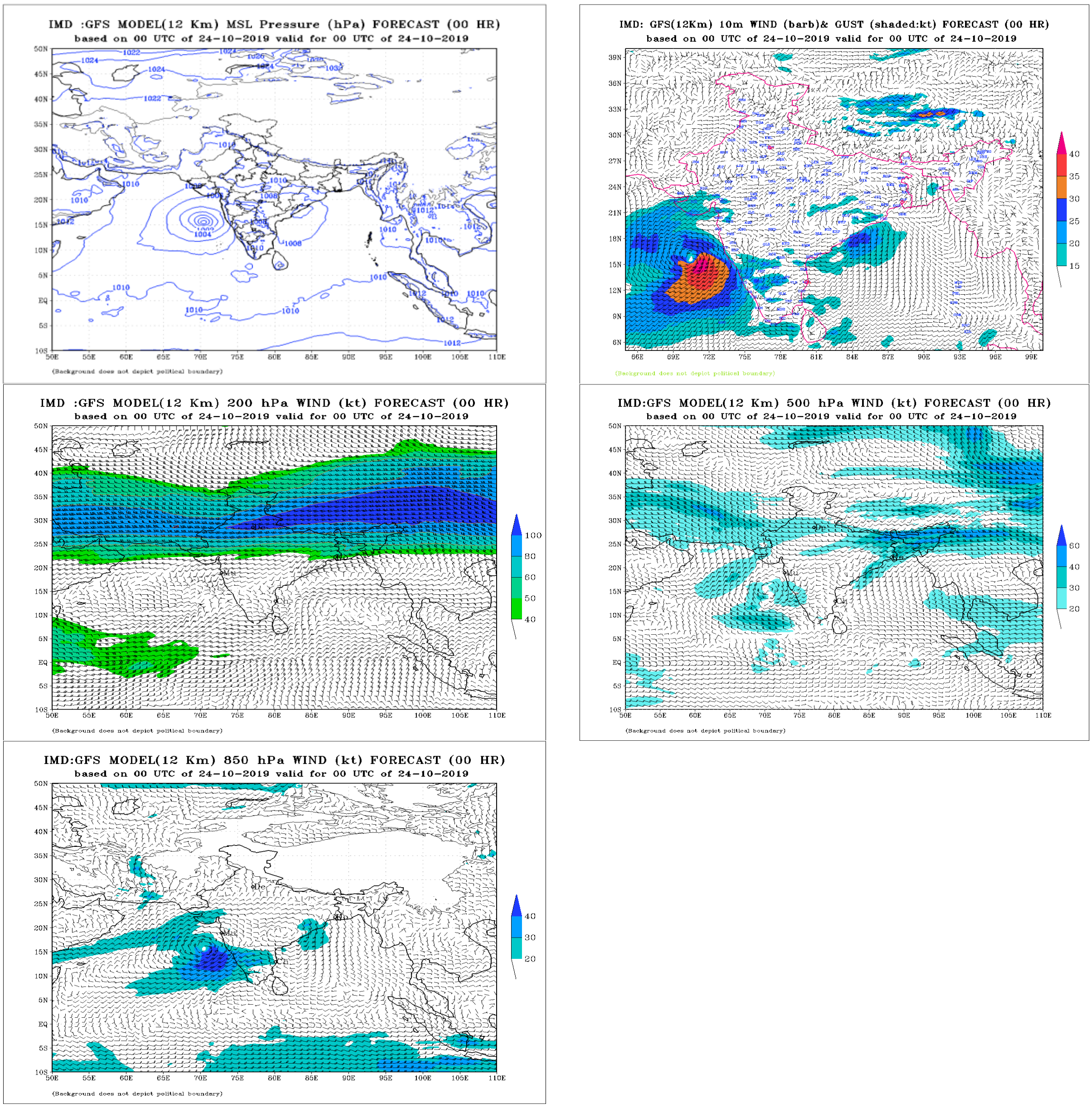

Fig. 11(a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 24 October 2019

IMD GFS (T1534) Analysis based on 0000 UTC of 25th October 2019 indicates that the model continued to overestimate the system intensity over east central AS, when the system had been a Cyclonic Storm.

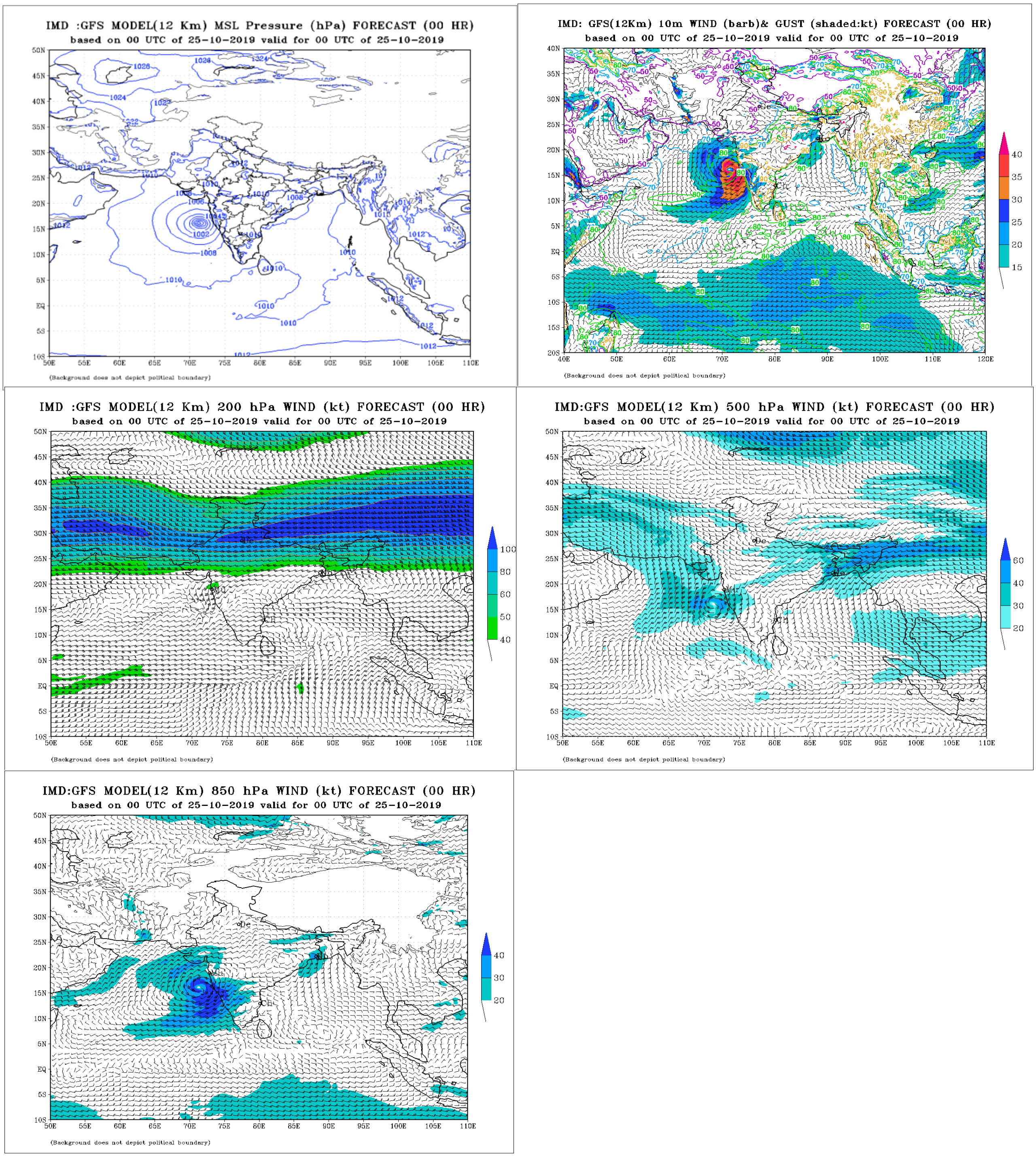

Fig. 11(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 25 October 2019

IMD GFS (T1534) Analysis based on 0000 UTC of 26th October 2019 indicates that the model continued to overestimate the intensity, when the system lay as a VSCS over east central AS.

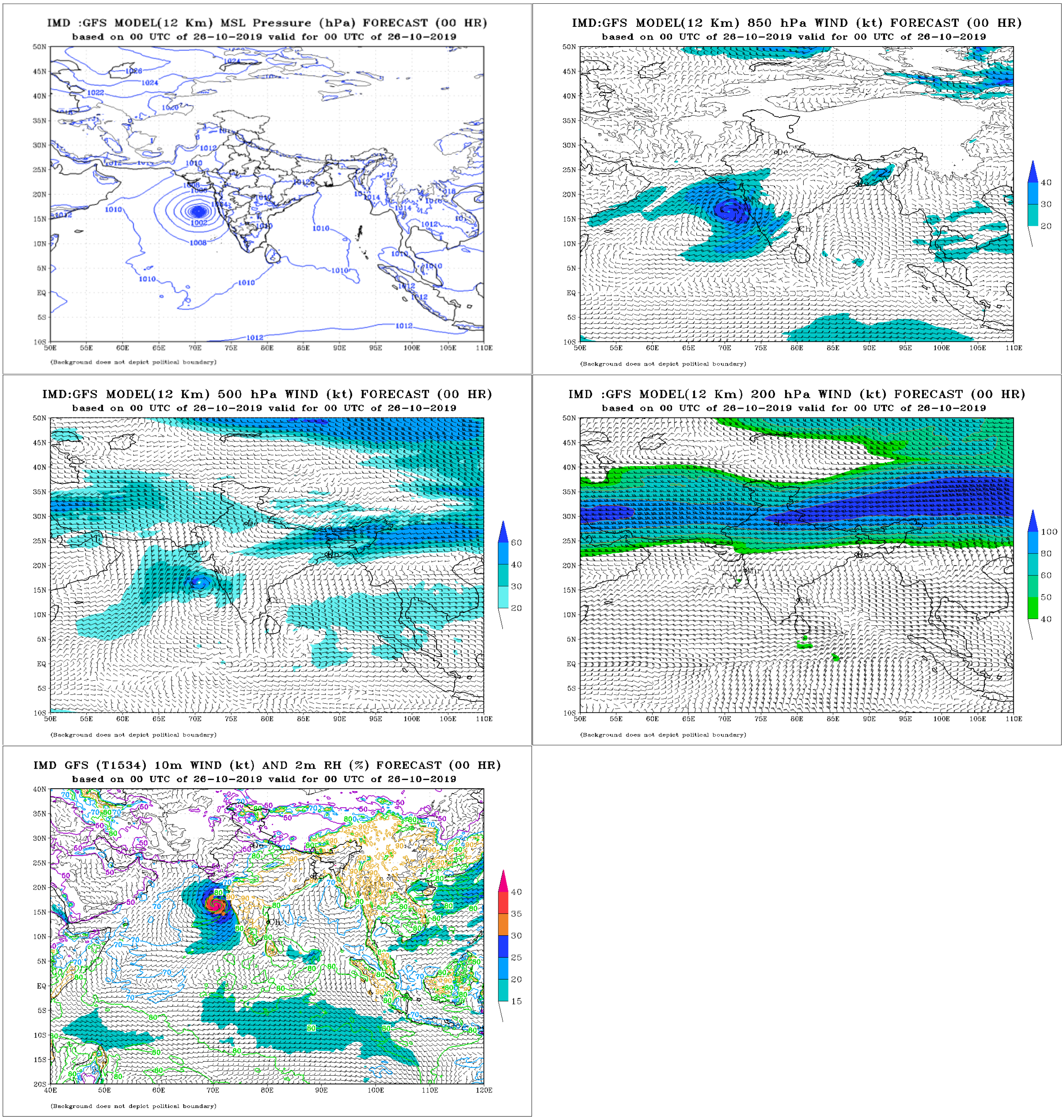

Fig. 11(c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 26 October 2019

IMD GFS (T1534) Analysis based on 0000 UTC of 27th October 2019 indicates that the model correctly simulated the intensity & location, when the system lay as an SuCS over east central AS.

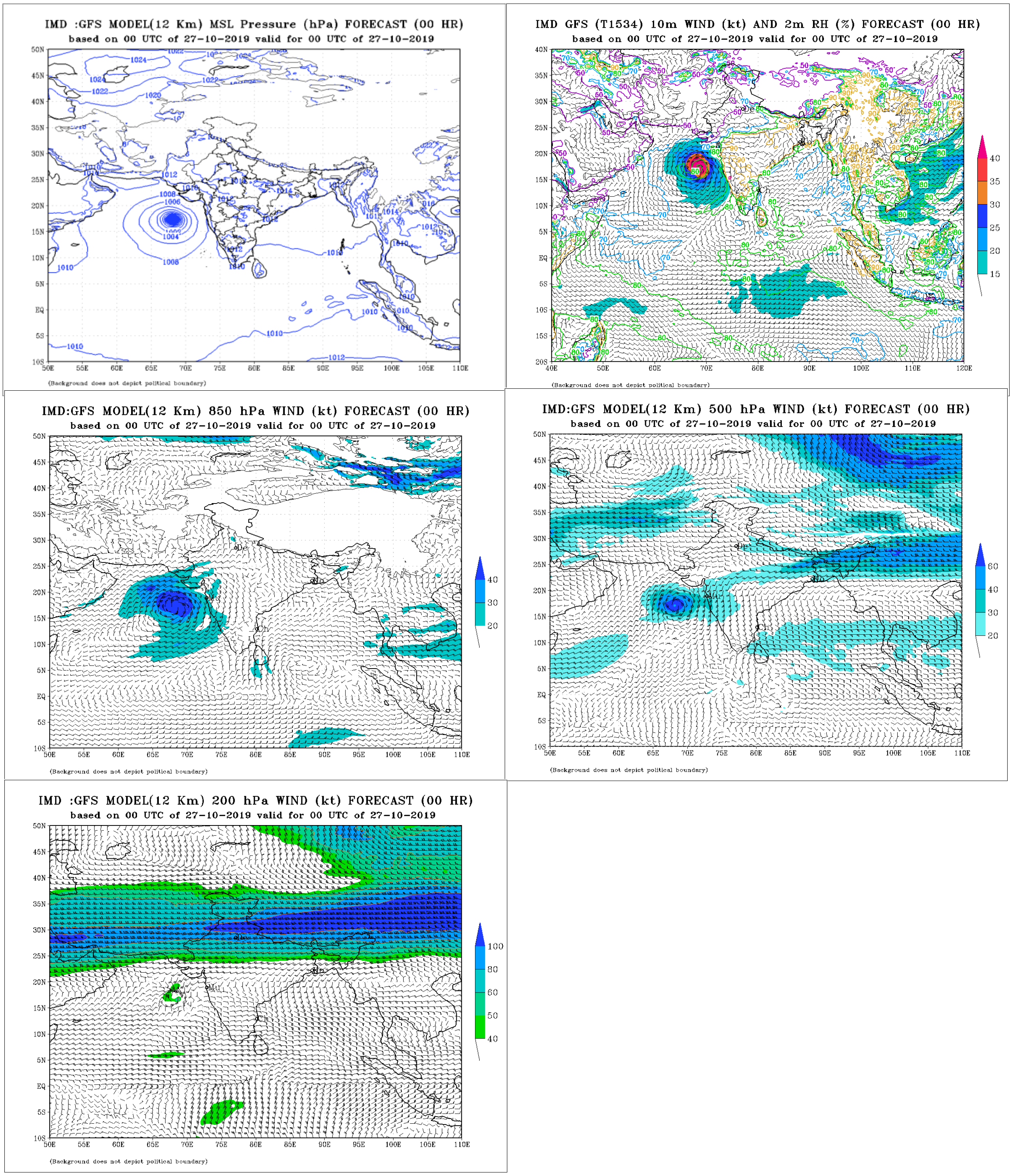

Fig. 11(d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 27 October 2019

IMD GFS (T1534) Analysis based on 0000 UTC of 28th October 2019 indicates that the model correctly simulated the intensity & location, when the system lay as a SuCS over central AS.

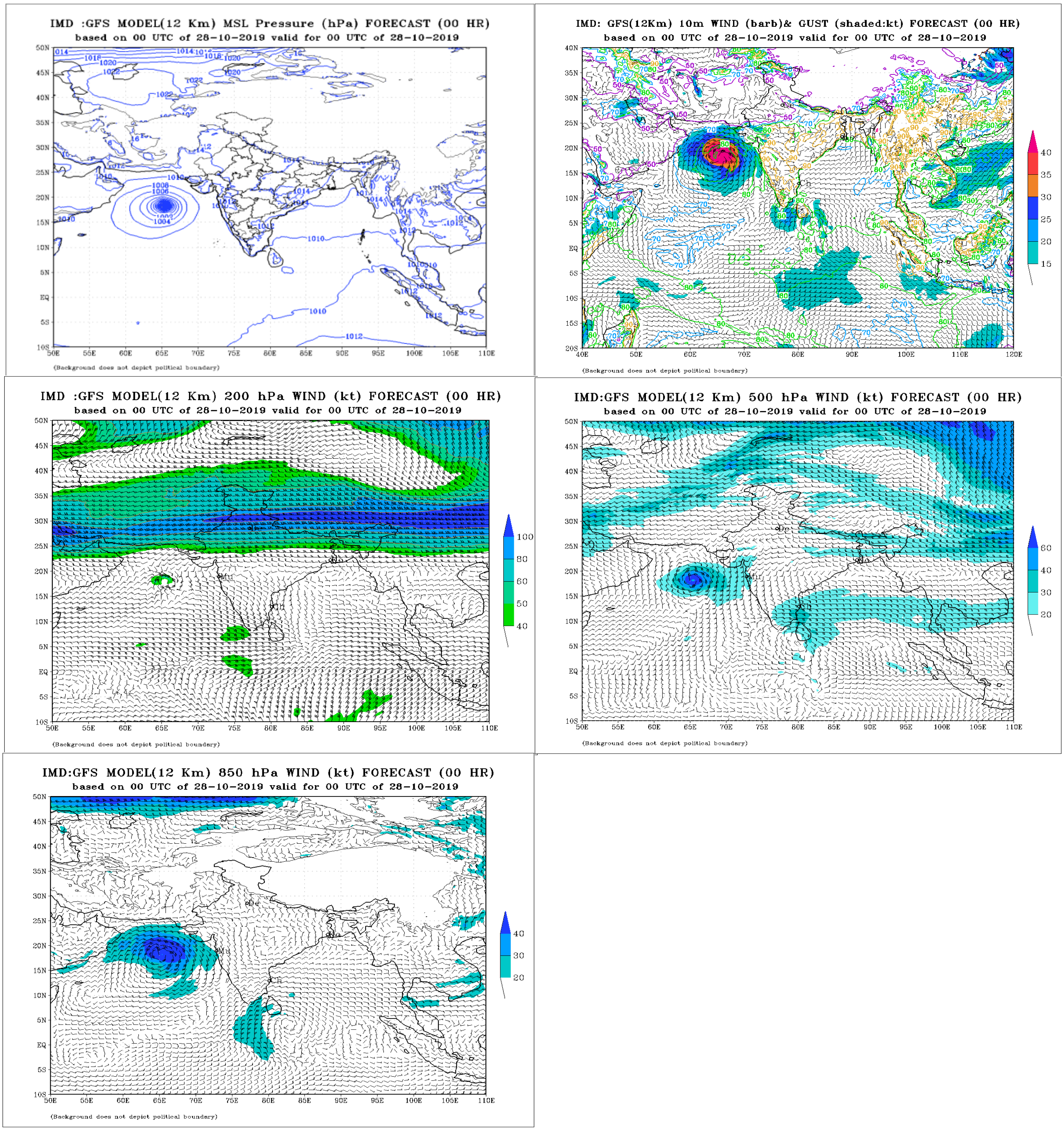

Fig. 11(e): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 28 October 2019

IMD GFS (T1534) Analysis based on 0000 UTC of 29th October 2019 indicates that the model correctly simulated the intensity & location, when the system slightly weakened and lay as an ESCS over west central AS.

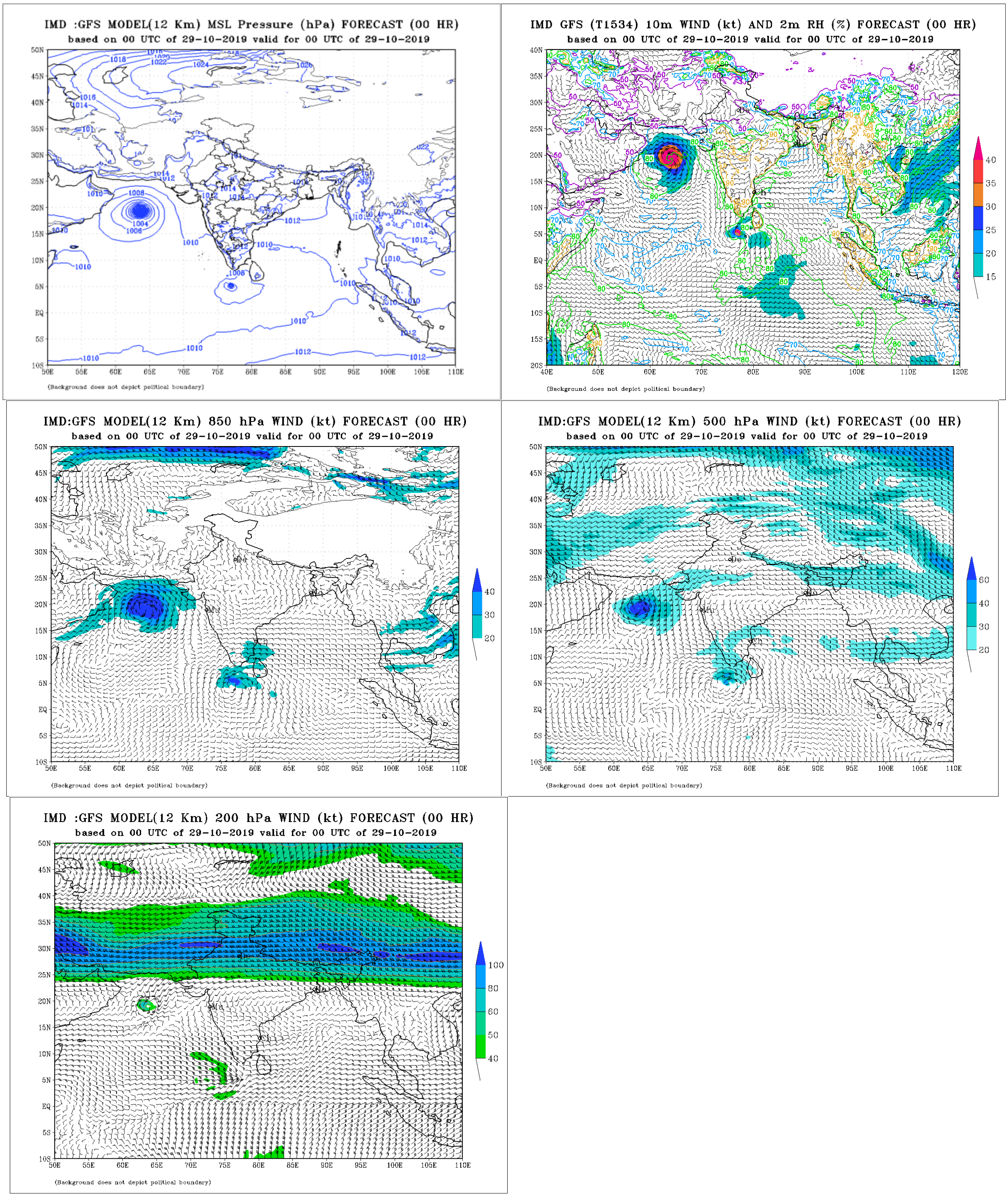

Fig. 11(f): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 29 October 2019

IMD GFS (T1534) Analysis based on 0000 UTC of 30th October 2019 indicates that the model correctly simulated the location, but the intensity has been overestimated. By 30th October 0000 UTC, the system had further weakened into a VSCS over west central AS.

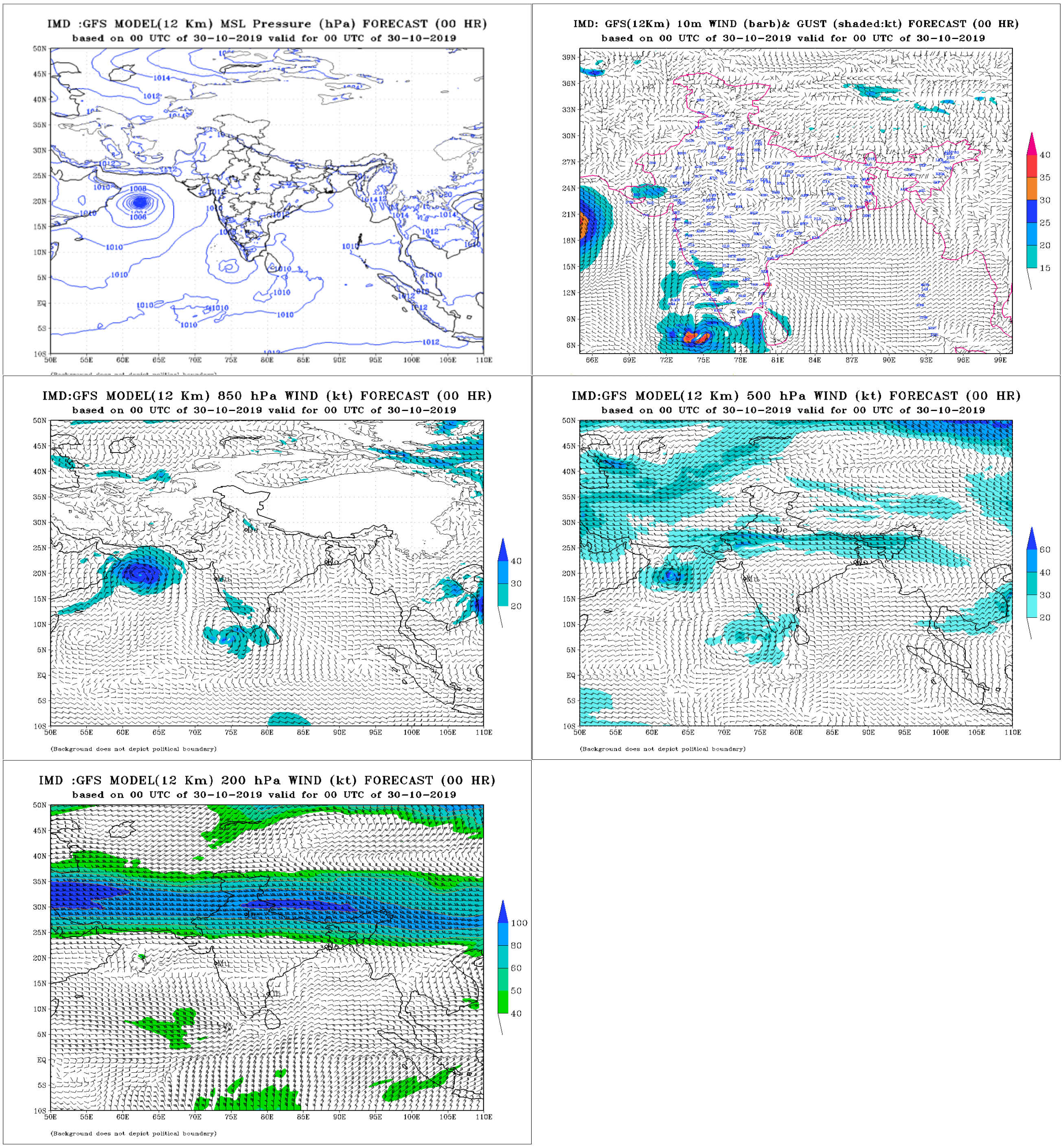

Fig. 11(g): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 30 October 2019

IMD GFS (T1534) Analysis based on 0000 UTC of 31st October 2019 indicates that the model correctly simulated the location as well as intensity of the system, when it had further weakened into a SCS over west central AS.

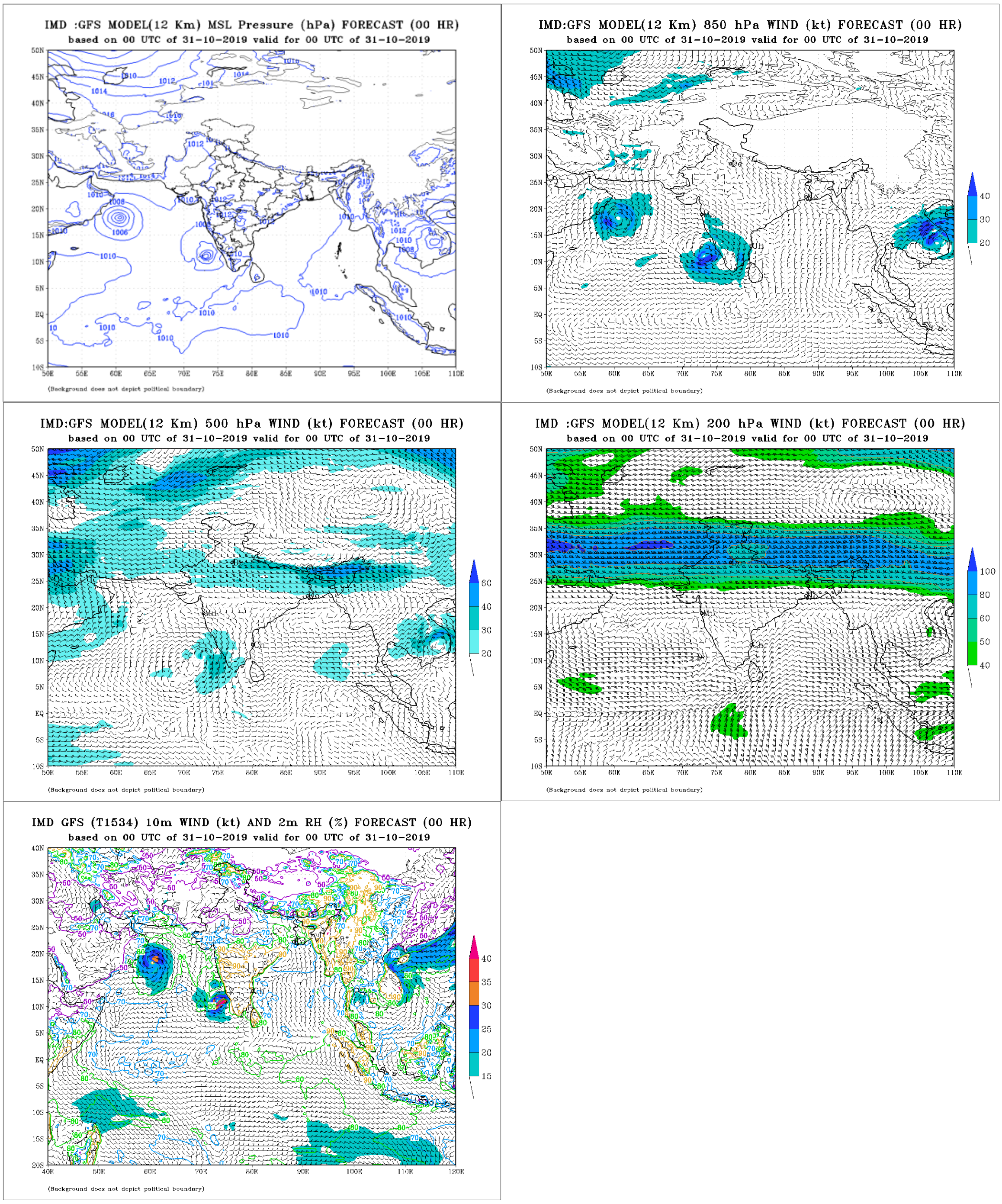

Fig. 11(h): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 31 October 2019

IMD GFS (T1534) Analysis based on 0000 UTC of 01st November 2019 indicates that the model correctly simulated the location, but the intensity has been overestimated. By 30th October 0000 UTC, the system had further weakened into a Depression over west central AS.

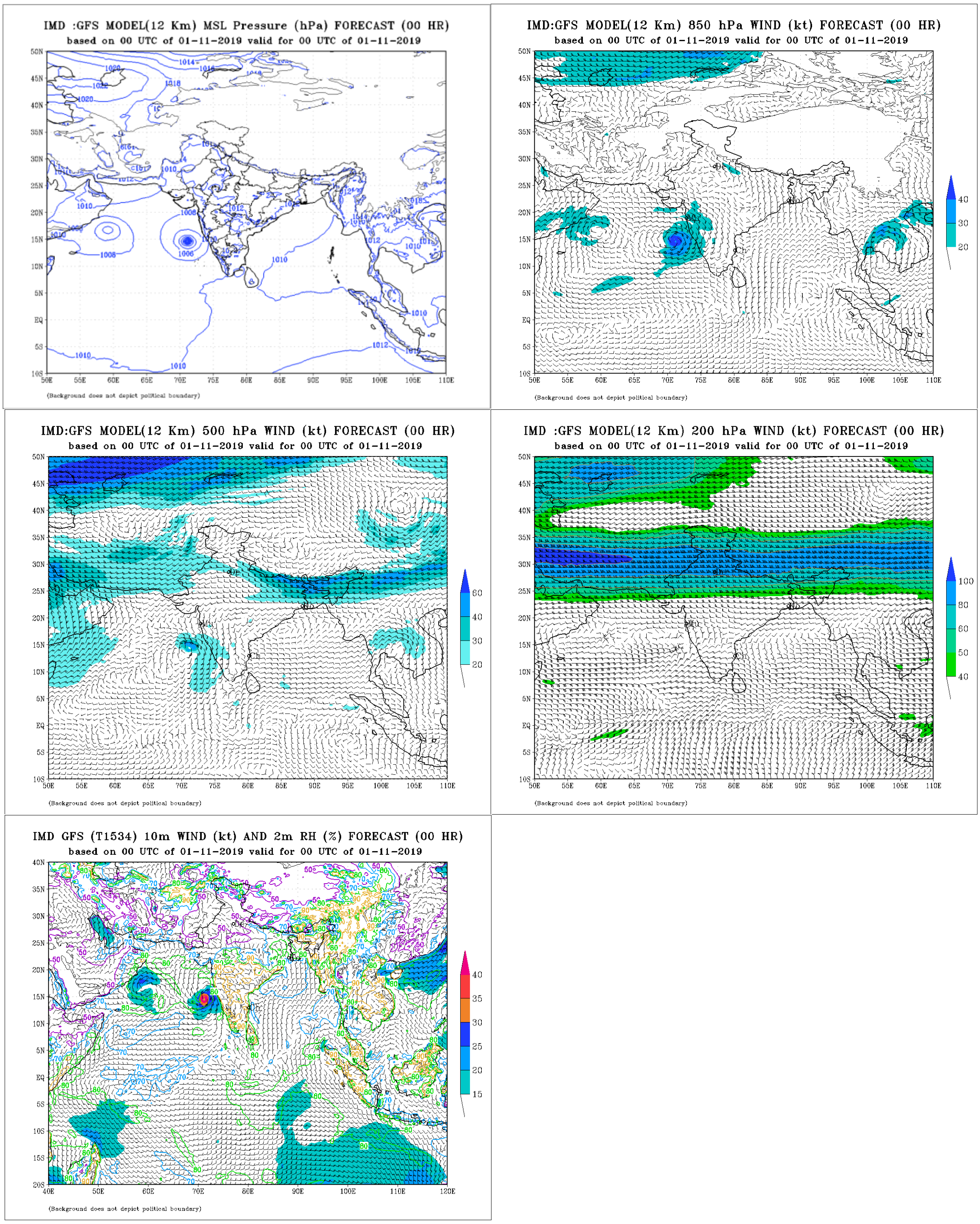

Fig. 11(i): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 01 November,2019

IMD GFS (T1534) Analysis based on 0000 UTC of 02nd November 2019 indicates that the model correctly simulated the location and intensity of the system, when it lay as a d over west central & adjoining southwest AS.

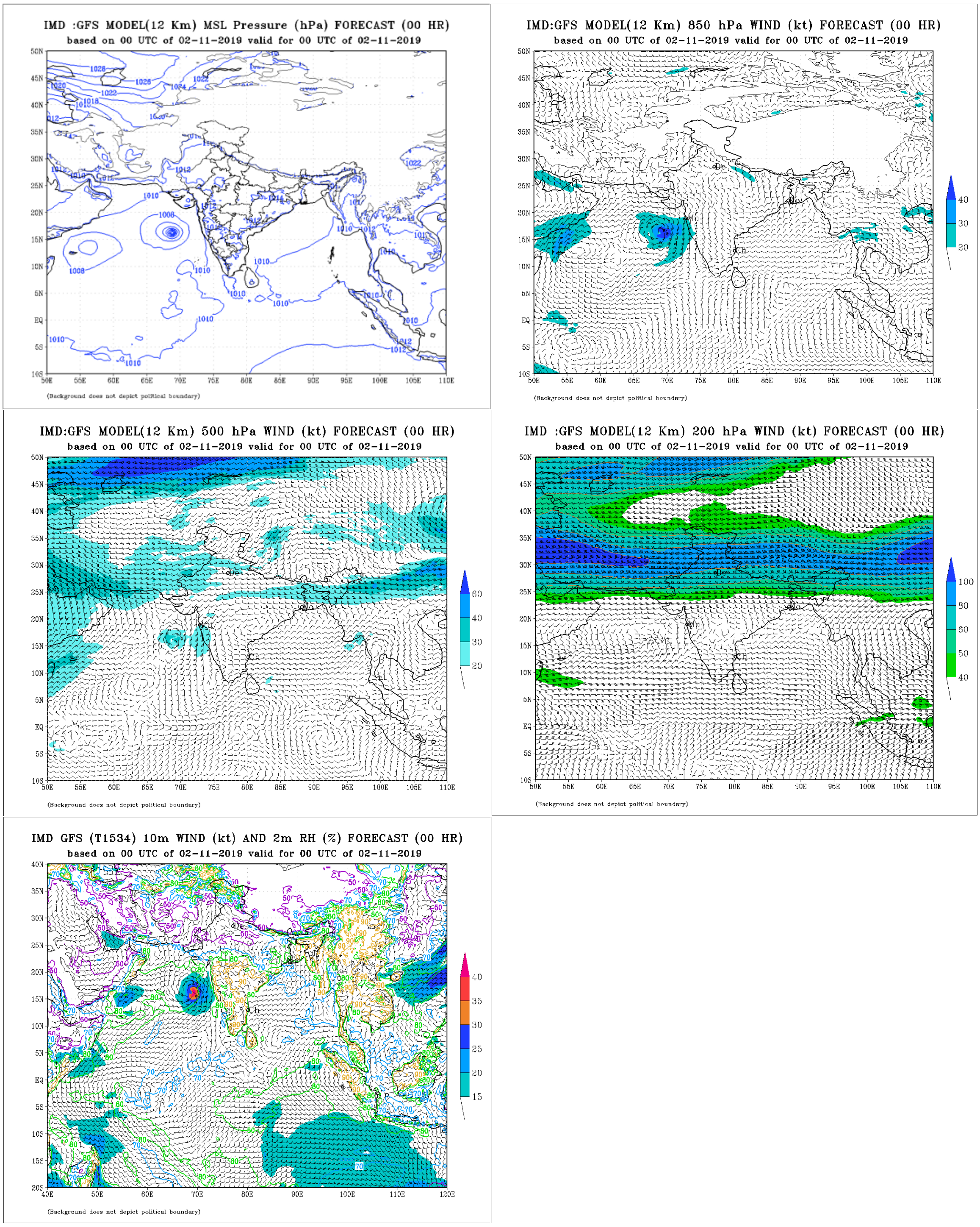

Fig. 11(j): IMD GFS (1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 02 November,2019

7. Realized Weather:

Rainfall associated with SuCS Kyarr based on IMD-NCMRWF GPM merged gauge 24 hours cumulative rainfall ending at 0300 UTC of date is depicted in **Fig 12**. The last 3 days of the rainfall maps also include the rainfall associated with ESCS 'Maha'.

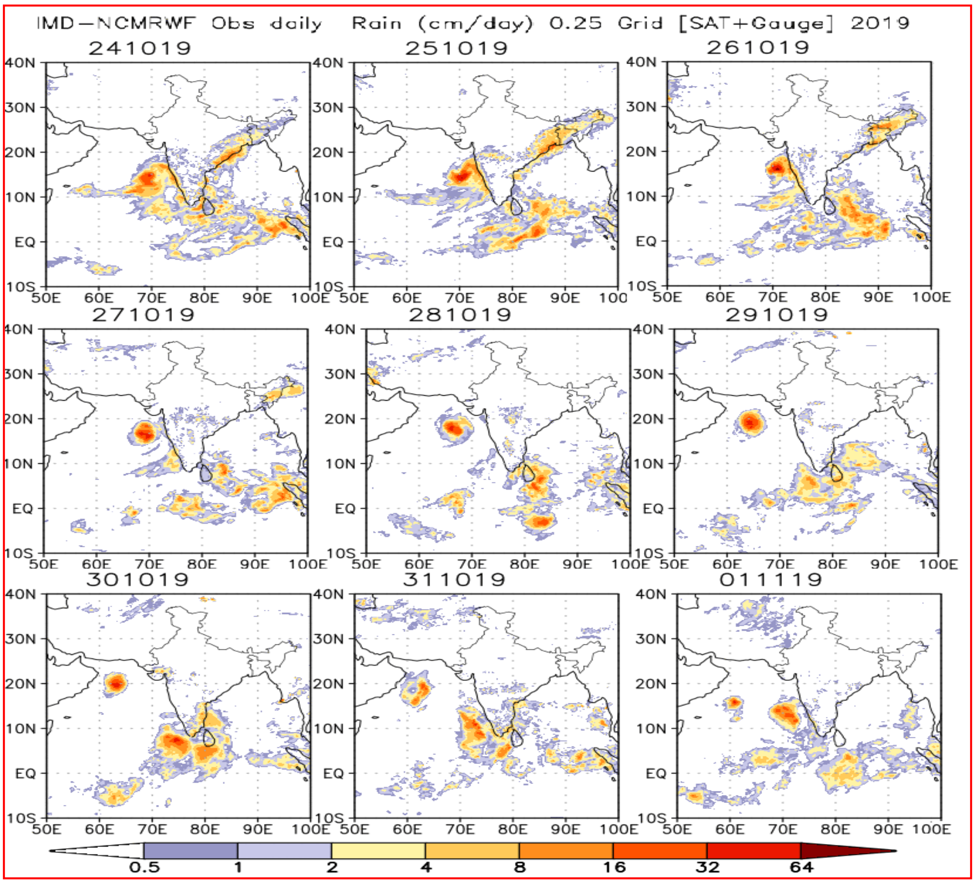

Fig.12: IMD-NCMRWF GPM merged gauge 24 hr cumulative rainfall (cm) ending at 0830 IST of date during 24th October – 1st November, 2019

The system caused heavy to very heavy rainfall at isolated places during 24th-26th November over Madhya Maharashtra, Konkan and Marathwada along the west coast of India. Rainfall amounts ≥7 cm recorded during the past 24 hours ending at 0300 UTC of date are given below:

24 October 2019

Konkan: Malvan and Vengurla -7 each

Marathwada: Badnapur-7

25 October 2019

Konkan: Malvan-8 and Dodamarg, Sawantwadi & Vengurla-7 each

Madhya Maharashtra: Pathardi and Akole-8 each

Marathwada: Manjlegaon & Manvat-9 each, Pathri & Ahmedpur-8 each and Georai-7.

26 October 2019
Konkan: Malvan-25, Devgad-18, Vengurla-14, Kudal-11 and Dodamarg, Sawantwadi & Rajapur-7 each
Madhya Maharashtra: Chandgad-7
Marathwada: Selu-10 and Parbhani, & Purna-7 each.

27 October 2019
Konkan: Sawantwadi-18

28 October 2019
Marathwada: Bhokar, Nanded & Dharmabad-7 each

7.2. Wind

Maximum sustained wind of 240-250 kmph gusting to 275 kmph prevailed around the system centre over eastcentral & adjoining west-central Arabian Sea.

8. Damage due to SuCS, KYARR

No major damage was reported from any of the states of India along the west coast and from Somalia and Socotra Islands, as the system moved away from the Indian coast & weakened over the Sea.
However, the fishing operations were disrupted over the Arabian Sea all through the Storm period.
Also, there had been damage to Agricultural crops in Maharashtra owing to the un-seasonal heavy to very heavy / extremely heavy rains.

9. 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 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 (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. The performance of the individual models, MME forecasts, SCIP, GPP, RII for SuCS KYARR are presented and discussed in following sections.

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

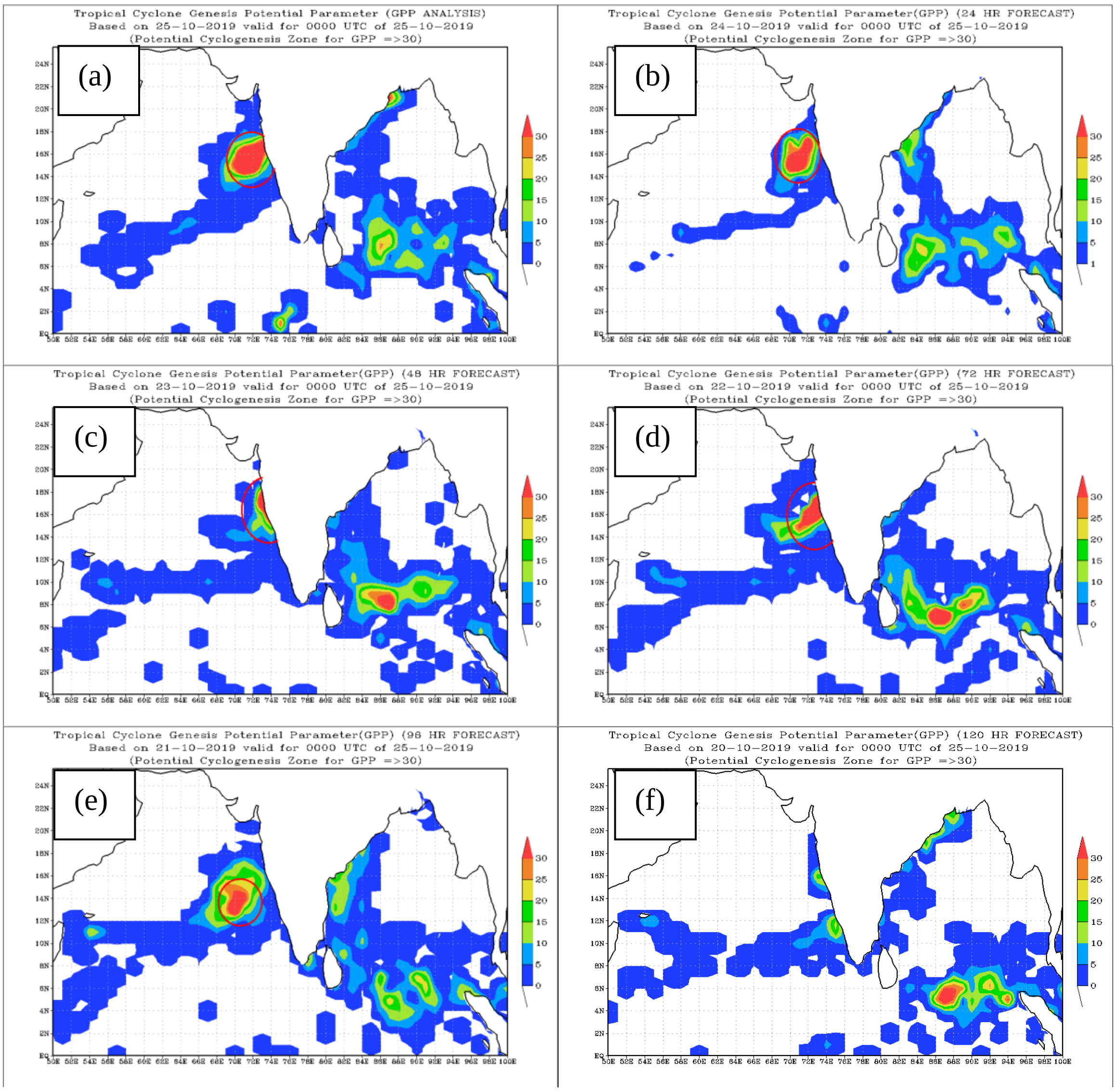

Fig.13 (a-f): Predicted zone of cyclogenesis for 0000 UTC of 24 October based on 0000 UTC of 20-25 Oct., 2019

Fig. 13 (a-f) indicates that the GPP could predict the potential zone for cyclogenesis on 21st October over east central AS about 120 hours in advance. However, it was not consistent in the subsequent 48 hours' forecasts.

Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages (T No. 1.0, 1.5, 2.0) of development. Average GPP ≥ 8.0 is the threshold value for system likely to develop into a cyclonic storm and average GPP < 8.0 indicates a nondeveloping system: The area average analysis of GPP during 20th – 24th October is presented in Fig. 14. The area average analysis was predicting the system to develop into a cyclonic storm since 20th October onwards.

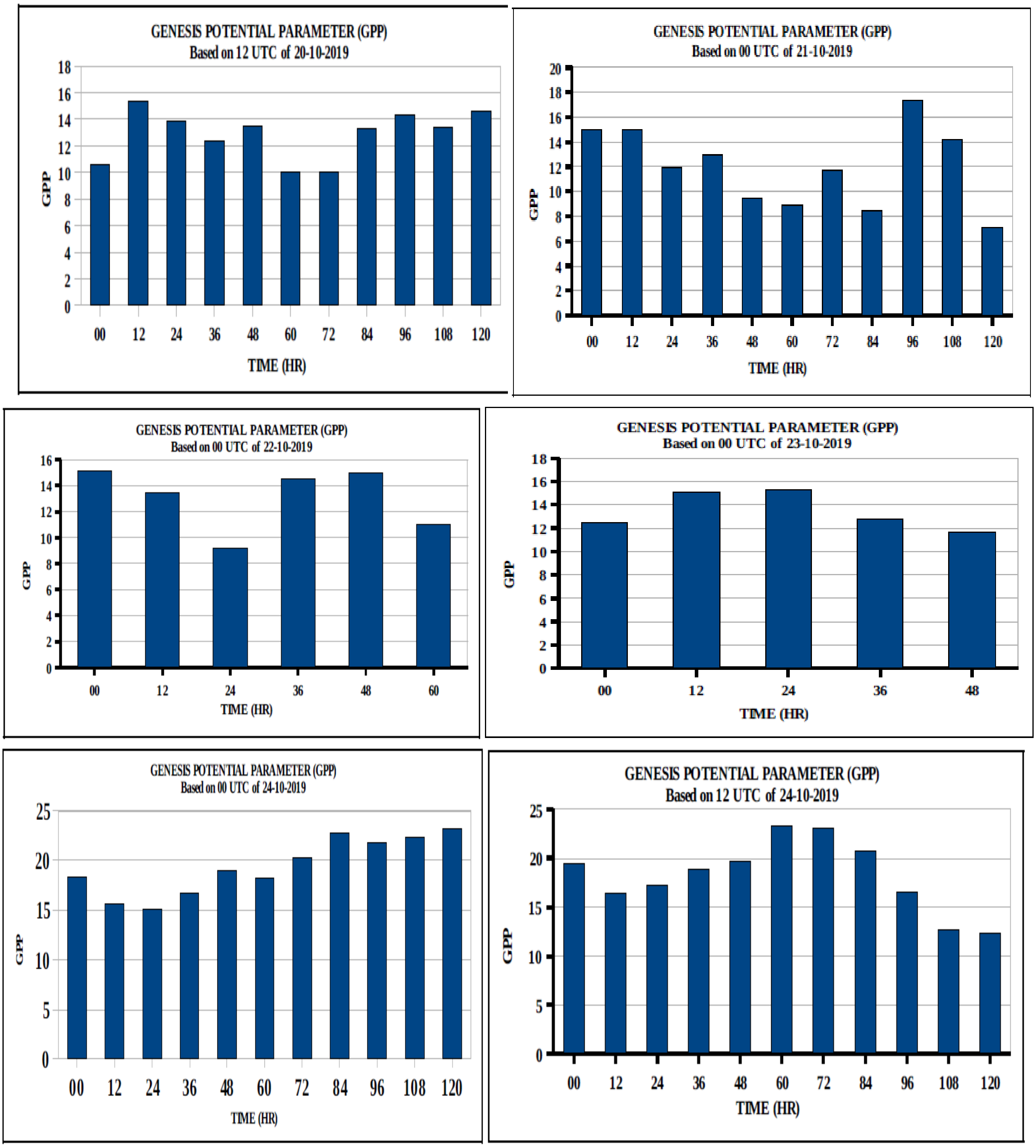

Fig. 14: Area average analysis and forecasts of GPP based on 20th – 24th October initial conditions.

9.2 Track prediction by NWP models

Track prediction by various NWP models is presented in **Fig.15**. Based on initial conditions of 0000 UTC of 24th October, most of the models indicated initial northeastward movement followed by northwestward re-curvature.

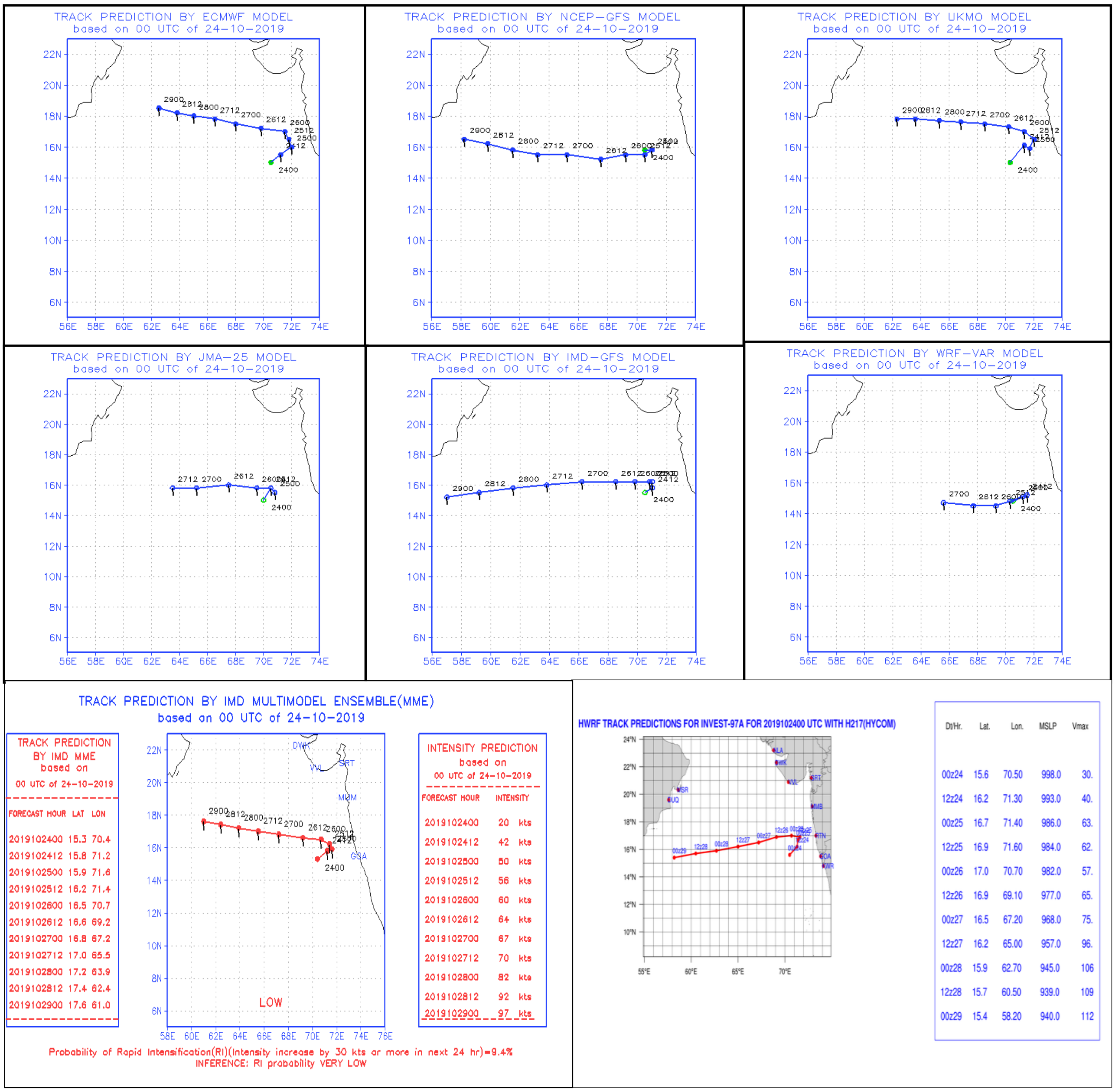

Fig. 15 (a): NWP model track forecast based on 0000 UTC of 24.10.2019

Based on initial conditions of 0000 UTC of 25th October, models including ECMWF, NCEP GFS and IMD MME indicated west-northwestward movement whereas UKMO indicated a more northwestward movement and WRF, more westwards.

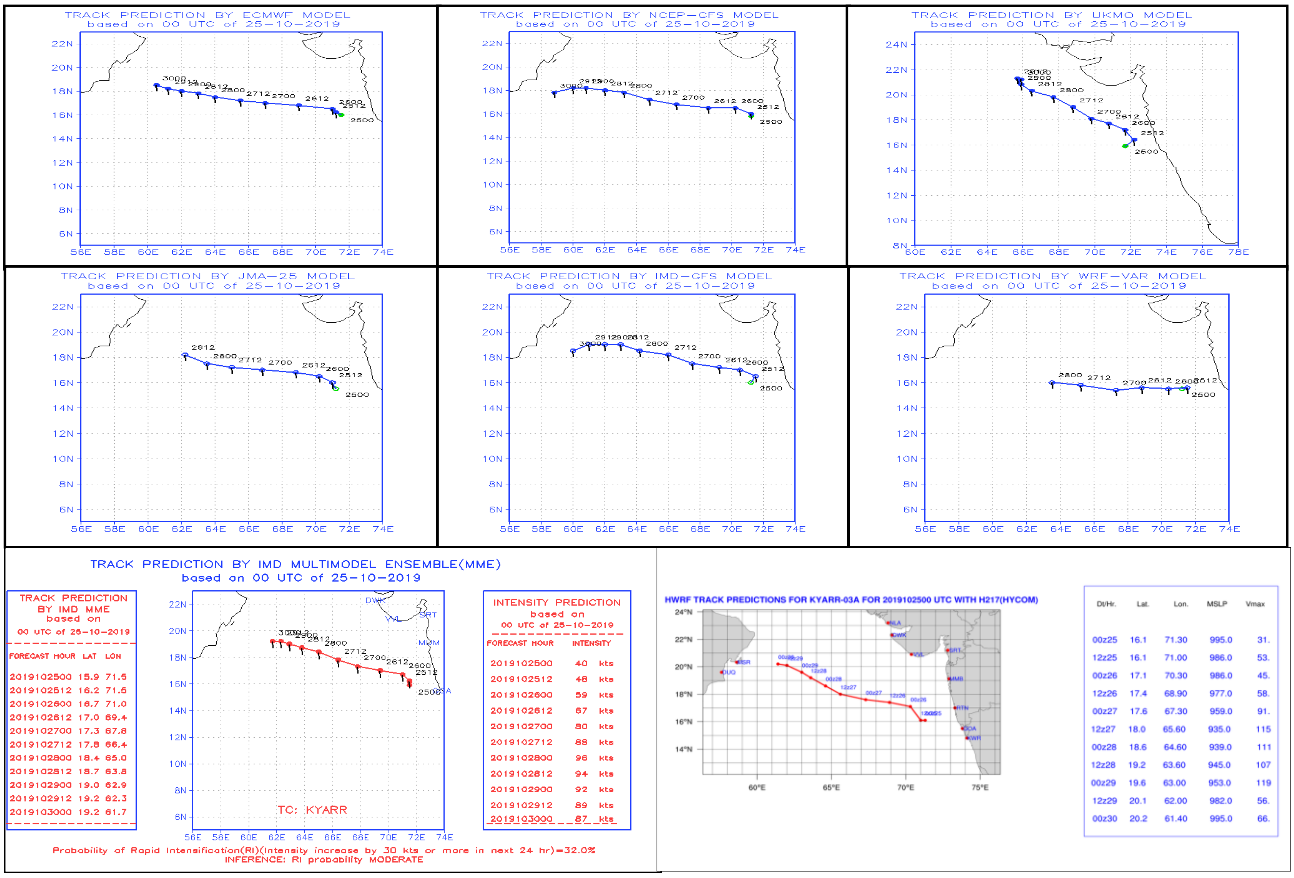

Fig. 15 (b): NWP model track forecast based on 0000 UTC of 25.10.2019

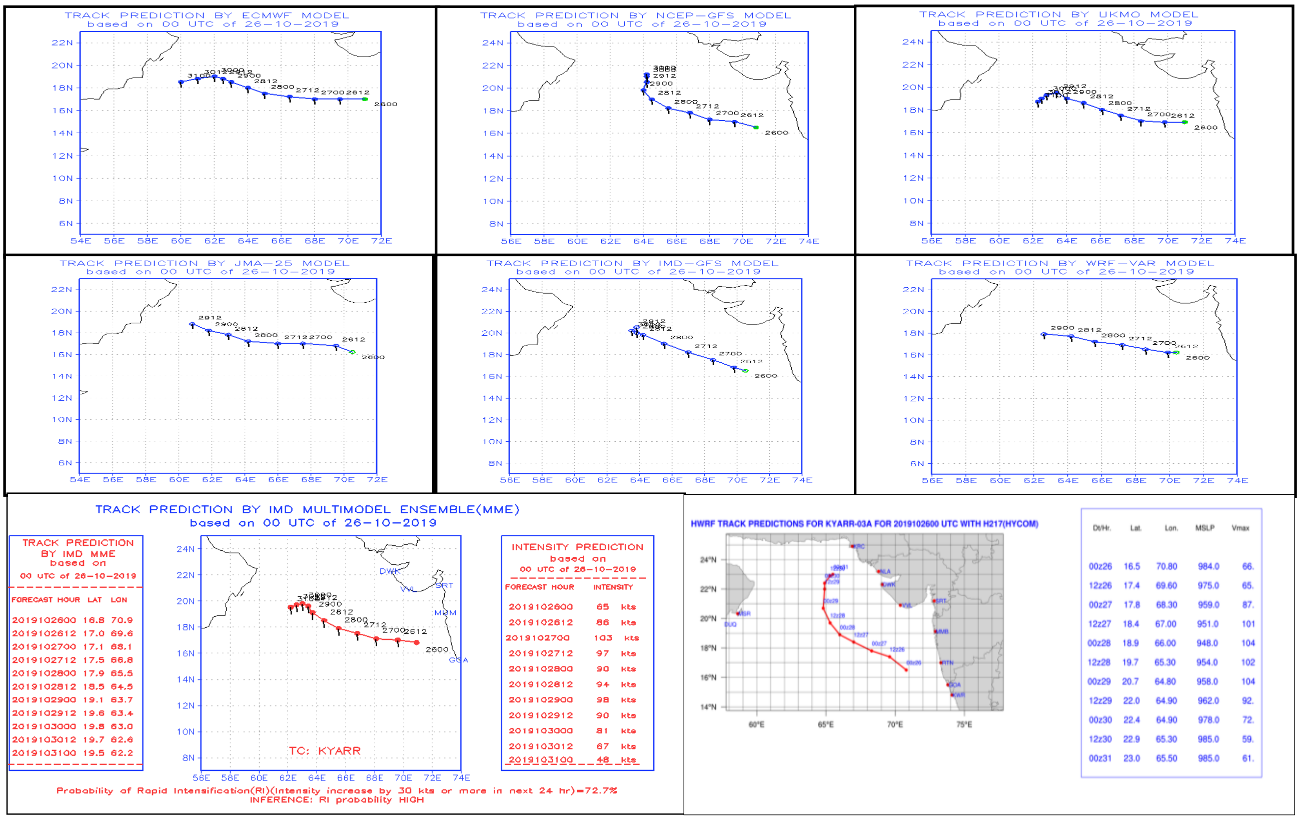

Fig. 15 (c): NWP model track forecast based on 0000 UTC of 26.10.2019

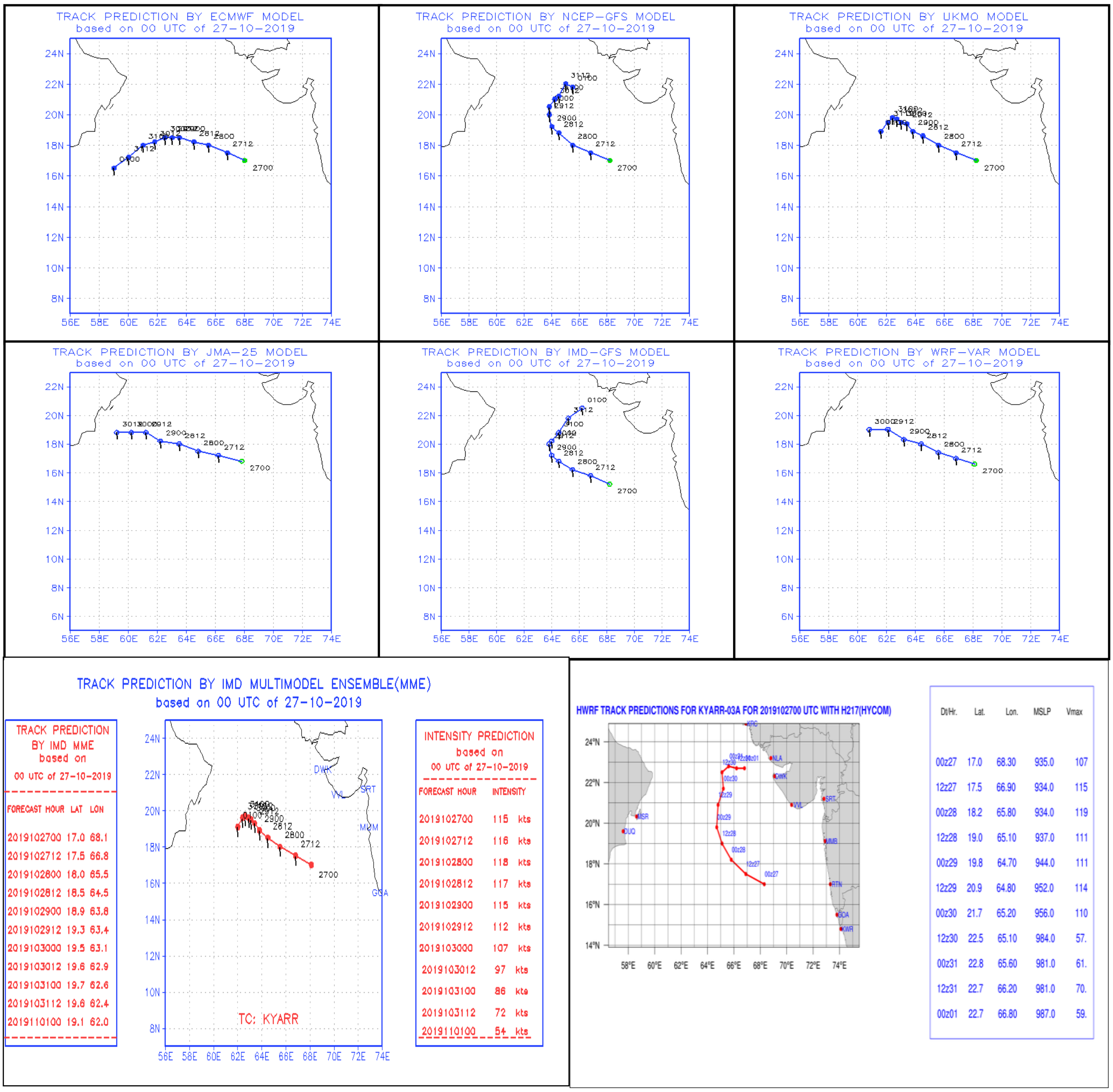

Fig. 15 (d): NWP model track forecast based on 0000 UTC of 27.10.2019

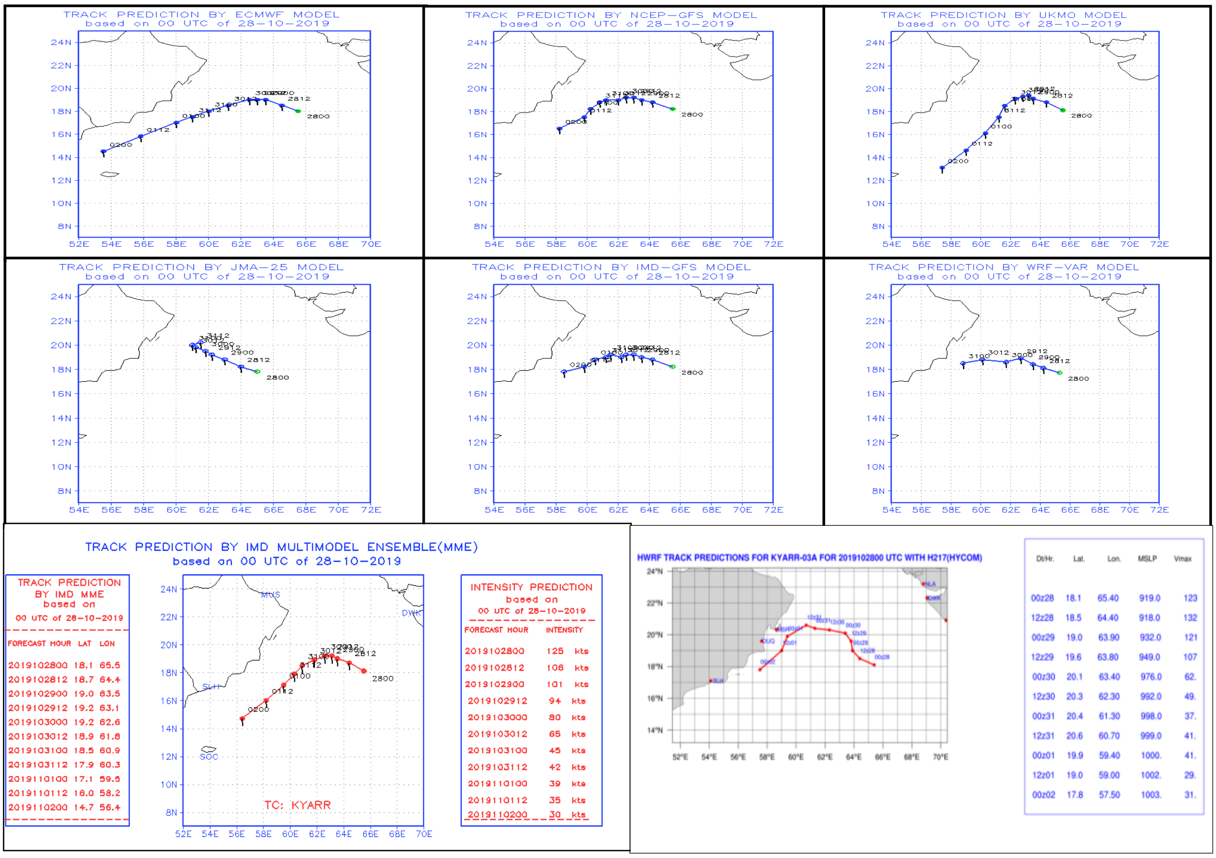

Fig. 15 (e): NWP model track forecast based on 0000 UTC of 28.10.2019

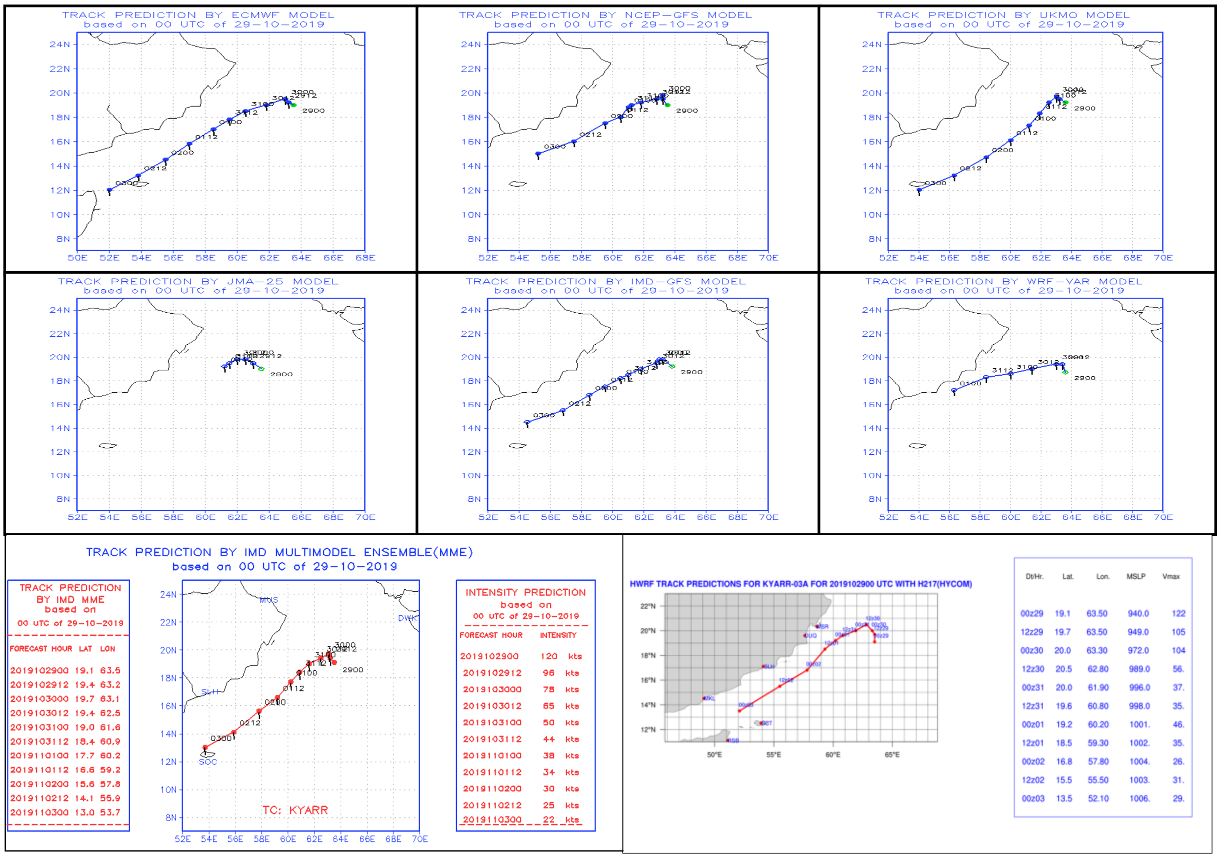

Fig. 15 (f): NWP model track forecast based on 0000 UTC of 29.10.2019

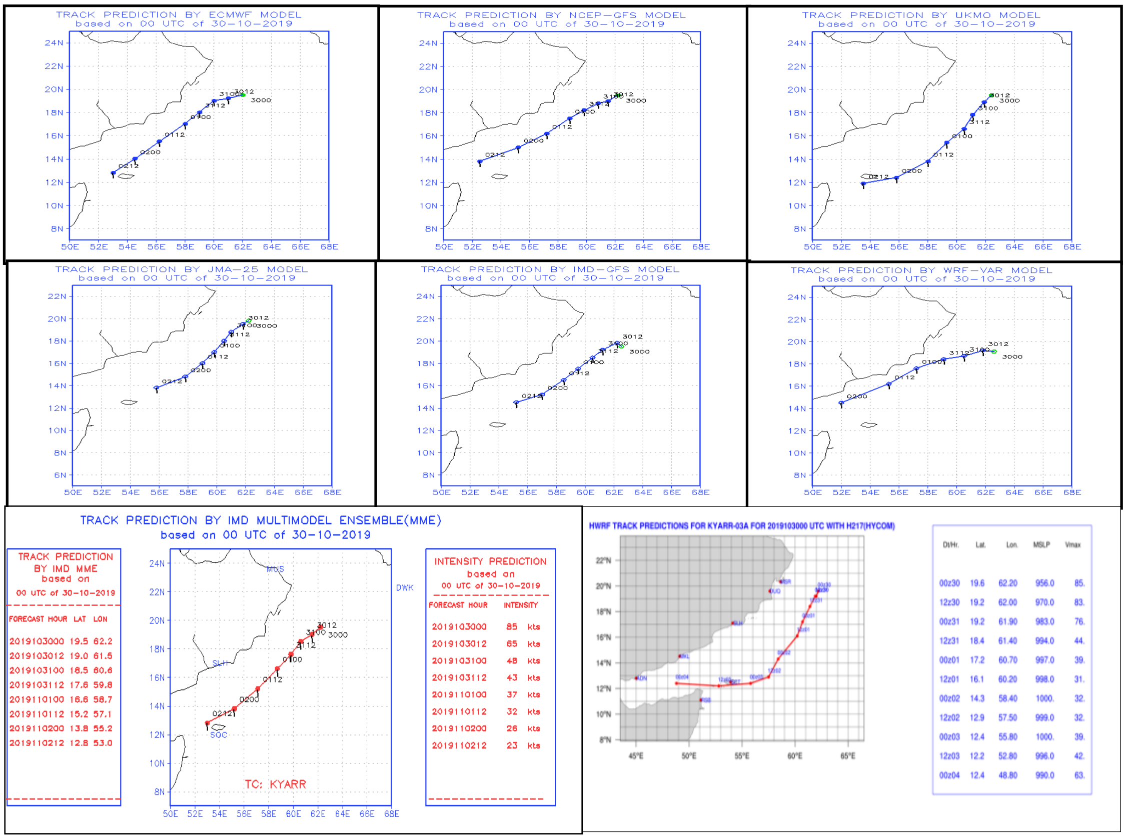

Fig. 15 (g): NWP model track forecast based on 0000 UTC of 30.10.2019

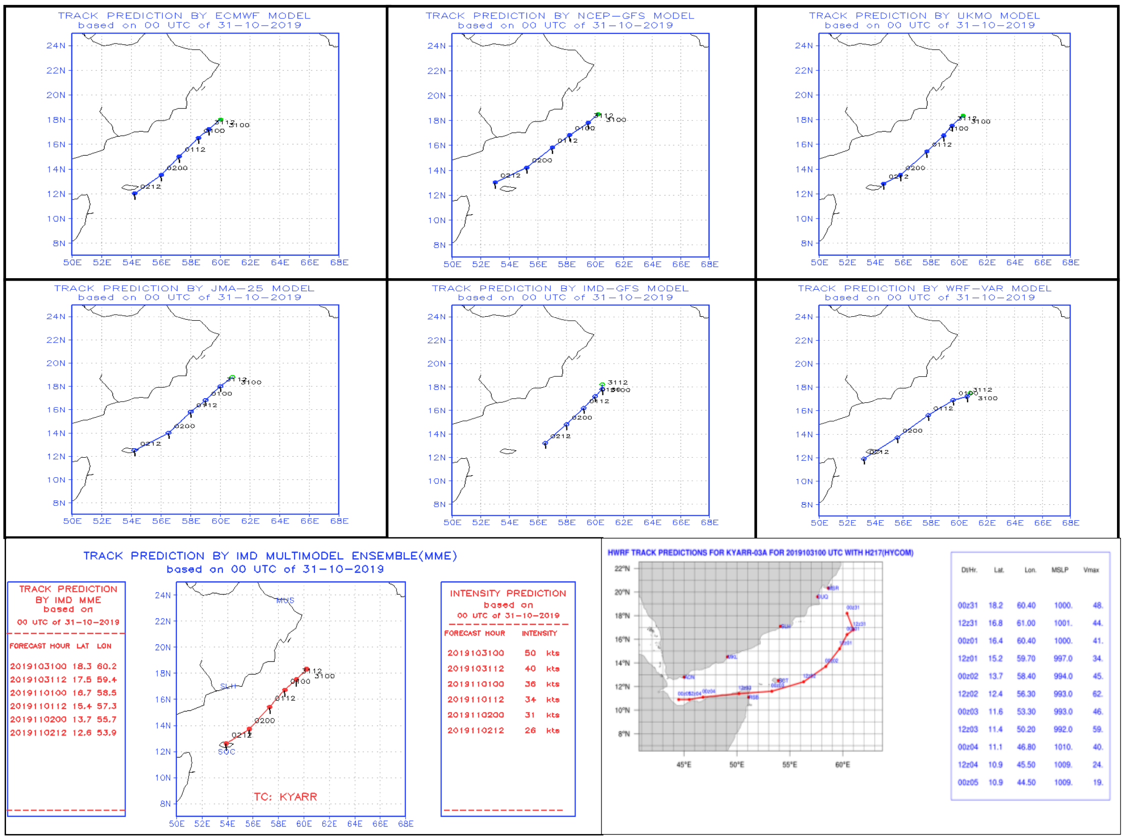

Fig. 15 (h): NWP model track forecast based on 0000 UTC of 31.10.2019

9.3. Track Forecast Errors:

- The track forecast errors for 24, 48 and 72 hrs lead period were 27, 65, and 100 km respectively against the average track forecast errors of 86, 132 and 178 km during last five years (2014-18) respectively (**Fig.16a)**.
- The track forecast skill was about 80%, 92%, and 86% against the long period average (LPA) of 58%, 70%, and 74% during 2014-18 for 24, 48 and 72 hrs lead period respectively (**Fig.16b)**.
- Fig. 16 (a & b) indicate that for all lead periods except 120 hrs, the track forecast errors and skill were significantly better than long period average during 2014-18, despite the fact that the system exhibited multiple re-curvatures.

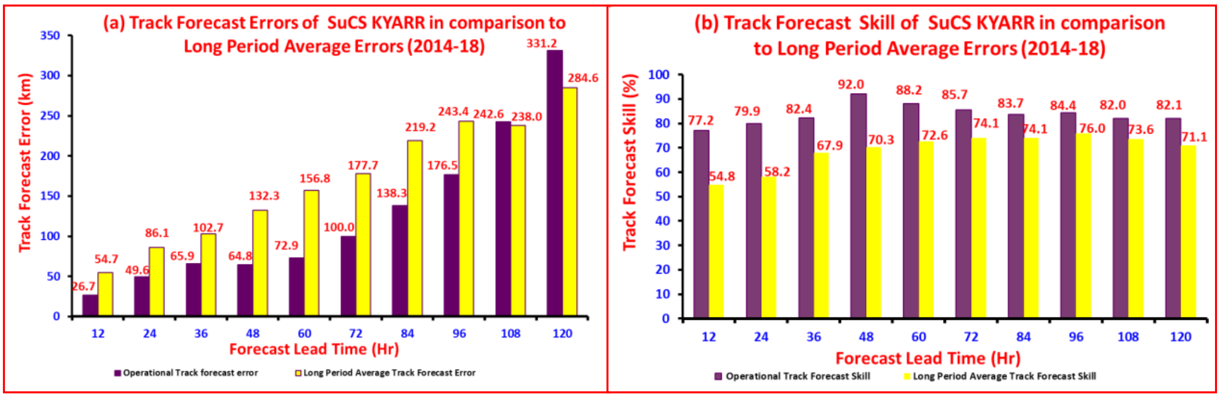

Fig. 17: Track forecast (a) errors and (b) skill of SuCS 'KYARR' as compared to long period average (2014-18)

Table-2: 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	33(16)	37(16)	47(16)	60(16)	64(15)	80(14)	106(13)	162(12)	212(11)	255(10)
ECMWF	47(16)	51(16)	60(16)	79(16)	98(15)	118(14)	102(13)	106(12)	135(11)	162(10)
NCEP-GFS	40(16)	56(16)	85(16)	100(16)	131(15)	196(14)	272(13)	381(12)	490(11)	592(10)
UKMO	43(16)	50(16)	81(16)	116(16)	132(15)	139(14)	157(13)	202(12)	271(11)	337(10)
JMA	51(16)	63(16)	90(16)	130(16)	192(15)	260(14)	336(13)	-	-	-
IMD-GFS	49(16)	72(16)	105(16)	145(16)	172(15)	217(14)	289(13)	392(12)	523(11)	689(10)
HWRF	70(36)	101(35)	147(31)	185(30)	223(28)	294(26)	301(24)	398(21)	427(19)	456(17)
WRF-VAR	56(16)	84(16)	101(16)	147(16)	202(15)	290(14)	-	-	-	-

Table-3: 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	56(36)	70(35)	85(31)	112(30)	132(28	145(26)	178(24)	176(21)	181(19)	197(17)

Table-4: 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	43(36)	64(35)	74(31)	92(30)	118(28)	169(26)	201(24)	292(21)	390(19)	412(17)

9.4. Intensity forecast errors

- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 09, 20 and 24 knots against the LPA of 10, 14 and 14 knots respectively **(Fig. 17a).**
- The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 12, 23 and 28 knots against the LPA of 13, 19 and 19 knots respectively **(Fig. 17b).**
- The skill in intensity forecast based on AE for 24, 48 and 72 hrs lead period was 45, 53 and 67 % against the LPA of 43, 68 and 72 % respectively **(Fig. 18 a).**
- The skill in intensity forecast based on RMSE for 24, 48 and 72 hrs lead period was 43, 56 and 70 % against the LPA of 49, 59 and 69 % respectively **(Fig. 18 b).**
- For longer lead period beyond 72 hrs, the skill was comparable to long period average skill.

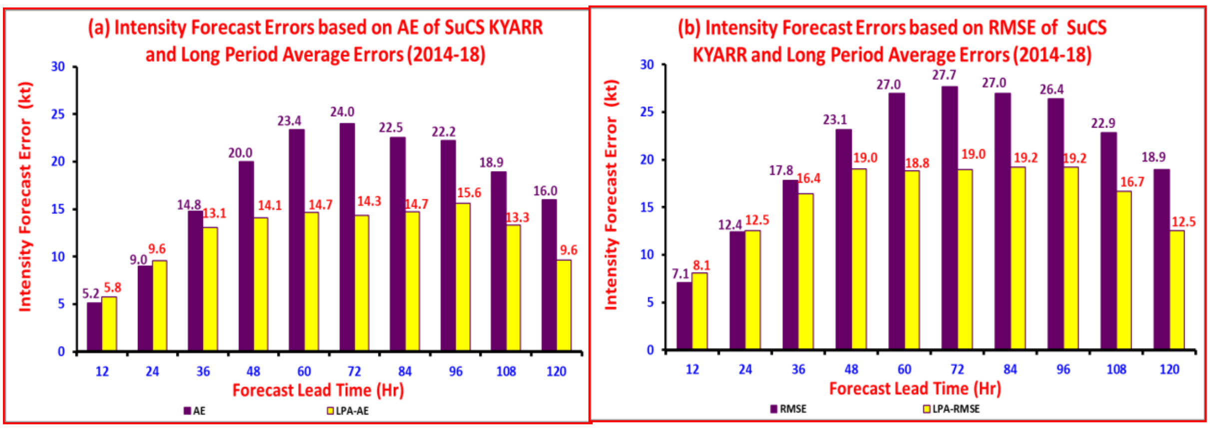

Fig. 17: (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) in intensity forecast (winds in knots) in association with SuCS 'KYARR' as compared to long period average (2014-18)

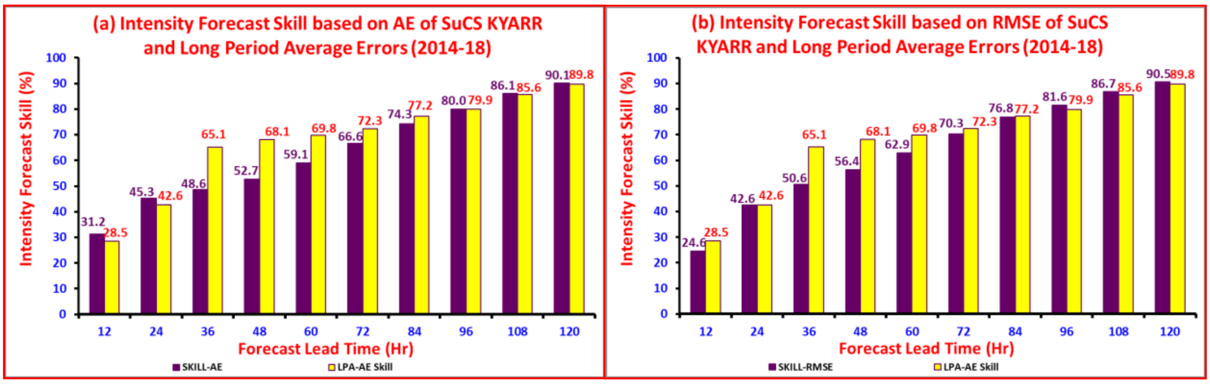

Fig. 18: Skill in intensity forecast (%) based on (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) in association with SuCS 'KYARR' as compared to long period average (2014-18)

Intensity prediction by models

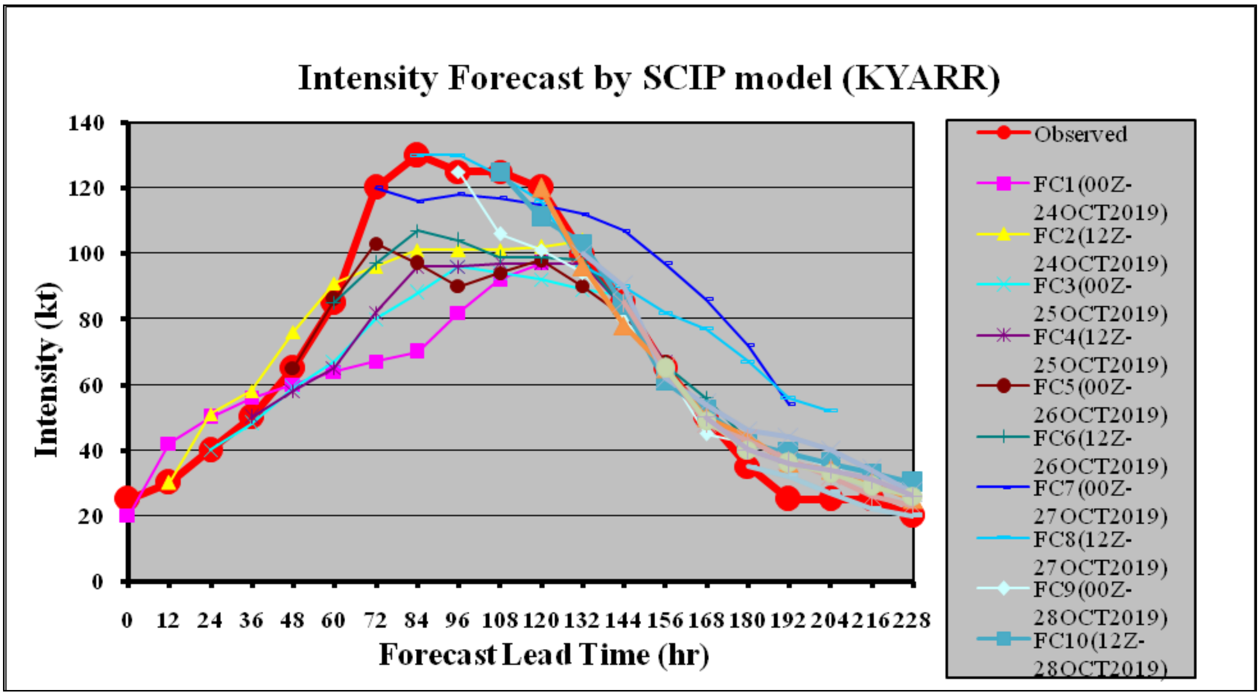

Fig. 19: Intensity prediction by SCIP Model

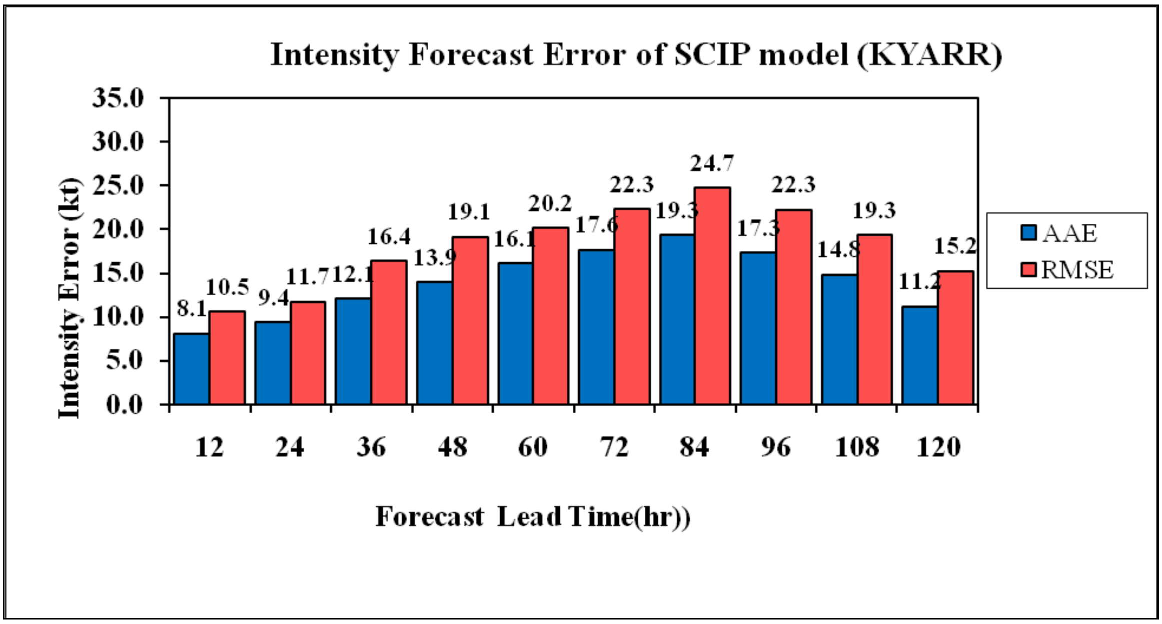

Fig. 20: SCIP Intensity Forecast Error (KYARR)

Table-6 Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of SCIP model (Number of forecasts verified is given in the parentheses)

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108 H	120H
IMD-SCIP (AAE)	7.8(16)	9.0(16)	11.3(16)	12.6(16)	15.5(15)	17.6(14)	19.3(13)	17.3(12)	14.8(11)	11.2(10)
HWRF (AAE)	7.1(36)	9.3(35)	13.7(31)	14.5(30)	17.5(28)	17.3(26)	11.6(24)	10.1(21)	10.5(19)	13.0(17)
IMD-SCIP (RMSE)	10.1	11.3	15.5	18.0	19.6	22.3	24.7	22.3	19.3	15.2
HWRF (RMSE)	9.2(36)	13.6(35)	15.9(31)	16.1(30)	18.5(28)	18.6(26)	13.2(24)	12.7(21)	12.6(19)	16.8(17)

10. Operational Forecast Performance

10.1. Genesis Forecast

- First information about possible cyclogenesis over east central Arabian Sea was given in in the extended range outlook issued on 17th October. In the extended range outlook issued on 24th October, when the system lay as a depression over east central Arabian Sea, the initial northeastwards movement and west-southwestwards re-curvature of system towards west-central Arabian Sea with high confidence (>75% probability) was predicted.
- First information about formation of an LPA over Lakshadweep area & neighbourhood during next 48 hours was issued at 0000 UTC of 17th. The LPA formed over southeast Arabian Sea & adjoining Lakshadweep area at 0300 UTC of 17th.

- At 1200 UTC of 20th, it was indicated that the system would intensify into a WML by 22nd October. It was also indicated that it would further intensify into Depression by 24th. It was also indicated that the system would initially move north northeastwards over east central Arabian Sea till 24th October and then recurve west northwestwards towards Oman Yemen coasts with gradual intensification. A WML formed in the afternoon (0900 UTC) of 22nd and Depression formed in the morning (0300 UTC) of 24th.

10.2 Track, Intensity and Landfall Forecast

- In the first bulletin issued at 1230 hrs IST (around 0700 UTC) of 24th October, it was indicated that the system would move initially east-northwestwards till 25th October evening and then recurve nearly westwards. Actually, system started re-curving westwards from early hours of 26th October (0130 hrs IST). It was also indicated that the system would intensify into a cyclonic storm during next 24 hours. Actually, the system intensified into cyclonic storm Kyarr in the early morning (0000 UTC) of 25th. Thus, the first re-curvature of the system could be correctly predicted correctly around 36 hours in advance and the intensification into cyclonic storm was also well predicted.
- In the subsequent bulletin issued at 0600 UTC of 26th October, it was predicted that the system would move west-northwestwards till 31st October & thereafter recurve southwestwards. It was also predicted that the system would intensify further into an ESCS by 27th October. Actually, the system intensified into an ESCS in the night of 26th October (1500 UTC) and re-curved southwestwards from 30th noon (0600 UTC).
- First information that the system would intensify into a super cyclonic storm was given in the bulletin issued at 0815 hrs IST (around 0300 UTC) of 27th October. It indicated that the system would intensify into a SuCS by noon (0600 UTC) of 27th. It was also indicated that the system would start weakening from 28th evening (1200 UTC). Actually system intensified into a SuCS in the early morning (0000 UTC) of 27th and maintained the intensity of SuCS till early morning of 29th.
- In the bulletin issued at 0530 hrs IST (0000 UTC) of 30th October, it was indicated that the system would reach close to Somalia as a WML in the evening of 3rd. Actually, the system weakened into a WML over west-central & adjoining southwest Arabian Sea off North Somalia coast in the midnight (1800 UTC) of 2nd.
- Typical observed and forecast track along with cone of uncertainty and wind distribution indicating accuracy in track prediction is presented in **Fig. 21**.

Thus the genesis and track of the system were well predicted by IMD. Since beginning, landfall was not predicted. However, with respect to intensity, operationally the weakening was predicted early. But the system maintained it’s intensity of SuCS/ESCS till early hours of 30th (0130 hrs IST of 30th October). Adverse weather like heavy rainfall and strong wind associated with the system were also well predicted by IMD. Since first bulletin, it was indicated that the system would not affect any of the Indian states and would move initially northeastwards and thereafter recurve west-northwestwards towards west-central AS. The southwestwards re-curvature was also well predicted. Since first bulletin, state of Sea and warnings for fishermen in deep Seas of south and central parts of Arabian Sea, Lakshadweep, Maldives & Comorin areas and along & off Konkan, Goa, Karnataka and Maharashtra coasts were issued both in textual and graphical form.

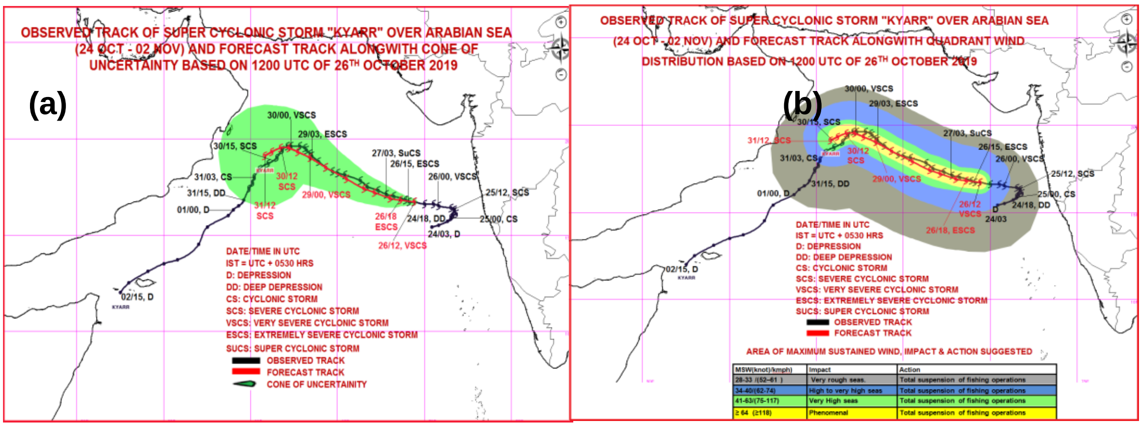

Fig.21: Observed and forecast track of SuCS 'KYARR' alongwith (a) cone of uncertainty and (b) wind distribution indicating accuracy in track and intensity predictions during life cycle of 'KYARR'

10.3 Adverse weather forecast verification

The verifications of adverse weather like heavy rainfall is given in Tabe-6. Since the system did not make any landfall, the verification gale wind and storm surge forecast is not included and since the beginning of the forecast, no landfall was expected and hence no storm surge warning was issued by IMD. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table 6: Verification of Heavy Rainfall Forecast

Date/Base Time of observation (0300 UTC)	**24 hr Heavy rainfall warning ending at 0300 UTC of next day**	**Realised 24-hour heavy rainfall ending at 0300 UTC of date**
23/10/2019	Light to moderate rainfall at most places with heavy to very heavy falls at a few places & extremely heavy falls at isolated places is very likely over coastal districts of Karnataka, Goa & south Konkan and isolated heavy rainfall over north Konkan during next 24 hours. Light to moderate rainfall at many places with heavy to very heavy falls at isolated places is very likely over coastal districts of Konkan & Goa during subsequent 24 hours and reduction in rainfall thereafter.	**24 October 2019** **Konkan:** Malvan and Vengurla -7 each Marathwada: Badnapur-7 **25 October 2019** **Konkan:** Malvan-8 and Dodamarg, Sawantwadi & Vengurla-7 each **Madhya Maharashtra:** Pathardi and Akole-
24/10/2019	-do-	
25/10/2019	Light to moderate rainfall at most places with	

	heavy to very heavy falls at isolated places is very likely over coastal districts of Karnataka, Goa & south Konkan and isolated heavy rainfall over north Konkan during next 24 hours.	8 each **Marathwada:** Manjlegaon & Manvat-9 each, Pathri & Ahmedpur-8 each and Georai-7. **26 October 2019** **Konkan:**Malvan-25,Devgad-18,Vengurla-14, Kudal-11and Dodamarg, Sawantwadi & Rajapur-7 each **Madhya Maharashtra:** Chandgad-7 Marathwada: Selu-10 and Parbhani, & Purna-7 each. **27 October 2019** **Konkan:** Sawantwadi-18 **28 October 2019** **Marathwada:** Bhokar, Nanded & Dharmabad-7 each
26/10/2019	Light to moderate rainfall at many places with heavy falls at isolated places very likely over Ratnagiri, Sindhudurg Districts of Maharashtra, Goa and Uttar Kannada & Uduppi districts of Karnataka during next 12 hours.	
27/10/2019	-do-	

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. 21(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. 21(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 Centre of IMD at Mumbai and Cyclone Warning Centres at Thiruvananthapuram, Goa and Ahmedabad to ports, fishermen, coastal and high Sea shipping community.
- **Fishermen Warning:** Regular warnings for fishermen were issued for deep Sea of south and central 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 hourly to all meteorological watch offices in Asia Pacific region for issue of significant meteorological information (SIGMET). It was also sent to Aviation Disaster Risk Reduction (ADRR) centre of WMO at Hong Kong.
- **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 are presented in Table 7.**

Table 7: Bulletins issued by RSMC New Delhi

S.N	Bulletin	No. of Bulletins	Issued to
1	National Bulletin	75	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	RSMC Bulletin	75	1. IMD's website 2. WMO/ESCAP member countries and WMO through GTS and E-mail including Somalia.
3	GMDSS Bulletins	35	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)	30	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	30	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)-2450 To general public to users registered with RSMC website from the states of Kerala, Karnataka, Goa, Gujarat and Maharashtra and National level disaster managers Through INCOIS on Ocean State Forecast-1,15,283
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	9 (once a day)	Disaster Managers, Media persons by email and uploaded on website
8.	Press Briefings	Frequently	Regular briefing daily

12. Summary

The Super Cyclonic Storm (SuCS) 'KYARR' originated from a Low Pressure Area (LPA) over southeast Arabian Sea (AS) and adjoining Lakshadweep in on 17th October. It concentrated into a depression over east-central Arabian Sea in the morning of 24th October, 2019. It intensified into CS 'KYARR' in the early morning of 25th October over the same region. It intensified into a Super Cyclonic Storm (SuCS) in the early morning of 27th October over east-central AS. The track forecast errors for 24, 48 and 72 hrs. lead period were 27, 65, and 100 km respectively against the average track forecast errors of 86, 132 and 178 km during last five years (2014-18) respectively. The track forecast skill was about 80%, 92%, and 86% against the long period average (LPA) of 58%, 70%, and 74% during 2014-18 for 24, 48 and 72 hrs. lead period respectively. The track forecast errors and skill were significantly better than long period average errors & skill, despite the fact that Kyarr exhibited multiple recurvatures. No major damage was reported from any of the coastal states of India and over Somalia and Socotra.

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 SuCS 'KYARR'. 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, Meteorological Centres Goa, Bengaluru, Office of Cyclone Detection Radar Kochi, Goa & Mumbai 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.