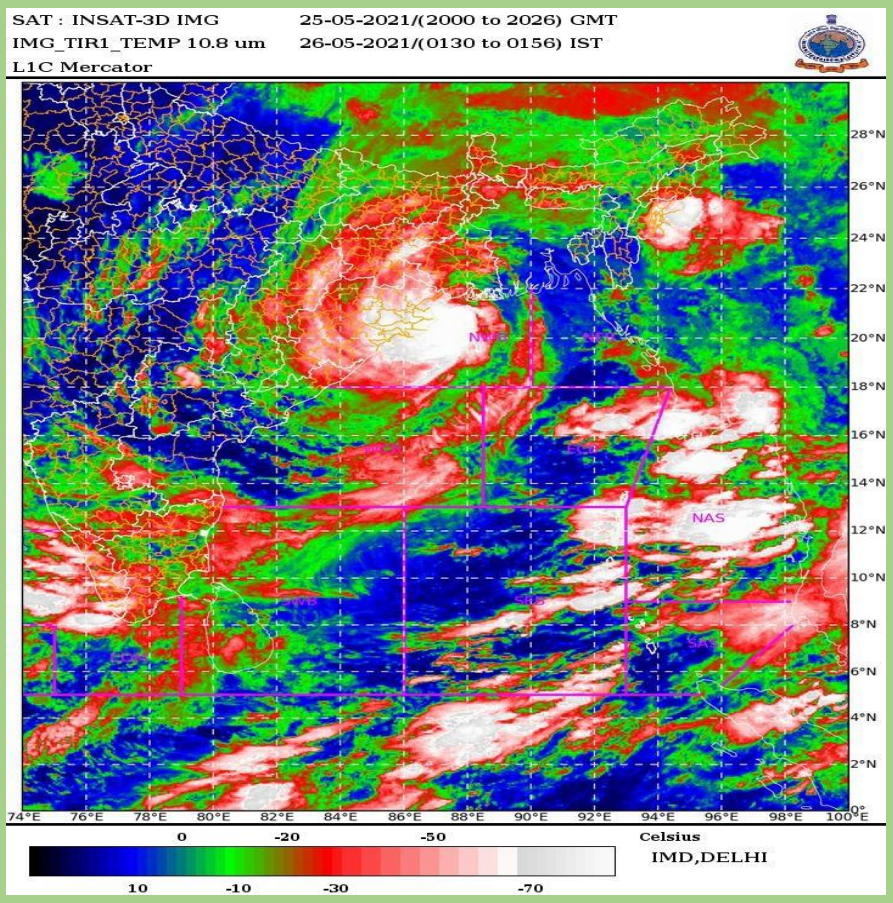
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Very Severe Cyclonic Storm, 'YAAS' over Bay of Bengal (23rd – 28th May, 2021): A Report



Observed track of VSCS YAAS during 23rd -28th May, 2021

Cyclone Warning Division

India Meteorological Department

New Delhi

June, 2021

Very Severe Cyclonic Storm "YAAS' over Bay of Bengal during 23rd May – 28th May, 2021

1. Introduction

- A low pressure area formed over eastcentral Bay of Bengal (BoB) in the morning (0830 IST/0300 UTC) of 22nd May. It lay as a well marked low pressure area (WML) in the same afternoon (1430 IST/0900 UTC) over eastcentral BoB.
- Under favourable environmental conditions, it concentrated into a depression over eastcentral BoB in the noon (1130 IST/0600 UTC) of 23rd May, 2021.
- It moved northwestwards and intensified into a deep depression (DD) over eastcentral BoB in the midnight (2330 IST/1800 UTC) of 23rd May and into the Cyclonic Storm(CS) "YAAS" in the early morning (0530 IST/0000 UTC) of 24th over the same region.
- It moved nearly north-northwestwards and intensified into a Severe Cyclonic Storm (SCS) in the midnight (2330 IST/1800 UTC) of 24th May over eastcentral BoB.
- It started moving northwards from the morning (0830 IST/0300 UTC) of 25th and intensified into a Very Severe Cyclonic Storm (VSCS) in the evening (1730 IST/1200 UTC) over northwest BoB.
- Thereafter, it moved north-northwestwards reached peak intensity of 75 knots(kt) and lay centred over northwest BoB about 30 km east of Dhamra Port, Odisha during early morning (0530 IST/0000 UTC) of 26th May.
- Continuing to move north-northwestwards, it crossed north Odisha coast near latitude 21.35°N and longitude 86.95°E, about 20 km to the south of Balasore as a VSCS with maximum sustained wind speed (MSW) of 75 kts gusting to 85 kts (130 -140 kmph gusting to 155 kmph) between 1030-1130 IST (0500-0600 UTC) of 26th.
- Further moving north-northwestwards, it weakened rapidly into a VSCS over north coastal Odisha in the afternoon (1430 IST/0900 UTC), into a VSCS over north Odisha in the evening (1730 IST/1200 UTC) and into a DD in the midnight (2330 IST/1800 UTC) of 26th over north interior Odisha and adjoining Jharkhand.
- It weakened into a depression over central parts of Jharkhand in the noon (1130 IST/0600 UTC) of 27th. Thereafter, it moved northwestwards and weakened into a well-marked low pressure area over Bihar and adjoining southeast Uttar Pradesh (UP) in the early morning (0530 IST/0000 UTC) of 28th May. It became a low pressure area over southeast UP and adjoining Bihar on 28th evening (1730 IST/1200 UTC) and became less marked on 29th morning (0530 IST/0000 UTC).

The observed track of the system is presented in Fig. 1. The best track parameters of the system are presented in Table 1.

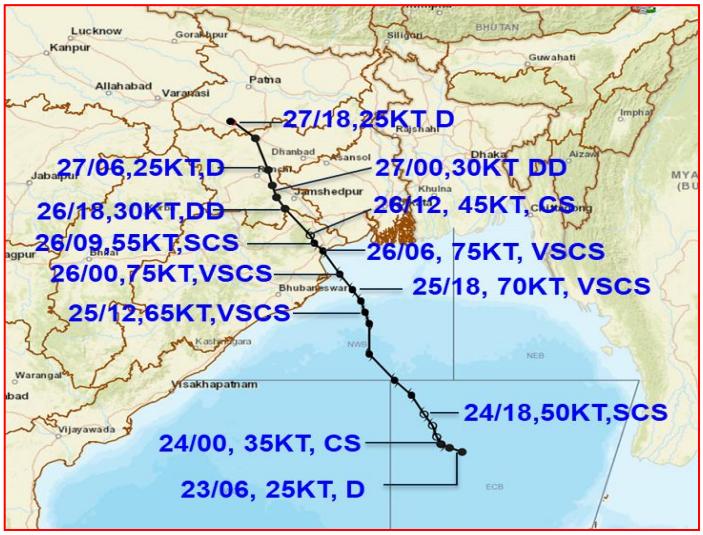


Fig.1: Observed track of VSCS, YAAS during 23rd-28th May, 2021

Table 1: Best track positions and other parameters of the Very Severe Cyclonic Storm, "YAAS" over the Bay of Bengal during 23 May- 28 May, 2021

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
23.05.21	0600	16.1	90.2	1.5	996	25	4	D
	1200	16.2	89.9	1.5	994	25	4	D
	1800	16.3	89.7	2.0	992	30	5	DD
24.05.21	0000	16.3	89.7	2.5	990	35	7	CS
	0300	16.5	89.6	2.5	988	40	8	CS
	0600	16.4	89.6	2.5	988	40	8	CS
	0900	16.8	89.5	2.5	988	40	8	CS
	1200	17.1	89.3	3.0	986	45	10	CS
	1500	17.4	89.2	3.0	986	45	10	CS
	1800	17.6	89.0	3.0	984	50	12	SCS
	2100	17.8	88.9	3.5	982	55	14	SCS
25.05.21	0000	18.0	88.6	3.5	980	55	16	SCS
	0300	18.3	88.3	3.5	980	55	16	SCS
	0600	18.7	88.0	3.5	978	60	18	SCS
	0900	19.1	88.1	3.5	978	60	18	SCS
	1200	19.5	88.0	4.0	976	65	20	VSCS
	1500	19.8	87.9	4.0	976	65	20	VSCS
	1800	20.1	87.8	4.0	974	70	24	VSCS
	2100	20.4	87.6	4.0	970	75	28	VSCS
26.05.21	0000	20.8	87.3	4.0	970	75	28	VSCS
	0300	21.2	87.1	4.0	970	75	28	VSCS
	Crossed north Odisha coast near Latitude 21.35°N and Longitude 86.95°E, about 20 km to the south of Balasore as a VSCS with maximum sustained wind speed of 75 knots gusting to 85 knots (130 -140 kmph gusting to 155 kmph) between 0500 & 0600 UTC							
	0600	21.4	86.9	-	970	75	28	VSCS
	0900	21.6	86.7	-	978	55	16	SCS
	1200	21.8	86.6	-	984	45	10	CS
	1500	22.2	86.2	-	986	40	8	CS
	1800	22.5	86.0	-	988	30	6	DD
27.05.21	0000	22.8	85.8	-	988	30	6	DD
	0300	23.1	85.7	-	990	30	6	DD
	0600	23.5	85.6	-	991	25	5	D
	1200	24.3	85.3	-	992	25	4	D
	1800	24.7	84.8		992	25	4	D
28.05.21	0000	Weakened into a well marked low pressure area over Bihar and adjoining east Uttar Pradesh						

2. Salient Features:

- It developed just after 4 days of the dissipation of extremely severe Very Severe Cyclonic Storm (ESCS) Tauktae over the Arabian Sea (14-19 May). Such back to back or simultaneous occurrence of cyclones over the BoB and Arabian Sea (AS) is not rare. Considering past 10 years statistics (2010-2020), similar back to back/simultaneous

occurrence of Very Severe Cyclonic Storms over BoB & AS has been observed in 2020 (Gati, AS-Nivar, BoB), 2019 (Maha, AS-Bulbul, BoB), 2018 (Luban, AS-Titli, BoB), 2018 (Sagar & Mekunu both AS), 2016 (Nada & Vardah both BoB), 2015 (Chapala & Megh both AS), 2013 (Helen, Lehar & Madi all BoB), 2010 (Laila, BoB- Bandu, AS).

- During satellite era (1965-2020), 3 VSCS and above intensity storms crossed Odisha coast (1 VSCS (May1989, 65 kt), 2 ESCS (May 1982, 90 kt & Fani, May 2019, 100 kt) in the month of May. YAAS was the 4th such storm (VSCS, 75 kt) crossing Odisha coast in the month of May during 1965-2021.
- It affected relatively less area as compared to Tauktae causing adverse weather over Andaman & Nicobar Islands, Odisha & West Bengal (till 26th May) and Jharkhand, Bihar and East UP after landfall.
- It had a straight north-northwestwards moving track (Fig. 1).
- The track length of the cyclone was 1100 km.
- It moved with 12 hour average translational speed of 10.9 kmph against LPA (1990-2013) of 13.7 kmph for VSCS category over BoB during pre-monsoon season (Fig.4a).
- The peak MSW of the cyclone was 130-140 kmph gusting to 155 kmph (75 kt gusting to 85 kt) during 0230 IST of 26th to 1130 IST of 26th over the northwest BoB. The lowest estimated central pressure was 970 hPa during the period with a pressure drop of 28 hPa at the centre compared to surroundings (Fig.4b).
- It had rapid weakening after landfall with intensity falling by 35 kt in just 9 hours. The system maintained the intensity of VSCS after landfall for 12 hours (0600 to 1800 UTC of 26th).
- The life period (D to D) of the system was 114 hours (4 days & 18 hours) against long period average (LPA) (1990-2013) of 134 hours (5 days & 14 hrs) for VSCS/ESVSCS categories over the BoB during pre-monsoon season. Thus, it had a comparatively lower life period.
- The Velocity Flux, Accumulated Cyclone Energy (a measure of damage potential) and Power Dissipation Index (a measure of loss) were 0.6 $X10^2$ kt, 3.6 X 10^4 kt^2 and 2.3 $X10^6$ kt^3 respectively.
- The track forecast errors for 24, 48 and 72 hrs lead period were 24.1, 53.1 and 81.6 km respectively against the LPA(2016-20) errors of 77, 117 and 159 km respectively
- The landfall point forecast errors for 12, 24, 48 and 60 hrs lead period were 7.8, 7.8, 7.8 and 38.9 km respectively against the LPA (2016-20) errors of 17, 32, 62 and 61 km during 2016-20 respectively. Thus there was almost zero landfall point forecast error 48 hrs in advance.
- The landfall time forecast errors for 12, 24, 48 and 60 hrs lead period were 1.0, 1.0, 2.5 and 3.5 hours respectively against the LPA errors (2016-20) of 1.3, 2.5, 5.0 and 5.3 hours during 2016-20 respectively. Thus there was almost zero landfall time forecast error 48 hrs in advance
- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 13.7, 12.9 and 14.1 knots against the LPA errors of 7.9, 11.4, and 14.1 knots during 2016-20 respectively
- Initially in its formative stage, it caused heavy to very heavy rainfall and Squally winds and tidal waves over Andaman & Nicobar Islands on 23rd & 24th May. It caused heavy to extremely heavy rainfall activity at isolated places over coastal Odisha on 25th May and heavy to very heavy rainfall at a few places and extremely heavy rains at isolated places on 26th May over north Odisha. It caused heavy to very heavy rainfall activity at isolated places over Gangetic West Bengal on 26th May and heavy to extremely heavy rainfall over Sub-Himalayan West Bengal on 27th. It also caused heavy to extremely heavy rainfall over Jharkhand on 26th and 27th, over Bihar and east UP on 27th and 28th May. As the system developed in the advance phase of monsoon, it had sufficient moisture and caused higher rainfall with heavy to extremely heavy rainfall activity over north Odisha, Jharkhand, West Bengal, Bihar and east UP.

- Gale wind speed reaching 130-140 kmph gusting to 155 kmph prevailed along and off Balasore, Bhadrak districts of north coastal Odisha and 100-120 gusting to 130 kmph prevailed along and off coastal districts of West Bengal (Purba Medinipur and south 24 Parganas district) and Kendrapara and Jagatsinghpur districts of North coastal Odisha during the time of landfall.
- Storm surge of about 2-4 meters height above astronomical tide inundated low lying areas of north coastal Odisha (Balasore and Bhadrak districts) and coastal West Bengal (South 24 Parganas, North 24 Parganas, Purba Medinipur districts) and 1-2 meters height above astronomical tide inundated low lying areas of Kendrapara and Jagatsinghpur districts of north coastal Odisha during the time of landfall.
- As the cyclone crossed the coast on the full moon day, there was combined impact of astronomical tide and storm surge leading to higher tidal wave. The astronomical tidal wave over Bhadrak, Balasore, Purba Medinipur and 24 Pargana districts on this day ranged from 3 to 5 meters. In addition the extremely heavy rainfall over north coastal Odisha districts helped in enhanced inundation of coastal areas.
- A total of 34 national bulletins, 32 RSMC bulletins to WMO/ESCAP Panel member countries, 9 Press Releases, 15 hourly bulletins on the day of landfall, 18 bulletins for International Civil Aviation, 69 lakhs SMS to fishermen, farmers & coastal population, very frequent updates on social networking sites were sent to trigger mass response and to sensitise masses about the impending disaster in association with the system. DGM IMD participated in National Crisis Management Committee Meetings under the chairmanship of Cabinet Secretary, and review meetings under the chairmanship of Hon'ble Prime Minister, Hon'ble Home Minister and Hon'ble Minister for Commerce and Industry and presented updated status about the system regularly.

3. Brief life history

3.1. Genesis

Under the influence of a cyclonic circulation over Andaman Sea and adjoining eastcentral BoB, a low pressure area formed over eastcentral BoB at 0300 UTC of 22nd May. At 0300 UTC of 22nd May, the Madden Julian Index (MJO) index lay in phase 5 with amplitude more than 1 and was forecast to continue in same phase till 24th May. Thus, MJO was conducive for enhanced convection over the BoB during next 3 days. The tropical cyclone heat potential (TCHP) was more than 100 KJ/cm^2 over major parts of BoB. It was slightly decreasing over extreme north BoB and along & off Andhra Pradesh, Odisha, West Bengal coasts. Sea surface temperature (SST) was around 30-31^{0}C over major parts of BoB. Easterly winds were prevailing in the upper level. Upper tropospheric ridge ran along 22.0^{0}N. An east-west oriented positive vorticity zone 70-80 x10^{-6} s^{-1} prevailed to the south of system centre over central BoB with vertical extension upto 200 hpa level. An east-west oriented positive zone of convergence zone (5-10 x 10^{-5} s^{-1}) lay to the south of system centre over central BoB. An east-west oriented zone of positive upper level divergence (10-20 x 10^{-5} s^{-1}) lay over central BoB. Low to moderate vertical wind shear (VWS) of 10-15 kts was prevailing over central & north BoB to the north of 12°N which was highly favourable for intensification of system. Also due to advance of southwest monsoon over Andaman Sea and southeast BoB, strong westerlies prevailed over the region. Under these favourable conditions, a low pressure area formed over eastcentral BoB on 22nd May. Similar conditions continued and the system lay as a WML at 0900 UTC of same day over the same region.

At 0600 UTC of 23rd May, it concentrated into a depression over eastcentral BOB. Similar sea and MJO conditions prevailed. Upper tropospheric ridge ran along 22.0^{0}N. A northeast-southwest oriented positive vorticity zone of 100-120 X10^{-6} s^{-1} prevailed to the south of system centre over central BoB with vertical extension upto 200 hPa level. Low level vorticity increased during previous 24 hours. An east-west oriented positive convergence

zone also increased and was 30-40 X 10^{-5} S^{-1} & lay to the south of system centre. An east-west oriented zone of positive upper-level divergence (30-40 X 10^{-5} S^{-1}) also increased and lay over central BOB. Moderate VWS (10-20 KTS) prevailed over central & north BoB to the north of 15°N and was decreasing becoming low (5-10 kts) over north BoB. The sea conditions and existing environmental features like enhanced low level vorticity, lower-level convergence, equatorward & poleward outflow, moderate VWS led to intensification of the the WML into a depression over eastcentral BoB at 0600 UTC of 23rd May.

3.2 Intensification and movement

At 1800 UTC of 23rd May, similar MJO conditions prevailed. The TCHP was more than 100 KJ/cm^2 over major parts of BoB. It was slightly decreasing over extreme north BoB and along & off Andhra, Odisha, West Bengal coasts. The SST was around 30-31^{0}C over major parts of BOB. Upper tropospheric ridge ran along 22.5^0 N. A northeast-southwest oriented lower-level positive vorticity zone 150x10^{-5} s^{-1} lay around system centre with vertical extension upto 200 hPa level. A northwest-southeast oriented lower level positive convergence zone (40-50x10^{-5} s^{-1}) lay to the southwest of system centre and east-west oriented zone of positive upper level divergence (30-40x10-^{5} s^{-1}) lay over entire central BoB. Moderate VWS (10-20 kts) prevailed over central & north BoB to the north of 15°N and was decreasing becoming low (5-10 kts) over north BoB off north Odisha & west Bengal coasts. Under favourable sea and environmental conditions like enhanced low level vorticity, lower-level convergence, equatorward & poleward outflow, moderate vertical wind shear, the system intensified into a deep depression at 1800 UTC of 23rd May.

At 0000 UTC of 24th May, similar sea conditions prevailed over the central and north BoB. The environmental conditions further consolidated. The northeast-southwest oriented positive vorticity zone became more circular and increased to 200-250 x10^{-6} s^{-1} around system centre with vertical extension upto 200 hPa level. The positive convergence zone became east-west oriented and increased to 50 x 10^{-5} s^{-1}) & lay to the southwest of system centre. The east-west oriented zone of positive upper level divergence remained the same (30-40 x10^{-5} s^{-1}) and lay over westcentral BoB. Low VWS (05-10 kts) prevailed over the system area and to the northeast of it. It was high to the west of the system centre and also over northwest BoB along and off N Odisha & West Bengal coasts. The sea conditions and existing environmental features like enhanced low level vorticity, lower-level convergence, strong poleward outflow, low to moderate VWS led to the further intensification of the system into the CS “Yaas” over eastcentral BoB.

At 1800 UTC of 24th, similar sea conditions continued. The upper tropospheric ridge ran along 21.5^{0}N. Positive low level vorticity was 250 x10^{-6} s^{-1} around system centre with vertical extension upto 200 hPa level. Low level convergence increased and was about 60 x 10^{-5} s^{-1} to the southwest of system centre. The positive upper level divergence was 20x10^{-5} s^{-1} and lay to the southwest of system centre. Moderate VWS (20-25 kts) prevailed over the system centre. Under these conditions, the system moved north-northwestwards and intensified into an SCS over eastcentral BoB at 1800 UTC of 24th.

At 1200 UTC of 25th May 1200 UTC, the TCHP was about 150 KJ/cm^2 over major parts of BOB. It was slightly decreasing over extreme north BOB and along & off Andhra, Odisha, west Bengal coasts. SST was around 30-31^{0}C over major parts of BOB. Positive low level vorticity increased and was around 300 x10^{-6} s^{-1} to the south of system centre with vertical extension upto 200 HPA level. Low level convergence was about 30 x 10^{-5} s^{-1} to the southwest of system centre. The positive upper-level divergence was 20x 10^{-5} s^{-1} to the southwest of system centre. Strong poleward and equatorward outflow was seen in the upper level. Moderate to high VWS (20-25 kts) was prevailing over the system centre. However, high SST, high TCHP and strong equatorward & poleward outflow led to further intensification of the system. The upper tropospheric ridge ran along 24.0^{0}N to the northeast of system centre. Moving north-northwestwards along the western periphery of the sub-tropical ridge to the northeast of system centre, the system intensified into a VSCS over northwest BoB.

Thereafter, the system underwent gradual intensification and reached peak intensity of 75 knots at 2100 UTC of 25th May. At 0300 UTC of 26th May, gale winds exceeding 50 knots commenced along & off north Odisha & adjoining West Bengal coasts. The TCHP over northwest BoB along & off north Odisha-West Bengal coasts was about 90-110 KJ/$cm^{2.}$. SST

was around 30-31^{0}C over northwest BoB. Positive low-level vorticity was about 250x10^{-6} s^{-1} over the system centre with vertical extension upto 200 hPa level. Low level convergence was about 20 x 10^{-5} s^{-1} to the southwest of system centre. The positive upper level divergence was 30x 10^{-5} s^{-1} to the west of system centre. Moderate to high VWS (20-25 kts) was prevailing over the system centre. The system was moving north-northwestwards along the western periphery of the sub-tropical ridge to the northeast of system centre. Under these conditions, the system moved north-northwestwards and crossed north Odisha coast near latitude 21.35°N and longitude 86.95°E, about 20 km to the south of Balasore as a VSCS with maximum sustained wind speed of 75 knots gusting to 85 knots (130 -140 kmph gusting to 155 kmph) between 0500 & 0600 UTC of 26th May.

Thereafter, the system continued to move north-northwestwards and weakened rapidly into an SCS over north coastal Odisha at 0900 UTC, into a CS over north Odisha at 1200 UTC and into a DD over north interior Odisha and adjoining Jharkhand at 1800 UTC of 26th. It further weakened into a depression over central parts of Jharkhand at 0600 UTC of 27th. Thereafter, it moved northwestwards and weakened into a well-marked low pressure area over Bihar and adjoining southeast Uttar Pradesh (UP) at 0000 UTC of 28th May, into a low pressure area over southeast UP and adjoining Bihar at 1200 UTC of 28th evening and became less marked at 0000 UTC of 29th May.

Typical TPW imageries during 23rd-26th May, 2021 are presented in Fig.2. These imageries indicate continuous warm and moist air advection from the southeast sector into the system, till 0900 UTC of 26th May. However, as the system approached coast, there was land interaction and moisture supply also reduced significantly from 1200 UTC of 26th May. The mean VWS and mean wind speed in deep and middle layer during life cycle of VSCS Yaas are presented in Fig. 3.

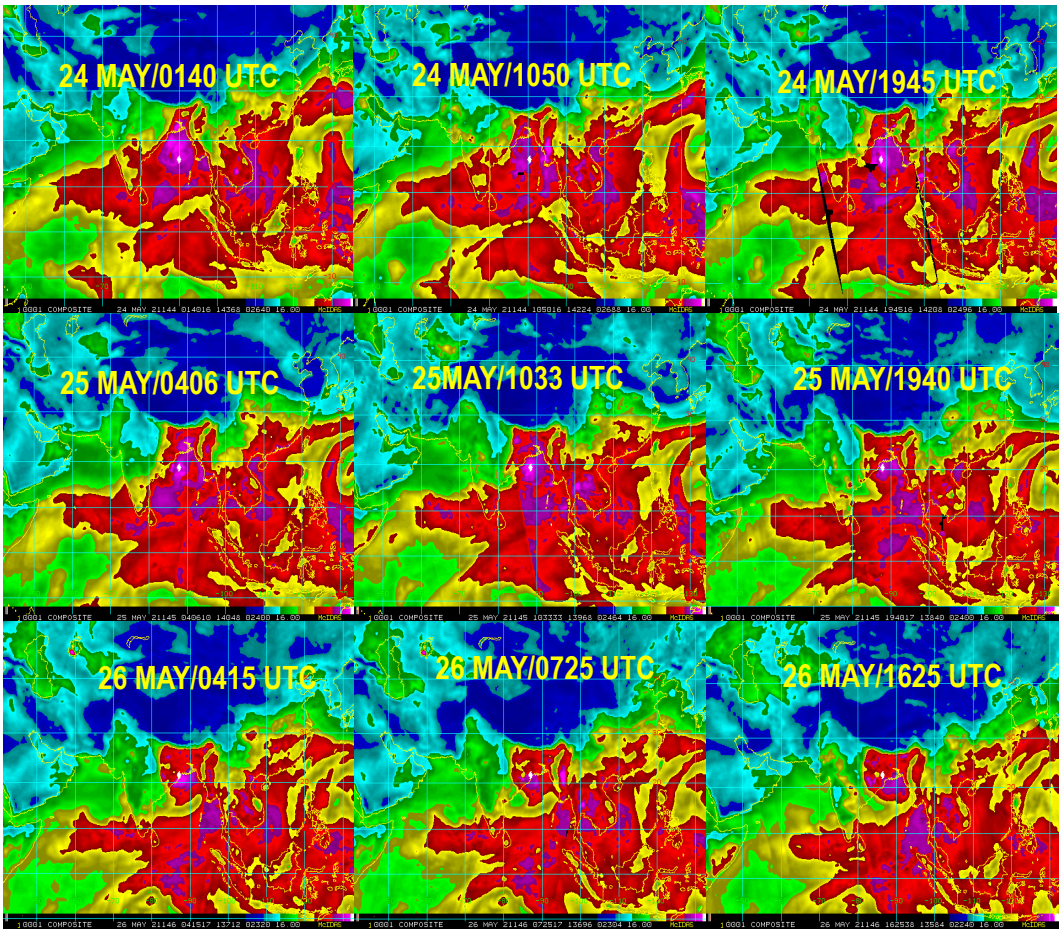


Fig. 2: Total Perceptible Water (TPW) imageries during 24th -26th May, 2021

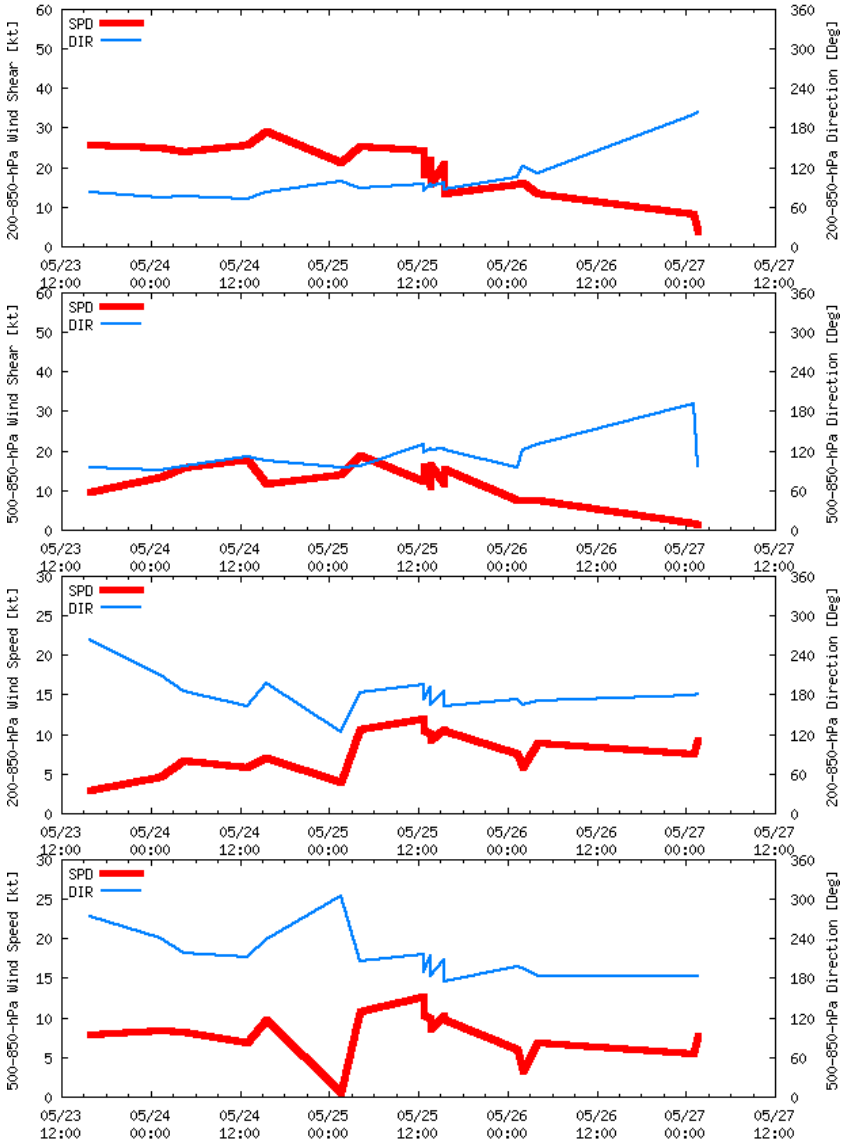


Fig.3: Mean wind shear and speed in the deep (200-850 hPa) and middle (500-850 hPa) layers during life cycle of VSCS YAAS

3.3 Maximum Sustained Surface Wind speed and estimated central pressure

The six hourly maximum sustained wind speed & estimated central pressure and translational speed are presented in Fig. 4(a) and 4(b). YAAS had a straight track and it moved relatively slower than long period average during 1990-2013 (Fig. 4a). After landfall, it moved relatively faster leading to rapid weakening of the system during 0600 to 1800 UTC of 26th May.

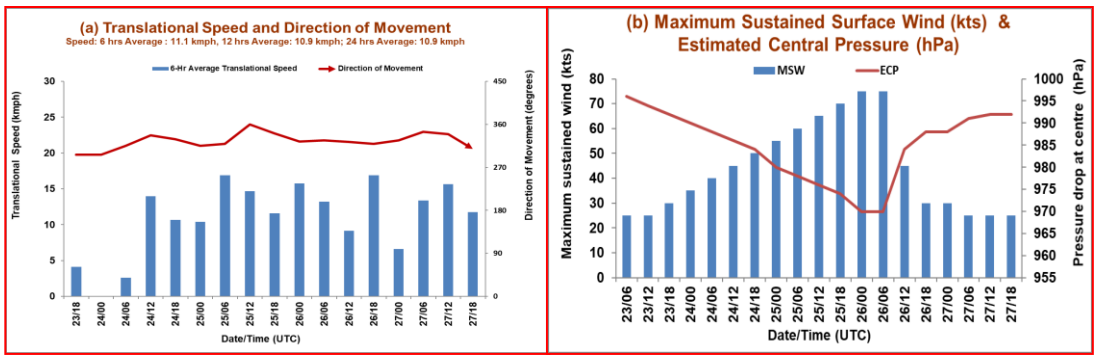


Fig. 4: (a) Translational speed & direction of movement and (b) Maximum sustained surface winds (kts) & Estimated Central Pressure

4. Monitoring of "YAAS":

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the cyclone was monitored since 13th May, about 9 days prior to the formation of low pressure area over eastcentral BoB on 22nd May and 10 days prior to formation of depression over eastcentral BoB on 23rd May. The cyclone was monitored with the help of available satellite observations from INSAT 3D and 3DR, SCAT SAT, polar orbiting satellites and available ships & buoy observations in the region. The system was also monitored by Doppler Weather Radar (DWR), Paradip. Various numerical weather prediction models run by Ministry of Earth Sciences (MoES) institutions, global models 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 products generation. Typical satellite and radar imageries during VSCS YAAS are presented in Fig. 5. Detailed features are discussed in Section 4.1 and satellite imageries during entire life cycle of Yaas are presented in Fig. 6.

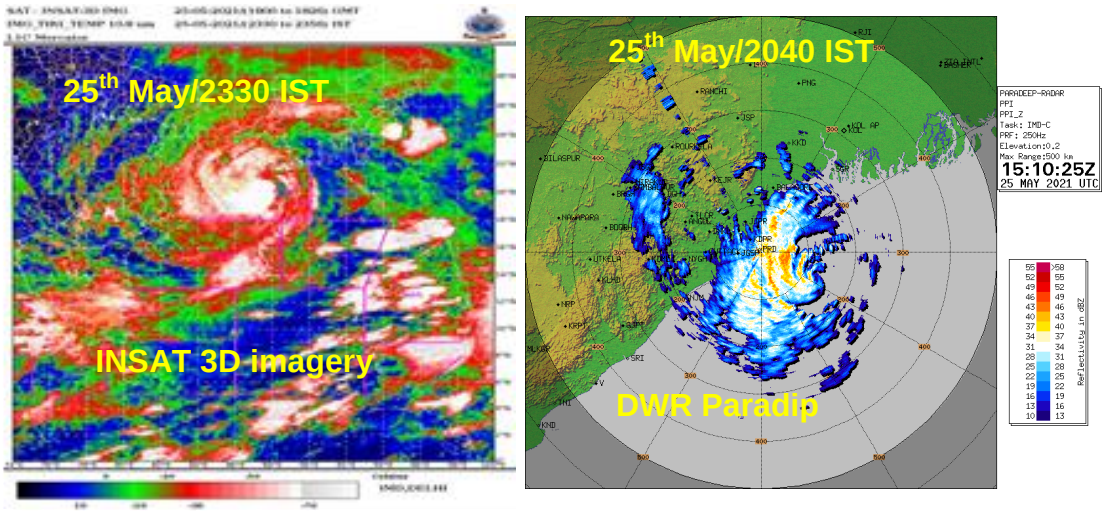


Fig.5: Typical INSAT 3D satellite and radar imagery from Doppler Weather Radar Paradip

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 & MTSAT 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.5. The system showed curved band pattern during genesis and growth stage upto the intensity of VSCS. It has central dense overcast (CDO) pattern during VSCS stage. It showed sheared pattern after landfall.

At 0600 UTC of 23rd May, the clouds associated with the system were organized in curved band pattern. Intensity of the system was characterised as T 1.5. Broken low and medium clouds with embedded intense to very intense convection

lay over eastcentral BoB, Andaman Sea and neighbourhood. Minimum cloud top temperature (CTT) was -93°C.

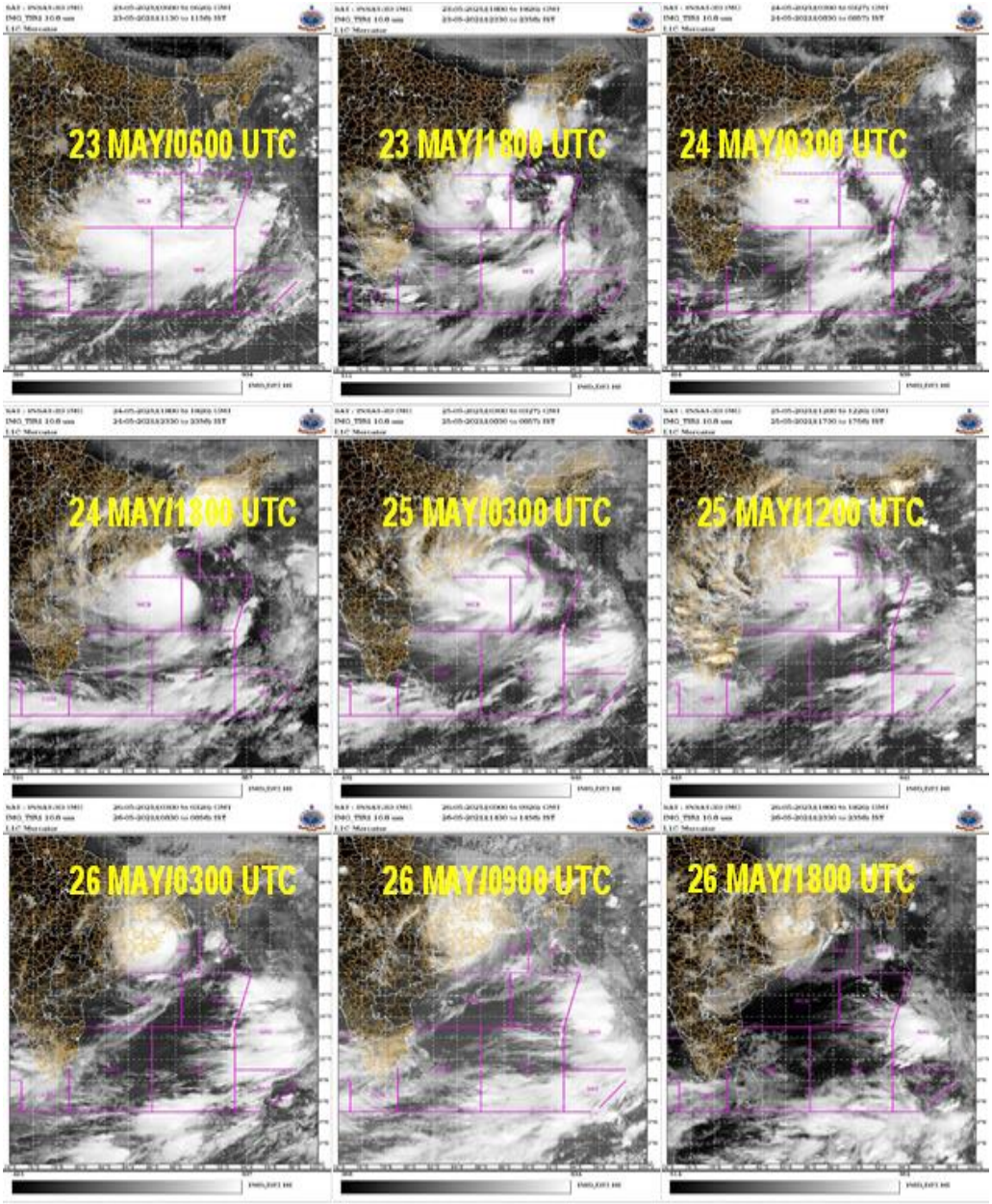


Fig.6(a): INSAT-3D IR imageries during life cycle of VSCS YAAS (23-27 May, 2021)

At 1800 UTC of 23rd May the depression intensified into a Deep Depression. As per satellite imagery based on 1800 UTC of 23rd May, the cloud mass was organised in shear pattern. Intensity of the system was characterised as T 2.0. Broken low and medium clouds with embedded intense to very intense convection lay over the area between latitude 7.0°N & 20.0°N and 82.0°E & 93.0°E and Andaman Islands. Minimum cloud top temperature is -93°celcius.

At 0000 UTC of 24th May the system intensified into a CS. As per satellite imagery based on 0000 UTC of, the 24th May, the vortex further intensified with a curved band pattern with wrap of 0.5 on log 10-degree spiral yielding a T=2.5. Broken low and medium clouds with embedded intense to very intense convection lay over the area between latitude 11°N & 20°N and 82°E & 94.0°E. Minimum cloud top temperature was -93°celcius

At 1800 UTC of 24th May the it intensified into an SCS. As per satellite imagery based on 1800 UTC of, the 24th May, the clouds were organised in curved band pattern with T 3.0. Broken low and medium clouds with embedded intense to very intense convection lay over the area between latitude 14.0°N & 21°N and 84.0°E & 90.0E. Minimum cloud top temperature was -93°C.

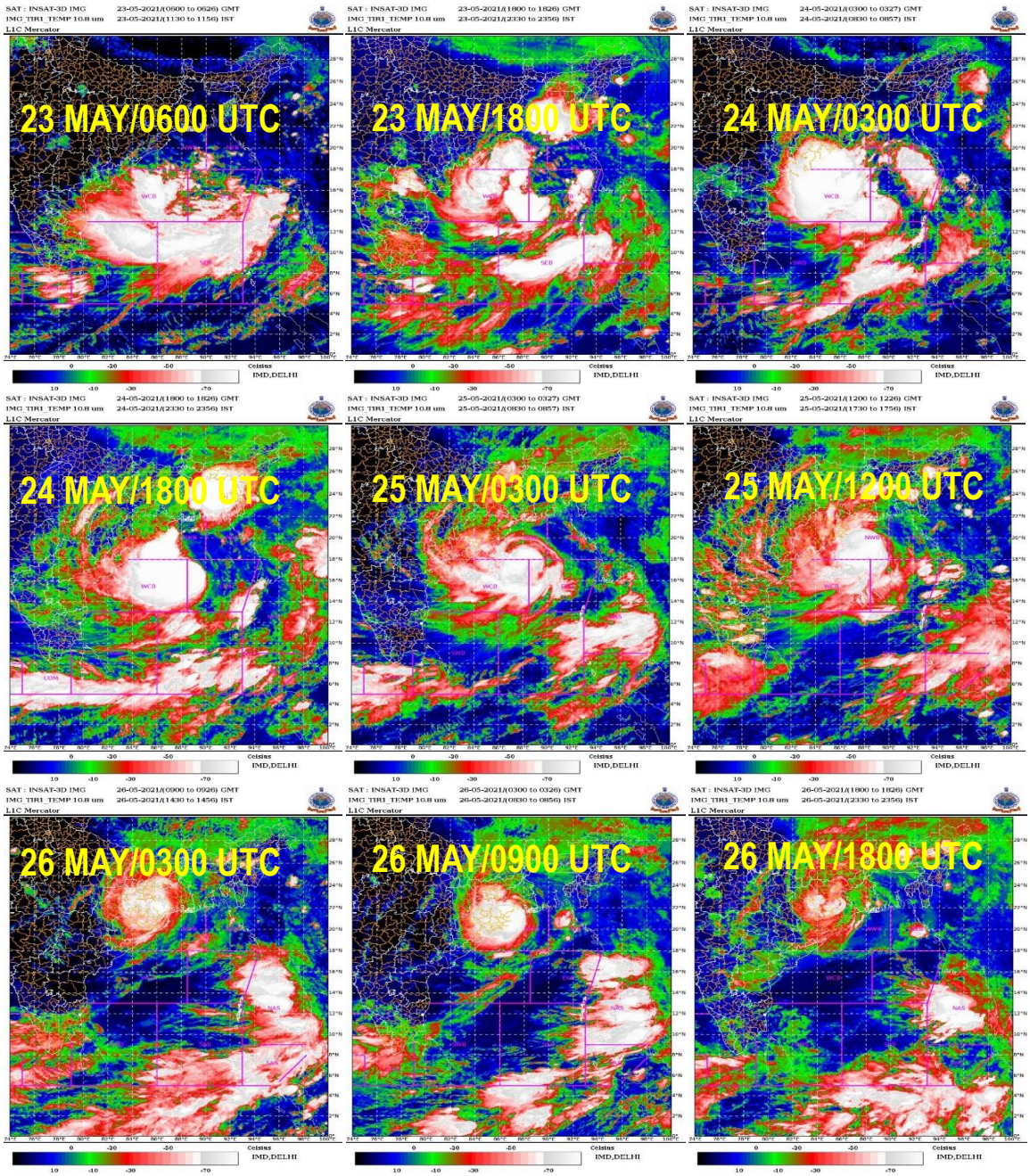


Fig. 6(b): INSAT-3D enhanced color imageries during life cycle of VSCS YAAS (23-27 May, 2021)

At 1200 UTC of 25th May it further intensified into VSCS. As per satellite imagery based on 1200 UTC of the 25th May, the central dense overcast (CDO) pattern became regular and compact. Outer spiral bands were entering into coastal Odisha leading to rainfall over the area. The intensity of the system was characterised as T 4.0. Broken low and medium clouds with embedded intense to very intense convection lay over the BoB between latitude 14.0°N & 20.0°N and 84.0°E & 91.0E Minimum cloud top temperature is -93°C.

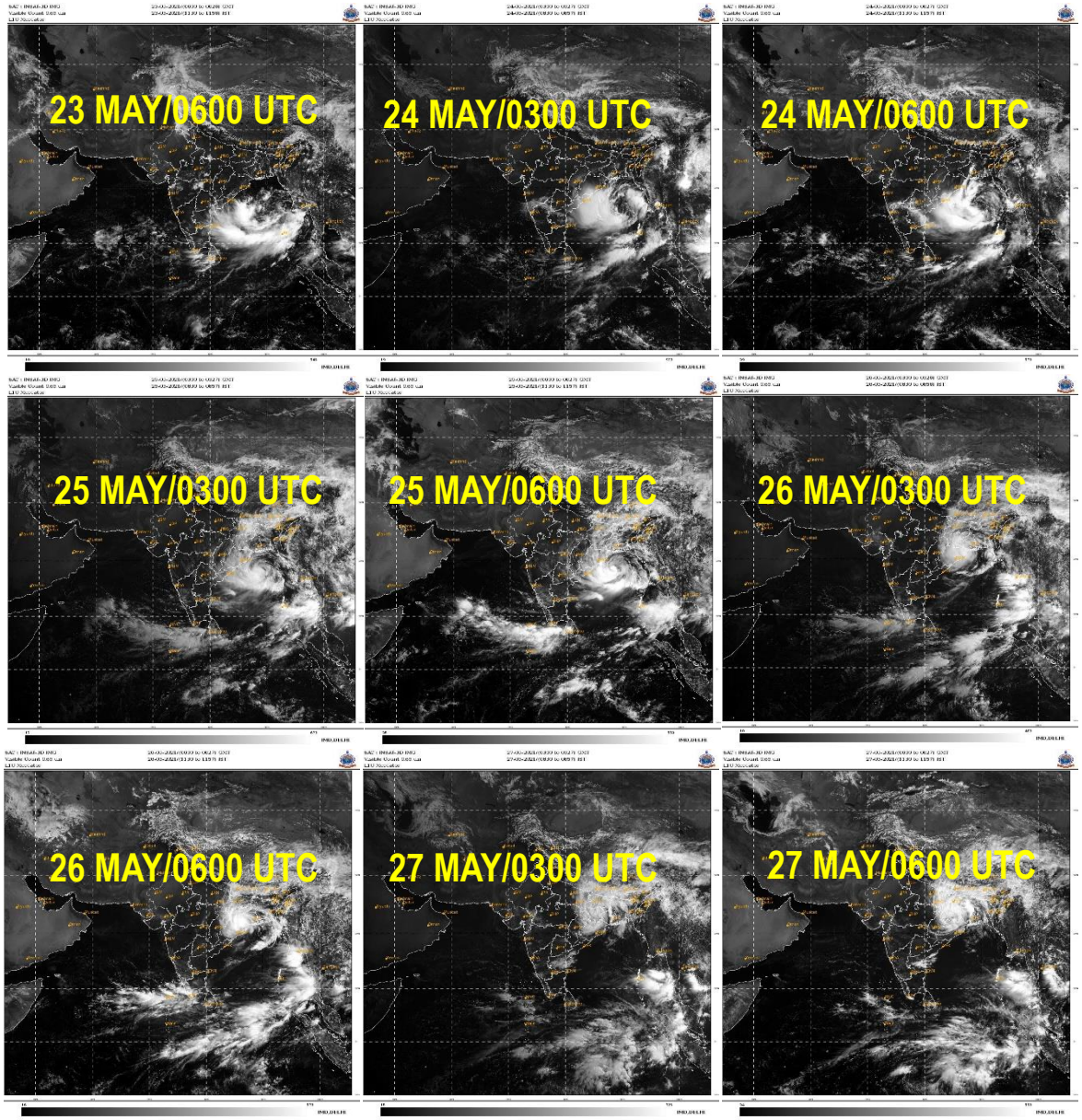


Fig. 6(c): INSAT-3D Visible imageries during life cycle of VSCS YAAS (23-27 May, 2021)

At 0300 UTC 26th May prior to landfall as per satellite imagery, the regular and compact outer spiral bands were entering coastal Odisha and west Bengal leading to rainfall over the area. The intensity of the system was characterised as T 4.0 with CDO pattern. Broken low and medium clouds with embedded intense to very intense convection lay over the northwest and between latitude 18.5^{o}N to 22.0^{o}N and long 85.0^{o}E to 88.5^{o}E. Minimum cloud top temperature was -93°C.

At 0900 UTC of 26th May the system weakened into an SCS and intense convective cloud mass was disorganizing and lay over north Odisha, Jharkhand and Chhattisgarh. At 1200 UTC of 26th May it further weakened and intense convective cloud mass lay over north Odisha, Jharkhand and adjoining south Bihar and Moderate to intense convection lies over south Odisha, north Chhattisgarh, north Bihar and Gangetic west Bengal. At 1800 UTC of 26th May the Very Severe Cyclonic Storm further became Deep Depression and intense convective cloud mass lay over southeast Jharkhand & north Odisha, Jharkhand and adjoining southeast Bihar and Moderate to intense convection lay over south Odisha, Chhattisgarh, north Bihar and Gangetic west Bengal.

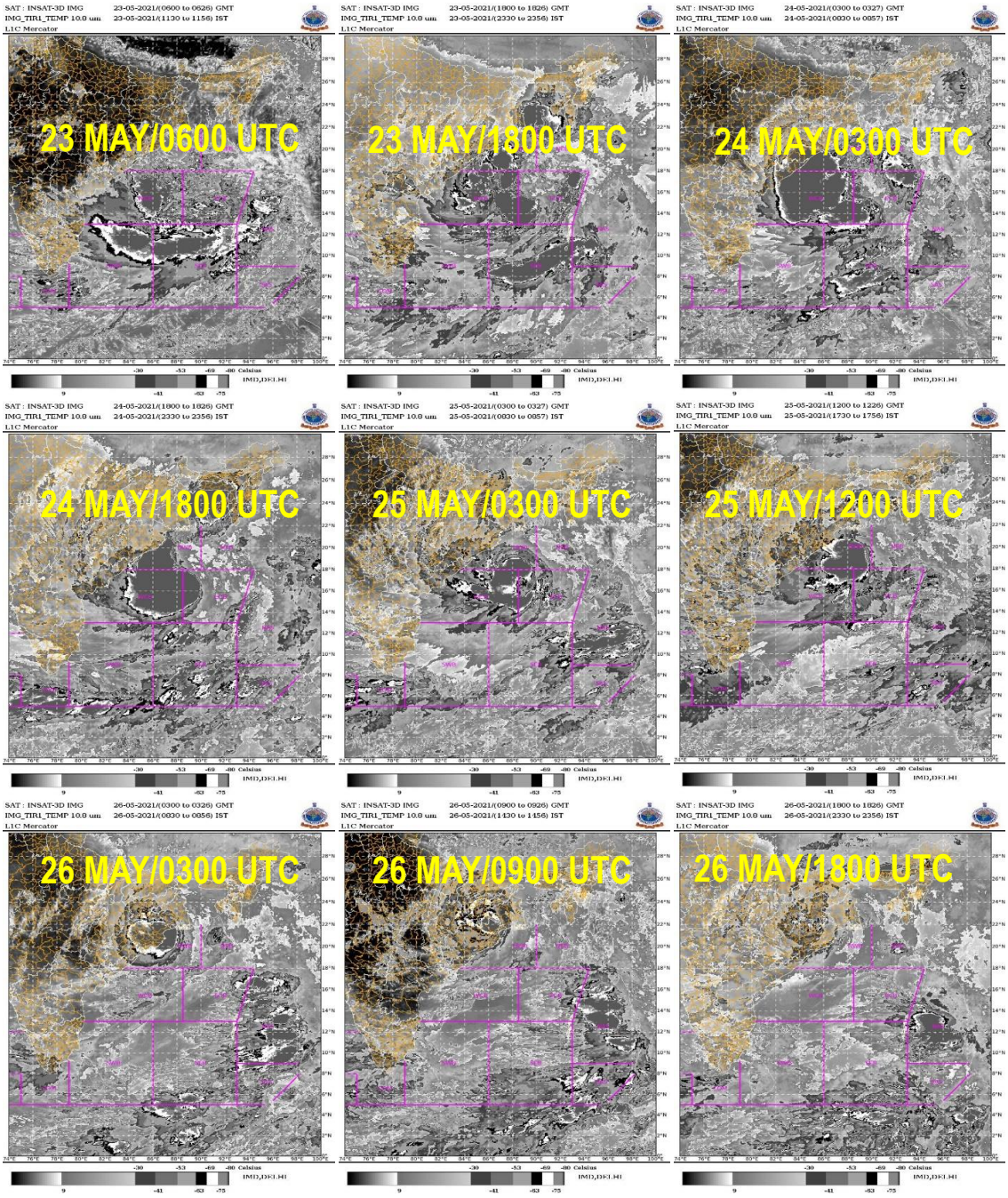


Fig. 6(d): INSAT-3D BD imageries during life cycle of VSCS YAAS (23-27 May, 2021)

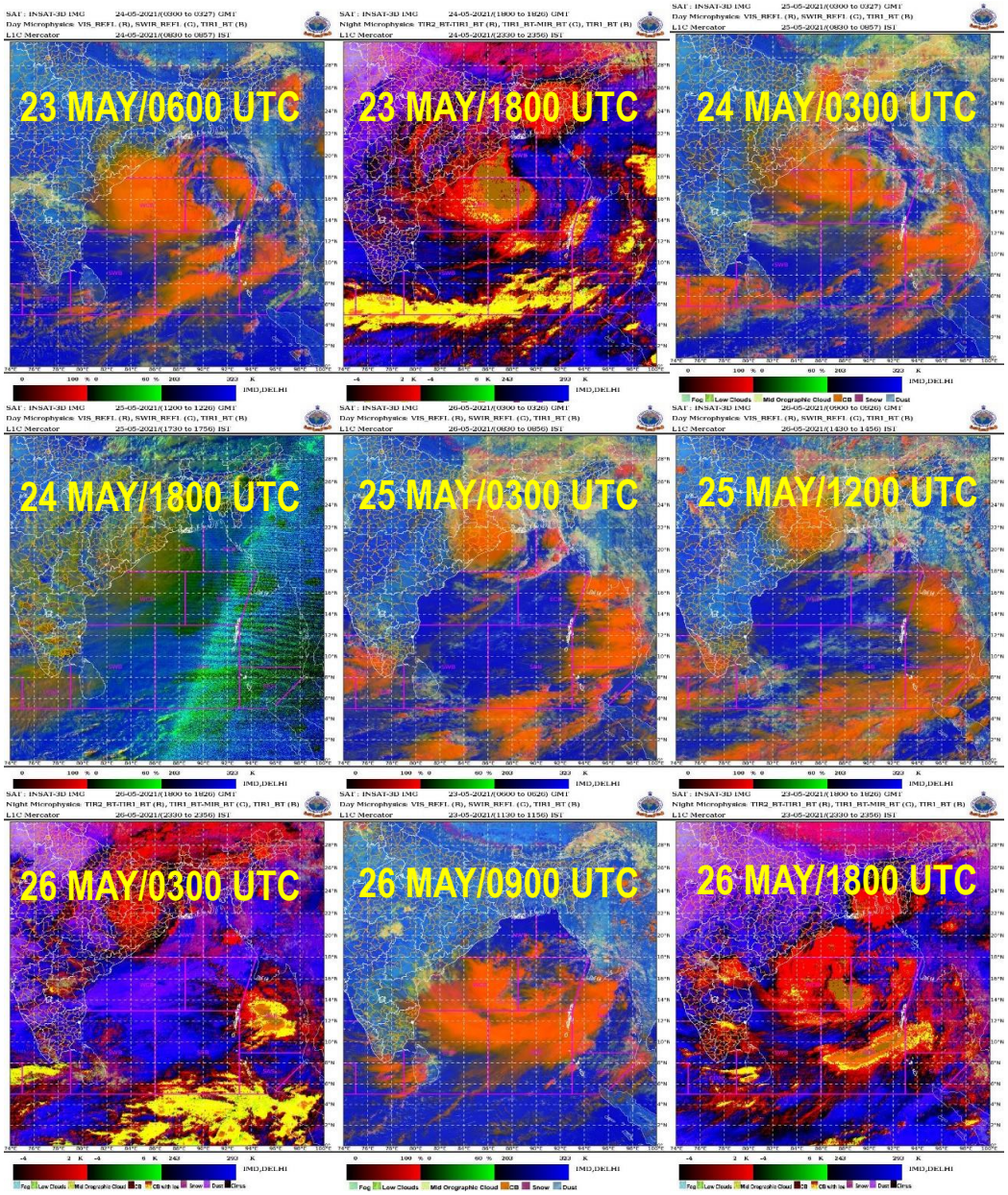


Fig. 6(e): INSAT-3D Microwave imageries during life cycle of VSCS YAAS (23-27 May, 2021)

Typical ASCAT imageries during 23rd to 26th May depicting the location and winds around the centre are presented in Fig. 6(f). It showed stronger winds in association with monsoon surge in the onset phase over the BoB during genesis stage over the area to the south of system centre.

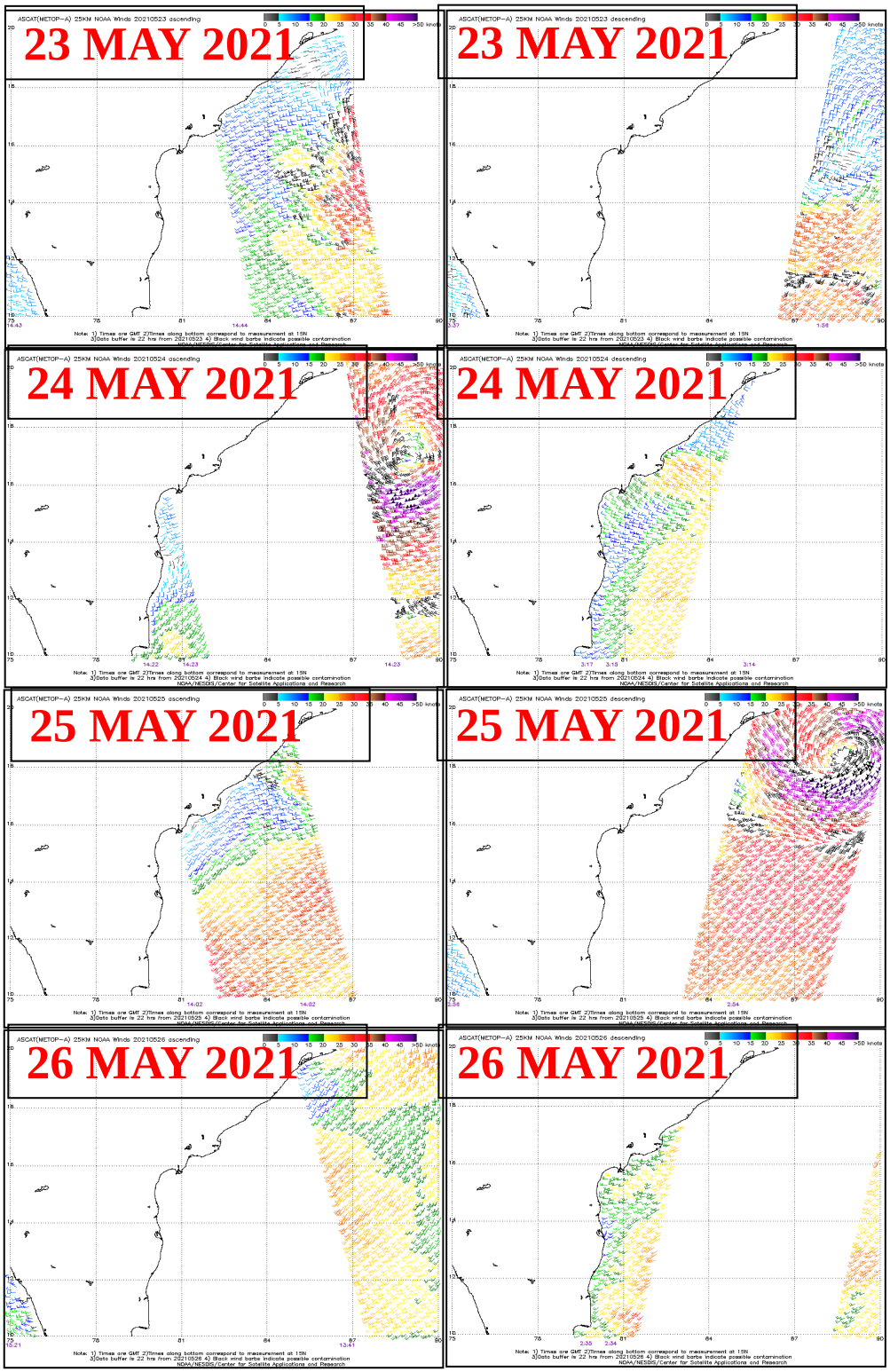


Fig. 6(f): ASCAT imageries during life cycle of VSCS YAAS (23th -27th May), since inception as low pressure area are presented in Fig.

The system was captured by Doppler Weather Radar (DWR) Paradeep on 25th. Typical imageries from DWR Paradeep depicting development of eye and curved bands around the system centre are presented in Fig. 6(g).

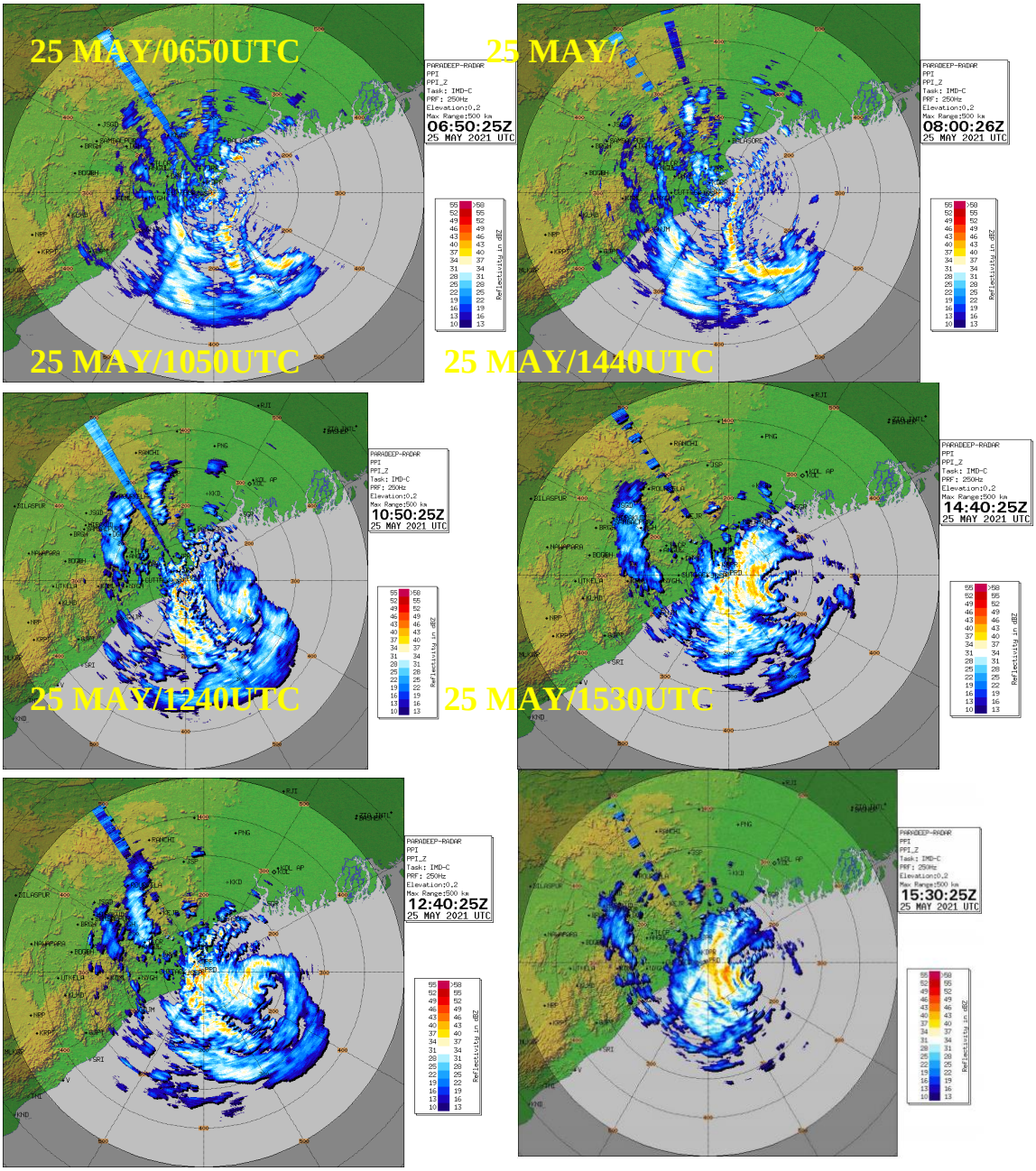


Fig. 6(g): RADAR imageries during life cycle of VSCS YAAS (23th -27th May), from DWR PARADEEP

6. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 22nd-27th May are presented in Fig.7. The analysis of IMD-GFS based on 0000 UTC of 22nd May, 2021 indicated a trough of low over central parts of BoB. However, at 0300 UTC of 22nd, the system lay as a WML over eastcentral BoB.

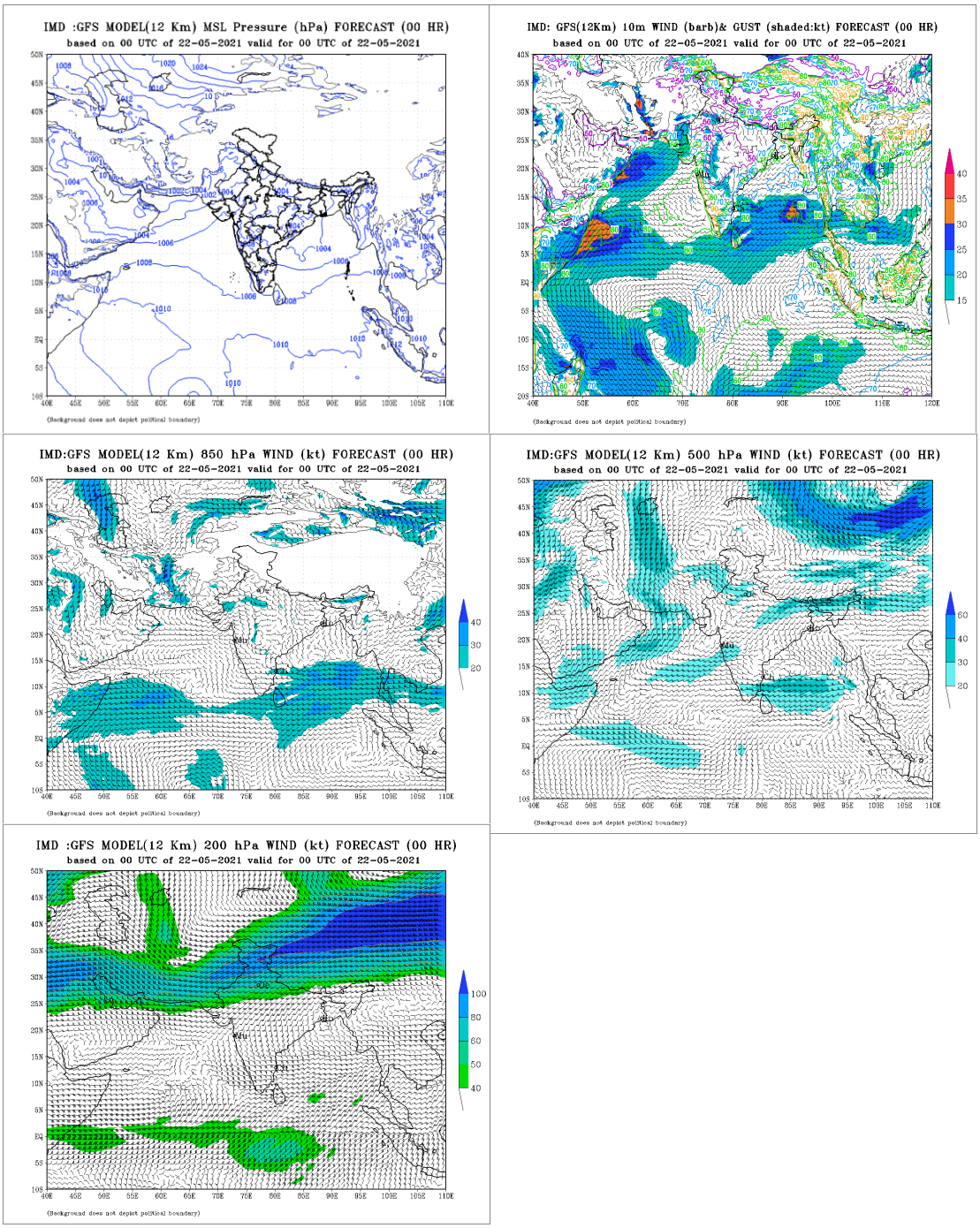


Fig. 7 (a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 22nd May,2021

The analysis of IMD-GFS based on 0000 UTC of 23rd May, 2021 indicated a low over central parts of BoB with vertical extension upto 500 hPa level. Upper tropospheric ridge was located near 25^{0}N. However, at 0000 UTC of 23rd, the system lay as a WML over eastcentral BoB.

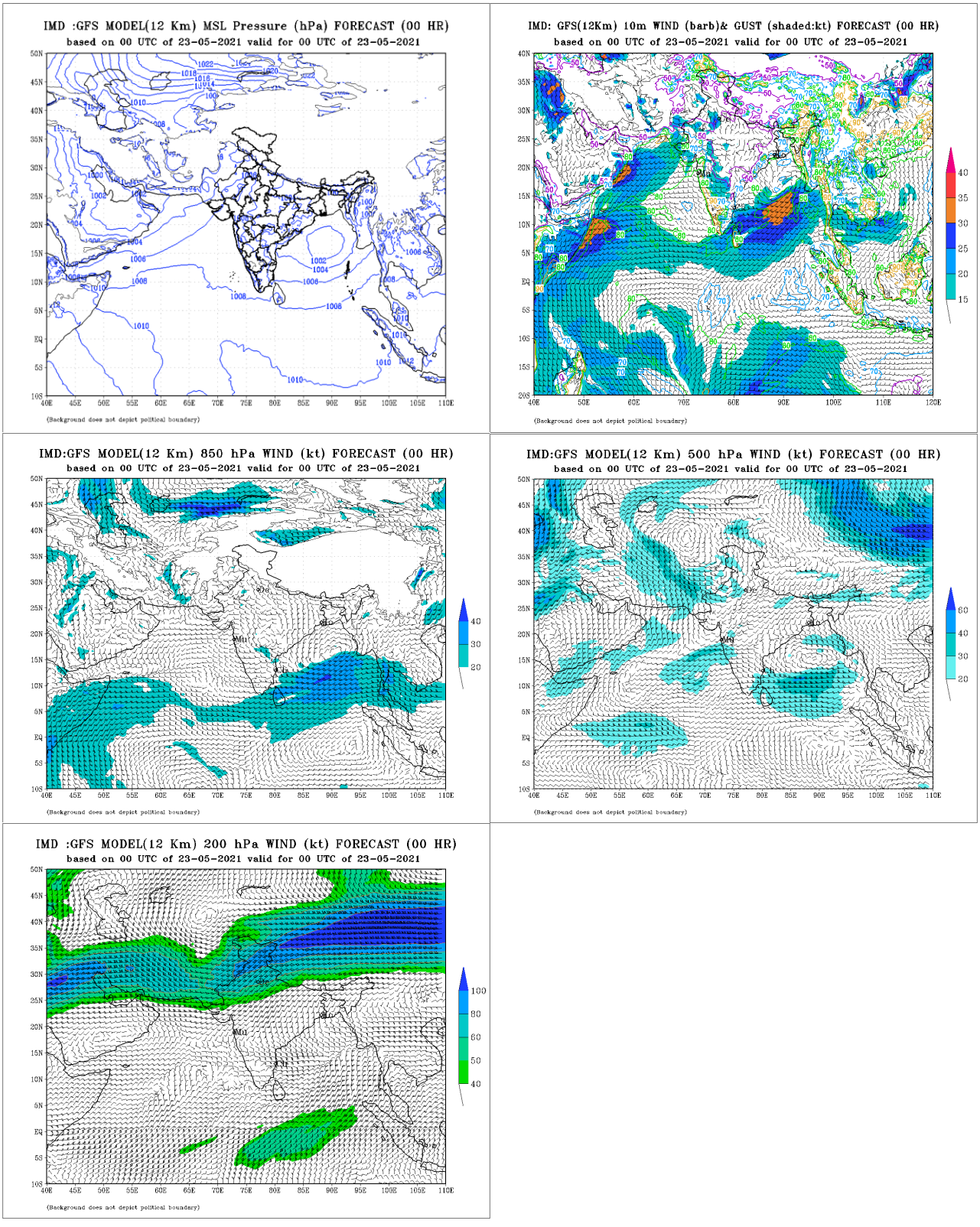


Fig. 7 (b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 23rd May,2021

The analysis of IMD-GFS based on 0000 UTC of 24th May, 2021 indicated an SCS over eastcentral BoB with vertical extension upto 500 hPa level. Upper tropospheric ridge was located near 25^0N. Actually at 0000 UTC of 24th, the system intensified into the cyclonic storm "YAAS" over eastcentral BoB. Thus, IMD GFS highly over-estimated the intensity of the system. However, the location of the system and steering winds were correctly captured by the model.

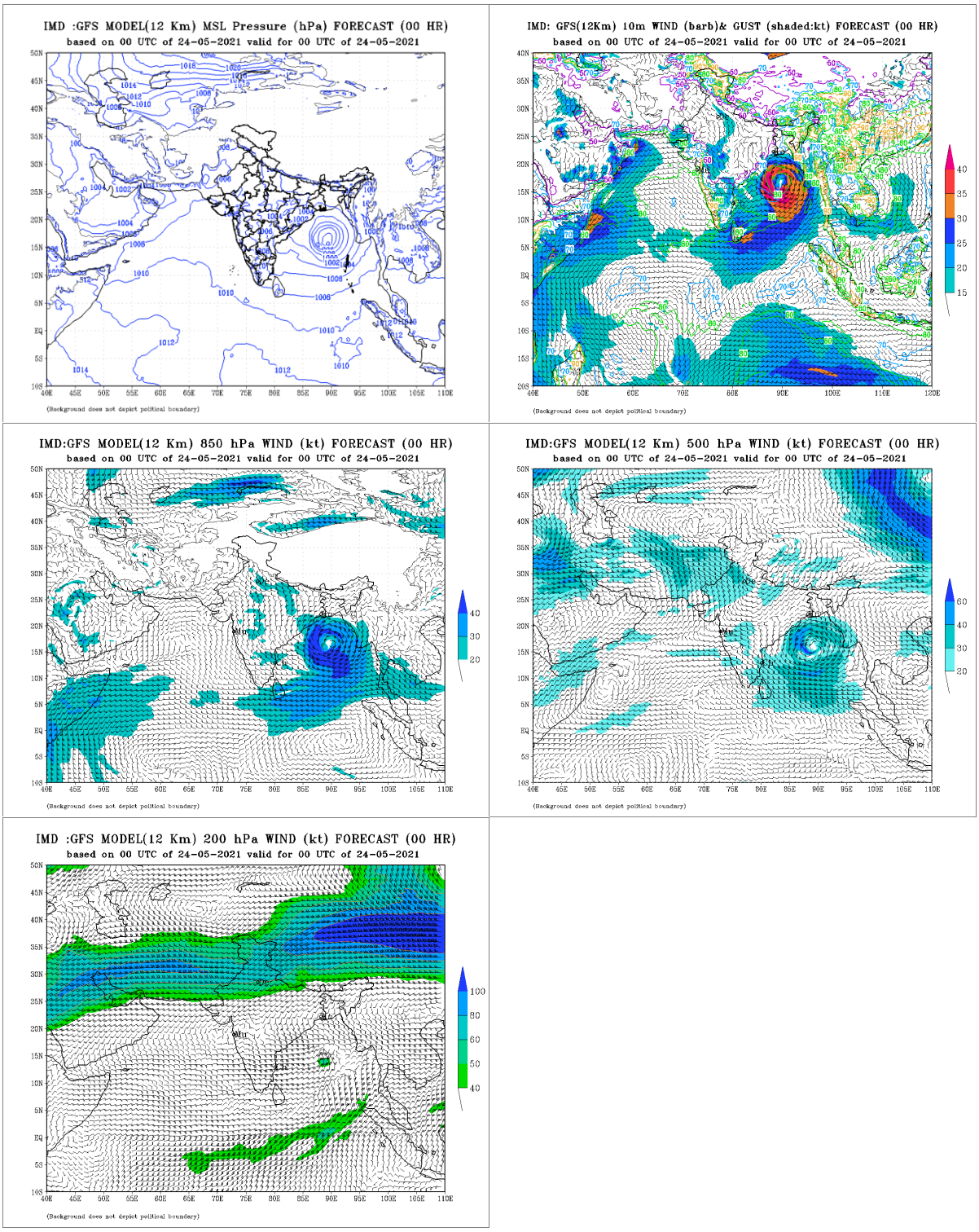


Fig.7(c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 24th May,2021

The analysis of IMD-GFS based on 0000 UTC of 25th May, 2021 indicated a VSCS over northwest BoB with vertical extension upto 500 hPa level. Upper tropospheric ridge was located near 25^0N. However, at 0000 UTC of 25th, the system lay as a WML over eastcentral BoB. IMD GFS reasonably estimated the intensity of the system on 25th alongwith the location of the system and steering winds were correctly captured by the model.

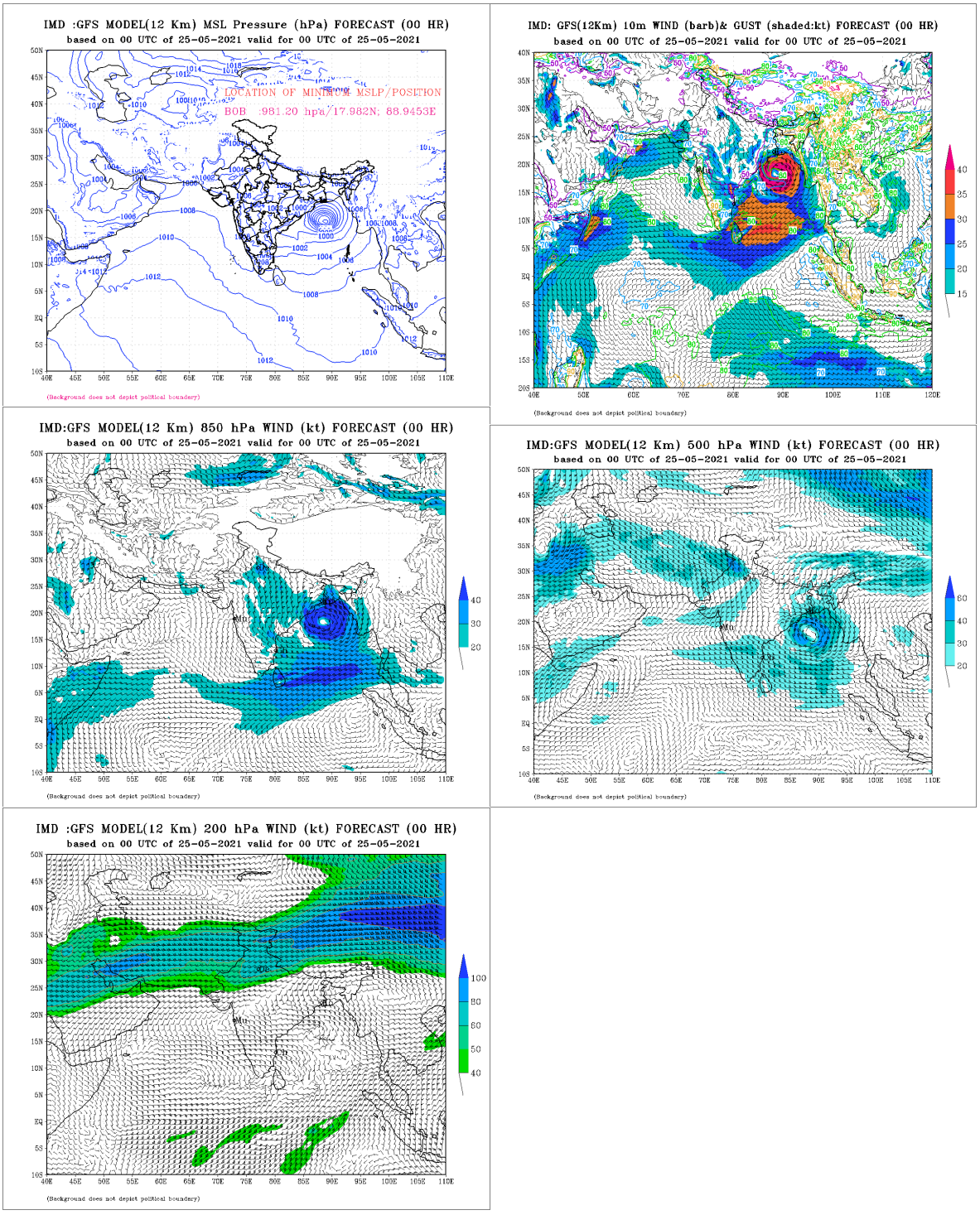


Fig. 7(d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 25th May,2021

The analysis of IMD-GFS based on 0000 UTC of 26th May, 2021 indicated a VSCS over northwest BoB very close to extreme north Odisha-West Bengal coasts near 21.1N/87.7E with vertical extension upto 500 hPa level. Upper tropospheric ridge was located near 25^0N. However, at 0000 UTC of 26th, the system lay as a VSCS over northwest BoB near 20.8N/87.3E. Thus, IMD GFS indicated the location slightly northeastwards as compared to actual location.

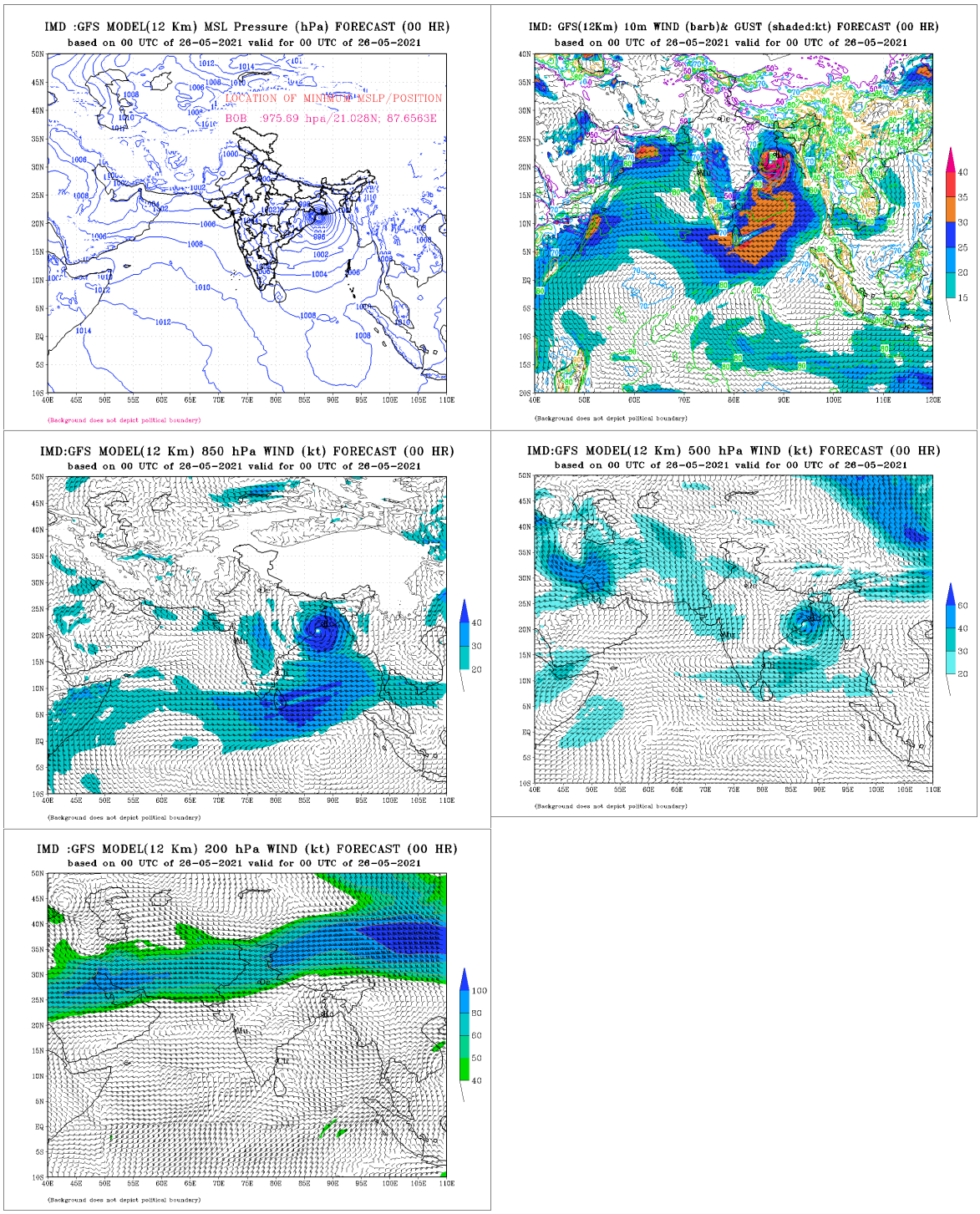


Fig. 7(e): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 26th May,2021

The analysis of IMD-GFS based on 0000 UTC of 27th May, 2021 indicated a DD over north Odisha and adjoining Bihar & West Bengal near 22.6N/85.9E with vertical extension upto 500 hPa level. Upper tropospheric ridge was located near 25^{0}N. However, at 0000 UTC of 27th, the system lay as a DD over Bihar near 22.8N/87.8E. Thus, IMD GFS indicated the location about two degrees longitudes eastwards as compared to actual location.

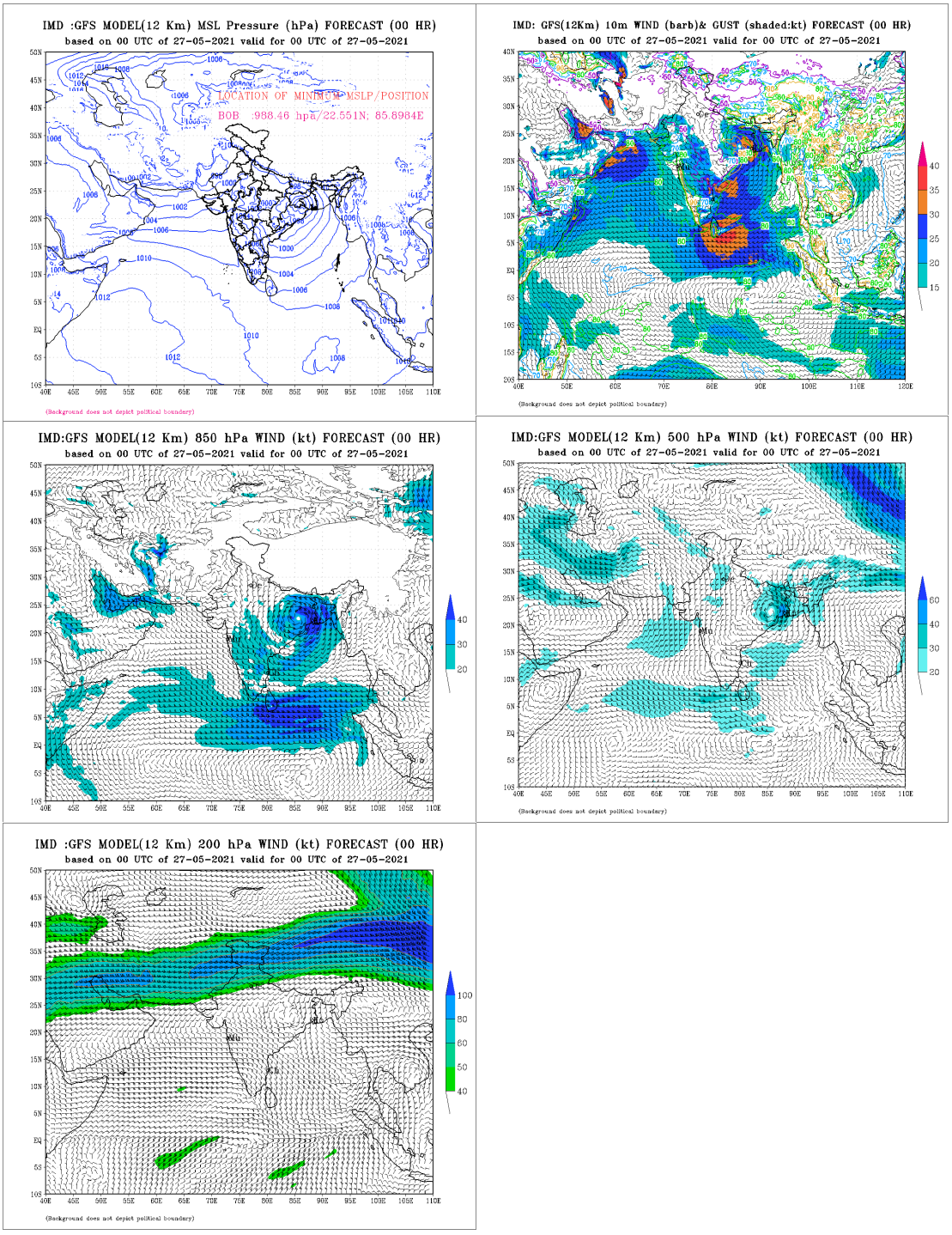


Fig. 7 (f): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 27th May,2021

7. Realized Weather:

7.1. Rainfall:

It caused heavy to very heavy rainfall and Squally winds and tidal waves over Andaman & Nicobar Islands on 23rd & 24th May. It caused heavy to extremely heavy rainfall activity at isolated places over coastal Odisha on 25th May and heavy to very heavy rainfall at a few places and extremely heavy rains at isolated places on 26th May. It caused heavy to very heavy rainfall activity at isolated places over Gangetic West Bengal on 26th May and heavy to extremely heavy rainfall over Sub-Himalayan West Bengal on 27th. It also caused heavy to extremely heavy rainfall over Jharkhand on 26th and 27th and over Bihar and east UP on 27th and 28th May. Rainfall associated with VSCS YAAS based on IMD-NCMRWF GPM merged gauge 24 hours cumulative rainfall ending at 0830 IST of date is depicted in **Fig 8**.

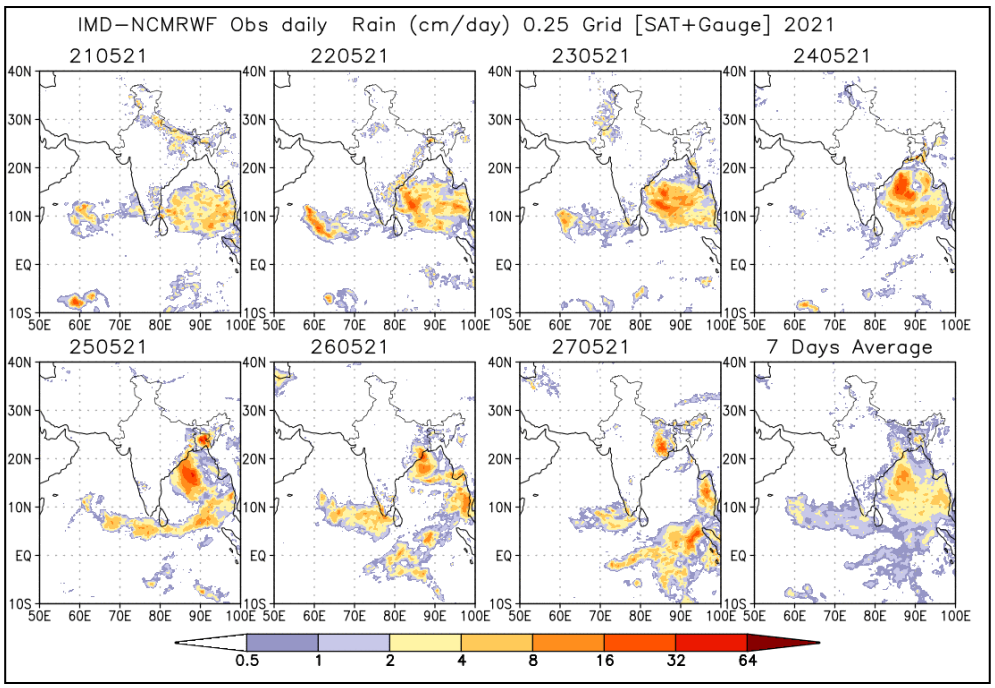


Fig.8: IMD-NCMRWF GPM and gauge merged 24 hr cumulative rainfall (cm) ending at 0830 IST of date during 21st– 27th May and 7 days average rainfall

Realized 24 hrs accumulated rainfall (≥7cm) ending at 0830 hrs IST of date during the life cycle of the system is presented below:

23 May 2021:
Andaman & Nicobar Islands: Long Island-10, Maya Bandar-9

24 May 2021:
Andaman & Nicobar Islands: Port Blair-7

25 May 2021:
Andaman & Nicobar Islands: Hut Bay-11, Carnicobar-8,
Gangetic West Bengal: Contai-9

26 May 2021:
Odisha: Chandbali-29, Rajkanika & Garadapur-25 each, Marsaghai & Kujanga-23 each, Nawana &Tirtol-21 each, Paradip -20, Pattamundai, Balikuda & Derabis-19 each, Astaranga-18, Bhadrak-17, Kendrapara, Dhamnagar & Soro-16 each, Jagatsinghpur-15, Tihidi, Bari & Alipingal-14 each, Jajpur, Nilgiri, Akhuapada & Basudevpur-13 each, Chandikhol & Bonth-12 each, Korei & Kakatpur-11 each, Danagadi-10, Jenapur, Nischintakoili & Bhograi-9 each, Niali & Anandpur & Kaptipada-8 each, Joshipur, Jaleswar, Salepur, Mahanga, Chandanpur, Rairangpur, NH5 Gobindpur, Balimundali, Betanati, Balasore & Jhumpura-7 each

27 May 2021
Odisha: Nawana-28, Joda-27, Joshipur-25, Lathikata & Jhumpura-21 each, Champua, Keonjhargarh & Panposh-20 each, Basudevpur-19, Chandikhol & Karanjia-17 each, Rajgangpur & Mandira Dam each, Swam-Patna & Deogarh-13 each, Tiring-12, Udala, Gurundia, Barkote, Hatadihi, Tihidi & Pallahara-11 each, Ghatagaon, Lahunipara, Sharpada, Soro & Bamra-10 each, Binjharpur, Laikera, Jajpur, Kirmira & Talcher- 9 each, Sukinda & Kuchinda-8 each, Telkoi, Kaptipada, Deogaon, Jenapur, Rairangpur, Bargaon, Kankadahad, Kolabira, Danagadi, Pattamundai & Bhadrak- 7 each

Jharkhand: Chaibasa-21, Mandar-18, Ranchi-15, Chakradharpur-13, Torpa-12, Kuru, Jamshedpur & Kharsema-11 each, Nimdih-10, Ramgarh & Jamshedpur-9 each, Chandil, Chatra, Manatu, Hariharganj & Hendigir-8 each, Shilaichak, Koner & Chandrapura-7 each,
Gangetic West Bengal: Diamond Harbour & Phulberia-11 each & Kharidwar-9, Labpur, Purihansa & Kalyani SMO-8 each, Uluberia, Mangalkote, Kangsabati Dam-7 each,
Sub-Himalayan West Bengal & Sikkim: Rongli, Damthang, Darjeeling & Gyalsing-9 each, Pedong & Pakyong-8 each, Sankalan, Mangan, Singhik & Khanitar- 7 each
Bihar: Sherghati-7
Uttar Pradesh: Light to moderate rainfall occurred at many places over East UP

28 May 2021
Sub-Himalayan West Bengal & Sikkim: Malda-31, Sukiapokhri & Darjeeling-11 each, Damthang & Gyalsing-8 each,
Gangetic West Bengal: Debagram-13, Barrackpur-12, Amtala & Durgachack-10 each, Dum Dum & Alipore-9 each, MO Salt Lake, Diamond Harbour, Kalyani SMO, Bagati, Nalhati – 7 each
Jharkhand: Rajmahal-23, Koner & Tilaiya-11 each, Koderma & Hariharganj-10 each, Hazaribagh-9, Tenughat-7
Bihar: Manihari-25, Kadwa-24, Barari-23, Purnea-21, Parsa & Katihar North-18 each, Amaur-16, Banmankhi, Arwal & Sheikhpura-15 each, Vaishali, Rupauli, Saraiya & Murliganj-14 each, Siswan, Umarkhand, Ghosi, Chapra, Madhipura & Jamui-13 each, Hisua, Koilwar, Gaya Aero, Mahua, Harnaut & Islampur-12 each, Ekangersarai, Narhat, Lakhisarai, Singheshwar, Bodh Gaya, Maharajganj, Sandesh, Sherghati & Nawada-11 each, Kursela, Pachrukhi, Balrampur, Marhaura/Amnaur, Chand, Barh, Udai Kishanganj & Rajgir-10 each, Halsi, Patahi, Jandhaha, Barahara, Patna Aerodrome, Bihta, Jalalpur, Barauni, Matihani, Morwa/Tajpur, Saurbazar, Dinara, Charpokhari & Goraul/Doli-9 each, Kako, Hathwa, Barhiya, Narpatganj, Colgaon & Bihar Shrif-8 each, Hussainganj, Barauli, Tekari, Khagadia, Simrii, Bikram, Adhwara, Rajauli, Makhdumpur, Mushari, Bhore, Motihari, Tarari, Suryagadha, Jahanabad, Supaul, Marsrakh, Chandan, Bagaha, Araria & Sangrampur – 7 each.
East Uttar Pradesh: Chanderdeepghat-13, Gaighat -10, Ballia & Ayodhya-7 each

29 May 2021
Bihar: Tribeni/Balmikinagar21, Darbhanga18, Bagaha & Basua17 each, Balrampur & Kadwa16 each, Hayaghat15, Gaunaha, Mushari & Kodawanpur-13 each, Ramnagar, Goraul/Doli, Rosera & Muzaffarpur-12 each, Jaley & Barh-11 each, Saraiya, Bairgania & Sonbarsa10 each, Matihani, Minapur, Jhanjharpur, Kishanganj, Jandhaha, Sheikhpura, Tarapur, Madhwapur, Bahadurganj, Supaul, Saurbazar, Jainagar & Umarkhand-9 each, Purnea, Belsand, Morwa/Tajpur, Dhengbridge, Samastipur, Madhipura, Thakurganj, Sangrampur, Nirmali & Barauni-8 each, Harnaut, Cheria B.Pur, Parbatta, Aryari, Vaishali, Patahi, Siswan, Barbigha & Nauihatta7 each
East Uttar Pradesh:
Bansi Tehsil-21, Nichlaul-19, Nautanwa-17, Trimohanighat & Maharajganj-15 each, Kakrahi & Pharenda-14 each, Chanderdeepghat & Balrampur TEH-11 each, Balrampur10, Bansi, Tulsipur, Uska Bazar-9 each, Gorakhpur8 and Shoharatgarh, Domeriaganj, Ramnagar & Birdghat7 each

(b) Peak wind speed (kmph) recorded by the Meteorological Observatories in association with the passage of YAAS
Gale wind speed reaching 130-140 gusting to 155 kmph prevailed along and off Balasore, Bhadrak districts of north coastal Odisha and 100-120 gusting to 130 kmph prevailed along and off coastal districts of West Bengal (Purba Medinipur and south 24 Parganas district) and Kendrapara and Jagatsinghpur districts of north coastal Odisha during the time of landfall.

(c) Storm Surge:

Estimated storm surge of about 2-4 meters height above astronomical tide inundated low lying areas of Balasore and Bhadrak districts of north coastal Odisha and coastal West Bengal districts(Purba Medinipur and 24 Pargana districts) and 1-2 meters height above astronomical tide inundated low lying areas of districts of Kendrapara and Jagatsinghpur districts of north coastal Odisha during the time of landfall.

7. Damage due to VSCS YAAS

In West Bengal, no death was reported. The state has incurred a total loss of more than Rs 20,000 crore due to Cyclone, Yaas which battered the state and around 2.21 lakh hectare of crops were damaged. 3 lakh houses were damaged in West Bengal; while around 1 crore people were affected in the state alone.

In Odisha, 2 deaths were reported as they were trapped in a collapsed house. 1,500 homes were damaged, 10 lakh people were effected and 18 people were injured in Jharkhand. An additional two people died in Ranchi after a five year-old bridge connecting the Tamar block to Bundu and Sonahatu block of the city collapsed. 75 hectares worth of farmland were destroyed. Seven people died in the state of Bihar due to floods produced by Yaas as it moved further inland. A few damage photographs are shown in Fig.9.

Fig. 9: (a) Rescue from flood in West Bengal(b)Devastated homes in West Bengal(c) Thatched hut nearby Dhamra worst affected by Cyclone & sea water (d)River Baitarani in Akhuapada (e) Electric Pole uprooted at Dhamra (f) damaged shoreline at a beach in Shankarpur(WB)(g) A bridge at river Kanchi after it collapsed due to heavy rain triggered by Cyclone Yaas, in Ranchi(source: https://www.timesnownews.com,dated 27 May 2021) (h) Flooding and heavy rains in coastal Digha-Shankarpur area in West Bengal.(source: https://www.news18.com/,dated 27 May 2021)

9. Performance of operational NWP models

9.1 Prediction of Cyclogenesis (Genesis Potential Parameter (GPP) for YAAS

The predicted zone of cyclogenesis for 0000 UTC of 23rd May based on forecast during 18th -23rd May 2021 is presented in Fig. 10(a-f). It indicates that GPP could forecast the potential zone over eastcentral BoB since 18th May.

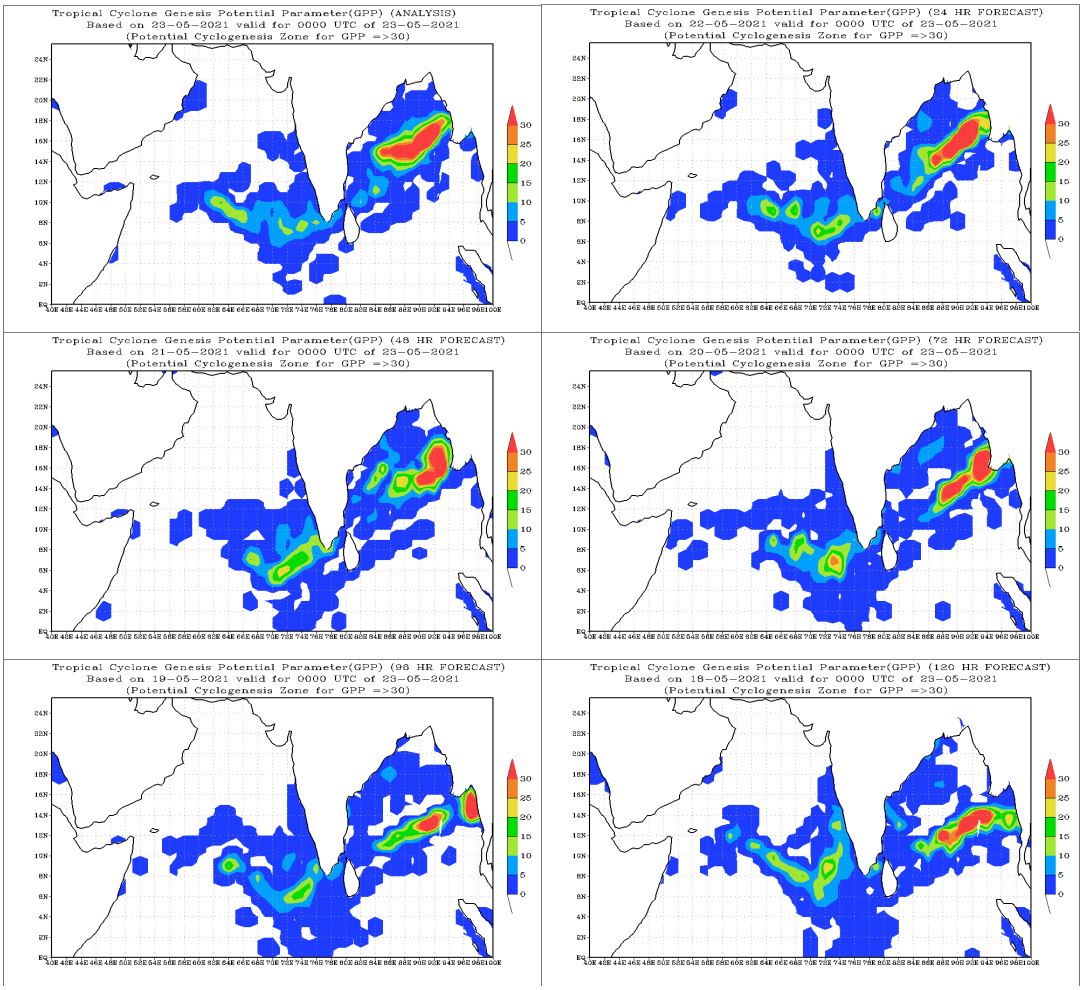


Fig.10 (a-f): Predicted zone of cyclogenesis for 0000 UTC of 23rd May based on forecast during 18th -23rd May 2021

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, UKMO, 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.

Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages (T No. 1.0, 1.5, 2.0) of development. Conditions for (i) Developed system: Threshold value of average GPP ≥ 8.0 and (ii) Non-developed system: Threshold value of GPP < 8.0. The

analysis and forecasts of GPP based on 00 UTC of 23rd May 2021 (Fig. 11 (a)) shows that the "LOW" over the Bay of Bengal has potential to intensify into a tropical cyclone and on 12 UTC of 23rd May 2021 (Fig. 11 (b)) shows that the "DEPRESSION" over the Bay of Bengal has potential to intensify into a tropical cyclone.

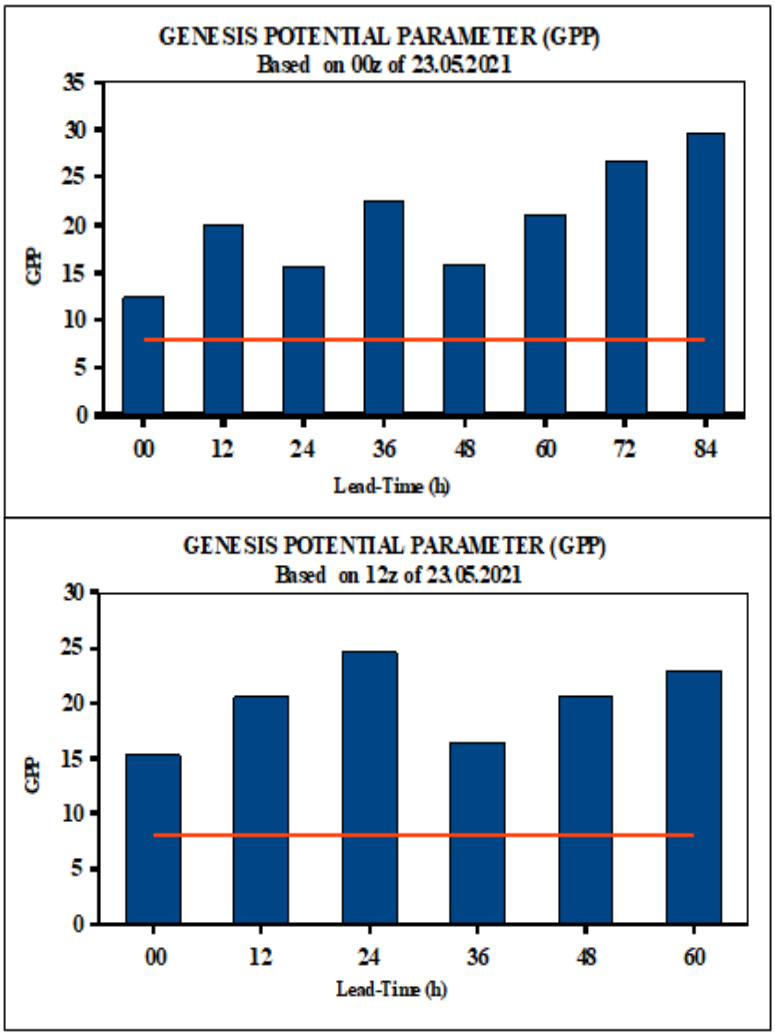


Fig.11. Area average analysis of Genesis Potential Parameter (GPP) based on (a) 00 UTC of 23rd May, 2021 (b) 12 UTC of 23rd May, 2021

9.2 Track prediction by NWP models

Track prediction by various NWP models is presented in **Fig.12**. Based on initial conditions of 0000 UTC of 23rd May, most of the models indicated north-northwestwards movement towards Odisha coast and crossing near actual 21°N/87°E between 0600 UTC to 1800 UTC of 26th May. However HWRF indicated crossing over West Bengal coast. Actually, the system crossed Odisha coast near 21.35°N/86.95°E around 0600 UTC of 26th May.

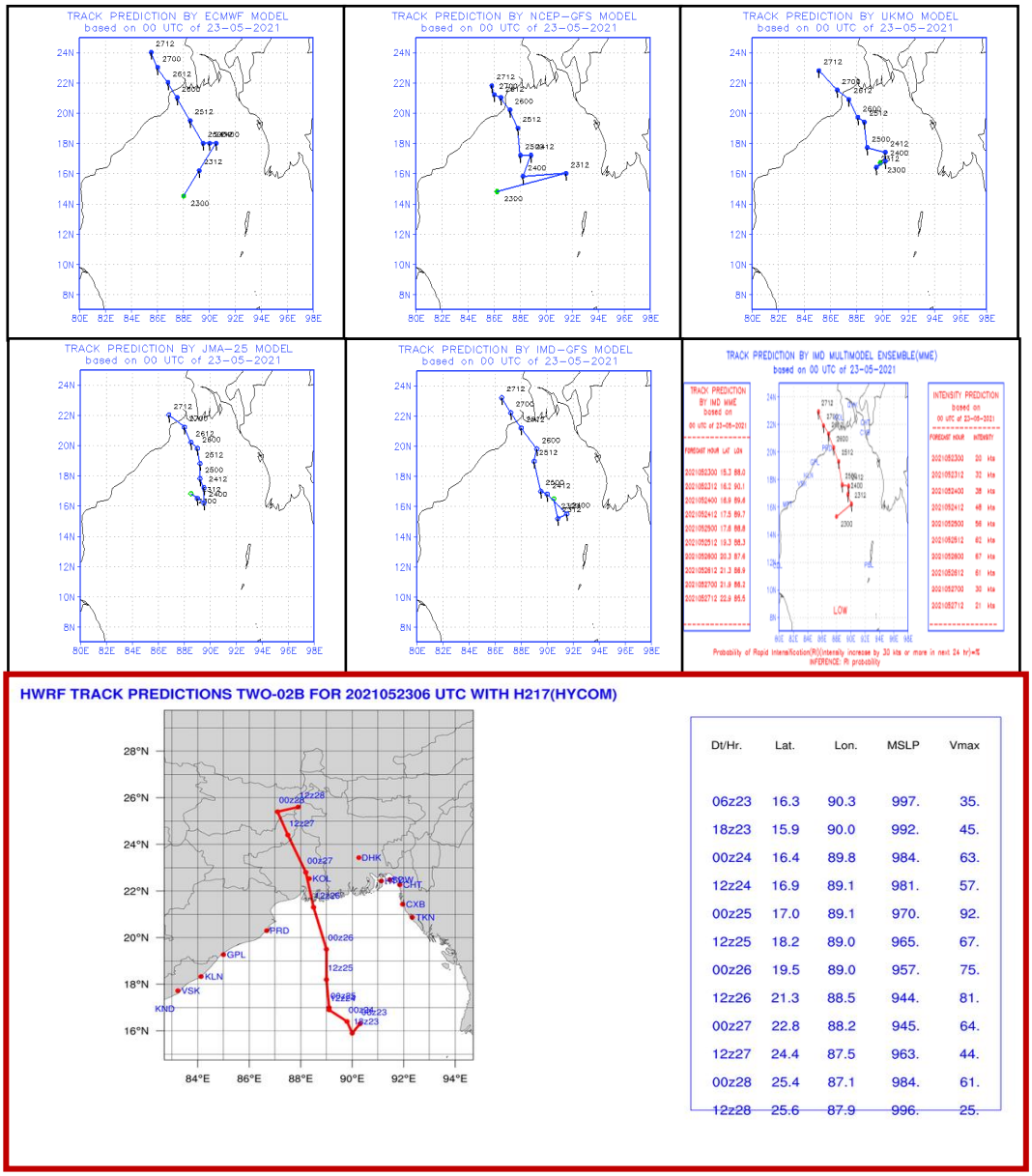


Fig.12 (a) Individual-tracks for tropical cyclone "YAAS" based on 0000 UTC of 23rd May 2021

Based on initial conditions of 1200 UTC of 23rd May, most of the models indicated north-northwestwards movement and landfall over north Odisha coast except bHWRF which indicated landfall over West Bengal coast.

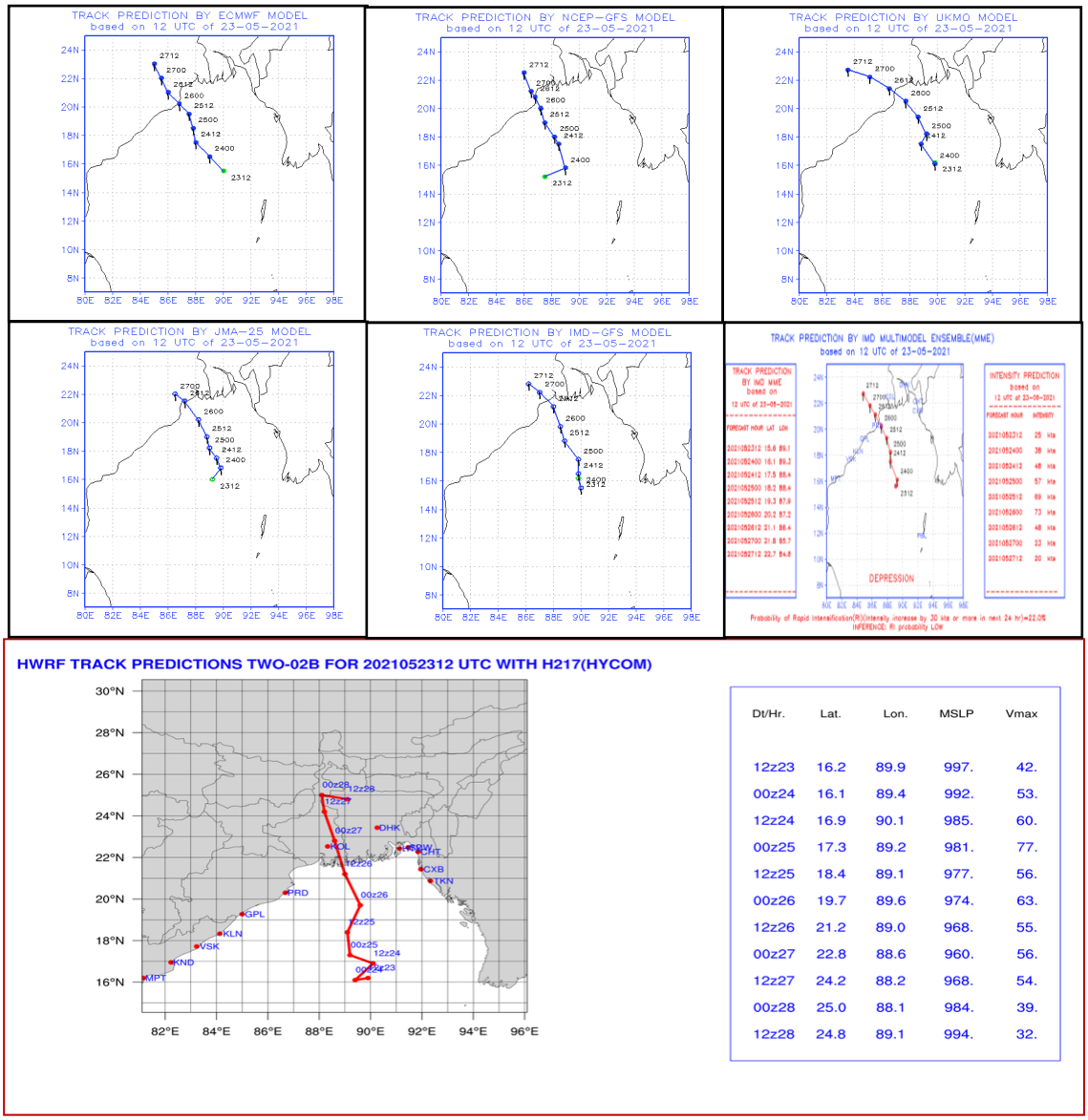
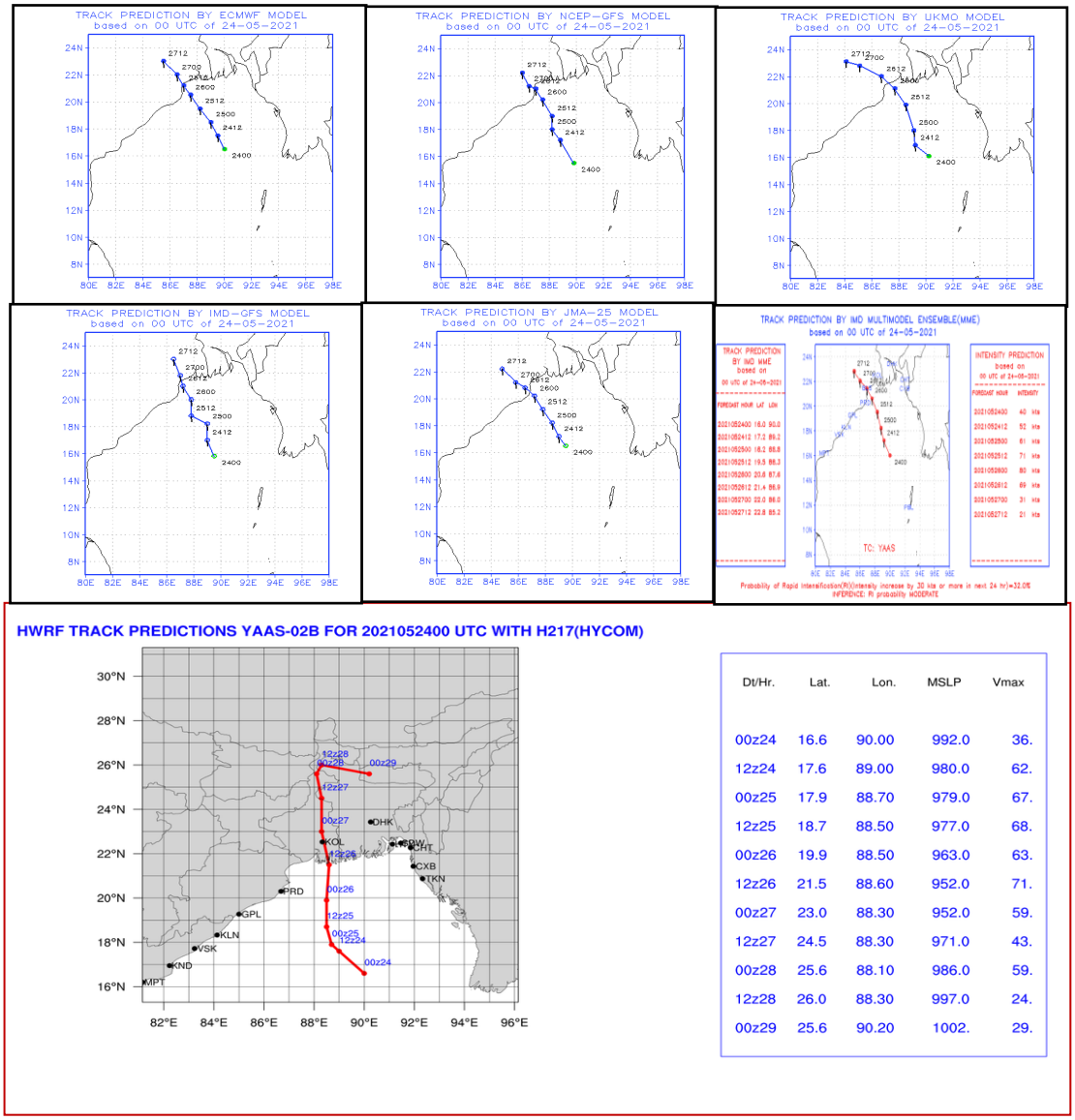


Fig 12 b: Individual-tracks for **tropical cyclone "YAAS" based on 1200 UTC of 23rd May**

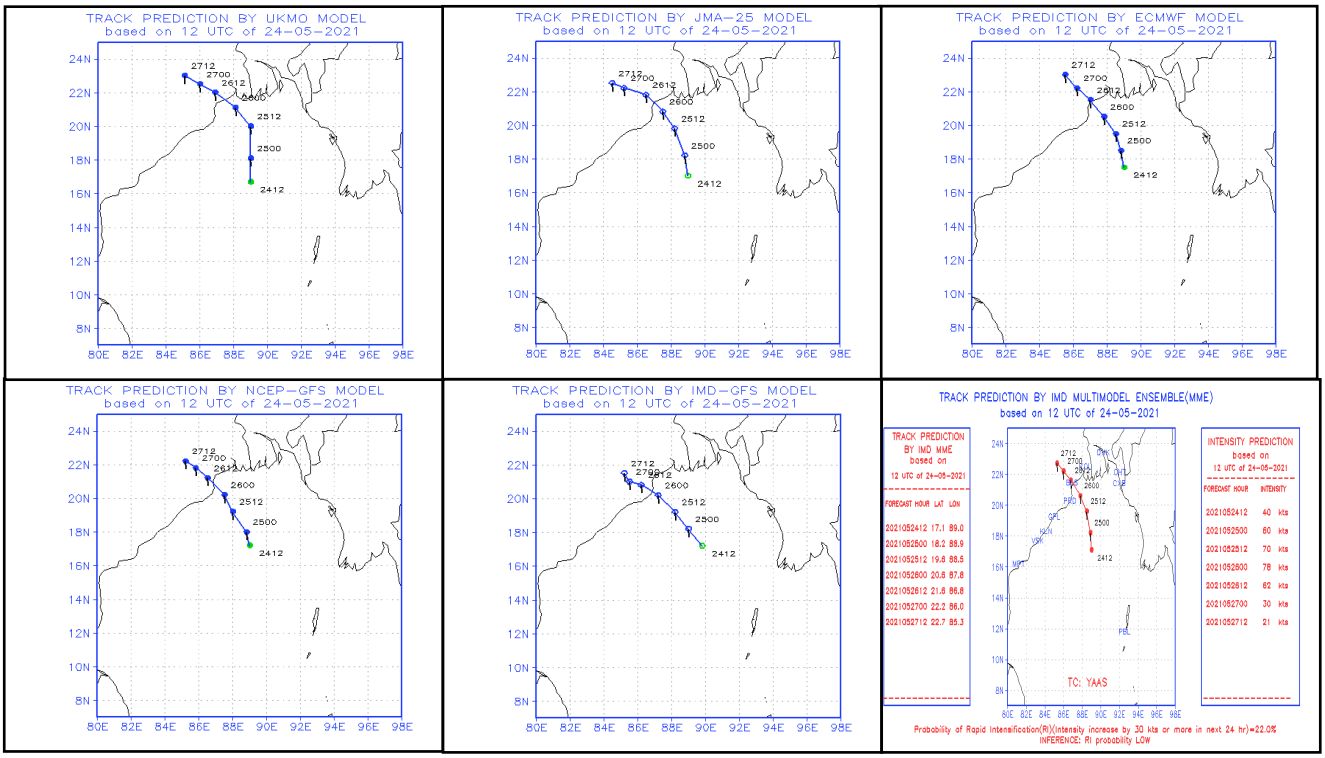
Based on initial conditions of 0000 UTC of 24th May, most of the models indicated north-northwestwards movement and landfall over north Odisha coast except bHWRF which indicated landfall over West Bengal coast.

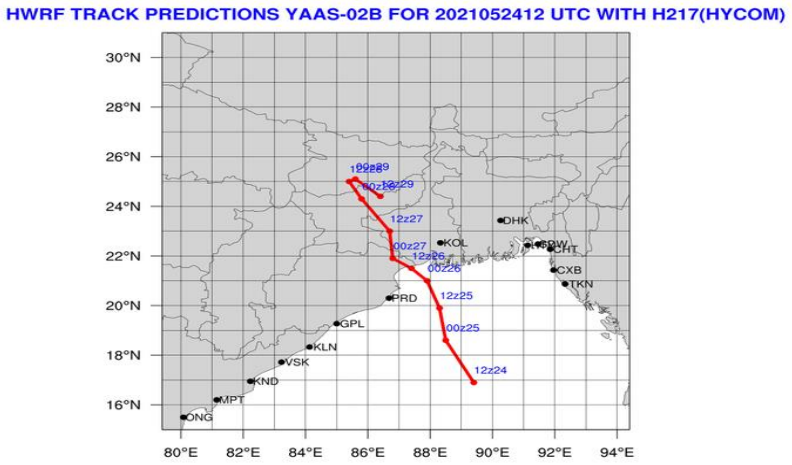


Dt/Hr.	Lat.	Lon.	MSLP	Vmax
00z24	16.6	90.00	992.0	36.
12z24	17.6	89.00	980.0	62.
00z25	17.9	88.70	979.0	67.
12z25	18.7	88.50	977.0	68.
00z26	19.9	88.50	963.0	63.
12z26	21.5	88.60	952.0	71.
00z27	23.0	88.30	952.0	59.
12z27	24.5	88.30	971.0	43.
00z28	25.6	88.10	986.0	59.
12z28	26.0	88.30	997.0	24.
00z29	25.6	90.20	1002.	29.

Fig 12 c: Individual-tracks for tropical cyclone "YAAS" based on 0000 UTC of 24th May 2021

Based on initial conditions of 1200 UTC of 24rd May, most of the models indicated north-northwestwards movement and landfall over north Odisha coast except bHWRF which indicated landfall over West Bengal coast.





Dt/Hr.	Lat.	Lon.	MSLP	Vmax
12z24	16.9	89.4	989.	42.
00z25	18.6	88.5	985.	59.
12z25	19.9	88.3	984.	50.
00z26	21.0	87.9	984.	42.
12z26	21.5	87.4	984.	37.
00z27	21.9	86.8	983.	39.
12z27	23.0	86.7	988.	34.
00z28	24.3	85.8	992.	42.
12z28	25.0	85.4	994.	33.
00z29	25.1	85.6	997.	28.
12z29	24.4	86.4	1000	21.

Fig. 12d: Individual-tracks for tropical cyclone "YAAS" based on 1200 UTC of 24th May 2021

Based on initial conditions of 0000 UTC of 25th May, most of the models indicated north-northwestwards movement and landfall over north Odisha coast.

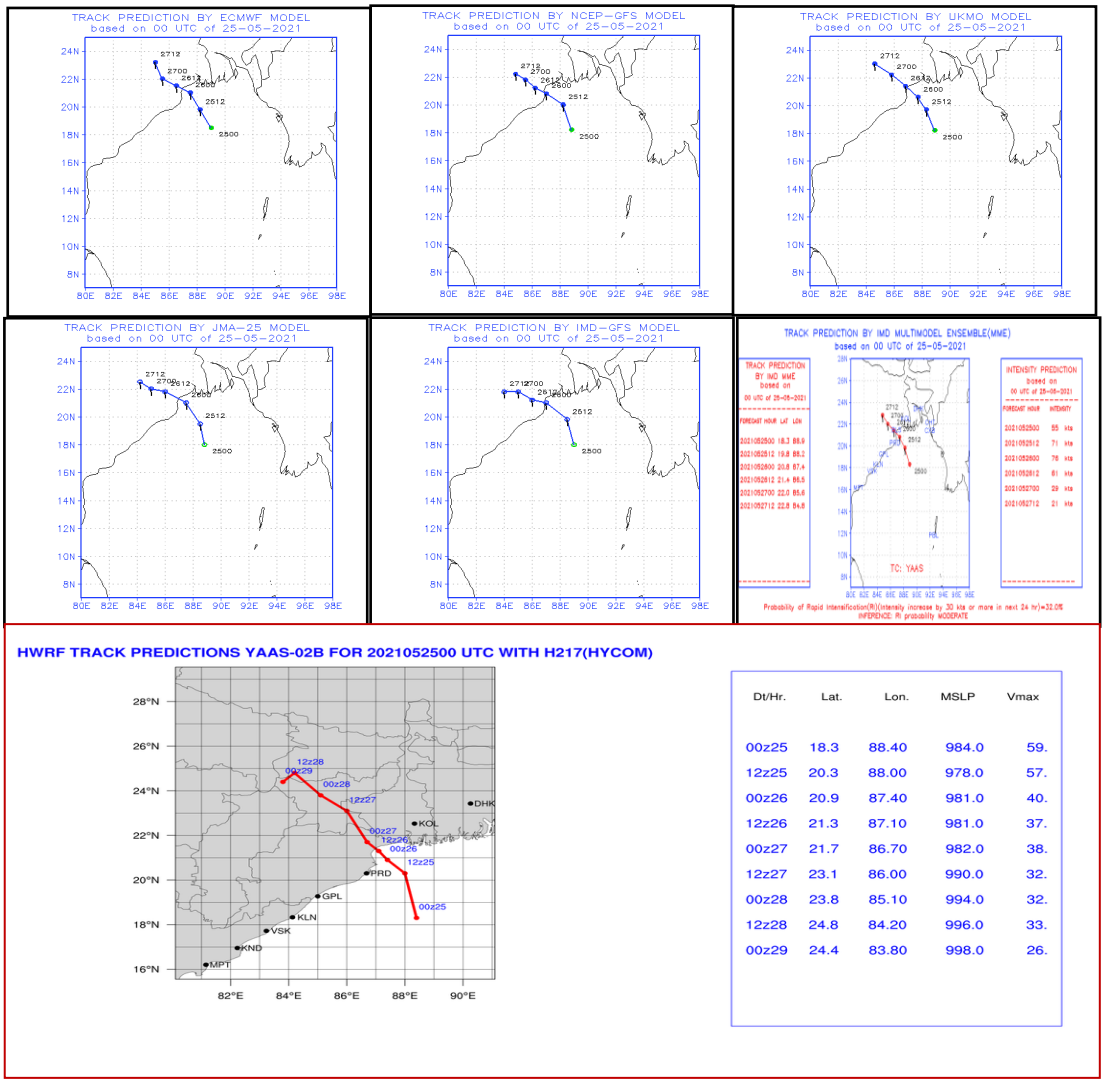


Fig. 12d: Individual-tracks for tropical cyclone "YAAS" based on 0000 UTC of 25th May 2021

Based on initial conditions of 1200 UTC of 25th May, most of the models indicated north-northwestwards movement and landfall over north Odisha coast.

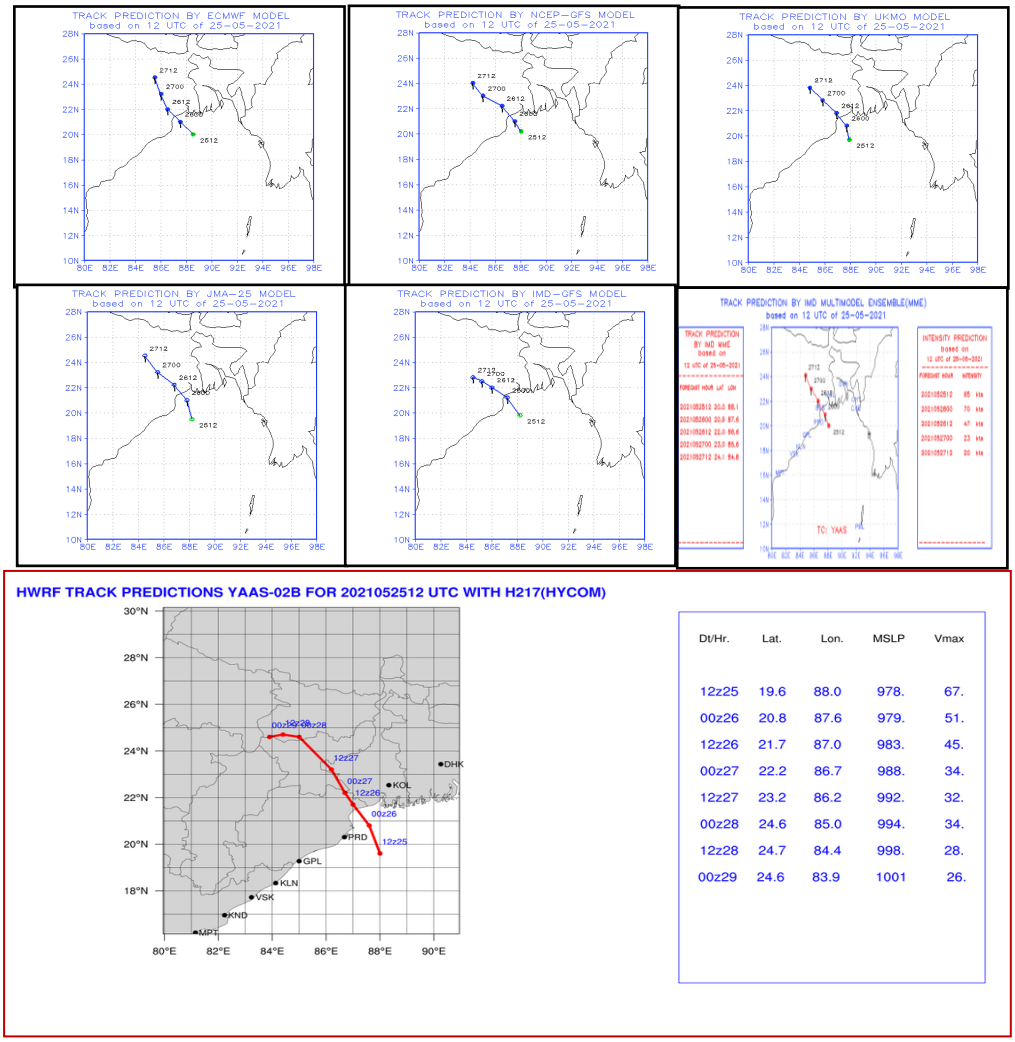


Fig. 12 f: Individual-tracks for tropical cyclone "YAAS" based on 1200 UTC of 25th May 2021

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**. From the verification of the forecast guidance available from various NWP models, it is found that the performed better in track forecast for 24 and 48 hrs and ECMWF for 72 and 96 hrs.

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	108h
IMD-MME*	33(6)	48(6)	43(6)	48(6)	81(5)	103(4)	114(3)	147(2)	157(1)
ECMWF	55	88	65	61	84	100	90	89	39
NCEP-GFS	72	70	65	92	119	151	175	196	282
UKMO	37	66	63	56	68	103	136	208	168
JMA-25	55	36	41	75	139	168	206	228	298

IMD-GFS	72	81	88	134	181	216	163	174	173
HWRF	54 (13)	56 (13)	86 (13)	141 (11)	183 (9)	218 (7)	242 (5)	257 (3)	246 (1)
NCUM	34(8)	47(8)	66(8)	99(9)	106(8)	129(7)	161(7)	169(7)	205(6)
NEPS	53(8)	51(9)	58(9)	78(10)	106(9)	124(8)	169(7)	190(6)	216(5)
GEFS	53(10)	63(9)	78(8)	136(7)	171(5)	205(4)	184(3)	170(2)	211(1)
ENS_MEAN	44(10)	45(9)	50(8)	115(7)	170(5)	181(4)	194(3)	215(2)	240(1)

** The numbers within the parentheses against DP Errors for IMD-MME indicate the number of forecasts issued corresponding to the lead-time. The number of forecasts, corresponding to a particular lead-time, is the same for all the models.*

9.4 Intensity forecast errors by various NWP Models

The intensity forecasts of IMD-SCIP model and HWRF model are shown in Table 3**.** It is found that errors were higher for HWRF followed by GEFS upto 72 hrs.

Table 3: Table- 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	108h
IMD-SCIP AAE	5.5(6)	3.3(6)	6.2(6)	5.5(6)	6.6(5)	3.2(4)			
IMD-HWRF AAE	13.8 (13)	13.7 (13)	9.8 (13)	10.1 (11)	12.1 (9)	18.7 (7)	22.2 (5)	26.7 (3)	21.0 (1)
GEFS CNTL AAE	-2(10)	-5(9)	5(8)	-6(7)	1(5)	10(4)	18(3)	10(2)	7(1)
GEFS ENS_MEAN AAE	-1(10)	-5(9)	5(8)	-2(7)	1(5)	7(4)	12(3)	10(2)	7(1)
IMD-SCIP RMSE	5.7	3.7	7.8	7.7	11.0	4.7			
IMD-HWRF RMSE	15.8 (13)	17.2 (13)	12.2 (13)	11.3 (11)	14.3 (9)	21.0 (7)	25.8 (5)	27.2 (3)	21.0 (1)
GEFS CNTL RMSE	5(10)	5(9)	4(8)	4(7)	4(5)	11(4)	12(3)	7(2)	7(1)
GEFS ENS_MEAN RMSE	14(10)	14(9)	11(8)	8(7)	8(5)	14(4)	12(3)	10(2)	7(1)

9.5 Landfall forecast errors by various NWP Models

From Table 5(a), it is found that the ECMWF model performed better.

Table-5 a. Landfall point forecast errors (km) of NWP Models at different lead time (hour)

('NLF' indicates No Landfall Forecst)

Forecast Lead Time (hour) →	5.5 h (25/12)	17.5 h (25/00)	29.5 h (24/12)	41.5 h (24/00)	53.5 h (23/12)	65.5 h (23/00)
ECMWF	07	08	17	07	126	16
NCEP GFS	07	50	52	39	63	63

UKMO	07	16	54	46	92	08
JMA	46	28	07	85	31	59
IMD-GFS	07	28	109	07	69	59
IMD-MME	07	28	07	07	63	08
HWRF LANDFALL POINT	71	63	39	18	125	153
GEFS LANDFALL POINT_CNTL	32	18	38	101	14	79
GEFS LANDFALL POINT_MEAN	25	16	13	77	35	130

Table-5 b. Landfall time forecast errors (hour:minute) at different lead time (hr)

('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	**5.5 h (25/12)**	**17.5 h (25/00)**	**29.5 h (24/12)**	**41.5 h (24/00)**	**53.5 h (23/12)**	**65.5 h (23/00)**
ECMWF	00:30	01:30	06:00	07:00	-05:00	00:30
NCEP GFS	00:30	-05:00	03:00	06:30	06:30	00:30
UKMO	03:30	06:00	01:30	00:30	03:30	13:30
JMA	00:30	-00:30	00:30	00:30	06:30	24:30
IMD-GFS	-04:30	-05:00	-00:30	12:30	00:30	12:30
IMD-MME	00:30	01:30	04:30	06:30	-02:30	06:30
HWRF LANDFALL	0	0	+9	+9	+9	+6
GEFS LANDFALL TIME_CNTL	0	0	-6	+1	+12	+9
GEFS LANDFALL TIME_MEAN	0	0	0	-6	+12	+6

9.6: Heavy rainfall and mean wind forecast by IMD HWRF

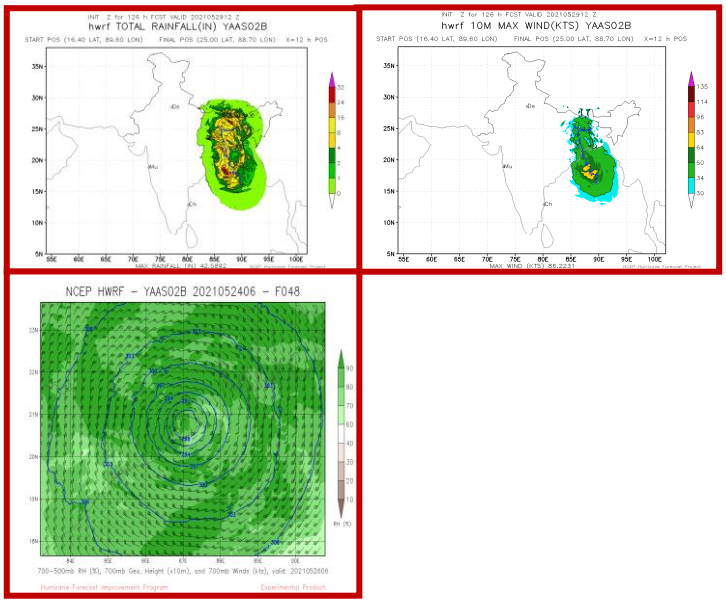


Fig. 13: (a) SWATH 10m WIND and SWATH RAIN (b) CORE Domain – (2km) – 700-500 hPa RH , GEO Ht. & 700 mb Winds based on HWRF model

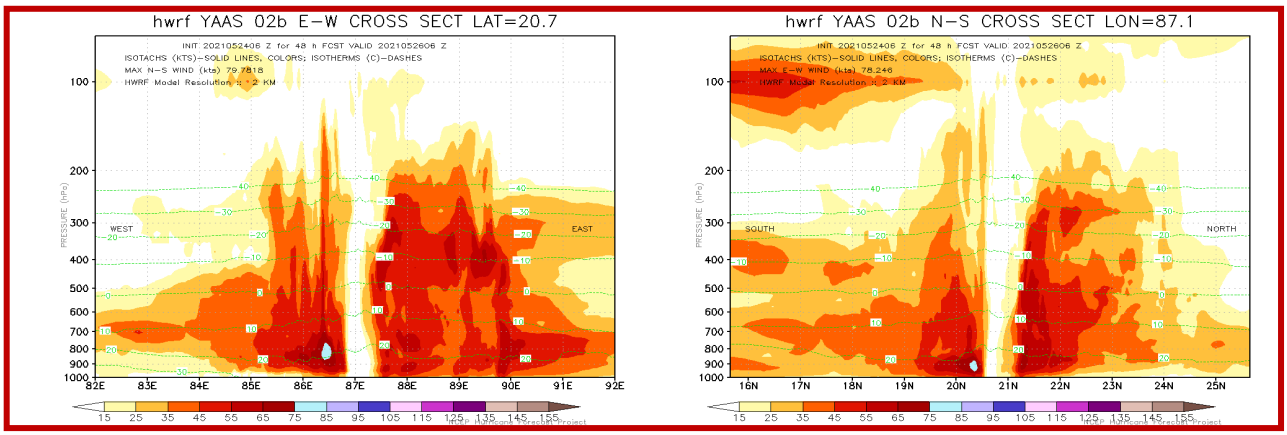


Fig. 13 (b) ISOTACHS and (h) ISOTHERMS – Cross section (E-W) (N-S) based on HWRF model

Fig.13(a) shows the rainfall and wind swath and Fig.13(b) shows the vertical structure of wind and temperature analyses at the time of landfall based on HWRF model

10. Operational Forecast Performance

10.1 i) Genesis Forecast

- First information about development of depression over eastcentral BoB with (1-33% probability) during 21st-23rd May was given in the extended range outlook issued on 13th May (**about 10 days prior to the formation of formation of depression** over eastcentral BoB on 23rd May).
- Subsequently, in the Press Release, Tropical Weather Outlook and national weather forecast bulletin issued at 1200 hrs IST of 19th May, it was indicated that a low pressure would form over north Andaman Sea and adjoining eastcentral BoB around 22nd May and that it would intensify further into a Very Severe Cyclonic Storm. It was also indicated that the system would move northwestwards and reach Odisha-West Bengal coasts on 26th May (about **3 days prior to formation of low pressure area** on 22nd May and **4 days prior to formation of depression** on 23rd May).
- The extended range outlook issued on 20th May (about **3 days prior to formation of depression on 23rd May and 6 days prior to the Very Severe Cyclonic Storm reaching near Odisha-West Bengal coasts on 26th May**) indicated with high probability (67-100%) that the system would move towards northwest BoB near Odisha-West Bengal coasts during 23rd-26th May. Accordingly, likely impact was also issued in the extended range outlook for fishermen, ships and ports along the east coast of India and adjoining Bangladesh & Myanmar coasts.
- **In the first bulletin issued at 1245 hrs IST of 22nd May on formation of low pressure area over eastcentral BoB,** it was indicated that the system would intensify upto VSCS and that the system would move northwestwards and reach north Odisha-West Bengal coasts around 26th morning **(about 90 hours prior to YAAS reaching Odisha-West Bengal coasts on 26th morning).**
- The first bulletin issued at 1350 IST of 23rd (**about 72 hours prior to landfall around noon of 26th**), it was indicated that the system would move north-northwestwards, reach close to north Odisha-West Bengal coasts around 26th morning and cross north Odisha coast by afternoon of 26th May.
- The bulletin issued at 0830 IST of 24th indicated that the system would cross coast close to south of Balasore, Odisha by afternoon of 26th as a Very Severe Cyclonic Storm (**about 54 hours prior to landfall) with almost zero landfall point error.**

- Actually, the VSCS YAAS moved nearly north-northwestwards and **lay centred over northwest BoB about 30 km east of Dhamara Port**, Odisha **during early morning (around 0530 IST) of 26th May**. Since first bulletin issued on 22nd May **(about 90 hours prior to landfall)** it was indicated that the system would reach north Odisha-West Bengal coasts around 26th morning.
- Also continuing to move north-northwestwards, YAAS crossed north Odisha coast near latitude 21.35°N and longitude 86.95°E, about 20 km to the south of Balasore as a VSCS with maximum sustained wind speed of 75 kts gusting to 85 kts (130 -140 kmph gusting to 155 kmph) between 0500 & 0600 UTC (103030 IST) of 26th as indicated since 24th May (**about 54 hours prior to landfall**) **with almost zero landfall point error (8 km) and about zero landfall time error (0.5-1.0 hour)**.
- Fig. 14-15 represent observed and forecast track, intensity & landfall forecast issued at various lead times indicating accuracy in track, landfall and intensity forecast.

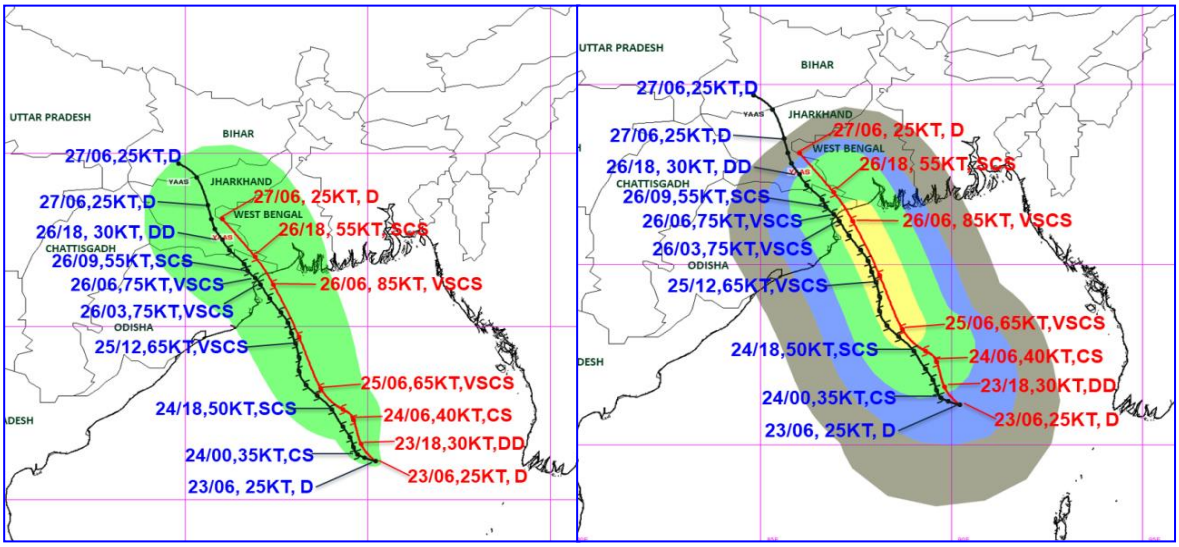


Fig.14 : Observed track (23-28 May) and first forecast track issued at 1350 hours IST of 23rd May based on 1130 hrs IST observations of 23rd May (about 72 hours prior to landfall) demonstrating accuracy in track, intensity and landfall.

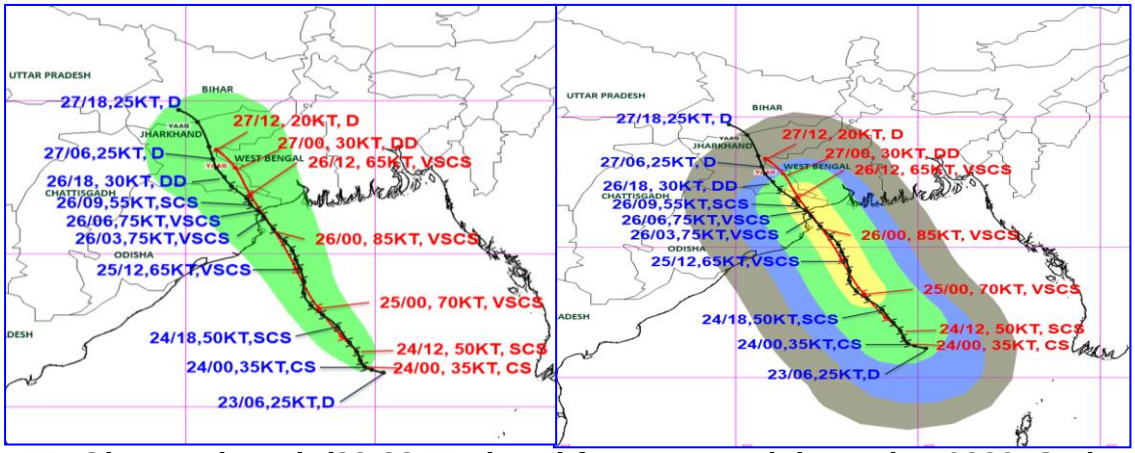


Fig.15: Observed track (23-28 May) and forecast track issued at 0830 IST based on 0530 IST observations of 24th May (about 54 hours prior to landfall) demonstrating accuracy in track, intensity and landfall

DATE/TIME IN UTC, IST = UTC + 0530 HRS, D: DEPRESSION, DD: DEEP DEPRESSION, VSCS: VERY SEVERE CYCLONIC STORM, SVSCS: SEVERE VERY SEVERE CYCLONIC STORM, VSCS: VERY SEVERE CYCLONIC STORM,

OBSERVED TRACK, FORECAST TRACK, CONE OF UNCERTAINTY

MSW(knot)/kmph)	Impact	Action
28-33 /(52–61)	Very rough seas.	Total suspension of fishing operations
34-40/(62-74)	High to very high seas	Total suspension of fishing operations
41-63/(75-117)	Very High seas	Total suspension of fishing operations
≥ 64 (≥118)	Phenomenal	Total suspension of fishing operations

10.2 Operational Track, Landfall and Intensity Forecast Errors:

The operational track, intensity and landfall point & time forecast errors are presented in Fig.16.

- The track forecast errors for 24, 48 and 72 hrs lead period were 24.1, 53.1 and 81.6 km respectively against the LPA errors (2016-20) of 77, 117, and 159 km respectively
- The landfall point forecast errors for 12, 24, 48 and 60 hrs lead period were 7.8, 7.8, 7.8 and 38.9 km respectively against the LPA errors (2016-20) of 17, 32, 62 and 61 km during 2016-20 respectively.
- The landfall time forecast errors for 12, 24, 48 and 60 hrs lead period were 1.0, 1.0, 2.5 and 3.5 hours respectively against the LPA errors (2016-20) of 1.3, 2.5, 5.0 and 5.3 hours during 2016-20 respectively.
- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 13.7, 12.9 and 14.1 knots against the LPA errors of 7.9, 11.4, and 14.1 knots during 2016-20 respectively
- The errors in track and landfall point & time were exceptionally less as compared to long period average errors during 2016-2020.

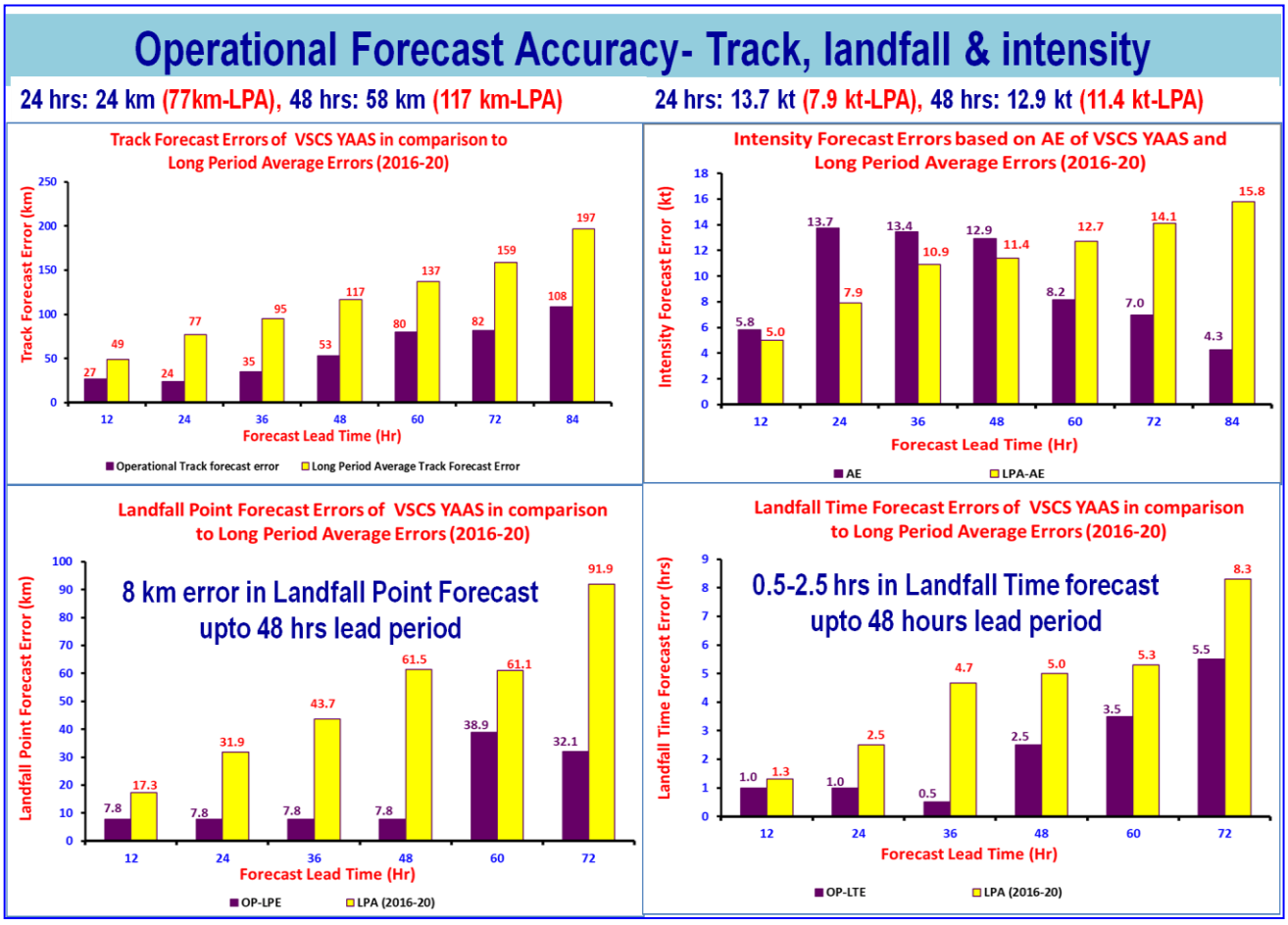


Fig. 16: Operational track, intensity, landfall point and time forecast errors during YAAS as compared to long period average (LPA) errors based on 2016-20

11. Adverse weather forecast verification

The verification of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Table 8-10. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table 8 Forecast verification of Gale wind

Forecast Winds (kmph)	Realised wind (kmph)
➢ Gale wind speed reaching 155-165 gusting to 185 kmph over north coastal districts of Balasore, Bhadrak Jagatsinghpur, Kendrapara of Odisha. It was modified to 130-140 gusting to 155 kmph on 25th night. ➢ Gale wind speed reaching 110-120 gusting to 130 kmph over coastal districts of West Bengal (Purba Medinipur and south 24 Parganas district) and during the time of landfall.	❖ Gale wind speed reaching 130-140 gusting to 155 kmph prevailed over north coastal districts of Balasore, Bhadrak and 100-120 kmph gusting to 130 kmph along and off Kendrapara and Jagatsinghpur districts of Odisha. ❖ Gale wind speed reaching 100-120 gusting to 130 kmph prevailed over coastal districts of West Bengal (Purba Medinipur and south 24 Parganas district) during the time of landfall

Table 9 Verification of Heavy Rainfall Warning

Forecast Rainfall	Realised 24 hr cumulative heavy rainfall ending at 0830 IST of date
❖ Heavy to very heavy rainfall over Andaman & Nicobar Islands on 23rd & 24th May. ❖ Heavy to extremely heavy rainfall at isolated places over coastal Odisha on 25th & heavy to very heavy rainfall at a few places & extremely heavy falls at isolated places on 26th May over North Odisha. ❖ Heavy to very heavy rainfall at isolated places over Gangetic West Bengal on 26th & heavy to extremely heavy rainfall over Sub-Himalayan West Bengal on 27th. ❖ Heavy to extremely heavy rainfall over Jharkhand on 26th & 27th, over Bihar and east UP on 27th & 28th May.	❖ Heavy to very heavy rainfall over Andaman & Nicobar Islands on 23rd & 24th May. ❖ Heavy to extremely heavy rainfall at isolated places over coastal Odisha on 25th May and heavy to very heavy rainfall at a few places and extremely heavy rains at isolated places on 26th May over North Odisha. ❖ Heavy to very heavy rainfall at isolated places over Gangetic West Bengal on 26th May and heavy to extremely heavy rainfall over Sub-Himalayan West Bengal on 27th. ❖ Heavy to extremely heavy rainfall over Jharkhand on 26th and 27th, over Bihar and east UP on 27th and 28th May.

Table 10 Verification of storm surge warning

Forecast Storm Surge (m)	Realised Storm Surge (m)
Tidal waves of height 2-4 meters above astronomical tide to inundate low lying areas of Balasore, Bhadrak Medinipur, South 24 Parganas, and about 1-2 meters above astronomical tide to inundate low lying areas of Kendrapara & Jagatsinghpur Districts around the time of landfall.	Estimated storm surge of about 2-4 meters height above astronomical tide inundated low lying areas of Balasore and Bhadrak districts of north Odisha and West Bengal (South 24 parganas, North 24 parganas, Purba Medinipur districts) and 1-2 meters height above astronomical tide inundated low lying areas of Kendrapara and Jagatsinghpur districts of north Odisha during time of landfall.

Thus, the track, intensity, landfall point & time and associated adverse weather like heavy rainfall, gale wind and storm surge were predicted by IMD well in advance with reasonable accuracy.

12. Warning & advisories issued by IMD

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… +84 hrs lead period commencing from 23rd May noon till the system weakened into a low pressure area in the morning of 28th. 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. The hourly updates were also provided 15 hours prior to landfall till the system maintained the intensity of Very Severe Cyclonic Storm over Odisha.
- **Cyclone structure forecast for shipping and coastal hazard management:** The radius of maximum wind and radii of MSW ≥28, ≥34, ≥50 and ≥64 knots wind in four quadrants of cyclone was issued every six hourly, commencing from 23rd May noon giving forecast for +06, +12, +18, +24, +36 and +84 hrs lead period.
- **Four stage Warning:**
- **Considering the development of VSCS** over Bay of Bengal, **1st Press Release** was issued on **19th May** (**3 days prior to formation of LPA on 22nd May**). Adverse weather warnings and advisories for fishermen issued.
- **2nd Press Release & Special Message were issued on 22nd May on formation of LPA (4 days prior to landfall**) indicating formation of Very Severe Cyclonic Storm over Bay of Bengal and system to reach northwest BoB near north Odisha-West Bengal coasts around 26th morning.
- **Pre cyclone watch** for Odisha-West Bengal coasts was issued at 1350 hrs IST of 23rd May, on development of depression over eastcentral BoB **(about 70 hours prior to landfall)**.
- **Cyclone alert** for Odisha-West Bengal coasts was issued at 0830 hrs IST of 24th May, on intensification of the system into the Very Severe Cyclonic Storm YAAS **(about 54 hours prior to landfall).**
- **Cyclone Warning** for Odisha-West Bengal coasts was issued at 2030 hrs IST of 24th May, when the system was a Very Severe Cyclonic Storm over eastcentral BoB **(about 39 hours prior to landfall)**
- **Post landfall outlook for interior districts of Odisha and West Bengal was** issued at 1700 hrs IST of 25th, when system was a severe Very Severe Cyclonic Storm over northwest and adjoining areas of BoB **(about 18 hours prior to landfall)**
- **Adverse weather warning bulletins:** The tropical cyclone forecasts alongwith expected adverse weather like heavy rain, gale wind and storm surge 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 and interior parts of north India across which the system moved including Tamilnadu, Andhra Pradesh, Andaman & Nicobar Islands, Puducherry, Odisha, West Bengal, Jharkhand, Assam,

Sikkim, Bihar, Meghalaya, Uttar Pradesh. The bulletins also contained the suggested action for disaster managers and general public in particular for fishermen. These bulletins were also issued to Defence including Indian Navy & Indian Air Force, NDRF, Indian Coast Guard, ports, Shipping, Fishery, Railways, Surface Transport & Aviation Authorities.

- **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 heavy rain, gale/squally wind & storm surge were also presented in graphiVSCS alongwith colour codes in the website.
- **Warning and advisory through social media:** Daily updates (every three hourly or whenever there was any significant change in intensity/track/landfall) were uploaded on Facebook and Twitter during the life period of the system since the development of low pressure area over the Bay of Bengal. However, from 25th night (2030 IST/1500 UTC) onwards, hourly updates were issued and sent to disaster managers by email, uploaded on websites, posted on Facebook and Twitter till the system maintained the intensity of Very Severe Cyclonic Storm over Odisha.
- **Press Conference, Press release and Media briefing:** Press and electronic media were given daily updates since inception of system through press release, e-mail, website, video capsules by DGM, Media Briefings by all concerned Officials at HQ as well as in Odisha & West Bengal 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 Kolkata, Chennai and Cyclone warning centres at Visakhapatnam and Bhubaneswar to ports, fishermen, coastal and high sea shipping community.
- **Fishermen Warning:** Regular warnings for fishermen for deep Sea of BoB and the states of Tamilnadu, Andhra Pradesh, Odisha, West Bengal and Andaman & Nicobar Islands were issued since 19th May.
- **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 prognostiVSCS and diagnostiVSCS of the systems were described in the RSMC bulletins.
- **Hourly Bulletin:** Hourly updates on the location, distance from recognised station, intensity and landfall commenced from 25th night (1500 UTC/2030 IST) onwards till the system maintained the intensity of Very Severe Cyclonic Storm.
- **Important Briefing Meetings attended by DGM IMD**

❖ High Level meeting chaired by Secretary, NDMA on 21st May.
❖ NCMC Meeting chaired by Cabinet Secretary on 22nd May

- ❖ Briefing meeting under Chairmanship of Hon'ble Prime Minister on 23rd May.
- ❖ Preparedness Meeting chaired by Union Home Minister on 24th May.
- ❖ Review Meeting under joint Chairmanship of Hon'ble Ministers of State for Ports, Shipping & Waterways (I/C), Commerce & Industry and Petroleum and Natural Gas on 24th May.
- ❖ Review meeting under chairmanship of Hon'ble Prime Minister on 27th May.

Statistics VSCS of bulletins issued by RSMC New Delhi, Area Cyclone Warning Centre Kolkata and CWC Visakhapatnam & Bhubaneswar in association with the VSCS YAAS are given in **Table 11-12.**

Table 11: Bulletins issued by Cyclone Warning Division, New Delhi

S.N	Bulletin	No. of Bulletins	Issued to
1	Bulletin from DGM IMD	6	To senior level Govt. Officials including Cabinet Secretary, Principal Secretary to Prime Minister, Secretary Ministry of Home Affairs, Ministry of Agriculture, Defence, Information & Broadcasting, Ministry of Earth Sciences, Deptt. of Science & Technology, Shipping & Surface Transport, Ministry of Home Affairs, Coast Guard, IAF, Indian Navy Director Punctuality, Indian Railways, Director All India Radio, Doordarshan, Secretary NDMA, Director General NDRF, Chief Secretaries of Tamilnadu, Andhra Pradesh, Andaman & Nicobar Islands, Puducherry, Odisha, West Bengal, Jharkhand, Assam, Sikkim, Bihar, Meghalaya, Uttar Pradesh.
2.	National Bulletins	34	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, PIB MoES, Headquarter Integrated Defence Staff, Coast Guard, IAF, Indian Navy Director General Doordarshan, All India Radio, National Disaster Response Force, UNI, Chief Secretary- Tamilnadu, Andhra Pradesh, Andaman & Nicobar Islands, Puducherry, Odisha, West Bengal, Jharkhand, Assam, Sikkim, Bihar, Meghalaya, Uttar Pradesh.
3	RSMC Bulletins	32	1. IMD's website 2. WMO/ESCAP member countries including Somalia and WMO through GTS and E-mail.
4	GMDSS Bulletins	32	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)

5	Tropical Cyclone Advisory Centre Bulletin (Text & GraphiVSCS)	13	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
6	Tropical Cyclone Vital Statistics VSCS	14	Modeling 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
7	Warnings through SMS	69,52,040	To disaster managers at national level and concerned states (every time when there was change in intensity)-130 To general public registered with RSMC website from the states of Odisha, West Bengal, Andhra Pradesh, Andaman & Nicobar Islands and National level disaster managers—2,97,785 To Fishermen through INCOIS on Ocean State Forecast- 36,69,472 To farmers of Andaman & Nicobar Islands, Odisha & West Bengal, Bihar & Jharkhand through Kisaan Portal-29,84,653
8	CAP Feeds	6.66 crores	Notifications were issued through Common Alerting Protocol
9	Notifications through Umang App	2,45,740	Notifications through Umang App
10	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 characteristiVSCS)
11	Hourly Bulletin	27	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, PIB MoES, Headquarter Integrated Defense Staff, Coast Guard, IAF, Indian Navy Director General Doordarshan, All India Radio, National Disaster Response Force, UNI, Chief Secretary- Kerala, Karnataka, Goa, Dadra & Nagar Haveli, Gujarat and Maharashtra and Administrator Lakshadweep Islands.
12	Press Release	10	Disaster Managers, Media persons by email and uploaded on website
13	Press Briefings	Frequently	Regular briefing daily

Table3: Statistics VSCS of bulletins issued by Area Cyclone Warning Centre Kolkata, Cyclone Warning Centre (CWC) Visakhapatnam and Bhubaneswar

S.N.	Type of Bulletin	ACWC Kolkata	CWC Bhubaneswar	CWC Visakhapatnam
1.	Sea Area Bulletins	16	-	-
2.	Coastal Weather Bulletins	16	31	13
3.	Fishermen Warnings	16	38	10
4.	Port Warnings	19	33	10
5.	Heavy Rainfall Warning	26	30	-
6.	Gale Wind Warning	18	23	-
7.	Storm Surge Warning	15	18	-
8.	Warning issued to State Government	28	36	5
9.	SMS	NIL	-	60
10.	No. of Press releases	26	10	5
11.	Impact based warnings	56	20	30
12.	Whatsapp messages	3,50,830	1,01,479	20
13.	Facebook updates	24	42	20
14.	No. of updates on tweeter	26	110	1
15.	Warning video released	1	12	-

14. . **Acknowledgement:**

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