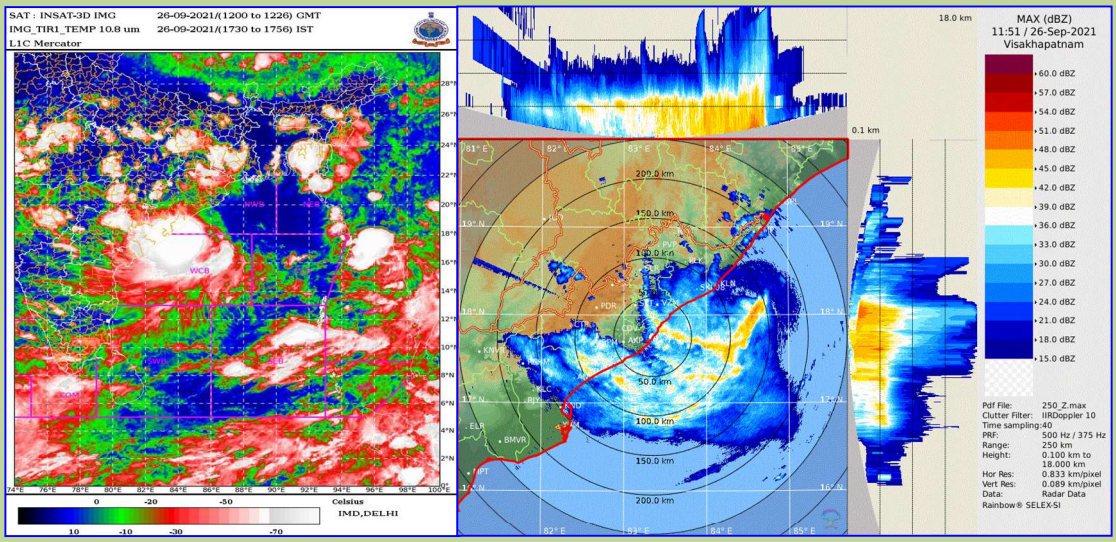
GOVERNMENT OF INDIA

MINISTRY OF EARTH SCIENCES

INDIA METEOROLOGICAL DEPARTMENT

Cyclonic Storm GULAB over Bay of Bengal during 24th – 28th September 2021



Typical satellite and radar imagery (DWR Visakhapatnam) at 1730 hours IST (1200 UTC) of 26th September on the day of landfall

Cyclone Warning Division

India Meteorological Department

New Delhi

September 2021

Cyclonic Storm GULAB over Bay of Bengal

(24–28th September 2021)

1. Life History:

- A low pressure area formed over eastcentral Bay of Bengal (BoB) and neighbourhood in the morning (0830 hours IST / 0300 UTC) of 24th September. It lay as a well marked low pressure area (WML) in the same afternoon (1430 hours IST) over eastcentral and adjoining northeast BoB.
- Under favourable environmental and Sea conditions, it concentrated into a **depression** over eastcentral and adjoining northeast BoB in the same evening (1730 hours IST/ 1200 UTC) of 24th September.
- Moving nearly westwards, it further intensified into a **deep depression** over north & adjoining central BoB in the early morning (0530 hours IST/ 0000 UTC) of 25th September.
- Continuing to move further westwards, it intensified into the Cyclonic Storm **"GULAB" (pronounced as GUL-AAB**) over northwest and adjoining west-central BoB in the same evening (1730 hours IST) of 25th September, 2021.
- Thereafter, it intensified gradually and reached it's peak intensity of 75-85 kmph gusting to 95 kmph around noon (1130 hours IST/0600 UTC) of 26th September.
- Continuing to move further westwards, it crossed North Andhra Pradesh and adjoining south Odisha coasts near Lat. 18.4°N/ Long. 84.2°E (20 km north of Kalingapatnam) with maximum sustained wind speed of 75-85 gusting to 95 kmph during 1930-2030 IST of 26th September.
- Thereafter, it weakened into a deep depression in the early hours (0230 hours IST) of 27th September over north Andhra Pradesh and adjoining south Odisha and into a depression over south Chhattisgarh in the evening (1730 hours IST) of 27th.
- It further weakened into a well marked Low pressure area over western parts of Vidarbha and neighbourhood around noon of 28th September.

Observed track of the system during 24th-28th September is presented in Fig.1.

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

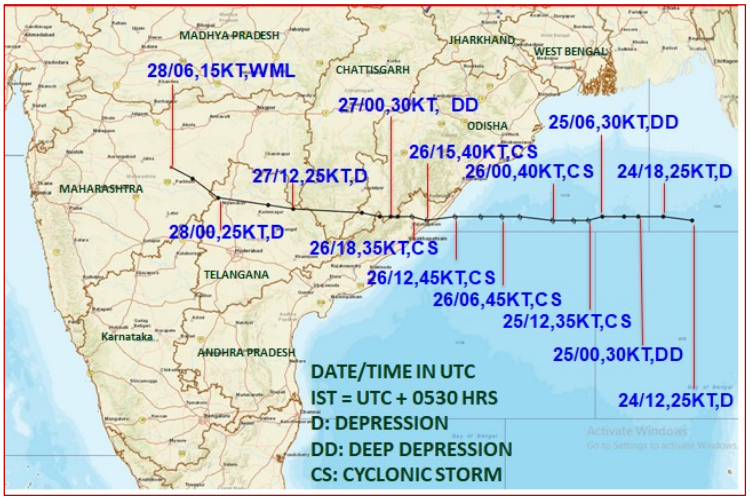


Fig. 1: Observed track of cyclonic storm "Gulab" during 24th – 28th September, 2021
KT: Knots (1 knot=1.86 kmph)

Table 1: Best track positions and other parameters of the Cyclonic Storm GULAB over Northwest Bay of Bengal and adjoining Odisha coast during 24 - 27 Sept, 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
24.09.2021	1200	18.3	91.2	1.5	1000	25	4	**D**
	1800	18.4	90.4	1.5	1000	25	4	D
25.09.2021	0000	18.4	89.7	2.0	999	30	5	**DD**
	0300	18.4	89.3	2.0	998	30	6	DD
	0600	18.4	88.7	2.0	998	30	6	DD
	1200	18.3	88.3	2.5	997	35	7	**CS**
	1500	18.3	88.1	2.5	997	35	7	CS
	1800	18.3	87.9	2.5	996	35	7	CS
	2100	18.3	87.6	2.5	996	35	7	CS
26.09.2021	0000	18.3	87.3	2.5	994	40	8	CS
	0300	18.4	86.4	2.5	994	40	8	CS
	0600	18.4	85.9	3.0	992	45	10	CS
	0900	18.4	85.3	3.0	992	45	10	CS
	1200	18.4	84.6	3.0	992	45	10	CS
		Crossed north Andhra Pradesh – south Odisha coasts near latitude 18.4^0 N and longitude 84.2^{0}E, about 20 km north of Kalingapatnam with a maximum sustained wind speed of 75-85 kmph gusting to 95 kmph during 1930 & 2030 hrs IST (1400-1500 UTC)						
	1500	18.3	83.8	-	992	45	10	CS
	1800	18.4	83.4	-	994	35	7	CS
	2100	18.4	83.0	-	996	30	6	**DD**
27.09.2021	0000	18.4	82.8	-	996	30	6	DD
	0300	18.4	82.5	-	996	30	6	DD
	0600	18.5	82.0	-	996	30	6	DD
	1200	18.6	80.1	-	998	25	4	**D**
	1800	18.7	79.4	-	998	25	4	D
28.09.2021	0000	19.0	78.2	-	998	25	4	D
	0300	19.4	77.3	-	999	20	3	D
	0600	Weakened into a well marked low pressure area over western parts of Vidarbha and neighbourhood						

2. Salient features:

- Climatologically, there had been 41 cyclonic storms (MSW≥34 knots) during 1891-2020 developing over the BoB region in the month of September. Out of these 15 were severe category storms (MSW≥48 knots). During this period there were 9 cyclones crossing Andhra Pradesh coast. Out of these there was 1 depression in the year 1948 (19 Sep. to 1 Oct.) that developed over eastcentral BoB, crossed central India, emerged into Arabian

Sea and intensified into a severe cyclonic storm. It crossed south Gujarat coast as a severe cyclonic storm and further emerged into Arabian Sea and crossed Oman coast as a depression. The climatological tracks are presented in Fig.2.

- The system developed during active phase of monsoon over Indian sub-continent. Warm Sea, warm moist air incursion into the core of the system, favourable Madden Julian Oscillation phase and low to moderate vertical wind shear over the region helped in development of cyclonic storm(CS), 'Gulab".
- It caused extremely heavy rainfall over Andhra Pradesh and heavy to very rainfall over Odisha.
- The system had a life period of about 90 hours against the long period average of 110 hours for cyclonic storms during monsoon season over the Bay of Bengal based on data during 1990-2013.
- The 12 hourly average translational speed of the system was 16.8 kmph against the long period average of 14.3 kmph based on data during 1990-2013(Fig. 3 a)
- The peak intensity of the system was 45 knots during 0600 to 1200 UTC of 26th (Fig. 3b).
- The velocity flux, accumulated cyclone energy and power dissipation index associated with the system were 2.35X10^2, 0.94 X10^4 and 0.38 X10^6 respectively.
- There had been a total of about 18 deaths in association with this system and its remnant over Andhra Pradesh, Telangana and Maharashtra.
- The system had a track length of 1440 km.

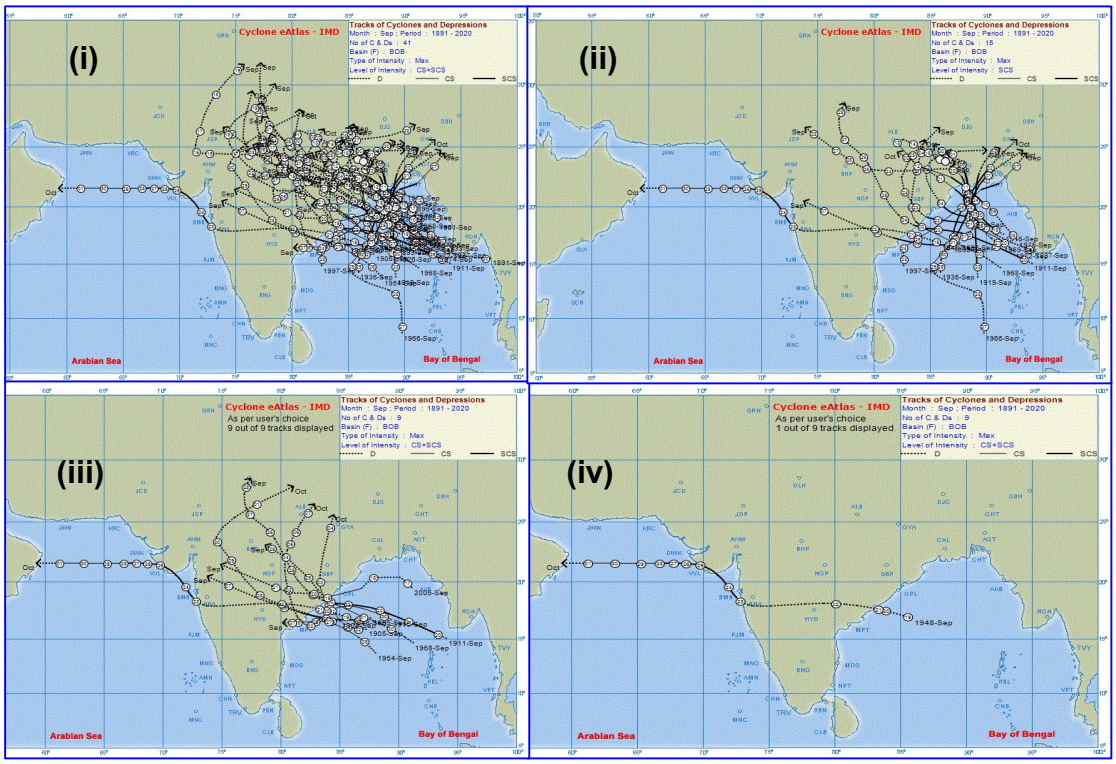


Fig.2: Tracks of (i) cyclones crossing east coast of India, (ii) severe cyclones crossing east coast of India, (iii) cyclones crossing Andhra Pradesh coast and (iv) cyclone crossing Andhra Pradesh coast and emerging into Arabian Sea (all during the month of September)

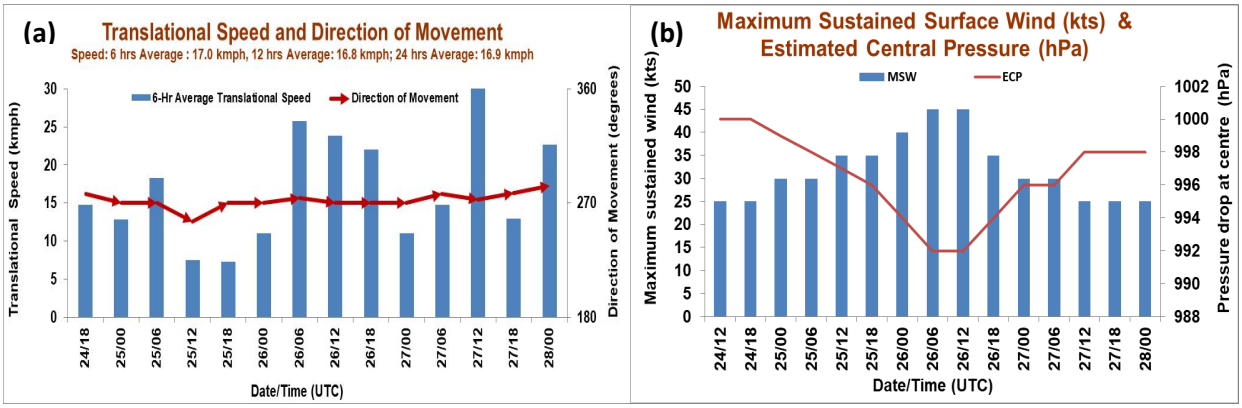


Fig. 3: (a) Average translational speed & direction of movement and (b) Maximum sustained surface wind speed (kts) & Estimated Central Pressure during life cycle of CS Gulab

3. Analysis of environmental features associated with the genesis, intensification & movement

3.1 Genesis

Under the influence of a cyclonic circulation over eastcentral BoB, a low pressure area formed over eastcentral BoB and neighbourhood at 0300 UTC of 24th September. On 24th, the Madden Julian Oscillation (MJO) index was lying in phase 4 with amplitude close to 1. The sea surface temperature (SST) was about 28-29°C over central & adjoining north BoB. The environmental conditions were also supportive. Under these conditions, the cyclonic circulation over eastcentral BoB concentrated into a low pressure area over eastcentral BoB and neighbourhood at 0300 UTC and further into a WML over eastcentral and adjoining northeast BoB at 0900 UTC of 24th September

At 1200 UTC, similar sea conditions prevailed over eastcentral BoB. A zone of positive low level vorticity ($80x10^{-6}s^{-1}$) lay to the south of system centre with vertical extension upto 200 hpa level. A zone of positive lower level convergence of 10 $x10^{-5}s^{-1}$ lay to the south of system centre. Positive upper level divergence of 10 $x10^{-5}s^{-1}$ lay to the south of system centre. The vertical wind shear (VWS) was low (05-10 kts) over north and adjoining central BoB. The sub-tropical ridge lay along 20.5^0N. Easterly to east-southeasterly winds to the south of the ridge steered the system nearly westwards. Under these favourable sea and environmental conditions, the system moved nearly westwards and intensified into a depression over eastcentral and adjoining northeast BoB at 1200 UTC of 24th September.

3.2. Intensification and movement

At 0000 UTC of 25th September, the positive low level vorticity increased and was about $100x10^{-6}s^{-1}$ around the system centre with vertical extension upto 500 hPa level. A zone of positive lower level convergence of 20 x10-5s-1 lay around the system centre. The positive upper level divergence also increased and was about 20 $x10^{-5}s^{-1}$ around the system centre. The vertical wind shear (VWS) was low (05-10 KTS) over north and adjoining central BoB. The sub-tropical ridge lay along lat. 20.5^0N. Easterly to east-southeasterly winds prevailing to the south of the ridge were steering the system nearly westwards. Under these favourable conditions the system moved nearly westwards and intensified into a deep depression at 0000 UTC of 25th over northwest and adjoining westcentral BoB. The mean wind speed and wind shear speed and direction during the life cycle of the system are presented in Fig. 4.

At 1200 UTC of 25th September, similar sea conditions prevailed over central and northwest BoB. MJO index was lying in phase 5 with amplitude close to 1, thereafter it was likely to move to phase 4 with amplitude becoming more than 1 for next 5 days. Thus, MJO was likely to support convective activity over the BoB region. Similar favourable environmental conditions prevailed with positive low level vorticity of $100x10^{-6}s^{-1}$ around the system centre and with vertical extension upto upper tropospheric level. Positive lower level convergence of 10 $x10^{-5}$s-1 lay to the northwest of system centre. Positive upper level divergence of 10 $x10^{-5}s^{-1}$ lay over the system centre. VWS was moderate (15-20 KTS) over northwest and adjoining central BoB and along the forecast track. The easterly to east-northeasterly winds prevailing over the system area in association with the anticyclone lying over the north India steered the system nearly westwards and it intensified into a cyclonic storm "Gulab".

At 0600 UTC of 26th September, favourable MJO and sea conditions prevailed. The positive low level vorticity increased further (150x10-6s-1) around the system centre with vertical extension upto mid tropospheric level. Positive lower level convergence increased and was around 20 $x10^{-5}s^{-1}$ to the southwest of system centre. Positive upper level divergence also increased and was about 20 $x10^{-5}s^{-1}$ to the southwest of system centre. However, VWS was moderate to high (20-25 kt) over northwest and adjoining central BoB and along the forecast track. The upper tropospheric ridge lay along 25°N. The system was lying in the southern periphery of the ridge near 25°N and was thus steered nearly westwards. Under these conditions, the system while moving nearly westwards, intensified further and reached it's peak intensity of 45 kt at 0600 UTC of 26th.

Continuing to move further westwards, the system crossed north Andhra Pradesh – south Odisha coasts near 18.4^0 N/84.2^0E, about 20 km north of Kalingapatnam with a maximum sustained wind speed of 75-85 kmph gusting to 95 kmph during 1400-1500 UTC of 26th.

Thereafter, due to land interactions, increased VWS and decreased moisture supply into the core of the system, it weakened into a deep depression at 2100 UTC of 26th, into a depression at 1200 UTC of 27th and into a WML over western parts of Vidarbha and neighbourhood at 0600 UTC of 27th.

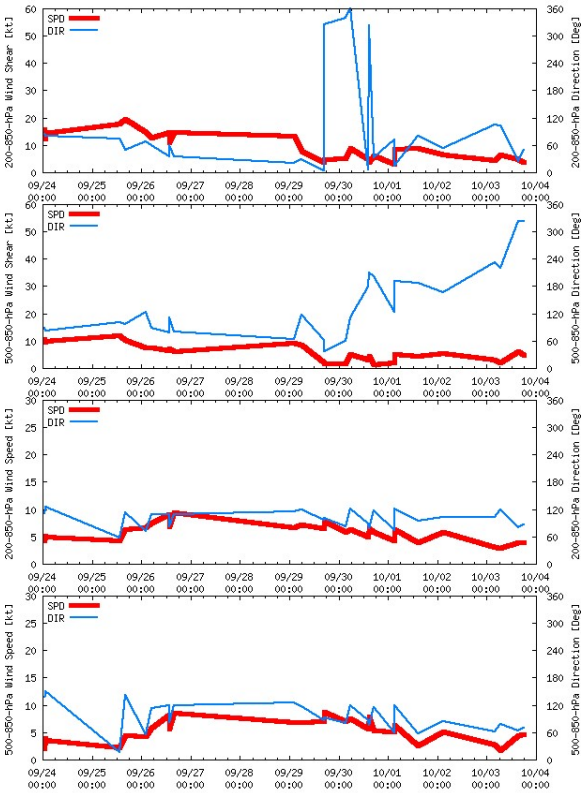


Fig.4: Mean wind shear and wind speed in the middle and deep layer around the system during 24-28 September, 2021

4 Monitoring:

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the system was monitored since 16th September, about 8 days prior to the formation of LPA over eastcentral BoB on 24th. The cyclone was monitored with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites and available ships & buoy observations in the region. The system was also monitored by Doppler Weather RADAR (DWR) Visakhapatnam (Andhra Pradesh). 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 system as well as associated adverse weather. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation.

4.1 Features observed through Satellite

Detailed satellite imageries from INSAT-3D, ASCAT & Microwave utilized for monitoring of CS Gulab are presented in Fig. 5 (a-f) respectively. As per INSAT 3D imagery at 1200 UTC of 24th September, convection over eastcentral & adjoining northeast BOB indicated further organization. The clouds got organized in curved band pattern. Associated minimum CTT was -93^{0}C. Intensity of the system was categorised as T 1.5. Associated broken low and medium clouds with embedded intense to very intense convection lay over eastcentral & adjoining northeast BOB and Arakan coast.

At 0000 UTC of 25th September, associated minimum CTT was -93^{0}C. Intensity of the system was categorised as T2.0. Associated broken low and medium clouds with embedded intense to very intense convection lay over north and adjoning central BoB.

At 1200 UTC of 25th Sep., there was gradual organisation of convection. The intensity of the system was categorised as T 2.5. Clouds were organised in CDO pattern. Minimum cloud top temperature was -93^{0}C. Total precipitable water vapour imagery at 0740 UTC of 25th indicated good warm moist air incursion into the core of system. Associated broken low and medium clouds with embedded intense to very intense convection lay over north and adjoining central BoB between latitude 16.0°N& 20.0°N and longitude 87.0°E& 91.5°E .

At 0600 UTC of 26th Sep., the clouds got organized in curved band pattern. The area of deep convection was seen to the west of low level circulation centre under the influence of easterly vertical wind shear. The intensity of the system was categorised as T 2.5. Minimum CTT was -93^0 C. Associated broken low and medium clouds with embedded intense to very intense convection lay over northwest and adjoining westcentral BoB between latitude 16.0°N & 19.5°N & longitude 83.5°E & 87.0°E and south coastal Odisha & north coastal Andhra Pradesh.

At 1200 UTC of 26th Sep., the intensity of the system was categorised as T 2.5. Minimum CTT was -93^{0}C. Associated broken low and medium clouds with embedded intense to very intense convection lay over northwest and adjoining westcentral BoB between latitude 15.5°N to 19.0°N and longitude 81.5°E to 85.5°E and south coastal Odisha & north coastal Andhra Pradesh.

At 2100 UTC of 26th Sep. minimum CTT was -93^{0}C. Associated broken low/medium clouds with embeded intense to very intense convection over coastal Andhra Pradesh adjoining Odisha, east Telangana adjoining south Chattisgarh and over west-central BoB between latitude 14.0^0 N to 18.5^0 N and longitude 80.0^0 E to 86.5^0 E.

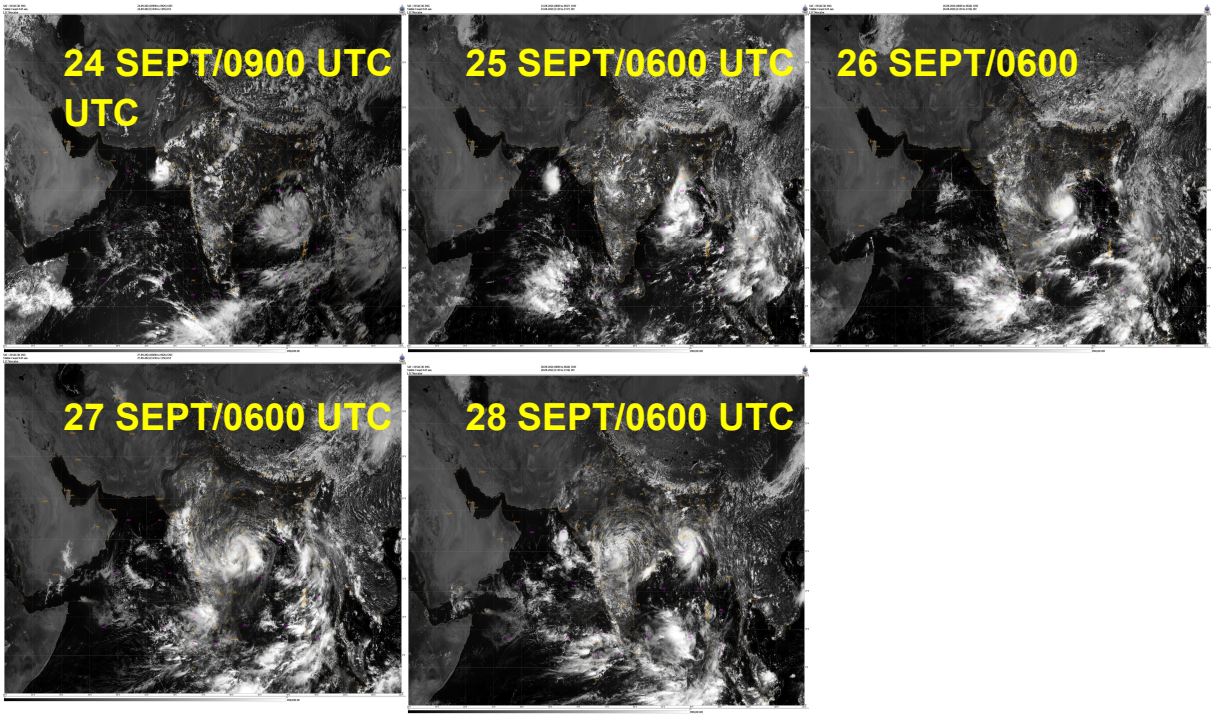


Fig. 5(a): INSAT-3D visible imageries during 24-28 September, 2021

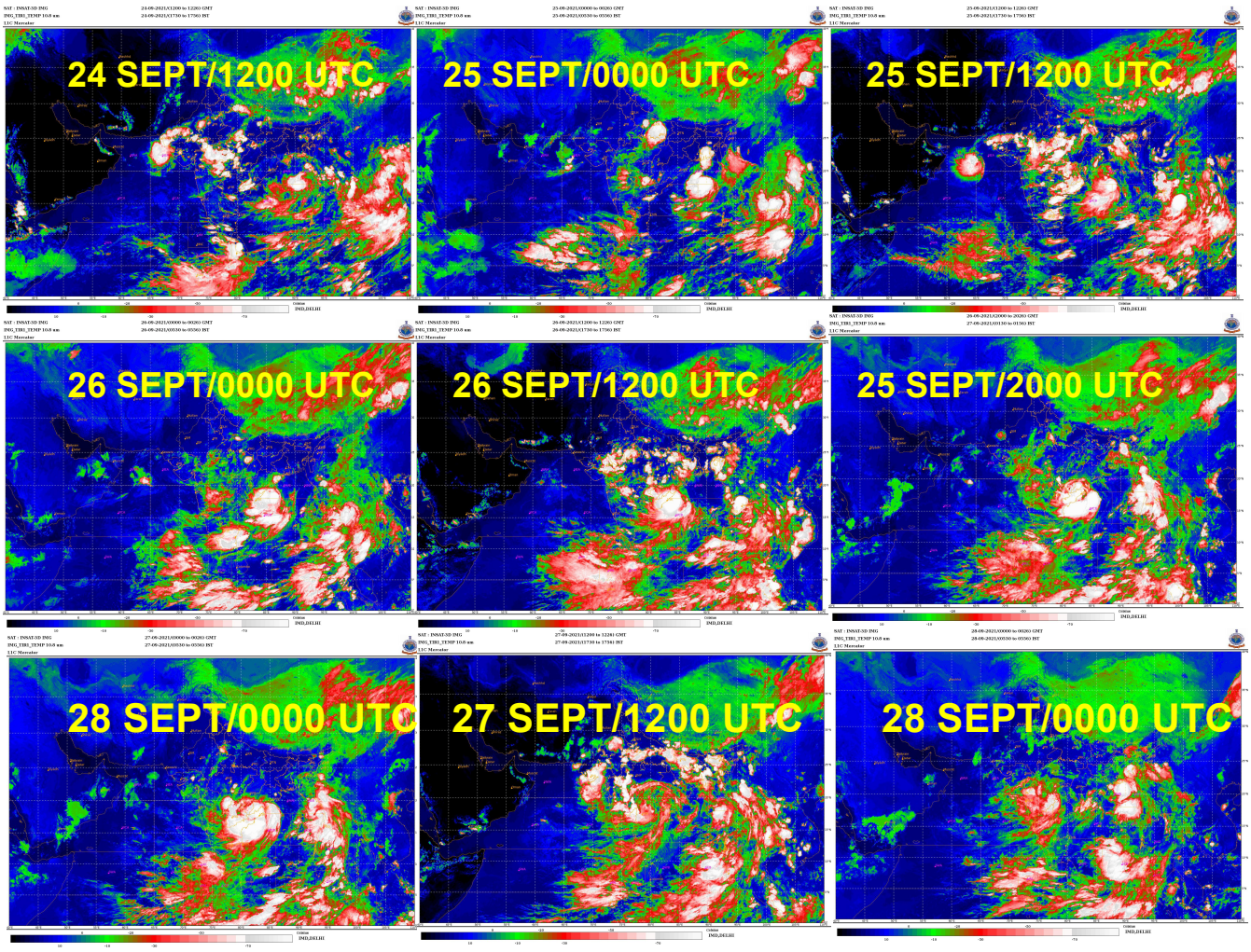


Fig. 5(b): INSAT-3D colour enhanced imageries during 24-28 September, 2021

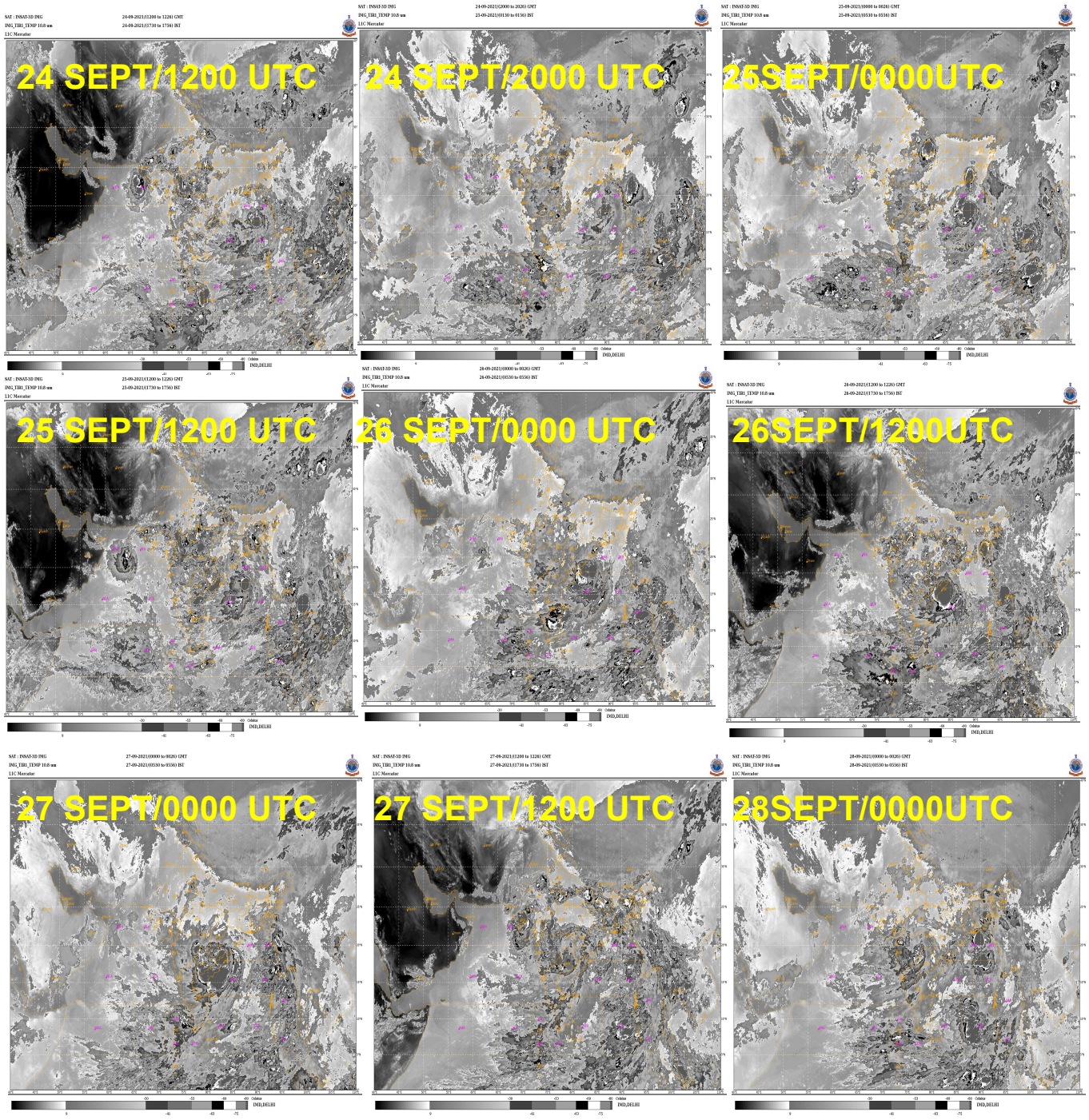


Fig. 5(c): INSAT-3D BD imageries during 24-28 September, 2021

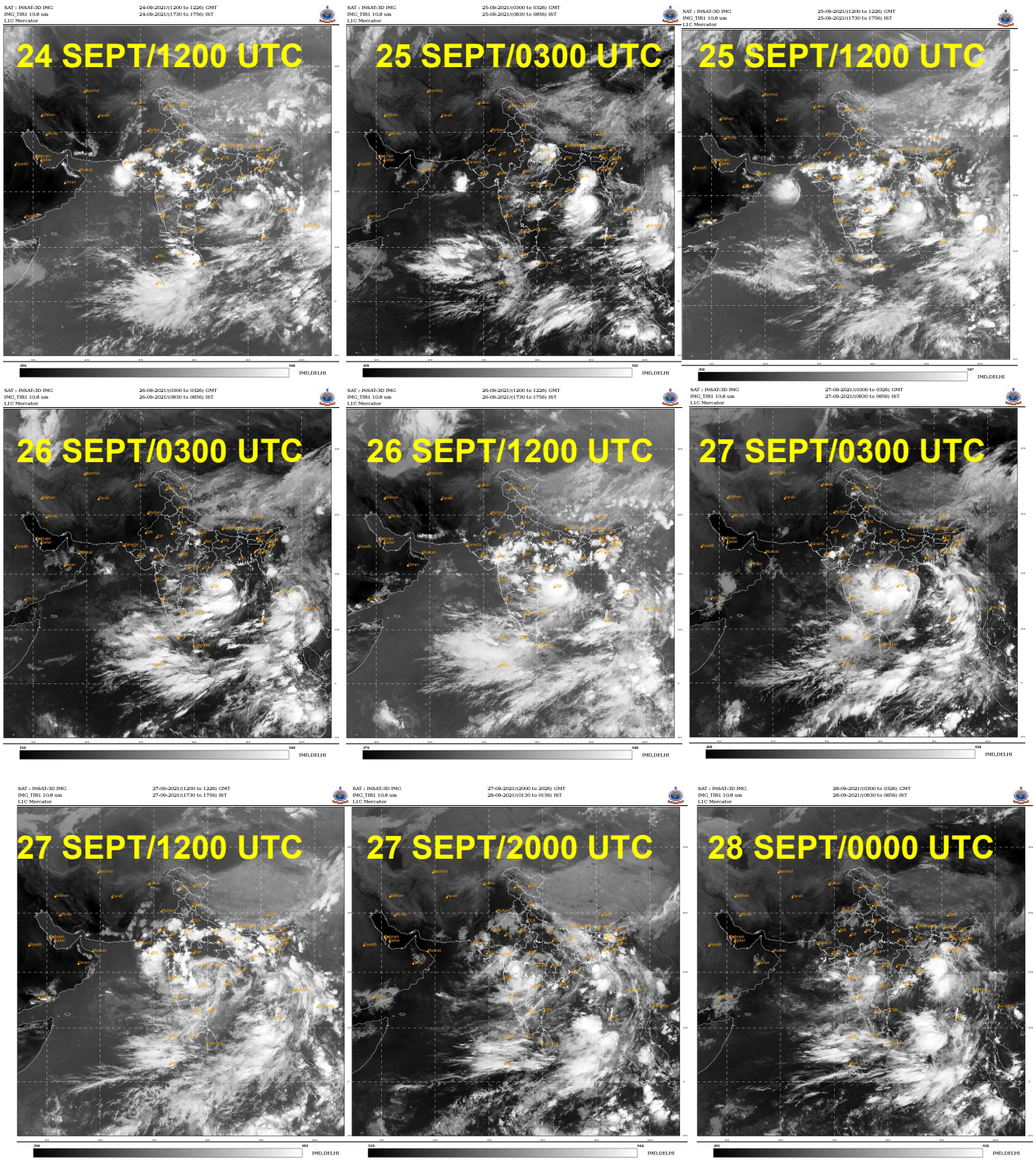


Fig. 5(d): INSAT-3D IR1 imageries during 24-28 September, 2021

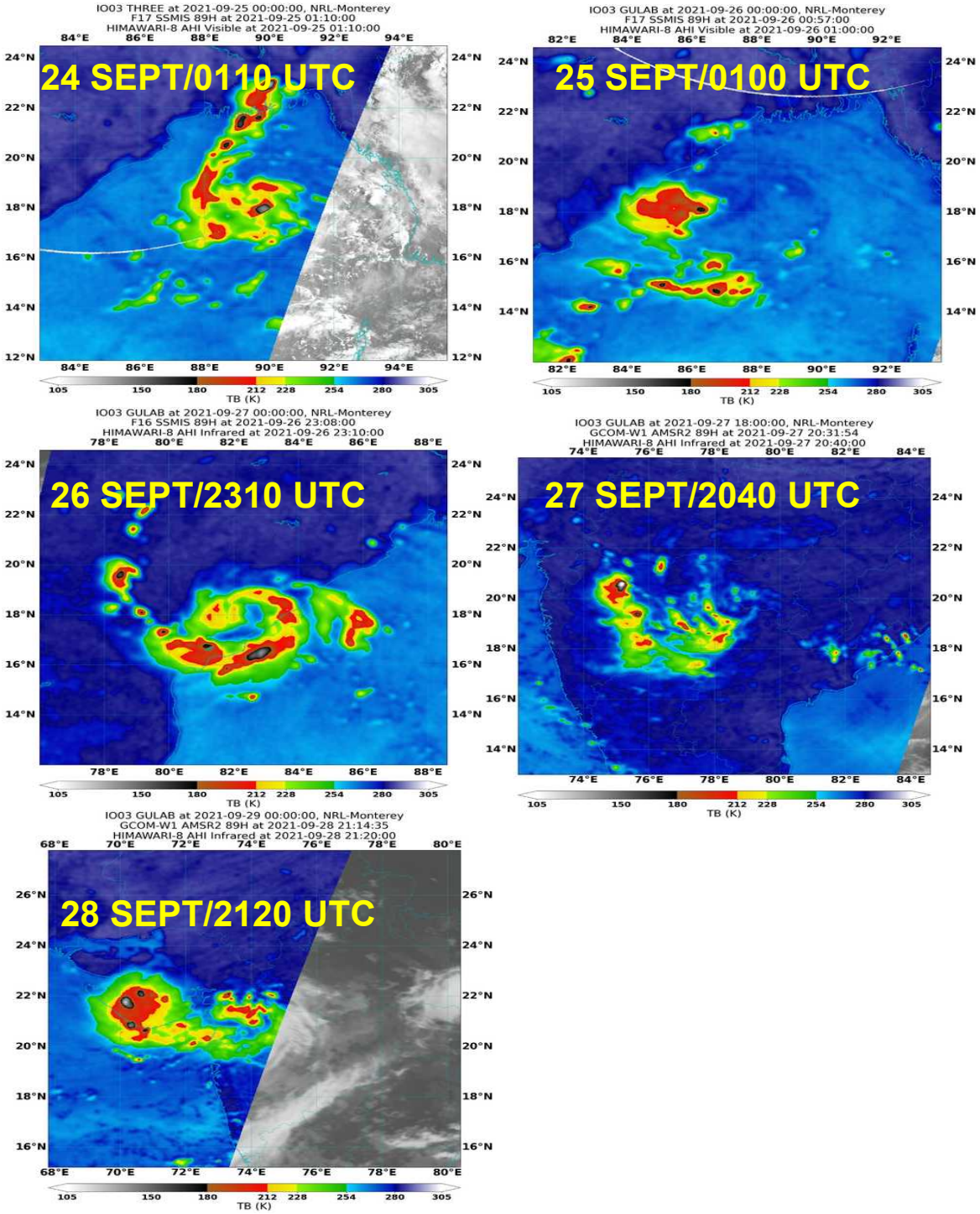


Fig. 5(e): Microwave imageries during life cycle of CS GULAB during 24-28 September, 2021

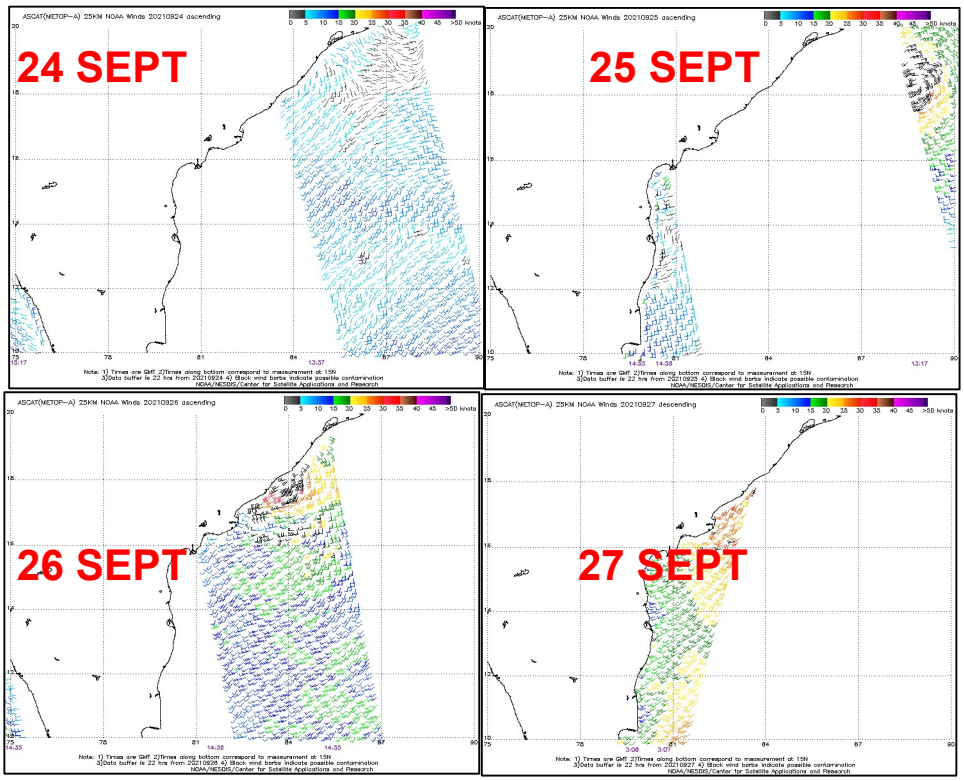


Fig. 5(f): ASCAT imageries during 24-27 September, 2021

4.2 Doppler Weather RADAR based observations

CS GULAB was monitored by the Doppler Weather Radars (DWR) at Vishakhapattanam on 26th September. Typical radar imageries are presented in Fig. 6. It could indicate the curved bands and deep convection in association with the system.

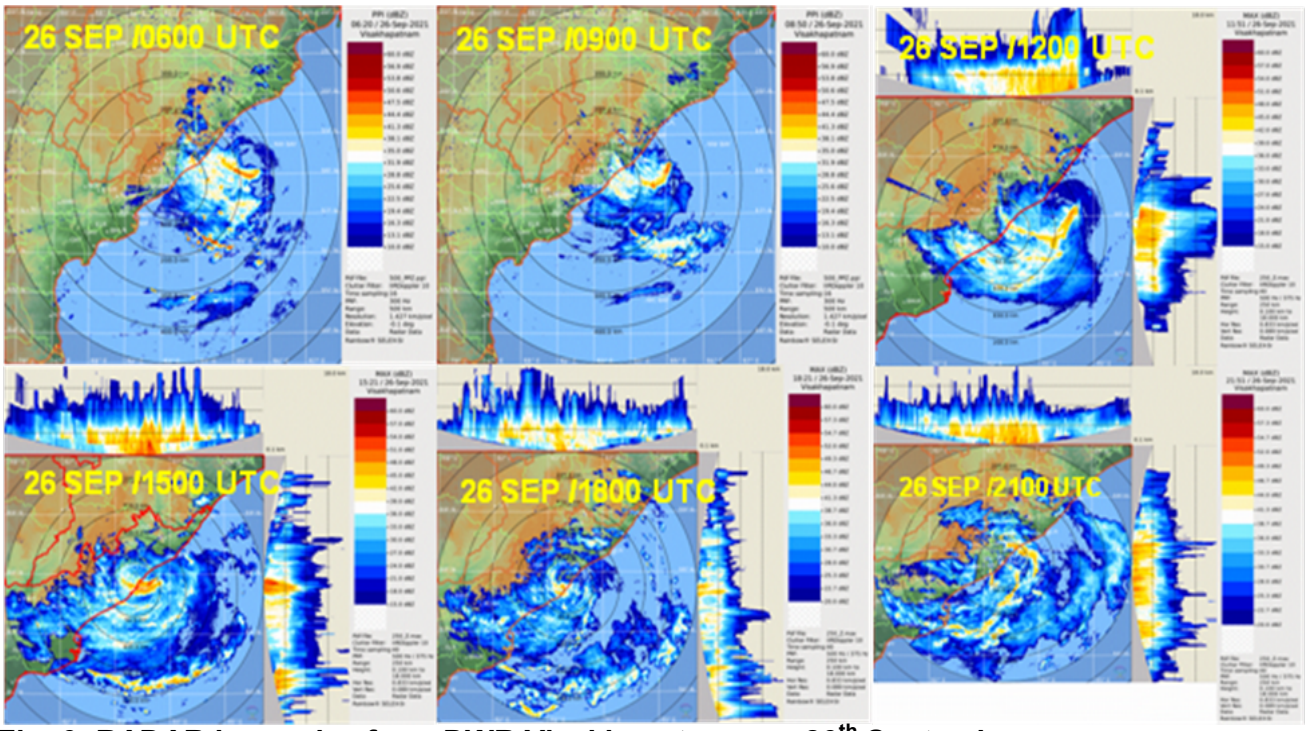


Fig. 6: RADAR imageries from DWR Visakhapatnam on 26th September

5 Dynamical Features

IMD GFS analysis of mean sea level pressure, winds at 10m, 850 hPa, 500 hPa and 200 hPa levels based on 0000 UTC during 24th-28th September are presented in Fig. 7 (a-e). On 24th IMD GFS was not capturing low pressure area over eastcentral BoB.

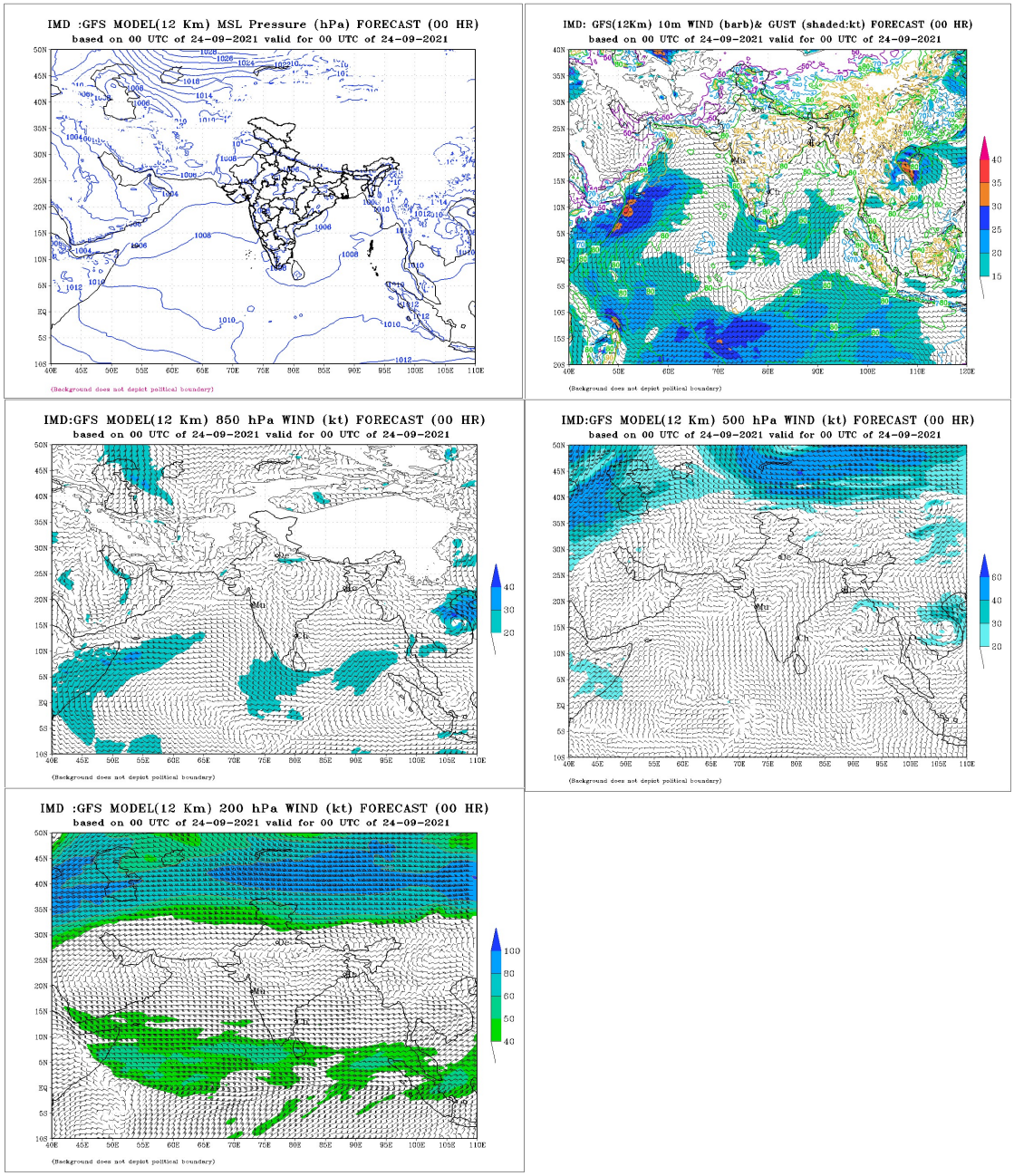


Fig. 7 (a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 24th September, 2021

The analysis fields based on 0000 UTC of 25th indicated a low pressure area over eastcentral BoB. However, at that time, the system lay as a deep depression over westcentral & adjoining northwest BoB. However, it could capture easterly flow over central and adjoining north BoB.

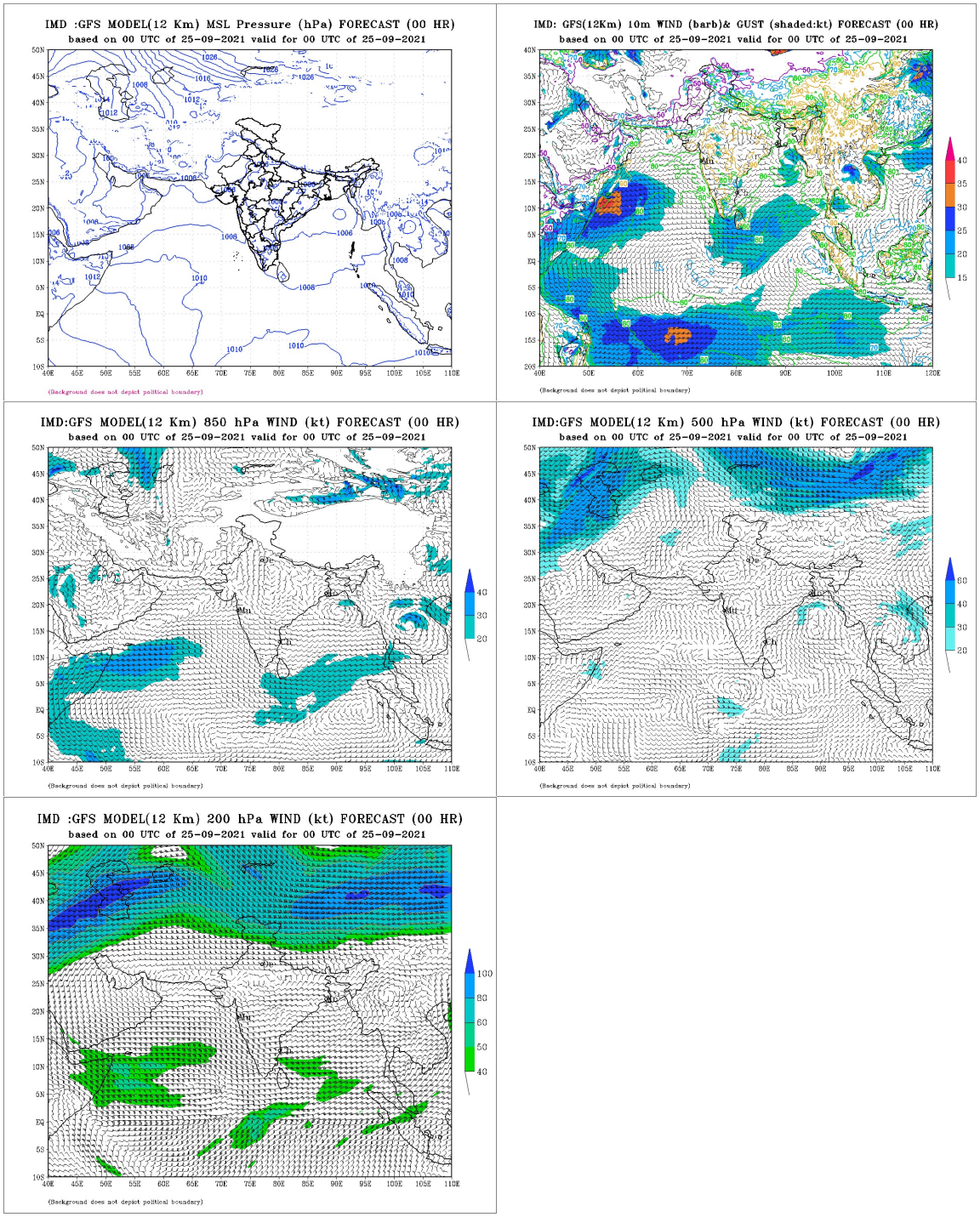


Fig. 7(b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 25th September, 2021

The analysis fields based on 0000 UTC of 26th indicated a cyclonic storm over westcentral BoB off north Andhra Pradesh and south Odisha coasts. The system extended vertically upto 500 hPa. At that time, the system lay as a cyclonic storm over northwest & adjoining westcentral BoB. The easterly flow over central and adjoining north BoB was also well captured.

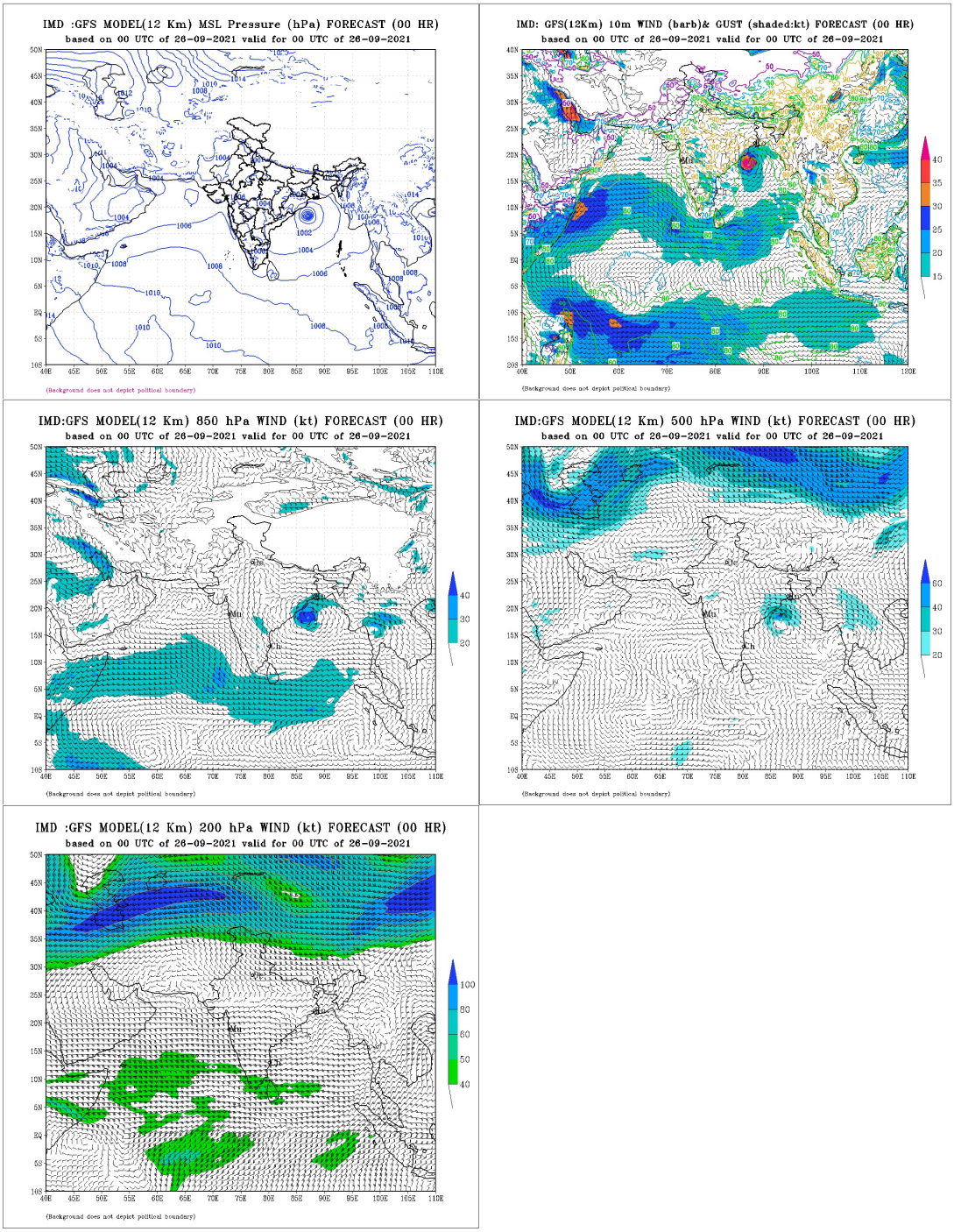


Fig. 7 (c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 26th September, 2021

The analysis fields based on 0000 UTC of 27th indicated that the system lay over northern parts of Andhra Pradesh as a depression. However, the system lay as a deep depression over south Odisha and adjoining Chattisgarh at that time.

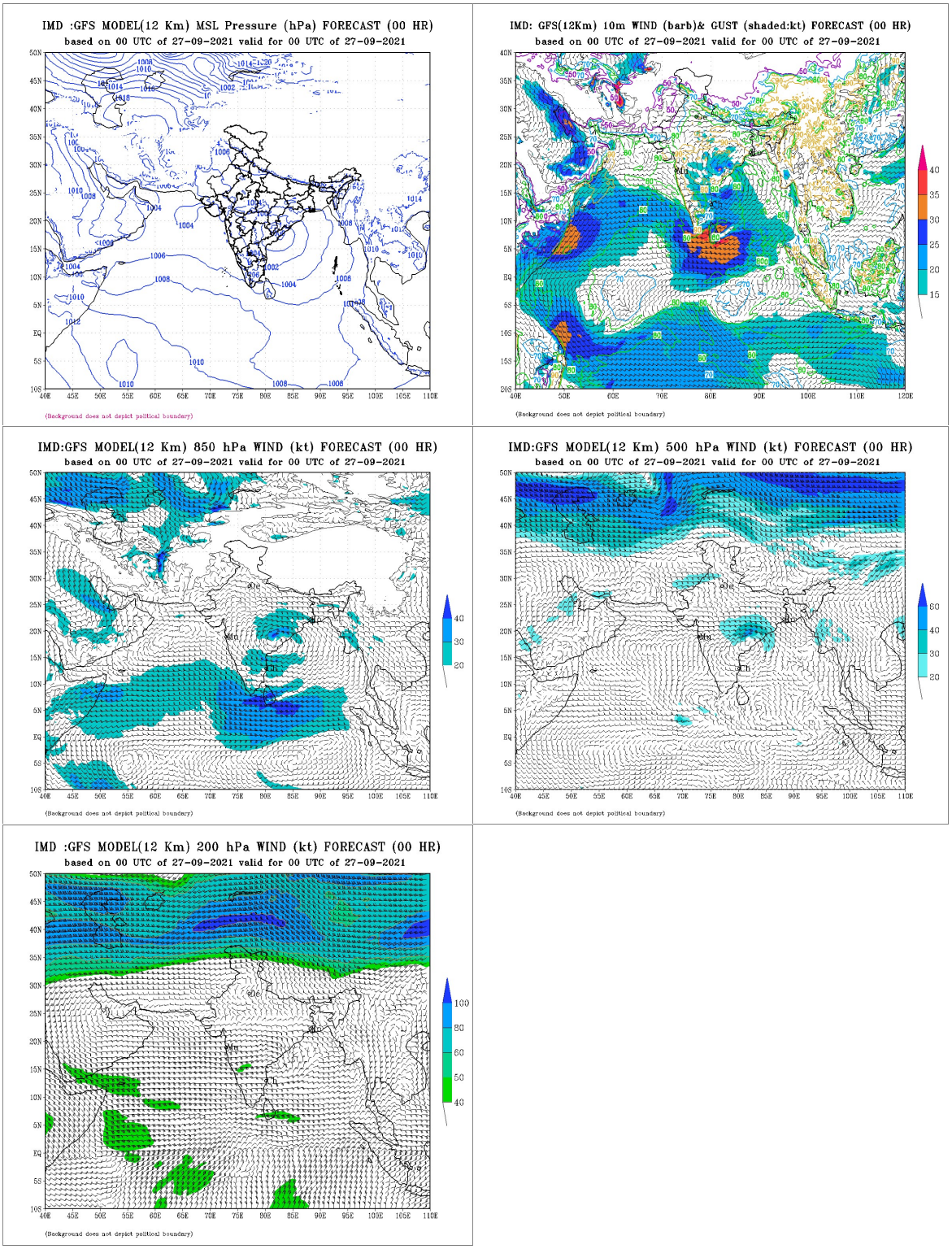


Fig. 7 (d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 27th September, 2021

The analysis fields based on 0000 UTC of 28th indicated that the system lay over north Telangana and adjoining Vidarbha as a depression with vertical extension upto 500 hPa level. The easterly flow in the upper levels that was steering the system westwards was also well captured.

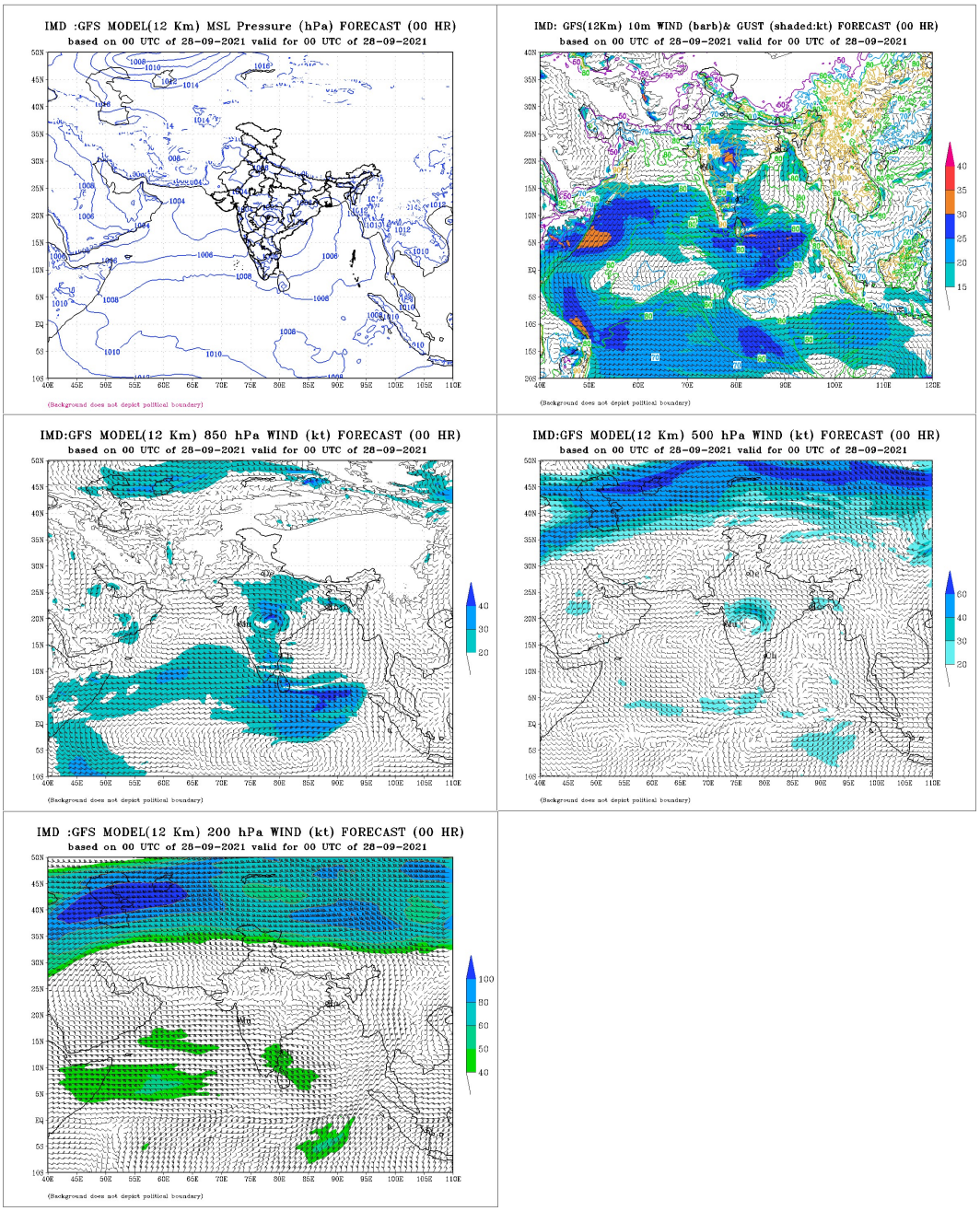


Fig. 7 (e): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 28th September, 2021

Thus, initially IMD GFS underestimated the intensity of the system. However, from 25th onwards, it correctly picked the intensity. It was lagging behind the best track positions as far as location and movement of the system concerned.

6. Realised Weather:

6.1. Rainfall

Rainfall associated with CS Gulab based on IMD-NCMRWF GPM and gauge merged 24 hours cumulative rainfall ending at 0830 IST of date is depicted in Fig 8. The figure shows that on 22nd & 23rd, when the system was in developing stage, it caused heavy rainfall at a few places over eastcentral BoB and eastcentral & adjoining northeast BoB respectively. The region of heavy to very heavy rainfall gradually moved westwards towards westcentral BoB during 24th & 25th. On 26th, it caused heavy to extremely heavy rainfall at a few places over north coastal Andhra Pradesh & adjoining south Odisha coasts. On 27th, the system caused heavy to very heavy rainfall over central parts of India extending from coastal Andhra Pradesh, Telangana, Madhya Pradesh, Marathwada, Gujarat region. On 28th Gujarat and Saurashtra region witnessed heavy to very heavy falls with extremely heavy rainfall at isolated places.

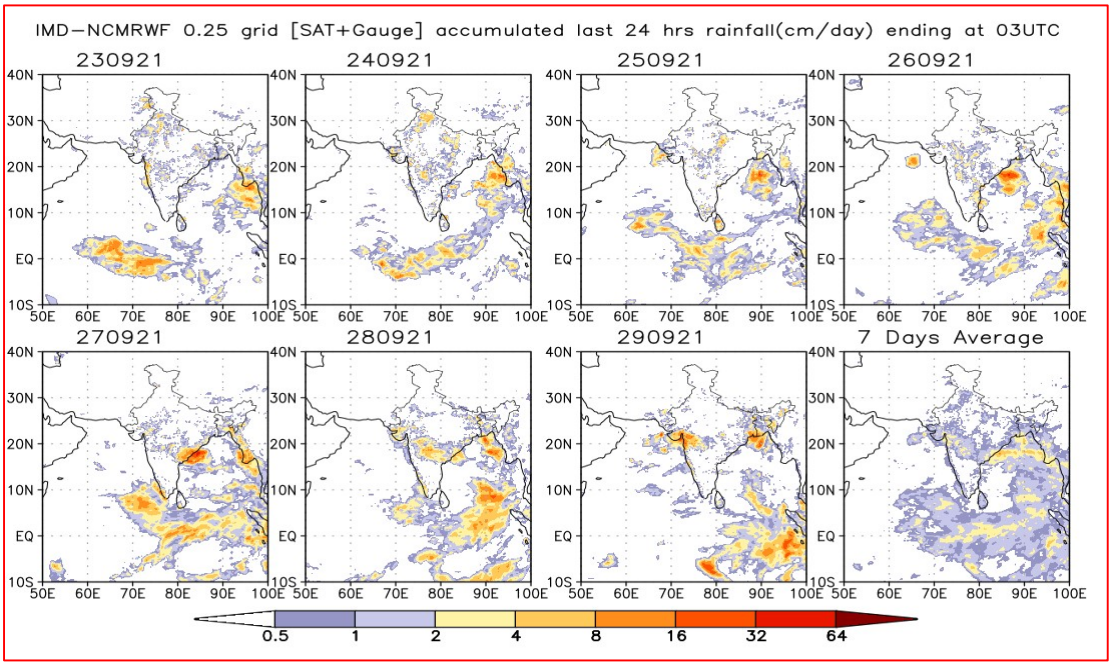


Fig.8: IMD-NCMRWF GPM and gauge merged 24 hour cumulative rainfall (cm) ending at 0830 IST of date during 23rd–29th September and 7 days average rainfall (cm/day)

Significant amounts of Rainfall (≥7cm) reported during the 24 hour period ending at 0830 hrs IST of date in cm are as follows:

<u>26.09.2021</u>
Odisha: Khariar-7
Coastal Andhra Pradesh & Yanam: Avanigada-14, Bapatla-7
Telangana: Golkonda-10, Sangareddy-10, Domakonda-8, Chandur-8,

TamilNadu, Puducherry and Karaikal: Marakkanam-13, Neyveli-8, Kurinjipadi-7, Cuddalore-7,

27.09.2021

Coastal Andhra Pradesh & Yanam : Visakhapatnam, Gajapathinagaram and Nellimarla - 28 each, Mentada - 25, Pusapatirega - 24, Garividi, Denkada and Gantyada - 19 each, Anakapalle and Salur - 18 each, Bondapalle 17, Cheepurupalle 16, Ranastalam and Therlam - 15 each, Chodavaram - 14, Vizianagaram, Vepada, Bheemunipatnam and Kalingapatnam 13 each, Bobbili, Araku Valley and Amalapuram - 12 each, Kakinada , Merakamudidam and Vijayawada - 11 each, Polavaram, Palakoderu, Chintalapudi and Koyyalagudem - 10 each, Chintapalle , Srungavarapukota, Palakonda, Tadepalligudem, Narsipatnam, Yanam, Bhimadole, Tanuku and Yelamanchili - 9 each, Palasa, Nuzvid, Seethanagaram and Parvathipuram - 8 each, Vararamachandrapur, Paderu, Balajipeta, Chintur, Eluru, Mandasa, Garugubilli, Tekkali, Kaikalur and Velairpad - 7 each.

Odisha: Pottangi - 15, Mahendragarh - 9, Mohana and Nandapur - 8, Lamataput , Semiliguda and R.Udayagiri - 7 each

28.09.2021

Odisha: Cuttack-13, Gajapati-8, Jajpur-7;

Chhattisgarh: Dantewada-18;

Coastal Andhra Pradesh & Yanam: Vishakhapatnam and West Godavari-13 each; Krishna and Vijaywada-8 each;

Telangana: Jakranpalle 23, Navipet 21, Dhar Palle 21, Ranjal , Dich Palle & Armur 18 each, Nandipet, Chandurthi & Sirsilla 17 each, Jammikunta & Bheemgal 16 each, Yeda Palle, Makloor , Ellanthukunta, Jukkal, Sarangapurnrl & Velpur 15 each, Nizamabad, Bodhan, Nirmal, Shriramsag pocha & Dilawarpur 14 each, Mudhole, Mogullapalle, Mallapur, Balkonda & Laxmanchanda 13 each, Srirampur, Nizam Sagar & Domakonda 12 each, Mortad, Venkatapur, Gundala, Elagaid, Tadwai Mlg & Peddapalle 11 each, Kusumanchi, Naga Reddipet, Konaraopeta, Kammar Palle,Metpalle, Madhira, Manthani, Machareddy & Bhiknur – 10 each, Sultanabad, Parkal, Kamareddy, Burgampadu, Pinapaka, Chegunta, Khanpur, Gambhiraopet,Thimmapur, Banswada, Madnur, Mulug, Boath, Ibrahimpatnam & Julapalle 9 each, Mustabad, Shadnagar, Choppadandi, Shayampet, Shamirpet, Papannapet, Karimnagar,Pitlam, Tupran, Govindaraopet, Dharmaram, Aswapuram & Dummugudem – 8 each and Yellareddypeta, Varni, Hakimpet, Kotgiri, Ramgundam, Bhupalpalle, Manuguru, Karimnagar, Venkatapuram, Manchal,Tekmal, Chigurumamidy, Lingampet, Birkoor, Bomraspeta, Ramayampet, Kothaguda,Bejjanki, Narayankhed, Tadwai, Kondurg, Bhadrachalam, Medak, Sadasivanagar – 7 each

Marathwada: Nanded-15, Aurangabad-13, Beed-11; Osmanabad and Latur-10 each; Jalna 8, Hingoli and Parbhani-7 each;

Vidarbha: Chandrapur-10; Buldana-9;

Madhya Maharashtra: Jalgaon-11, Kolhapur-7;

West Madhya Pradesh: Dewas-7;

Gujarat Region: Mehsana-9; Saurashtra & Kutch: Amreli-12, Gir Somnath-8. Jamnagar, Junagarh, Morbi and Porbandar-7 each

29.09.2021

Gujarat Region: Khanvel-37, Silvassa-22 & Umerpada-22 each, Palsana-19, Bharuch-18, Maktampur & Madhbun-17 each, Dang, Nanipalson & Garudeshwar-16, Kaprada, Dholera, Tilakwada & Dediapada-15 each, Khambhat & Nizer-14 each, Hansot, Narmadakvk & Dangkvk-13 each, Waghai-12, Rajpipala, Kukarmunda, Uchchhal & Dholka-11 each, Subir, Dhandhuka, Choryasi, Nandod, Ukai, Valsad & Naswadi-10 each, Vagra, Surat City, Gandevi, Valia, Ankleshwer, Vansda, Sagbara, Kamrej, Surat, Khergam, Tarapur, Borsad & Pardi-9 each, Vadodara, Songadh, Daman, Netrang & Jhagadia-8 each, Navasari, Vapi, Dharampur, Sojitra, Mahuva, Nadiad, Bardoli, Karjan, Arnej, Dabhoi, Umergam & Valod-7 each

Saurashtra & Kutch: Jamnagar-14, Targhadia-11, Lodhika, Gondal & Barvala-10 each, Rajkot, Kotdasangani & Botad-9 each, Chuda, Junagadh & Babra-8 each, Chotila, Jamkandorna, Vadia, Chotila, Jetpur & Dhoraji-7 each

Madhya Maharashtra: Shahada-18, Harsul-15, Akkalkuwa & Shrirampur-14 each, Peth-13, Surgana, Taloda & Jamner-12 each, Nandurbar, Igatpuri & Yeola-11 each, Ozharkheda-10, Dhadgaon/Akrani, Trimbakshwar & Lonavala-9 each, Nandgaon & Girnadam-8, Shirpur, Savlivihir Agri, Parola, Pachora & Bhadgaon-7 each

Marathwada: Khultabad-14, Vaijapur-11, Paithan-10, Gangapur-9, Kannad-7,

6.2. Realised wind

Maximum Wind Speed of 52 knots (95 kmph) was reported at Kalingapatnam on 26.09.2021 at 1349 UTC (19:19 hrs IST) around the time of landfall.

7. Performance of operational NWP models

IMD operationally runs a regional model, a Global model T1534 for medium range prediction (10 days), a regional Weather Research & Forecast Model (WRF) for short-range prediction (3 days) and a cyclone specific ocean atmosphere coupled Hurricane Weather Research & Forecast (HWRF) model for short to medium range prediction (5 days). The GFS T1534 is run at 12 km resolution in horizontal over the tropics with ENKF based Grid point Statistical Interpolation (GSI) scheme as the global data assimilation scheme for the forecast up to 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 45^0N long 40^0E to 120^0E. 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. The HWRF is run at horizontal resolution of 18 km for parent domain and 6km & 2 km for intermediate and innermost nested domains following the center of cyclonic storm. The model is run with 61 vertical

levels with parent domain, intermediate and innermost domain covering area of 80^{o}x80^{o}, 24^{o}x24^{o} and 7^{o} x7^{o} respectively.

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 (T 3.0) and forecast for potential cyclogenesis zone. The multi-model ensemble (MME) for predicting the track (at 12h interval up to 120h) of tropical cyclones for the Indian Seas is developed applying multiple linear regression technique using the member models, viz., IMD-GFS, IMD-UKMO, GFS (NCEP), ECMWF and JMA. The statistical cyclone intensity prediction (SCIP) model is used for 12 hourly intensity predictions up to 72-h and a rapid intensification index (RII) is used for the probability forecast of rapid intensification (RI). Decay model is used for prediction of intensity after landfall.

National Centre for Medium Range weather Forecasting (NCMRWF) Centre also runs global (NCUM-G), regional (NCUM-R) Unified Model adapted from UK Meteorological Office. NCUM-G has a horizontal grid resolution of ~12 km and 70 vertical levels. NCUM-R has a horizontal grid resolution of ~4 km and 80 vertical levels.

In addition, the Ministry of Earth Sciences (MoES) has commissioned two very high resolution (12 km grid scale) state-of-the-art global Ensemble Prediction Systems (EPS) for generating operational 10-days probabilistic forecasts of weather. The EPS involves the generation of multiple forecasts by slightly varying initial conditions. The Global Ensemble Forecast System (GEFS) model is run at Indian Institute of Tropical Meteorology (IITM) Pune and NCMRWF EPS (NEPS) is run at NCMRWF. These models are run twice a day based on 00 & 12 UTC initial conditions. The performance of these individual models is presented in following sections.

7.1 Prediction of cyclogenesis(Genesis Potential Parameter (GPP)) for CS GULAB

Fig. 9 (a-d) shows the analysis and forecast fields of GPP based on 0000 UTC of 25th September. It indicates the potential zone of cyclogenesis over eastcentral BoB with gradual westwards movement towards south Odisha-north Andhra Pradesh coasts.

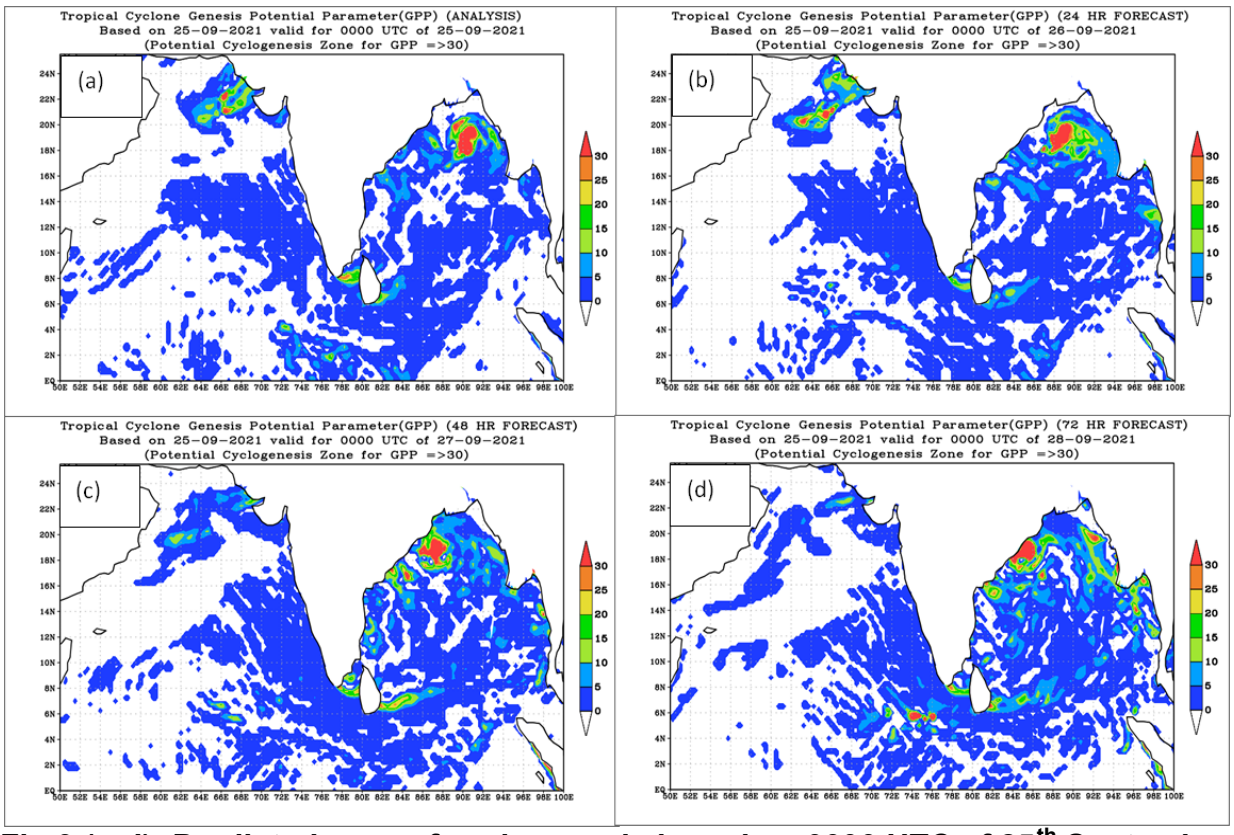


Fig.9 (a-d): Predicted zone of cyclogenesis based on 0000 UTC of 25th September, 2021

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 the system to develop into a CS and average GPP < 8.0 indicates a non-developing system. The area average analysis of GPP based on 0000 UTC of 25th Sept is presented in Fig. 10. The area average analysis predicted the system to develop into a CS from 0000 UTC run of 25th September.

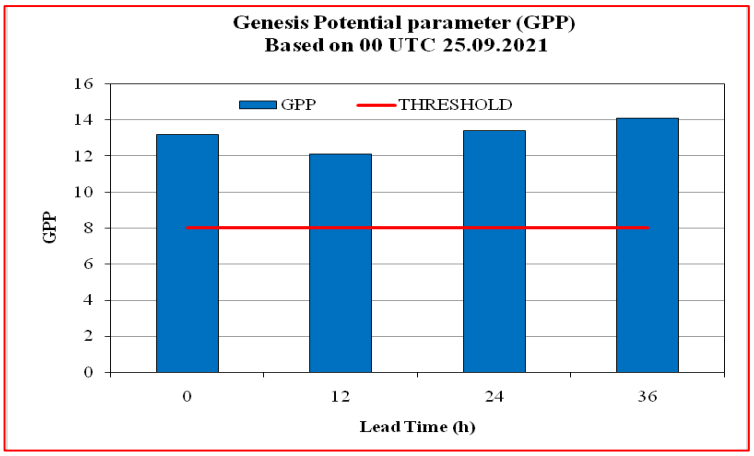


Fig. 10: Area average analysis and forecasts of GPP based on 0000 UTC of 25.09.2021.

7.2 Track prediction by NWP models

Tracks predicted by various NWP models including IMD GFS, IMD MME, IMD HWRF, WRF-VAR, NCMRWF Unified Model (NCUM), UM Regional, NCMRWF Ensemble Prediction System (NEPS), NCEP GFS, ECMWF, UKMO and JMA during 25th to 26th Sept are presented in Fig.11. Based on initial conditions of 0000 UTC of 25th Sept, all the models were indicating landfall over south Odisha-north Andhra Pradesh coasts. However, there was large variation among the models with respect to landfall point and time with ECMWF, UKMO, JMA, MME indicating landfall between Visakhapatnam and Gopalpur. GEFS control and mean tracks were indicating landfall over south Odisha close to Gopalpur and north coastal Andhra Pradesh respectively. HWRF (HYCOM) indicated northward shift of track with landfall between Gopalpur and Paradeep. Predicted landfall time also varied between 1200 UTC of 26th (IMD GFS, NCEP GFS JMA, MME, HWRF) to 0000 UTC of 27th September (ECMWF, UKMO).

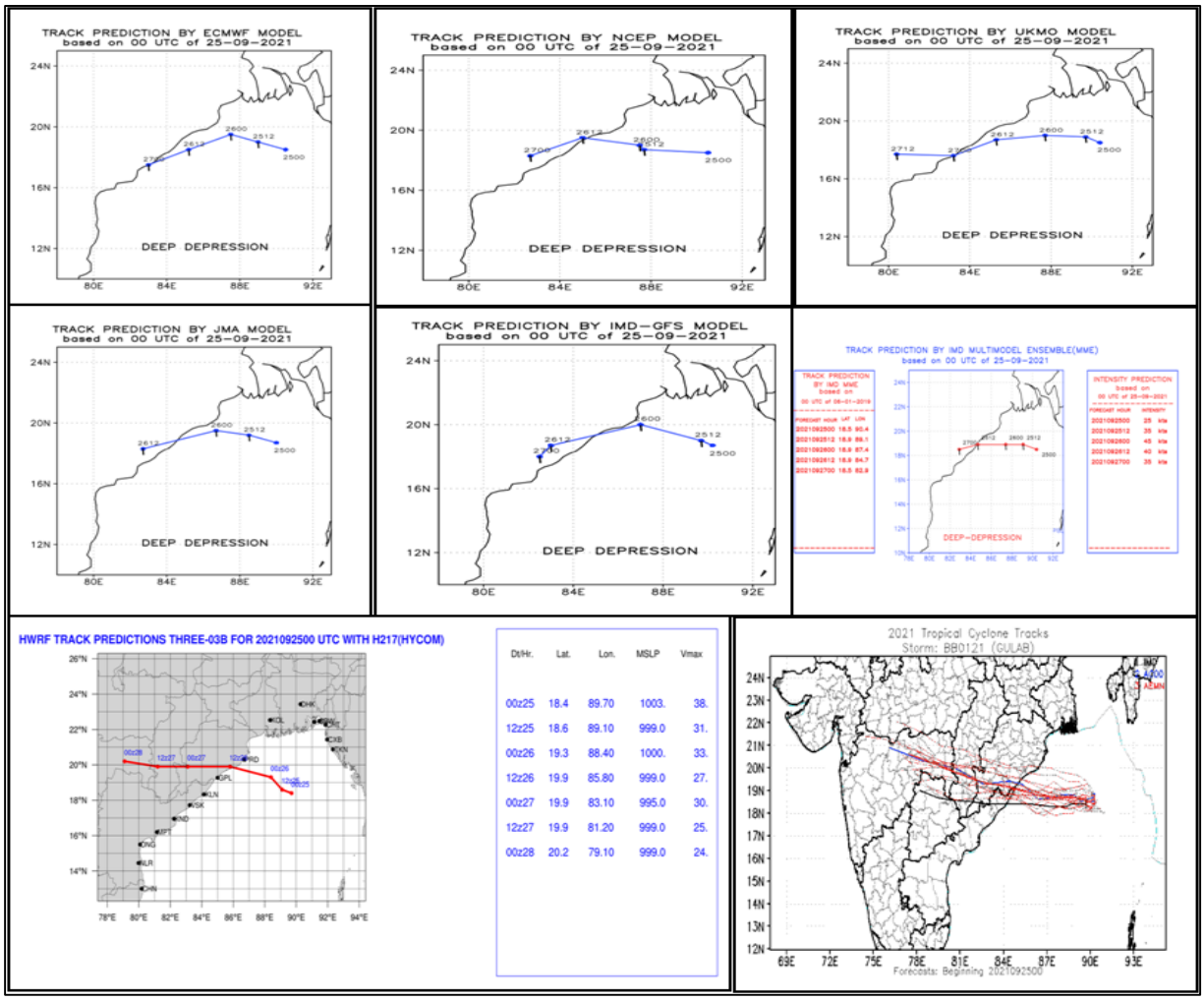


Fig. 11 (a): NWP model for tropical cyclone "GULAB" based on 0000 UTC of 25th Sept 2021

Based on initial conditions of 1200 UTC of 25th Sept, all the models except IMD GFS were indicating landfall over north Andhra Pradesh coast. ECMWF and UKMO were indicating quite south of the actual landfall and IMD GFS was not showing landfall. HWRF (HYCOM) indicated landfall between Kalingapatnam and Gopalpur. MME predicted landfall near Kalingapatnam

around 1800 UTC of 26th. Predicted landfall timings also varied significantly between 1200 UTC of 26th (NCEP GFS JMA, MME, HWRF) to 0000 UTC of 27th September (ECMWF, UKMO).

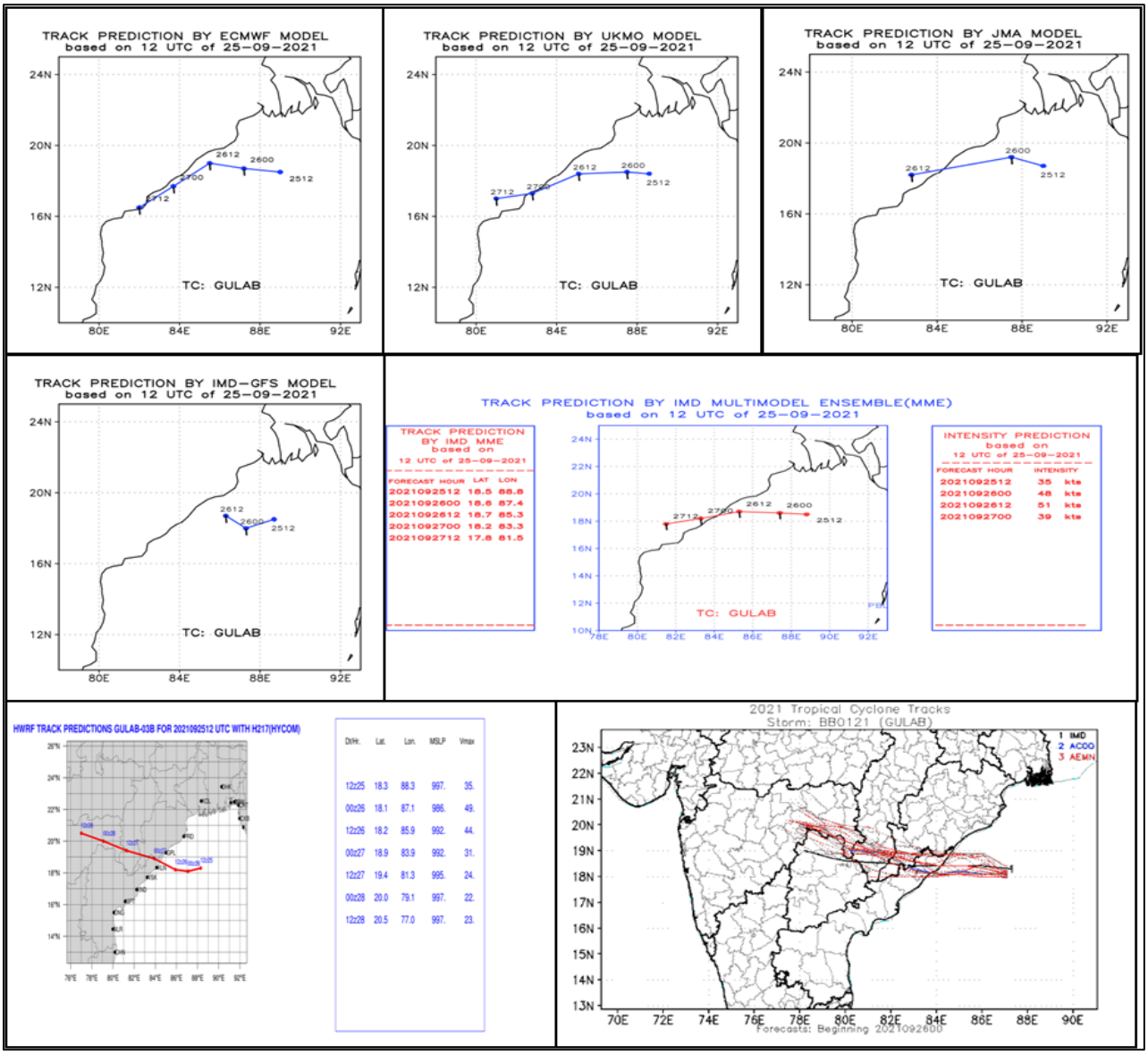


Fig. 11 (b): NWP model for tropical cyclone "GULAB" based on 1200 UTC of 25th Sept 2021

Based on initial conditions of 0000 UTC of 26th Sept, most of the models indicated landfall close to Kalingatpatnam (ECMWF, UKMO, JMA, MME and HWRF). NCEP GFS and GEFS control and mean runs were biased towards south. Landfall time varied between 1200 UTC & 1800 UTC of 26th September except NCEP GFS and JMA which showed around 0900 UTC of 26th September.

Thus, overall MME picked up landfall point and time more correctly since 0000 UTC of 25th September.

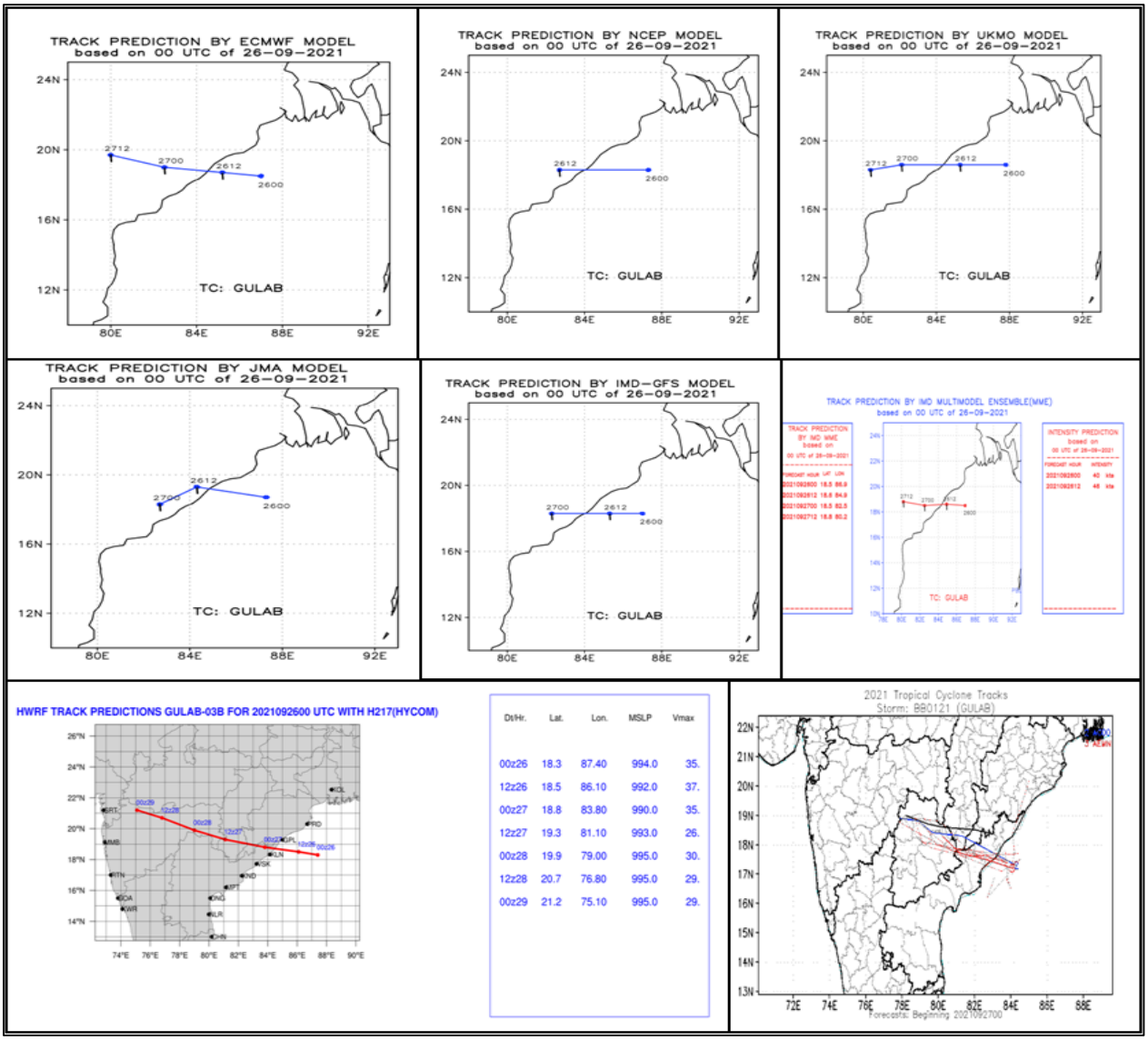


Fig. 11 (c): NWP model for tropical cyclone "GULAB" based on 0000 UTC of 26th Sept 2021

7.3 Track forecast errors

Average track forecast errors by various NWP models is presented in Table 2(a). For 24 hrs lead period track forecast error was the least for IMD MME, followed by GEFS control, UKMO and NCEP GFS. For 48 hrs lead period, the track forecast error was the least for NCEP GFS followed by IMD GFS and JMA.

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**
IMD-MME	60.4(3)	60.7(3)	46.1(3)	93.9(2)

ECMWF	74.8(3)	108.2(3)	103.3(3)	205.2(2)
NCEP-GFS	125.0(2)	80.6(1)	129.3(1)	17.5(1)
UKMO	89.8(3)	72.8(3)	83.0(3)	150.1(1)
JMA-25	103.1(3)	126.7(3)	164.0(2)	55.6(1)
IMD-GFS	91.9(3)	143.3(3)	173.0(1)	54.6(1)
HWRF	91 (9)	138 (9)	137 (9)	138 (7)
GEFS (CNTL)	75(6)	71(6)	95(5)	126(4)
GEFS (ENS_MEAN)	92(6)	91(5)	99(5)	106(4)

* The numbers within the parentheses against DP Errors indicate the number of forecasts issued corresponding to the lead-time.

7.4. Landfall forecast errors by various NWP Models

The Landfall forecasts errors of various models are presented in Table 3. For 12 hours lead period, the landfall point error was the least for GEFS followed by IMD GFS, NCEP GFS and IMD MME. For 24 hours lead period, the landfall point error was the least for MME, JMA and HWRF.

Table-3. Landfall point forecast errors (km) of NWP Models at different lead time (hour)

('-' indicates No Landfall Forecast)

Forecast Lead Time (hour) →	**36 h (25/00)**	**24 h (25/12)**	**12 h (26/00)**
ECMWF	162	315	71
NCEP GFS	155	-	24
UKMO	130	192	48
JMA	55	34	85
IMD-GFS	131	-	24
IMD-MME	77	11	24
HWRF	102	46	39
GEFS (CNTL)	156	153	15
GEFS (ENS_MEAN)	144	85	17

The Landfall time forecasts errors of various models are presented in Table 4. For 12 hours lead period, the landfall time error was the least for IMD MME & ECMWF followed by UKMO, HWRF and GEFS. For 24 hours lead period, the landfall time error was the least for GEFS, followed by HWRF and MME.

Table-4. Landfall time forecast errors (hour) at different lead time (hr)

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

Forecast Lead Time (hour) →	36 h (25/00)	24 h (25/12)	12 h (26/00)
ECMWF	09:30	21:30	00:30
NCEP GFS	-3.5	-	-5.5
UKMO	09:30	09:30	01:30
JMA	-7:30	-5:30	-4:30
IMD-GFS	-8:30	-	3:30
IMD-MME	-2:30	03:30	00:30
HWRF	69	3	3
GEFS (CNTL)	-3	0	-3
GEFS (ENS_MEAN)	-3	0	-3

7.5. Intensity forecast errors by various NWP Models

The intensity forecasts errors of various models are presented in Table 5. It is seen that intensity prediction error was the least in case of IMD SCIP followed by HWRF for different lead periods.

Table-5 Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of various models (Number of forecasts verified is given in the parentheses)

Lead time →	12H	24H	36H	48H
IMD-SCIP (AAE)	3.0(3)	5.5(2)	7.0(2)	5.0(1)
IMD-SCIP (RMSE)	4.7	5.5	7.3	5.0
HWRF (AAE)	4.0 (9)	7.1 (9)	5.8 (9)	6.7 (7)
HWRF (RMSE)	4.9 (9)	8.4 (9)	7.8 (9)	9.2 (7)
GEFS CNTL (AAE)	-12(6)	-14(6)	-18(5)	-19(4)
GEFS CNTL (RMSE)	14(6)	16(6)	20(5)	21(4)
GEFS ENS_MEAN (AAE)	-11(6)	-15(5)	-16(5)	-16(4)
GEFS ENS_MEAN (RMSE)	12(6)	17(5)	18(5)	19(4)

Intensity forecast by IMD-SCIP model is presented in Fig. 12. It is seen that at 0000 UTC of 25th, IMD SCIP model underestimated the intensity of the system. At 1200 UTC, it overestimated intensity for all lead periods. At 0000 UTC of 26th, correctly picked intensity of the system.

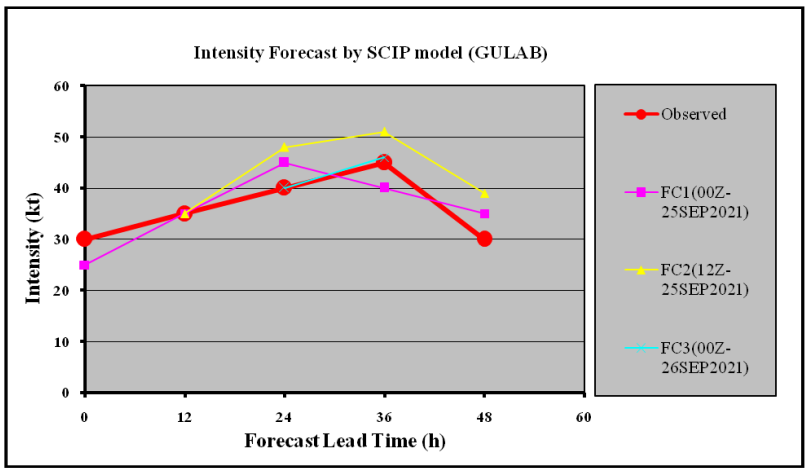
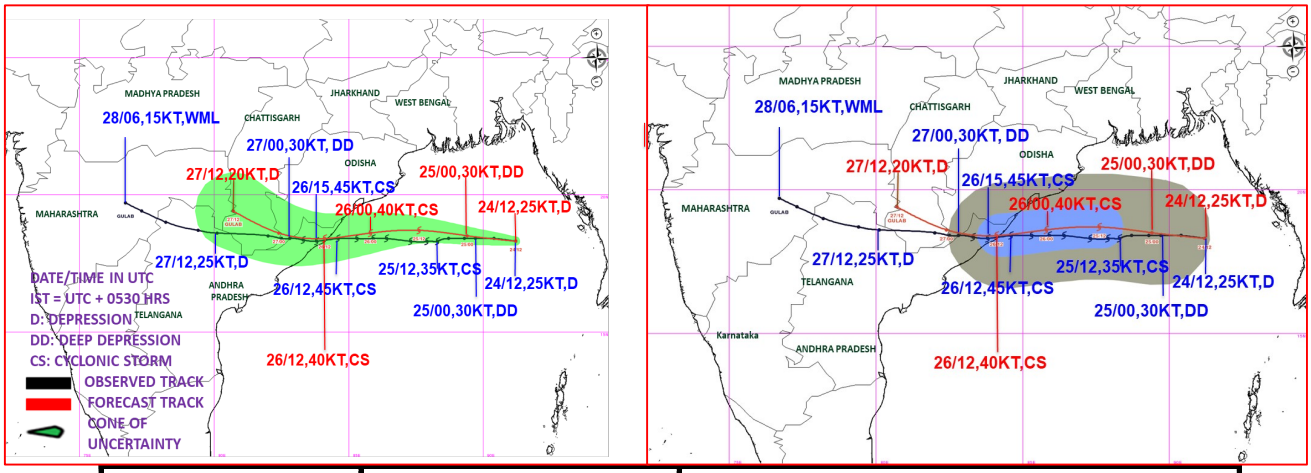


Fig. 12: SCIP Intensity Forecast Error (GULAB)

8. Operational Forecast Performance:

8.1. Genesis, track, landfall and intensity forecast performance:

- First information about likely formation of low pressure area over central parts of BoB during the week 24th Sep. to 30th Sep. was given in extended range outlook issued on 16th September (about 8 days prior to formation of LPA over eastcentral BoB). It was also indicated that the system would move west-northwestwards towards Odisha coast.
- The tropical weather outlook issued at 1130 hours IST of 23rd further reiterated that an LPA would form over northeast and adjoining eastcentral BoB around 24th evening. It was also indicated that the system would move west-northwestwards towards Odisha coast during subsequent 48 hours (till 26th).
- Special Message issued at 1630 IST of 24th September on formation of WML indicated that it would intensify further into a depression within next 12 hours and move towards south Odisha-north Andhra Pradesh coasts. Fishermen were advised not to venture into eastcentral and adjoining northeast BoB on 24th & 25th Sep. and into westcentral BoB and along & off Odisha, West Bengal & North Andhra Pradesh coasts from 24th night till 27th Sep.
- The first bulletin with formation of depression issued at 2030 hours IST of 24th September (**about 48 hours prior to landfall**) indicated that system would cross coast around Kalingapatnam by 26th evening with maximum sustained wind speed of 70-80 gusting to 90 kmph. The bulletin also indicated that the system would cross coast around 26th evening.
- Subsequent bulletin issued at 2030 hours IST of 25th September (**about 24 hours prior to landfall**) further indicated that cyclone would cross coast with wind speed of 75-85 gusting 95 kmph. The maximum wind speed in gustiness has been reported as 95 kmph over Kalingapatnam at the time of landfall.
- Thus, the genesis, track, landfall and intensity could be predicted reasonably well with a lead period of 48 hours approximately. Typical observed and forecast track of cyclone Gulab demonstrating accuracy in track, landfall and intensity prediction are presented in Fig. 13 (a and b).



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

Fig. 13: Observed and forecast track alongwith (a) cone of uncertainty and (b) quadrant wind distribution based on 1730 hours IST (1200 UTC) of 24th September of cyclone Gulab demonstrating accuracy in track, landfall and intensity prediction

8.2. Operational landfall forecast error

The landfall point and time Forecast errors (Forecast – Actual) compared to long period average (LPA) errors during 2016-20 are presented in Fig.14 (a-b) and Table 6. The landfall point forecast errors for 24, 36 and 48 hrs lead period were 31, 0 and 0 km respectively against the LPA errors (2016-20) of 31.9, 43.7 and 61.5 km during 2016-20 respectively. The landfall time forecast errors for 24, 36 and 48 hrs lead period were 0.5, 3.0, and 3.0 hours respectively against the LPA errors (2016-20) 2.5, 4.7 and 5.0 hours during 2016-20 respectively. For all lead periods, the landfall point errors were exceptionally less than the LPA errors during 2016-20. There was almost zero landfall point error for 36 and 48 hours lead period. Landfall time error was also significantly less for all lead periods from 24 to 48 hours.

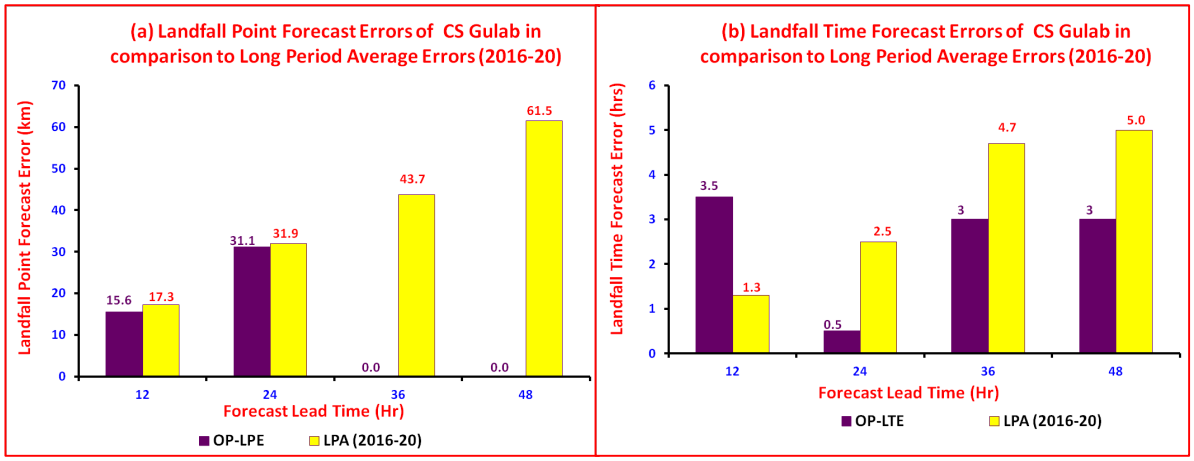


Fig.14: Operational Landfall (a) point and (b) time forecast errors of CS 'GULAB" as compared to long period average (2016-20)

Table 6: Operational Landfall point and time forecast errors of CS 'GULAB" as compared to long period average (2016-20)

Lead Period (hrs)	Base date/Time (UTC)	Forecast Latitude (Deg)	Forecast Longitude (Deg)	Actual latitude (Deg)	Actual Longitude (Deg)	OP-LPE (km)	Forecast Time (UTC)	Actual Time (UTC)	OP-LTE (hrs)
12	26/00	18.5	84.3	18.4	84.2	15.6	26/1800	26/1430	+3.5
24	25/12	18.6	84.4	18.4	84.2	31.1	26/1500	26/1430	+0.5
36	25/00	18.4	84.2	18.4	84.2	0.0	26/1130	26/1430	-3.0
48	24/12	18.4	84.2	18.4	84.2	0.0	26/1130	26/1430	-3.0

OP-LPE: Operational Landfall Point Error, OP-LTE: Operational Landfall Time Error, '+': forecast is Delayed, '-': Forecast is Early

8.3. Track forecast error and skill

The track forecast errors (Forecast position – Actual position of Cyclone centre) and skill as compared to Climatological and Persistence (CLIPER) forecast are presented in Fig.15 (a-b) and Table 7. The track forecast errors for 24, 48 and 72 hrs lead period were 82.4, 65.9, and 110.0 km respectively against the LPA errors (2016-20) of 77.5, 116.8, and 158.8 km respectively (Fig.15 a). The track forecast skill was about 79%, 89%, and 92% against the LPA skill of 64%, 76%, and 78% for 24, 48 and 72 hrs lead period respectively (Fig. 15b). The track forecast error for 48-72 hours lead period was significantly less than the LPA errors. Skill in track forecasting was better than LPA skill for all lead periods.

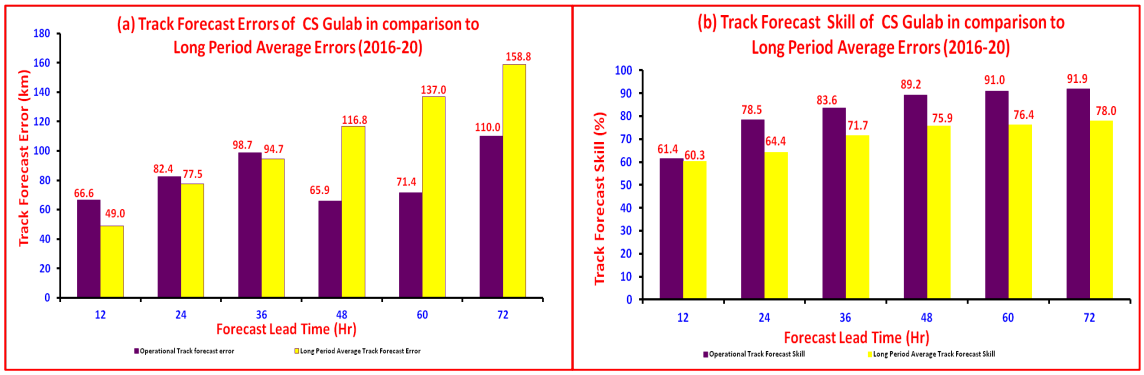


Fig. 15: Operational Track forecast (a) errors and (b) skill of CS 'GULAB" as compared to long period average (2016-20)

Table 7: Operational Track forecast errors and skill of CS 'GULAB" as compared to long period average (2016-20)

Lead Period (hrs)	N	Operational Track forecast error (km)	Operational Track Forecast Skill (%)	Long Period Average (2016-20)	
				Track Forecast Error (km)	Track Forecast Skill (%)
12	12	66.6	61.4	49.0	60.3
24	8	82.4	78.5	77.5	64.4
36	7	98.7	83.6	94.7	71.7
48	5	65.9	89.2	116.8	75.9
60	4	71.4	91.0	137.0	76.4
72	1	110.0	91.9	158.8	78.0

N: no. of forecasts verified

8.4. Intensity forecast error and skill

The intensity forecast errors (Forecast wind – Actual wind) and skill based on absolute errors and root mean square errors are presented in Fig.16 & and Table 8 respectively. The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 1.3, 2.2 and 5.0 knots against the LPA errors of 7.9, 11.4, and 14.1 knots during 2016-20 respectively (Fig. 16 a). The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 2.5, 3.3 and 5.0 knots against the LPA errors of 9.9, 13.8, and 16.7 knots respectively (Fig. 16b). The skill (%) in intensity forecast as compared to persistence forecast based on AE for 24, 48 and 72 hrs lead period was 90%, 95% and 88% against the LPA of 52%, 72% and 75% respectively (Fig.17a). The skill(%) in intensity forecast based on RMSE for 24, 48 and 72 hrs lead period was 87%, 92% & 88% against the LPA of 60%, 69% and 78% respectively (Fig.17 b).

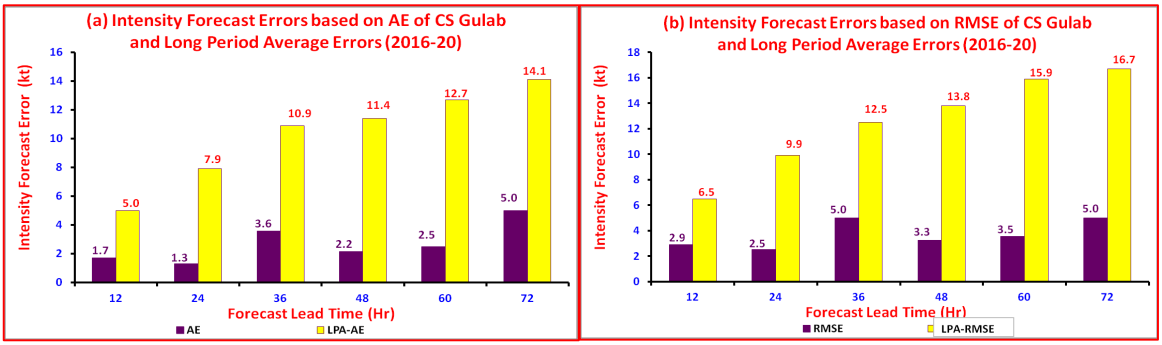


Fig. 16: (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) in intensity forecast (winds in knots) of CS 'GULAB" as compared to long period average (2016-20)

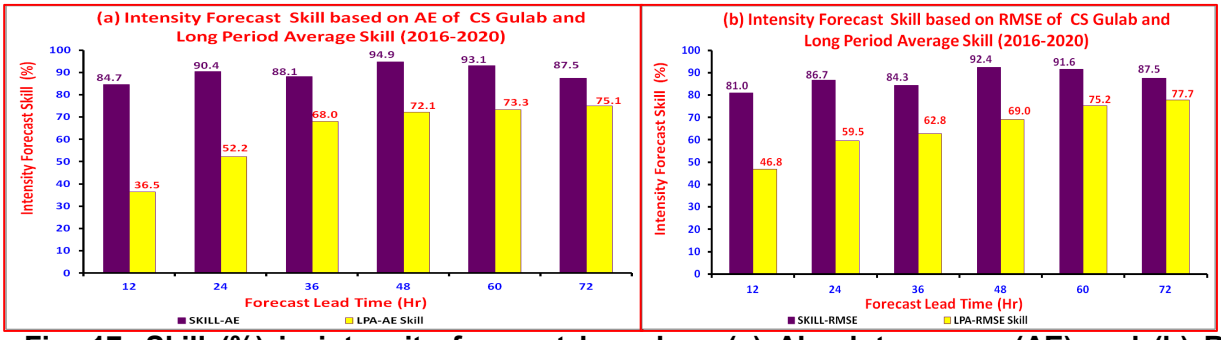


Fig. 17: Skill (%) in intensity forecast based on (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) of CS 'GULAB" as compared to long period average(2016-20)

Table 8: Operational AE and RMSE and corresponding skill in intensity forecast of CS 'GULAB" as compared to long period average(2016-20)

Lead Period	N	AE	RMSE	Skill-AE	Skill-RMSE	Long Period Average (2016-20)			
						AE	RMSE	Skill-AE	Skill-RMSE
12	12	1.7	2.9	84.7	81.0	5.0	6.5	36.5	46.8
24	8	1.3	2.5	90.4	86.7	7.9	9.9	52.2	59.5
36	7	3.6	5.0	88.1	84.3	10.9	12.5	68.0	62.8
48	5	2.2	3.3	94.9	92.4	11.4	13.8	72.1	69.0
60	4	2.5	3.5	93.1	91.6	12.7	15.9	73.3	75.2
72	1	5.0	5.0	87.5	87.5	14.1	16.7	75.1	77.7

N: No. of observations verified, AE: Absolute error, RMSE: Root Mean Square Error, LPA: Long Period Average

9. Warning Services:

- **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… +72 hrs lead period commencing from 24th September 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 on the day of landfall till the system maintained the intensity of cyclonic storm over Odisha.

- **Cyclone structure forecast for shipping and coastal hazard management:**

  The radius of maximum wind and radii of MSW ≥28 and ≥34 knots wind in four quadrants of cyclone was issued every six hourly, commencing from 24th September giving forecast for +06, +12, +18, +24, +36 and +72 hrs lead period.

- **Four stage color coded warnings:**
  - **24th September/1630 IST**: Special Message on formation of Well Marked Low Pressure Area over Eastcentral & adjoining Northeast BoB. It indicated that the system would move towards south Odisha-north Andhra Pradesh coasts. Fishermen were advised not to venture into eastcentral & adjoining northeast BoB on 24th & 25th September and into westcentral BoB and along & off Odisha, West Bengal and North AP coasts from 24th night till 27th Sep.
  - **24th September/2100 IST**: Pre-Cyclone Watch for north Andhra Pradesh and adjoining south Odisha coasts (about 48 hours prior to landfall) on formation of depression over eastcentral & adjoining northeast BoB
  - **25th September/0830 IST**: Cyclone Alert (Yellow Message) (about 36 hours prior to landfall) on formation of deep depression over north & adjoining eastcentral BoB
  - **25th September**/2030 IST: Cyclone Warning (Orange Message) (about 24 hours prior to landfall) on formation of cyclonic storm over northwest & adjoining westcentral Bay
  - **26th September**/0830 IST: Cyclone Warning & Post Landfall Outlook (Red Message) (about 12 hours prior to landfall) for south Odisha, north Andhra Pradesh, south Chhattisgarh and adjoining Telangana.

- **Adverse weather warning bulletins:**

  The tropical cyclone forecasts along with 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 West Bengal, Odisha, Andhra Pradesh, Puducherry, Tamilnadu, Andaman & Nicobar Islands, Telangana, Chhattisgarh, Madhya Pradesh, Maharashtra, Gujarat, Daman & Diu and Karnataka. 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, 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 graphics along with 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 26th afternoon (1230 IST/0700 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 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 Hqrs as well as in West Bengal, Odisha, Andhra Pradesh, Puducherry, Tamilnadu, Andaman & Nicobar Islands, Telangana, Chattisgarh, Madhya Pradesh, Maharashtra, Gujarat, Daman & Diu and Karnataka and SMS were also issued.
- **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 West Bengal, Odisha, Andhra Pradesh, Puducherry, Tamilnadu, Andaman & Nicobar Islands and Telangana were issued since 22nd September onwards.
- **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 prognostics and diagnostics 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 26th afternoon (0700 UTC/1230 IST) onwards till the system maintained the intensity of cyclonic storm.

- **Important Briefing Meetings attended by DGM IMD**

  Dr. M. Mohapatra, DGM IMD participated in the National Crisis Management Committee Meeting on cyclone Gulab on 25th September.

Statistics of bulletins issued by RSMC New Delhi, Cyclone Warning Centre Visakhapatnam (CWC VZK) & Area Cyclone Warning Centre Kolkata (ACWC KOL) in association with the CS Gulab are given in Table 9 (a & b).

Table 9 (a): Bulletins issued by RSMC New Delhi

S. No.	Bulletin type	No. Of Bulletins	Issued to
1	National Bulletin	25	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, Secretary MOES, Headquarter Integrated Defense Staff, IAF, Indian Navy, Coast Guard, Director General Doordarshan, All India Radio, PIB MOES,UNI,DG National Disaster Response Force, Director, Punctuality, INDIAN RAILWAYS, Chief Secretary: Government of Odisha, Andhra Pradesh , Tamil Nadu, Andaman & Nicobar Islands, West Bengal, Maharashtra.
2	Bulletin from DGM IMD	5	To senior level Govt. Officials including Cabinet Secretary, Principal Secretary to Prime Minister, Secretary Ministry of Home Affairs, Ministry of Agriculture, Defence, IAF, Indian Navy, Information & Broadcasting, Ministry of Earth Sciences, Deptt. of Science & Technology, Shipping & Surface Transport, Ministry of Home Affairs, Director Punctuality, Indian Railways, Director All India Radio, Doordarshan, Secretary NDMA, Director General NDRF, Coast Guard, Chief Secretaries of West Bengal, Odisha, Andhra Pradesh, Puducherry, Tamilnadu, Andaman & Nicobar Islands, Telangana, Chattisgarh, Madhya Pradesh, Maharashtra
3	RSMC Bulletin	17	1. IMD's website 2. WMO/ESCAP member countries through GTS and E-mail.
4	GMDSS Bulletins	15	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	9	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	9	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 etc.
7	Warnings through SMS	About 11 lakhs	SMS to disaster managers at national level and concerned states (every time when there was change in track, intensity and landfall characteristics) (i)2,27,730 to General Public by IMD Headquarters (ii) 8732126 to farmers by Kisaan Portal to farmers of Andhra Pradesh, Odisha, Maharashtra, West Bengal, West Bengal, Chattisgarh, Gujarat and Telangana.
8	Warnings through Social Media	Daily	Cyclone Warnings were uploaded on Social networking sites (Facebook and Twitter) since inception to weakening of system (every time when there was change in track, intensity and landfall characteristics)
9	Press Release	4	Disaster Managers, Media persons by email and uploaded on website
10	Press Briefings	Daily	Regular briefing daily
11	Hourly Updates	14	Disaster Managers, Media persons by email and uploaded on website

Table 9(b): Statistics of bulletins issued by Cyclone Warning Centre Visakhapatnam (CWC VZK) & Area Cyclone Warning Centre Kolkata (ACWC KOL)

S.No.	Type of Bulletin	CWC VZK	ACWC KOL	CWC BBN
1.	Sea Area Bulletins	----	16	N/A
2.	Coastal Weather Bulletins	16	9	08
3.	Fishermen Warnings issued	20	NIL	19
4.	Port Warnings	09	NIL	16
5.	Heavy Rainfall Warning	17	NIL	21
6.	Gale Wind Warning	01	NIL	20
7.	Storm Surge Warning	10	NIL	11
8.	Information & Warning issued to State Government and other Agencies	12	2	22
9.	SMS	-	NIL	-
10.	No. of Press releases	07	2	03
11.	No. of impact based warnings for a. District b. City	 60 150	NIL	20
12.	No. of whatsapp messages	75	1850	Around 27763

13.	No. of updates on facebook	15	2	35
14.	No. of updates on tweeter	15	2	86
15.	No. of Forecast / Warning video released	3	2	08

10. Damage due to cyclonic storm Gulab

As per media reports about 4 persons in Andhra Pradesh, 3 in Telangana and 11 in Maharashtra lost their lives due to cyclonic storm Gulab. The damage photographs are presented in Fig.18.

Fig 18(a): Submerged paddy field at Pinagadi in Visakhapatnam district (Source-https://www.newindianexpress.com/ dated:29 Sept), (b) Road network to several villages in the coastal mandals of Srikakulam was cut off due to the downpour (Source: https://timesofindia.indiatimes.com/ dated: 28 Sept),

Fig 18 (c) Waterlogged roads in Hyderabad (Source: https://www.hindustantimes.com/ dated:27 Sept), (d) Uprooted trees in Santhabommali mandal (source: https://www.thehansindia.com/ dated 27 Sept), (e) Flooded Visakhapatnam International Airport (Source: https://www.livemint.com/ dated:27 Sept.) (f) Ramakrishna Junction main road seen inundated due to incessant rains in Visakhapatnam.(source: https://www.deccanchronicle.com/ dated:28 Sept.)

11. Acknowledgement:

IMD acknowledges contribution from all the stake holders and disaster management agencies who contributed to the successful monitoring, prediction and early warning service of CS Gulab. IMD and RSMC New Delhi duly acknowledge the contribution from the World Meteorological Organisation and all the 13 WMO/ESCAP Panel member countries. 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, Kolkata, Mumbai Cyclone Warning Centre (CWC) Bhubaneswar, Visakhapatnam and Ahmedabad, Meteorological Centre (MC) Amaravati, Hyderabad, RMC, Nagpur, Doppler Weather Radar Station at Visakhapatnam and coastal observatories. The contribution from Numerical Weather Prediction Division, Satellite and Radar Divisions, Surface & Upper air instruments Divisions, New Delhi, Agromet Advisory Division and Information System and Services Division at IMD is also duly acknowledged. IMD also acknowledges the support and cooperation from all national and state level disaster management agencies, various stakeholders and press and electronic media.
