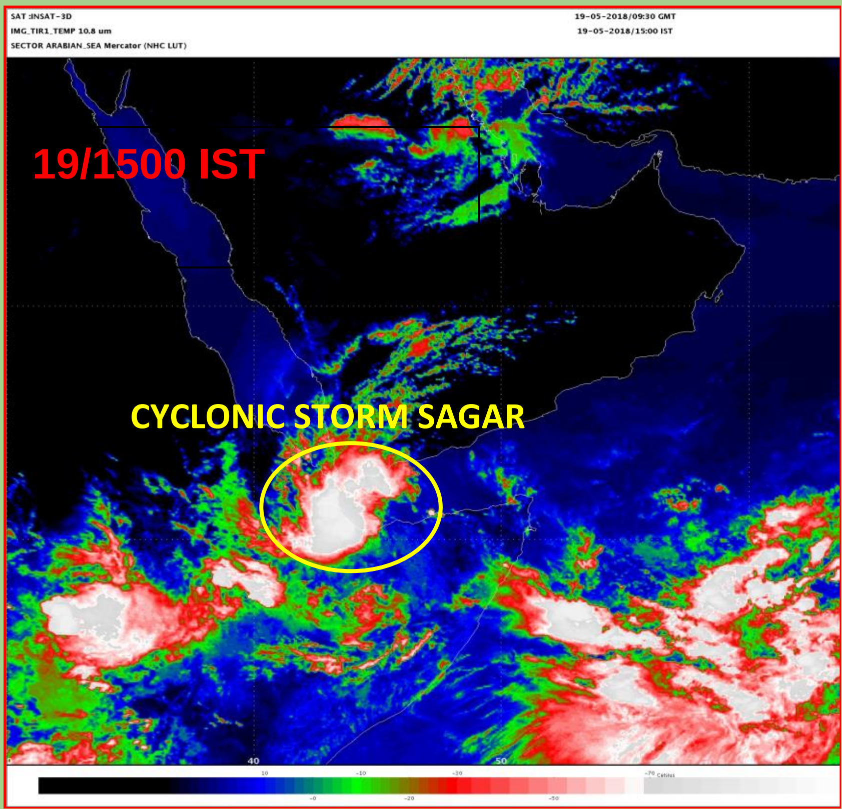
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Cyclonic Storm, 'SAGAR' over the Arabian Sea (16 – 21 May 2018): A Report



INSAT-3D enhanced colored IR imagery of 19th May, 2018

Cyclone Warning Division

India Meteorological Department

New Delhi

JUNE 2018

Cyclonic Storm "Sagar" over Arabian Sea
(16 – 21 May 2018)

1. Introduction

The Cyclonic Storm (CS) Sagar originated from a low pressure area which formed over southwest Arabian Sea in the morning (0300 UTC) of 14th May. It became a well marked low pressure area in the early morning (0000 UTC) of 15th over the same region. Under favourable environmental conditions, it concentrated into a Depression (D) over Gulf of Aden in the evening (1200 UTC) of 16th May. Moving west-northwestwards it intensified into a deep depression (DD) in the early morning (0000 UTC) and further into a cyclonic storm (CS) **"Sagar**" in the morning (0300 UTC) of 17th May 2018 over Gulf of Aden. Thereafter, it moved west-southwestwards and crossed Somalia coast near latitude 10.65^{0}N and longitude 44.0 ^{0}E as a cyclonic storm with maximum sustained wind speed (MSW) of 70-80 kmph gusting to 90 kmph between 1330 and 1430 IST of 19th May. Moving further west-southwestwards, it weakened into a DD in the mid night (1800 UTC) of 19th, D in the early morning (0000 UTC) of 20th and well marked low pressure area (WML) over Ethiopia and adjoining Somalia in the morning (0300 UTC) of 20th. The salient features of the system are as follows:

- The CS, Sagar is the first cyclone to cross coast to the west of longitude 45^{0}E during satellite era (since 1965).
- Last cyclone developing and passing through Gulf of Aden was cyclone Bandu (19-23 May, 2010, MSW-40 kts) which dissipated over Gulf of Aden without making landfall.
- It had an anticlockwise and west southwestward recurving track.
- The peak maximum sustained surface wind speed (MSW) of the cyclone was 80-90 kmph gusting to 100 kmph (45 knots) during 0000 UTC of 18th to 0300 UTC of 19th May.
- The lowest estimated central pressure was 994 hPa (from 0000 UTC of 18th to 0300 UTC of 19th May).
- The life period of cyclone was 87 hours (3 days & 15 hours) against long period average (LPA) (1990-2013) of 3.7 days for cyclonic storm over Arabian Sea.
- The track length of the cyclone was 766 km.
- The 12 hour average translational speed of the cyclone was 10.6 kmph against LPA (1990-2013) of 13.6 kmph over AS.

The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were 4.55 X10^{2} knots, 1.9 X 10^{4} knots^{2} and 0.8 X10^{6} knots^{3} respectively against LPA (1990-2013) of 1.89 X10^{2} knots, 1.4 X 10^{4} knots^{2} and 1.2 X10^{6} knots^{3} during pre-monsoon season for AS.

Brief life history, characteristic features and associated weather along with performance of NWP and operational forecast of IMD are presented and discussed in following sections.

2. Monitoring of CS, 'SAGAR'

The cyclone was monitored & predicted continuously since its inception by India Meteorological Department (IMD). The observed track of the cyclone over BoB during 28-31 May is shown in **Fig.1**. The best track parameters of the systems are presented in **Table 1.**

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) prior to it's genesis as low pressure area over AS from 11th May onwards. The system was monitored mainly with satellite observations from INSAT 3D and 3DR, SCAT Sat, polar orbiting satellites, scatterometer observations and available ships & buoy observations in the region. Various national and international numerical weather prediction models and dynamical-statistical models were utilized to predict the genesis, track and intensity of the cyclone. Tropical Cyclone Module, the digitized forecasting system of IMD was utilized for analysis and comparison of various models guidance, decision making process and warning product generation. IMD issued regular bulletins to WMO/ESCAP Panel member countries including Yemen, Oman and Somalia, National & State Disaster Management Agencies, general public and media since inception of the system over AS.

3. Brief life history

3.1. Genesis

The Cyclonic Storm (CS) Sagar originated from a low pressure area which formed over southwest Arabian Sea in the morning (0300 UTC) of 14th May. It became a well marked low pressure area in the early morning (0000 UTC) of 15th over the same region. On 16th may 2018, considering the environmental parameters, the sea surface temperature (SST) was 30-32^{0}C over the system area. The tropical cyclone heat potential is about 80-100 kJ/cm^2 over the region of the low pressure system and it was less than 50kJ/cm^2 over the Gulf of Aden. There was a maxima of 10x10^{-5} s^{-1} in low level convergence to the southwest of the system centre. The upper level divergence was about 20x10^{-5} s^{-1} to the north of system centre. The vorticity at 850 hpa level was about 100x10^{-6} s^{-1} around the system centre and was extending upto 500 hpa level. Vertical wind shear was low to moderate (10-15 kts) around the system centre and over Gulf of Aden. It increased towards Yemen and Oman coasts. Upper tropospheric ridge lay along latitude 18.0^{0}N near longitude 50^{0}E. It favoured poleward outflow and hence increase in the upper level divergence. The Madden Julian Oscillation (MJO) index lay over phase 1 with amplitude greater than 1. The middle and upper level winds indicated the system to move initially west-northwestwards across Gulf of Aden during next 24 hrs. Under these favourable environmental conditions, it concentrated into a Depression (D) over Gulf of Aden in the evening (1200 UTC) of 16th May.

3.2. Intensification and Movement

The similar environmental conditions like SST and Ocean thermal energy continued on 17th May. The low level convergence increased and there was a maxima of 30x10^{-5} s^{-1} at 0000 UTC of 17th May to the south of the system centre. The upper level divergence was about 20x10^{-5} s^{-1} over the system centre. The vorticity at 850 hpa level was about 100x10^{-6} s^{-1} around the system centre and was extending upto 500 hpa level. The vertical wind shear continued to be low to moderate (10-15 kts) around the system centre and over Gulf of Aden. It increased towards Yemen and Oman coasts. The upper tropospheric ridge lay along latitude 17.0^0N near longitude 50^0E. It favoured poleward outflow and hence increase in the upper level divergence. The MJO index continued to be in phase 1 with amplitude greater than 1. The middle and upper level winds indicate that the system would move initially westwards during next 12 hours and then west-southwestwards across Gulf of Aden during subsequent24 hrs.

Under these conditions, the depression moved west-northwestwards and intensified into a deep depression (DD) in the early morning (0000 UTC) and further into a cyclonic storm (CS) **"Sagar**" in the morning (0300 UTC) of 17^{th} May 2018 over Gulf of Aden. Thereafter, it moved west-southwestwards maintaining maximum intensity of 45 knots (CS) till 0300 UTC of 19^{th} May.

On 19^{th} morning, the tropical cyclone heat potential is about 50kJ/cm^2over the region of the system. The lower level convergence decreased and was about 20 $x10^{-5}$ s^{-1} to the south southeast of the system centre. The upper level divergence continued to be about 30 $x10^{-5}$ s^{-1} around the system centre. The vorticity at 850 hpa level also continued to be about $100x10^{-6}$ $s^{-1}$to the south of the system centre. The vertical wind shear decreased and was low (05-10kts) around the system centre. It increased towards Yemen and Oman coasts. Upper tropospheric ridge ran along latitude 14.0^0N near longitude 45^0E. As the system moves west-southwestwards, it was coming closer to land surface and hence there was increased land interaction. The total precipitable water (TPW) imagery indicates relatively dry air condition in the periphery of the system in southern sector covering Somalia. However, system maintained intensity of CS due to favourable vertical wind shear, though it showed marginal decrease in intensity.

It crossed Somalia coast near latitude 10.65^0N and longitude 44.0 ^{0}E as a cyclonic storm with maximum sustained wind speed (MSW) of 70-80 kmph gusting to 90 kmph between 0800 and 0900 UTC of 19^{th} May. Moving further west-southwestwards, it weakened into a DD in the mid night (1800 UTC) of 19^{th}, D in the early morning (0000 UTC) of 20^{th} and well marked low pressure area (WML) over Ethiopia and adjoining Somalia in the morning (0300 UTC) of 20^{th}

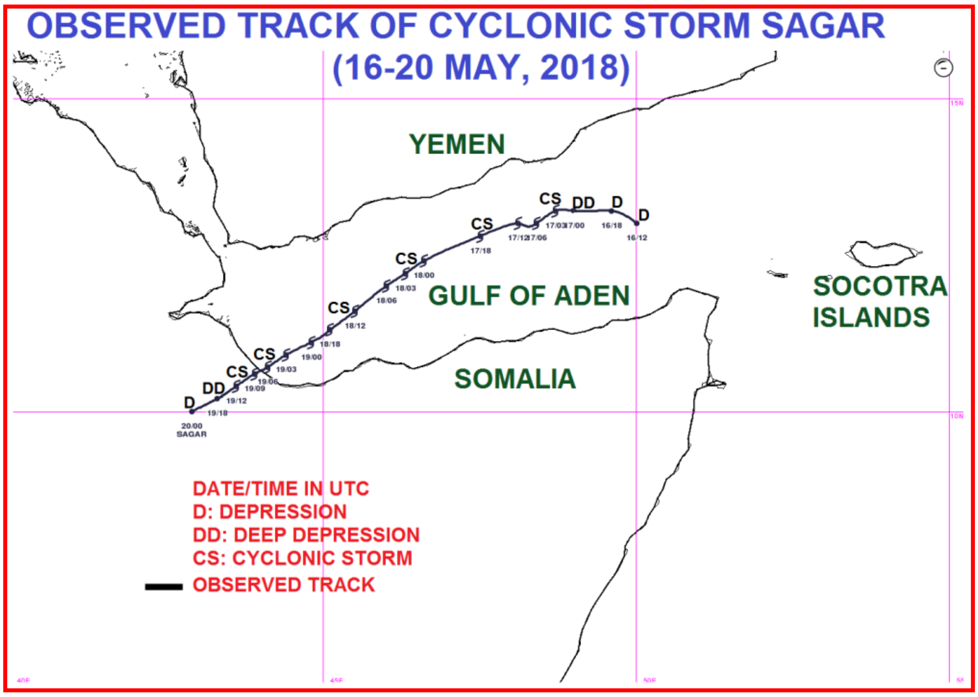


Fig.1 Observed track of CS Sagar (16- 21 May, 2018) over Arabian Sea

Table 1: Best track positions and other parameters of the Extremely Severe Cyclonic Storm, 'Sagar' over the Arabian Sea during 16-21 May, 2018

Date(DD/MM/YYYY)	Time (UTC)	Latitude (lat)	longitude (Long)	CI No [or "T. No"]	Estimated Central Pressure (hPa) [or "E.C.P"]	Maximum Sustained	Pressure Drop (hPa)[or "delta	Grade (text)
16/05/2018	1200	13.0	50.0	1.5	1001	25	3	D
	1800	13.2	49.6	1.5	1001	30	4	D
17/05/2018	0000	13.2	49.0	2.5	999	30	5	DD
	0300	13.2	48.7	2.5	997	35	7	CS
	0600	13.0	48.4	2.5	997	35	7	CS
	0900	13.0	48.3	2.5	997	35	7	CS
	1200	13.0	48.1	2.5	996	40	8	CS
	1500	13.0	47.8	2.5	996	40	8	CS
	1800	12.8	47.5	2.5	996	40	8	CS
	2100	12.7	47.2	2.5	996	40	8	CS
18/05/2018	0000	12.4	46.6	3.0	996	45	10	CS
	0300	12.2	46.3	3.0	994	45	10	CS
	0600	12.0	46.0	3.0	994	45	10	CS
	0900	11.8	45.6	3.0	994	45	10	CS
	1200	11.6	45.5	3.0	994	45	10	CS
	1500	11.4	45.3	3.0	994	45	10	CS
	1800	11.3	45.1	3.0	994	45	10	CS
	2100	11.2	45.0	3.0	994	45	10	CS
19/05/2018	0000	11.1	44.8	3.0	994	45	10	CS
	0300	10.9	44.4	3.0	994	45	10	CS
	0600	10.8	44.1	3.0	996	40	08	CS
	Crossed Somalia coast near latitude 10.65^{0}N/44.0^{0}E between 0800-0900 UTC							
	0900	10.6	43.9	-	998	40	08	CS
	1200	10.4	43.6	-	1000	35	7	CS
	1800	10.2	43.3	-	1001	30	5	DD
20/05/2018	0000	10.0	42.9	-	1003	25	3	D
	0300	Weakened into well marked low pressure area over Ethiopia						

The TPW imageries during 16-20 May, 2018 are presented in **Fig.2**. These imageries indicate continuous warm and moist air advection from the southeast sector into the system till 19th May, even when the system was located in Gulf of Aden. Thereafter, the system started interacting with land surfaces and moisture supply also reduced from southeast sector. However, it maintained the intensity due to low vertical wind shear over the region.

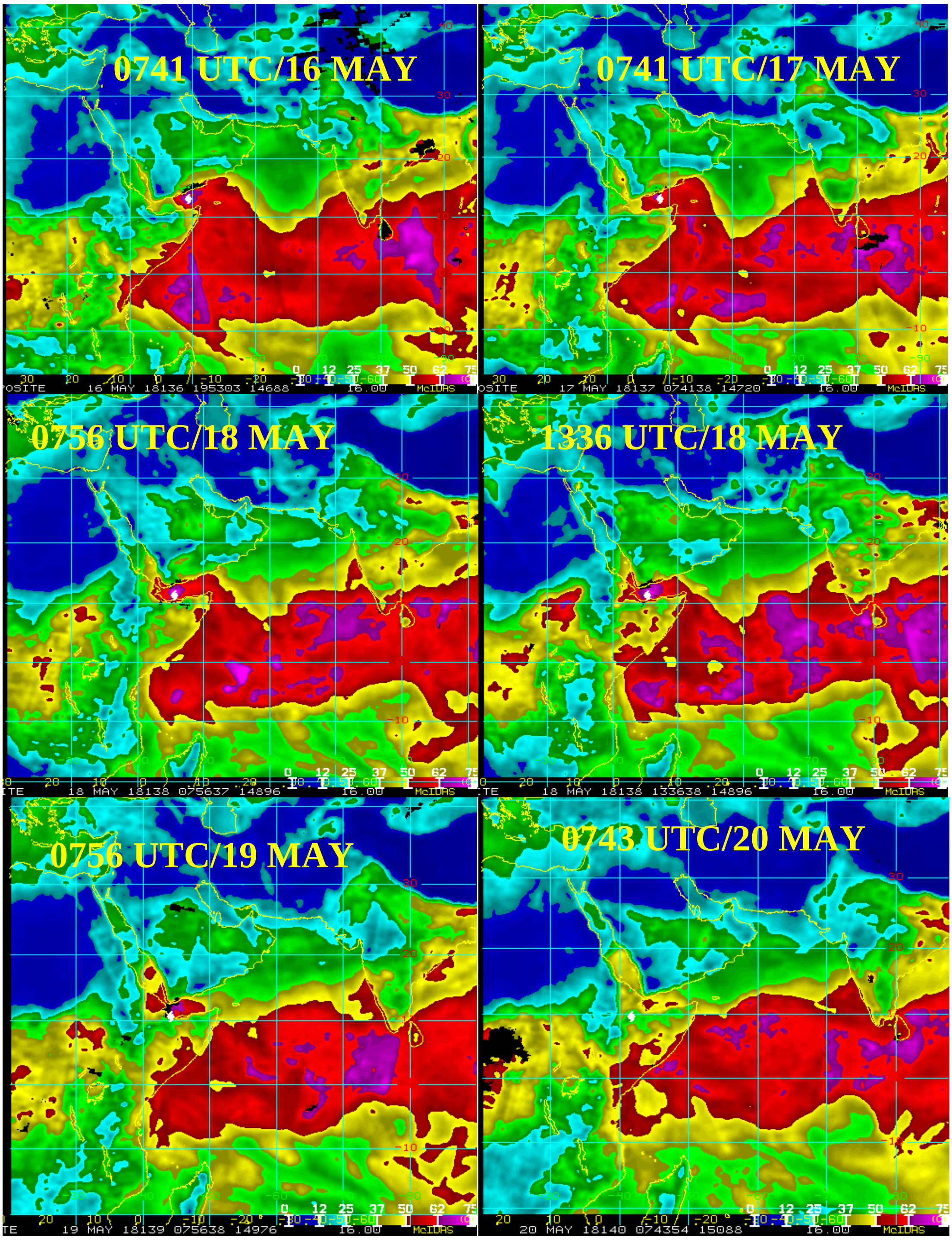


Fig. 2: Total Precipitable Water (TPW) imageries during 16-20 May, 2018

The wind speed in middle and deep layer around the system centre is presented in **Fig.3**. The wind shear around the system between 200 & 850 hPa levels remained steady being about 10-20 knots. It was less than 10 knots at the time of genesis of the system, i.e. on 16th and early hrs of 17th May. It increased during the dissipation stage on 20th May. The direction of 200-850 hPa wind shear was southeasterly till 0600 UTC of 19th May and then it became northeasterly. It thus sheared the cloud mass to southwest sector of system from 19th May.

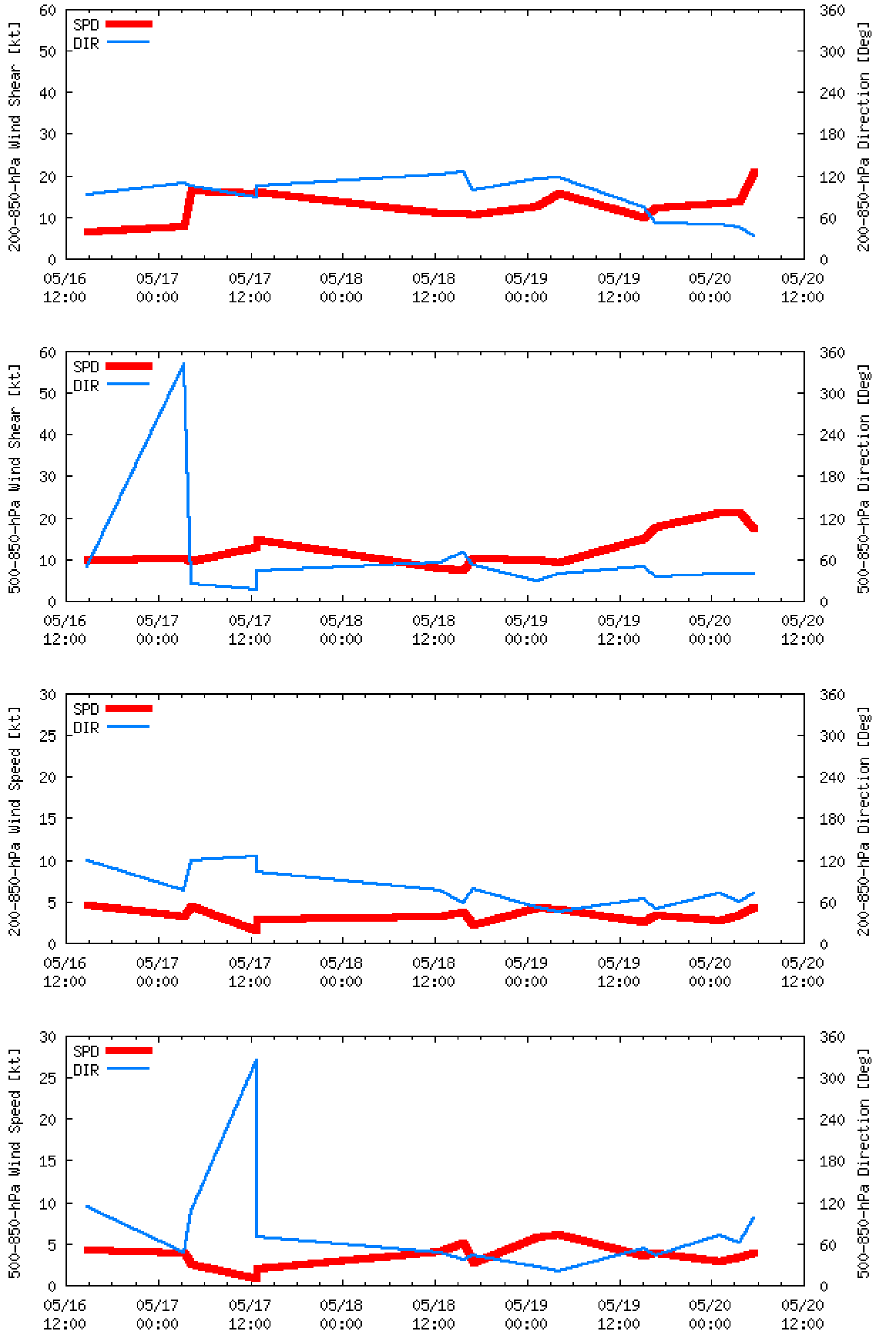


Fig.3 Wind shear and wind speed in the middle and deep layer around the system during 16th to 20th May 2018.

From **Fig.3**, it indicates that from 16th May onwards, the mean deep layer winds between 200-850 hPa levels steered the system west–northwestwards till 17th and then southwestwards. The initial west-northwesterly movement of the system was in association with the upper tropospheric ridge lying to the north of the system centre in association with the anticyclonic circulation lying to the northeast of the system centre. Thereafter, it moved southwestwards till dissipation in association with the anti-cyclonic circulation lying to the northwest of the system centre

The twelve hourly movement of CS Sagar is presented in **Fig.4**. The 12 hour average translational speed of the cyclone was about 10.6 kmph and hence was slow moving in nature. There was in general increasing trend in translational speed till 0000 UTC of 18th. Thereafter there was a decreasing trend.

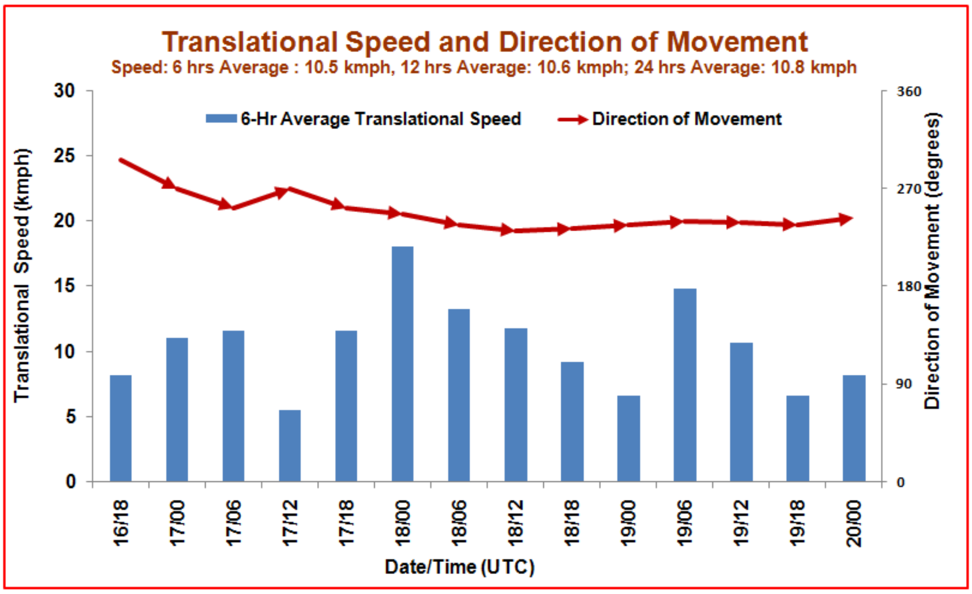


Fig.4 Twelve hourly average translational speed (kmph) and direction of movement in association with CS Sagar

4. Maximum Sustained Surface Wind speed and estimated central pressure

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig.5**. The lowest estimated central pressure had been 994 hPa during 0300 UTC of 18th to 0300 UTC of 19th. The estimated maximum sustained surface wind speed (MSW) was 45 knots during the same period. At the time of landfall, the ECP was 996 hPa and MSW was 40 knots (cyclonic storm). The ECP and Vmax graph indicate that the system intensified gradually till 0600 UTC of 18th, maintained its intensity till 0300 UTC of 19th and started weakening gradually.

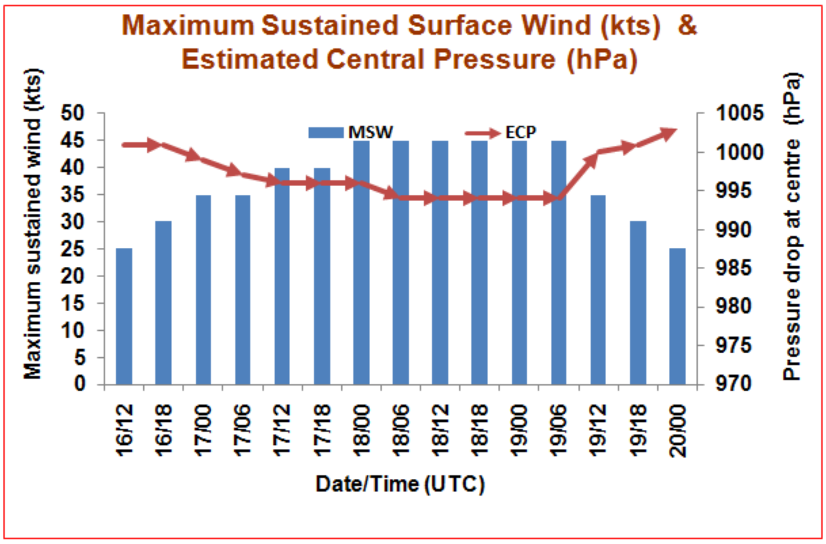


Fig.5. Lowest estimated central pressure and the maximum sustained wind speed

5. Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly Kalpana-1 and INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7 & 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.6**.

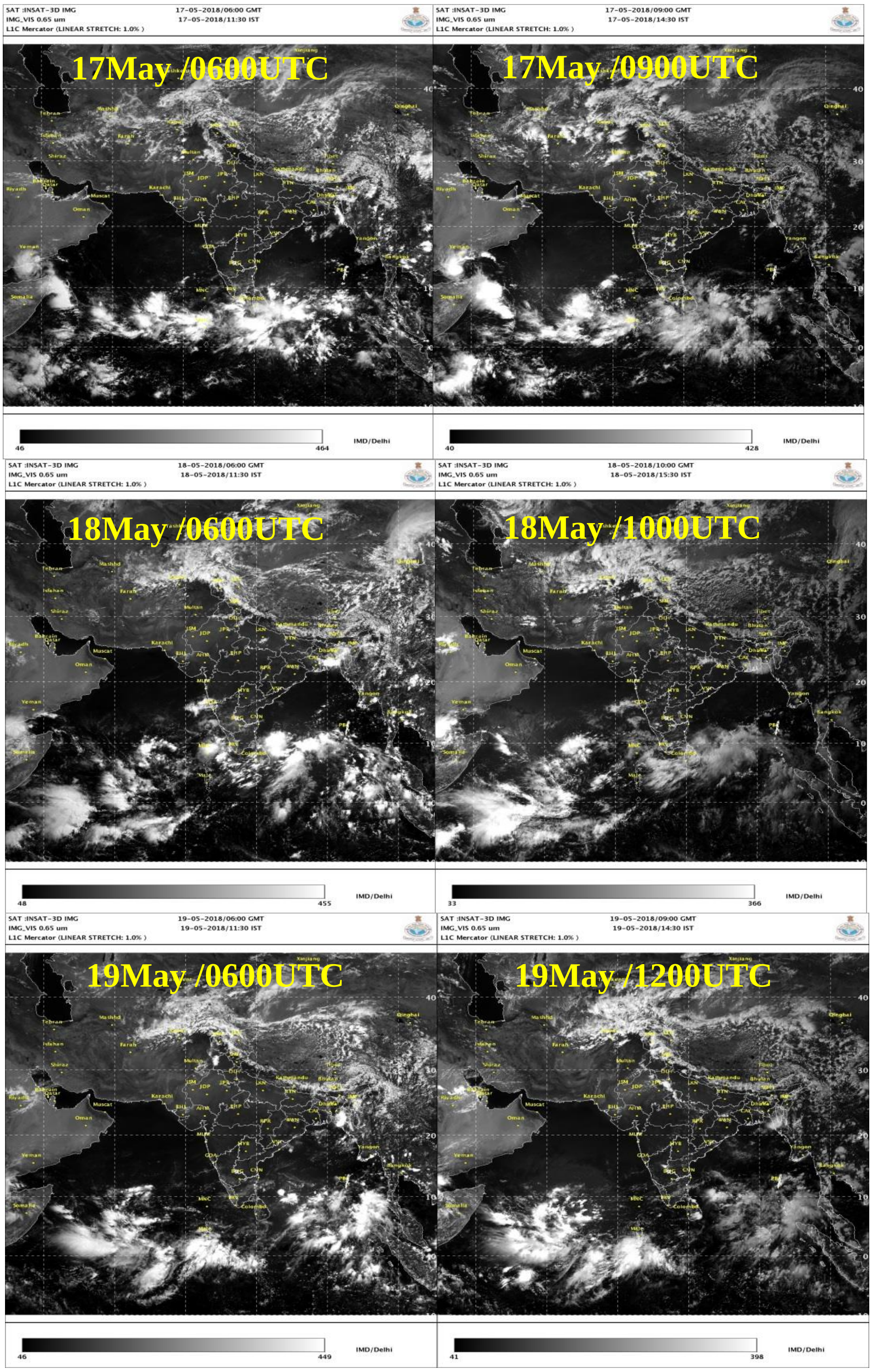


Fig. 6a: INSAT-3D visible imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

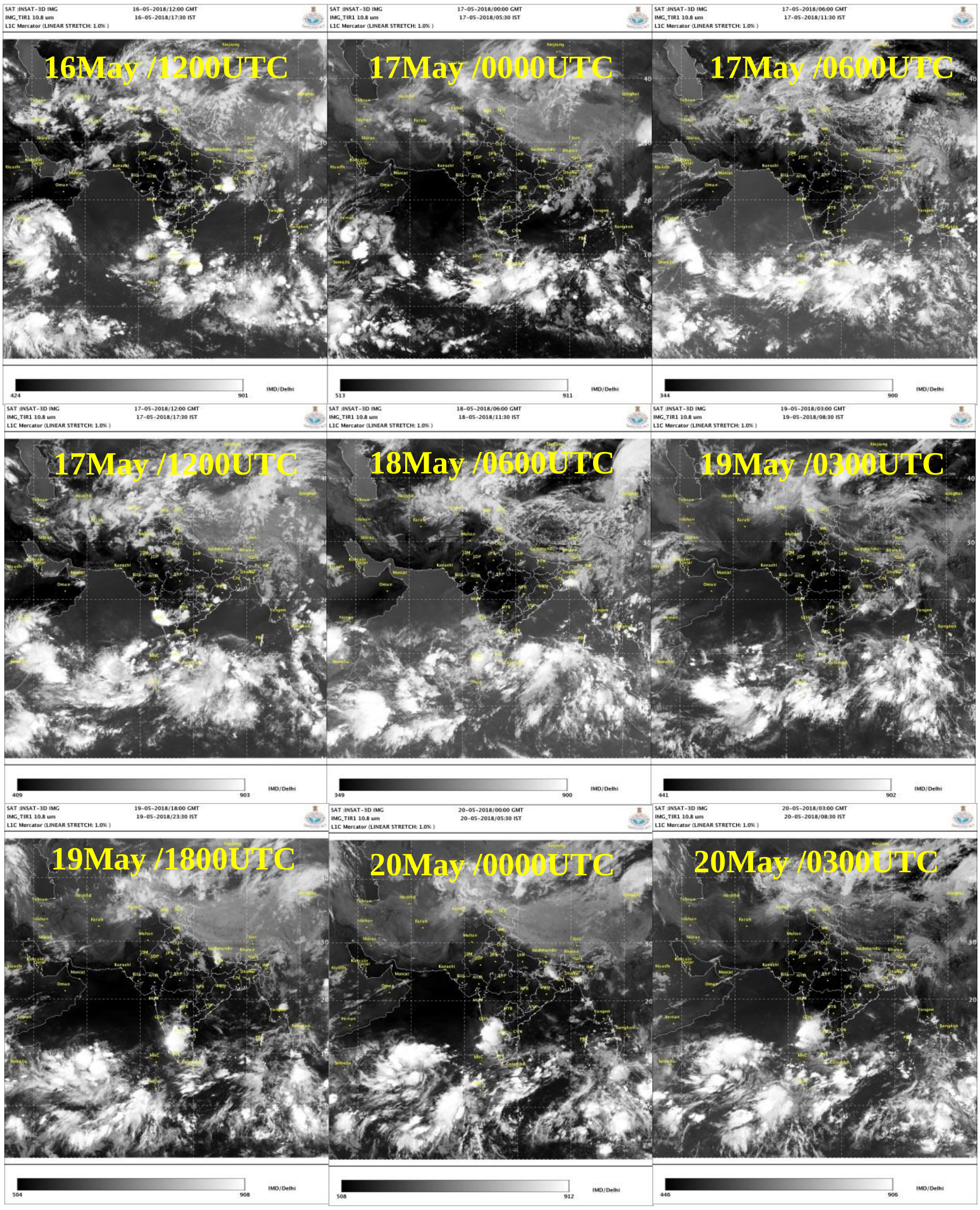


Fig. 6b: INSAT-3D IR imageries during life cycle of CS SAGAR (16-21 May, 2018)

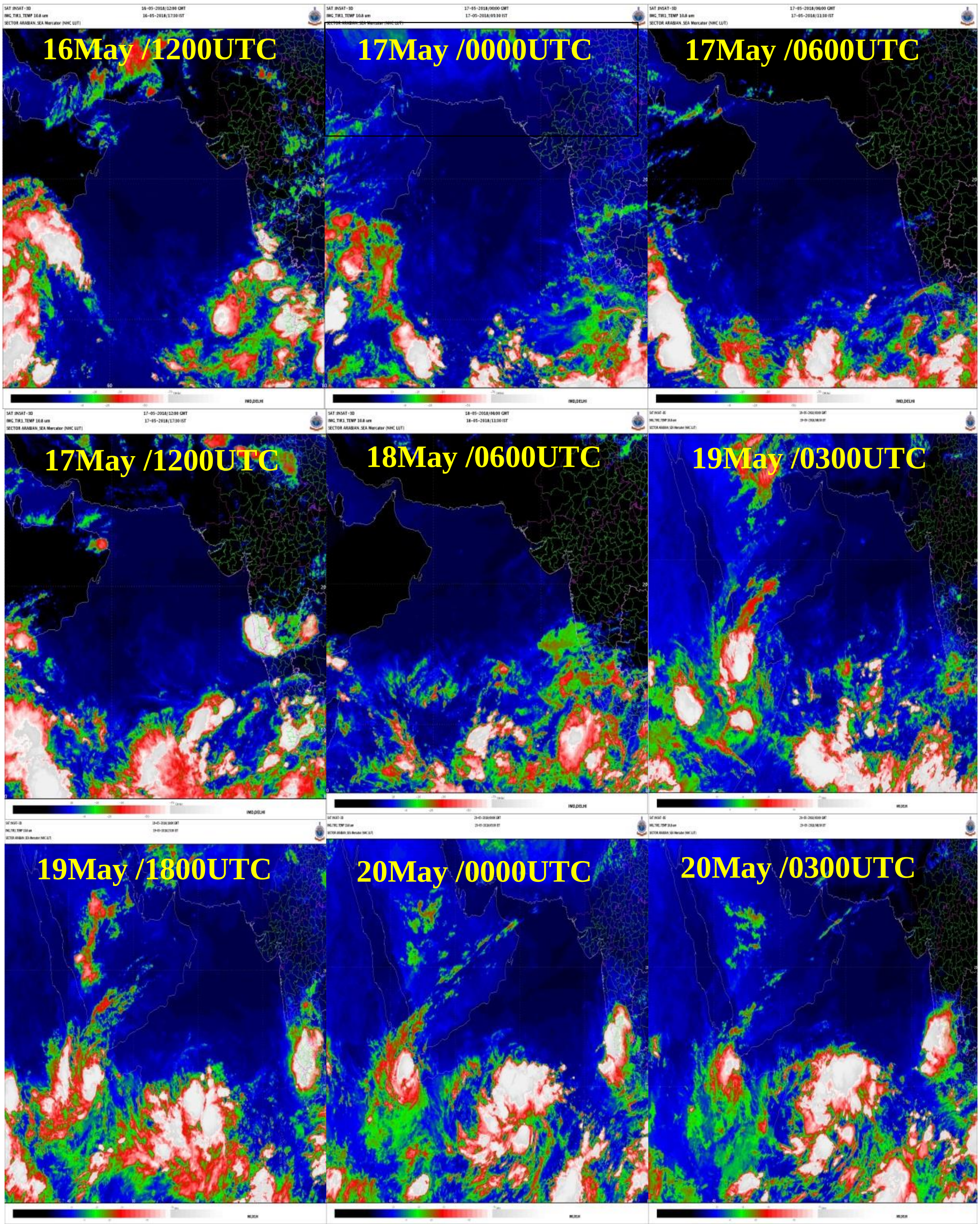


Fig. 6c: INSAT-3D enhanced colored imageries during life cycle of CS SAGAR (16-21 May, 2018)

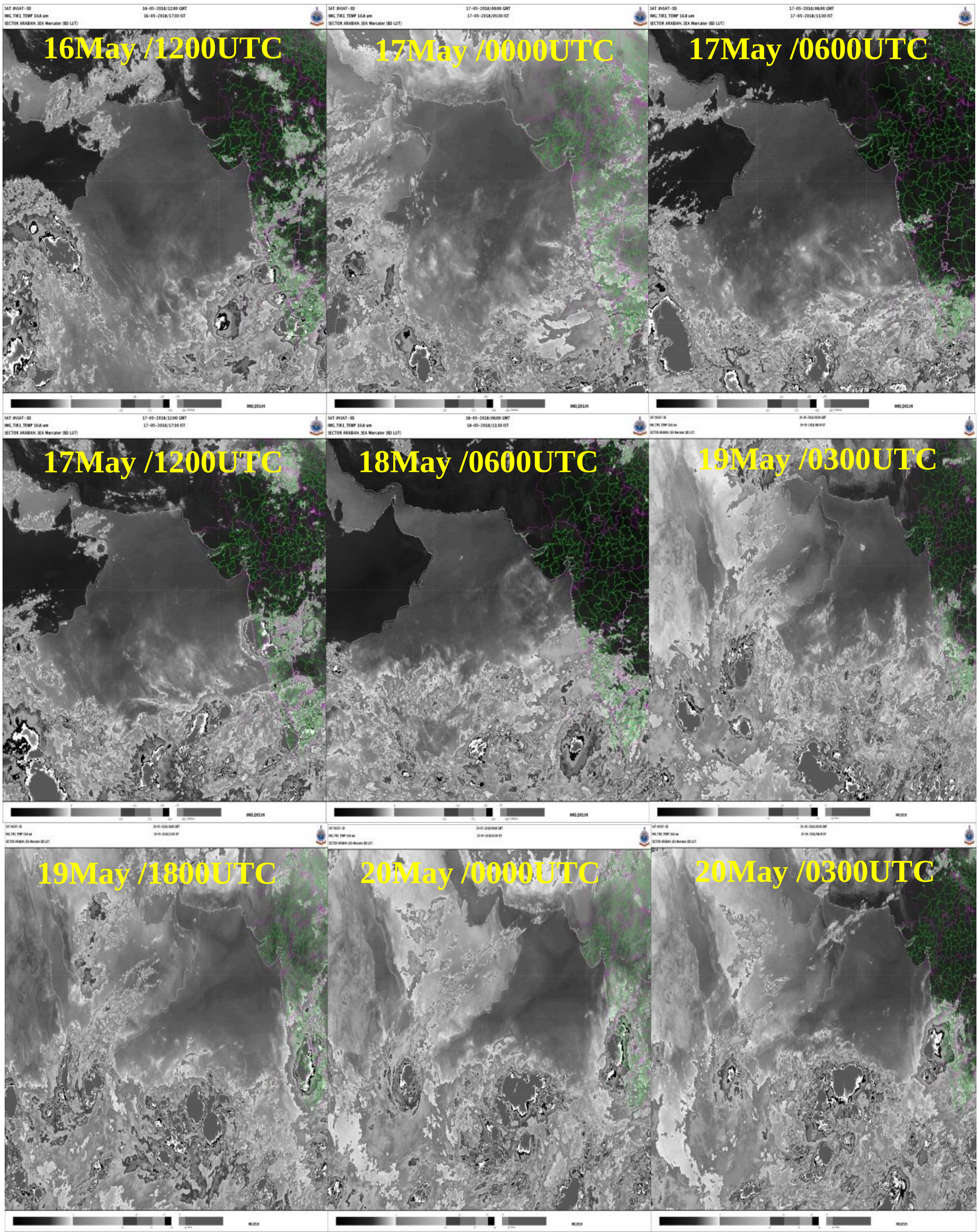


Fig. 6d: INSAT-3D cloud top brightness imageries during life cycle of CS SAGAR (16-21 May, 2018)

6. **Dynamical features**

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 16th-19th May are presented in Fig.7. GFS (T1534). Based on 0000 UTC observations of 16th, the model predicted formation of extended low over southwest and adjoining westcentral Arabian and Gulf of Aden with associated cyclonic circulation extending upto 500 hPa level.

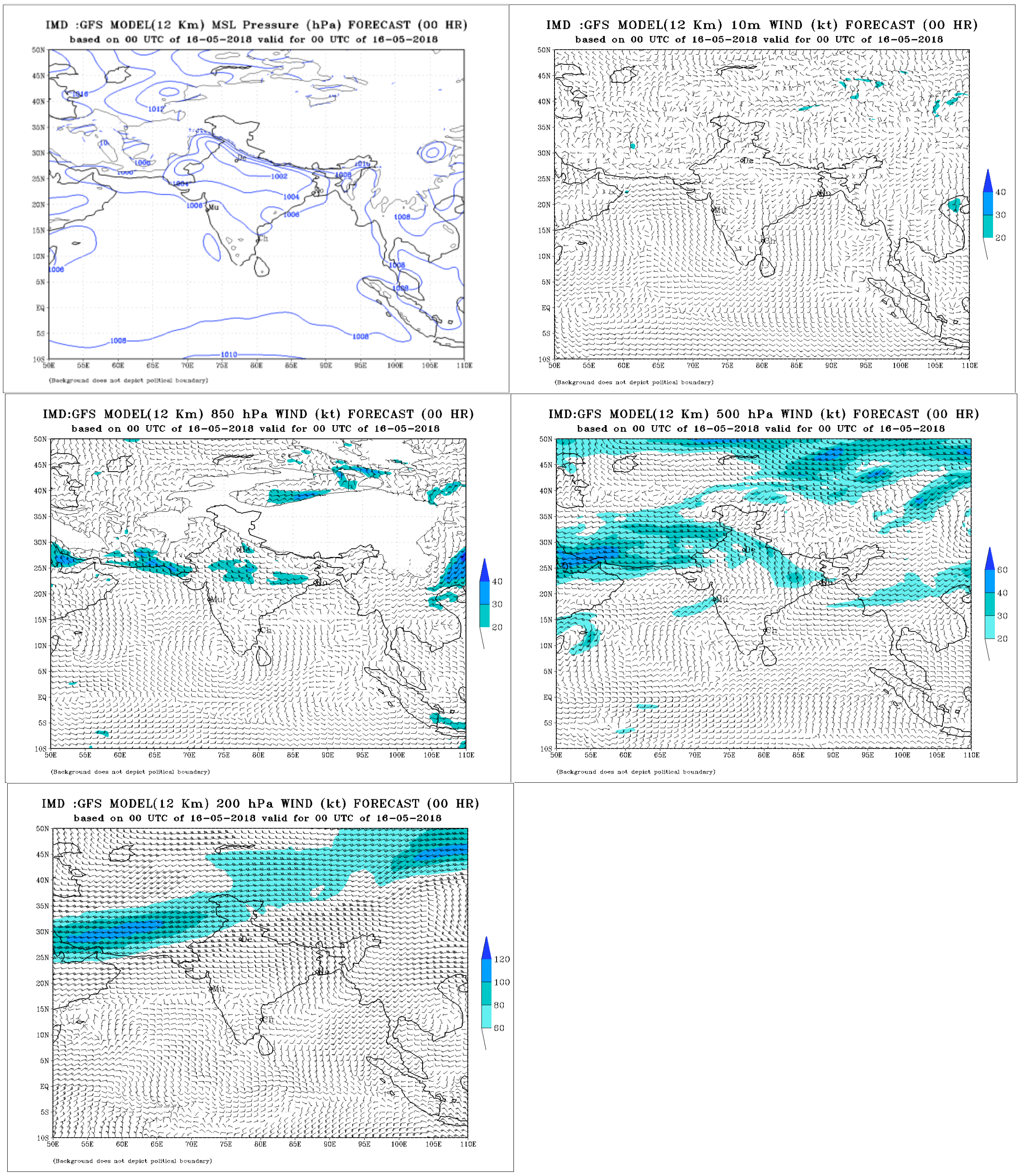


Fig. 7(a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 16th May

Analysis based on 0000 UTC of 16th to 19th May, indicates that the model highly underestimated the intensity of the system.

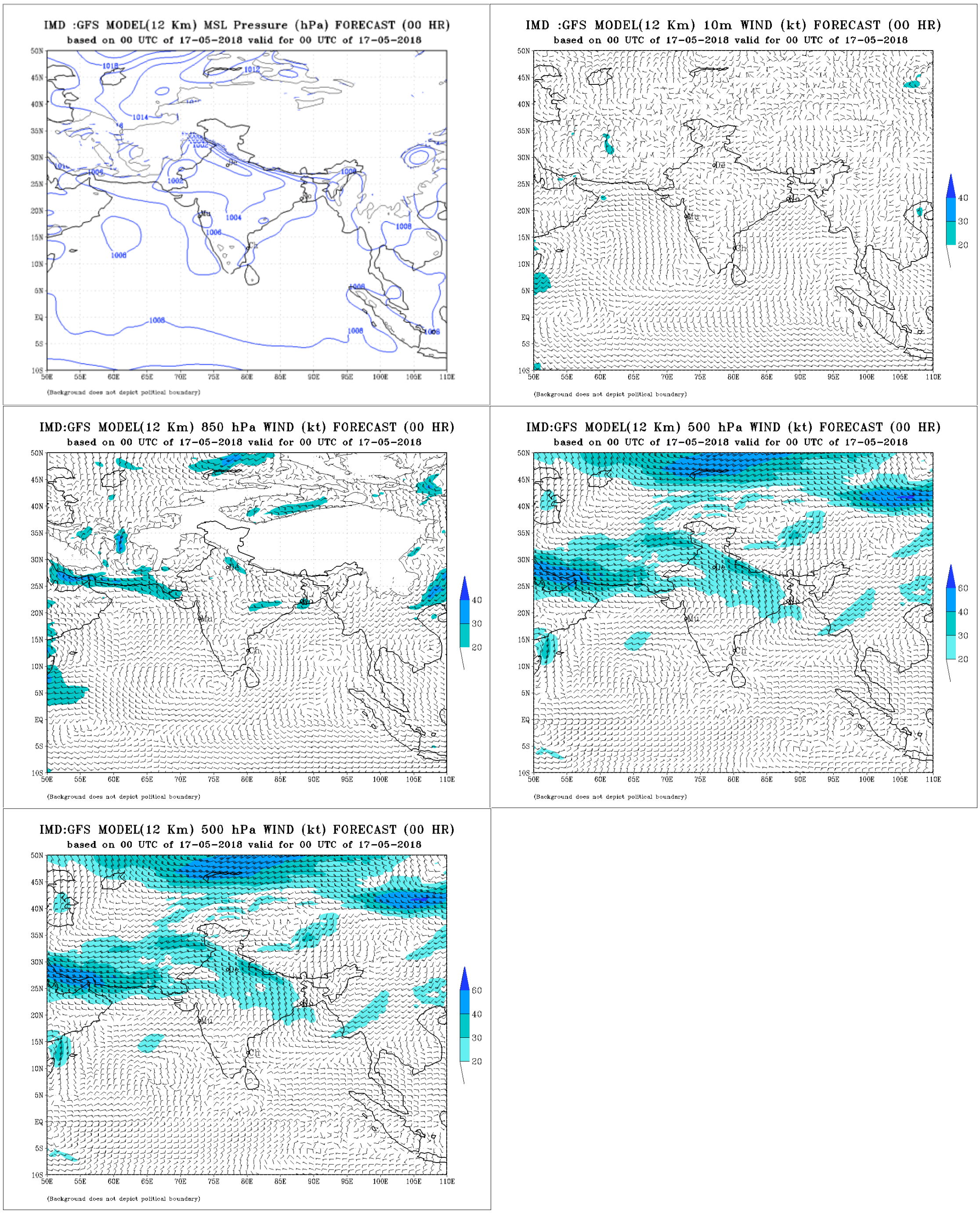


Fig. 7(b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 17th May

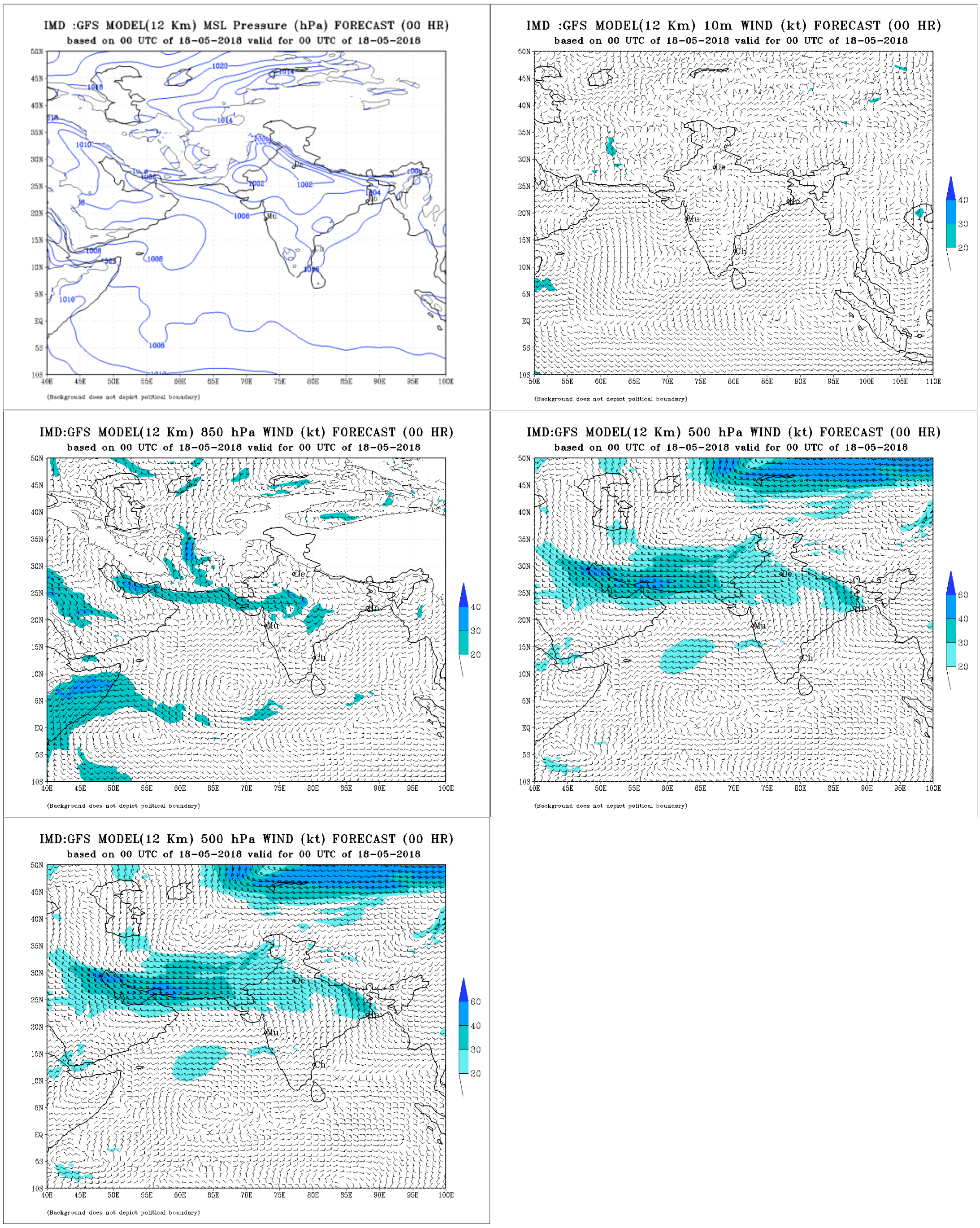


Fig. 7(c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 18th May

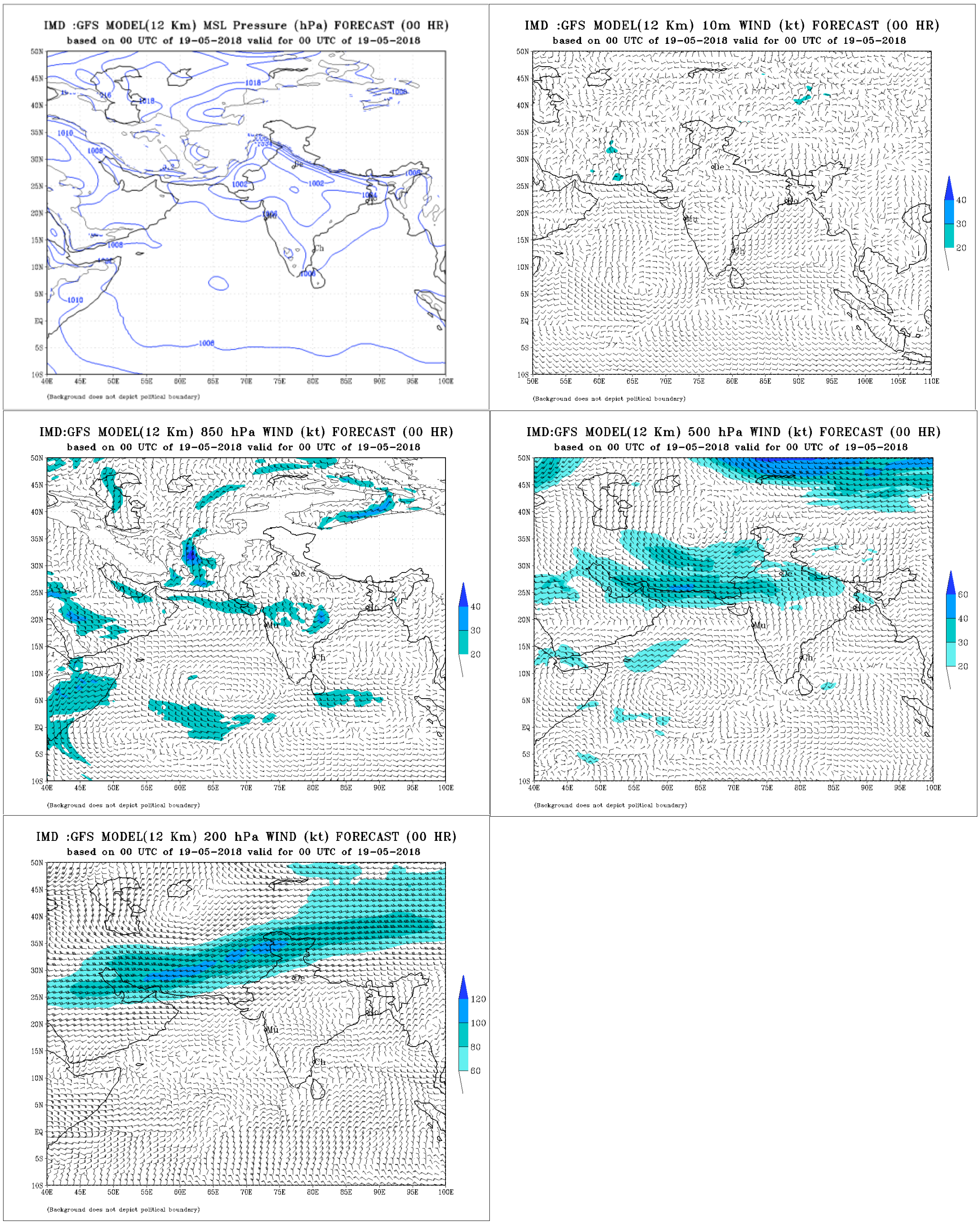


Fig. 7(d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th May

7. Realized Weather:

Rainfall associated with CS, Sagar based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig 8**. It shows that the rainfall was maximum over Yemen coast on 16th and 17th and over north Somalia and Ethiopia on 18th and 19th May 2018.

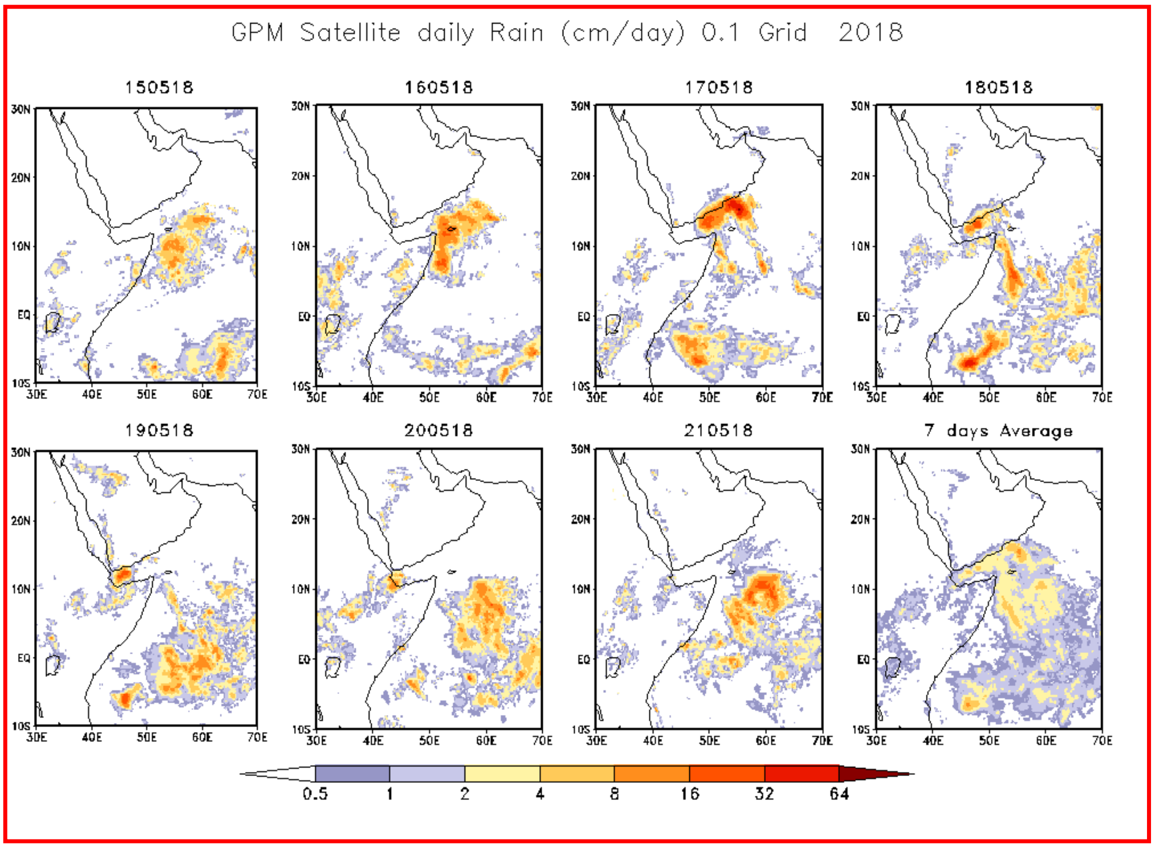


Fig.8: IMD-NCMRWF GPM merged gauge rainfall during 16th May– 21th May and 7 days average rainfall (cm/day)

8. Damage due to CS, Sagar

According to media report, along its rare trajectory through the Gulf of Aden, Cyclonic Storm Sagar caused rainfall in coastal Yemen, northern Somalia, Djibouti, and Ethiopia. The storm first affected Yemen's Socotra Island. Later, strong winds from Sagar damaged houses on Yemen's mainland. Heavy rainfall along the coast caused isolated flooding, which damaged roads and electric infrastructure.

In Djibouti, flooding damaged about 10,000 houses, with 2,000 of them severely damaged, which displaced 3,150 people. The rains flooded crops, streets, and buildings. Three people are reported to be killed.

In the Somalia Region of eastern Ethiopia, Sagar produced strong winds and heavy rainfall, resulting in flooding and landslides. Near the border of SNNPR and Oromia, a landslide killed 23 people. The storm damaged schools, health facilities, and houses, displacing 194,000 people. The village of Dambal was almost entirely washed away, affecting 150 households.

Beginning on May 17, Sagar caused heavy rainfall in northern Somalia and Somaliland, A total of 53 deaths were reported in Somalia as a result of the cyclone – 50 in Somaliland and 3 in Puntland. Typical damage photographs are presented in **Fig.9**.

Fig. 9(a). Flooding in eastern Africa due to CS, Sagar

Fig.9(b) Damage due to CS, Sagar (Source:Djib-Live)

9. Performance of operational NWP models

IMD operationally runs a regional models, WRF for short-range prediction and one Global model T1534 for medium range prediction (10 days). The WRF-VAR model is run at the horizontal resolution of 9 km and 3 km with 38 Eta levels in the vertical and the integration is carried up to 72 hours over three domains covering the area between lat. 25^0S to 45^0 N long 40^0 E to 120^0 E. Initial and boundary conditions are obtained from the IMD Global Forecast System (IMD-GFS) at the resolution of 12 km. The boundary conditions are updated at every six hours interval.

Global models are also run at NCMRWF. These include GFS and unified model adapted from UK Meteorological Office. In addition to the above NWP models, IMD also run operationally dynamical statistical models. The dynamical statistical models have been developed for (a) Cyclone Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction, (d) Rapid intensification and (e) Predicting decay in intensity after the landfall. Genesis potential parameter (GPP) is used for predicting potential of cyclogenesis (T3.0) and forecast for potential cyclogenesis zone. The multi-model ensemble (MME) for predicting the track (at 12h interval up to 120h) of tropical cyclones for the Indian Seas is developed applying multiple linear regression technique using the member models IMD-GFS, IMD-WRF, GFS (NCEP), ECMWF and JMA. The SCIP model is used for 12 hourly intensity predictions up to 72-h and a rapid intensification index (RII) is developed and implemented for the probability forecast of rapid intensification (RI). Decay model is used for prediction of intensity after landfall. In this report performance of the individual models, MME forecasts, SCIP, GPP, RII for cyclone Sagar are presented and discussed.

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

Fig.10 (a-d) shows the predicted zone of cyclogenesis for CS Sagar.

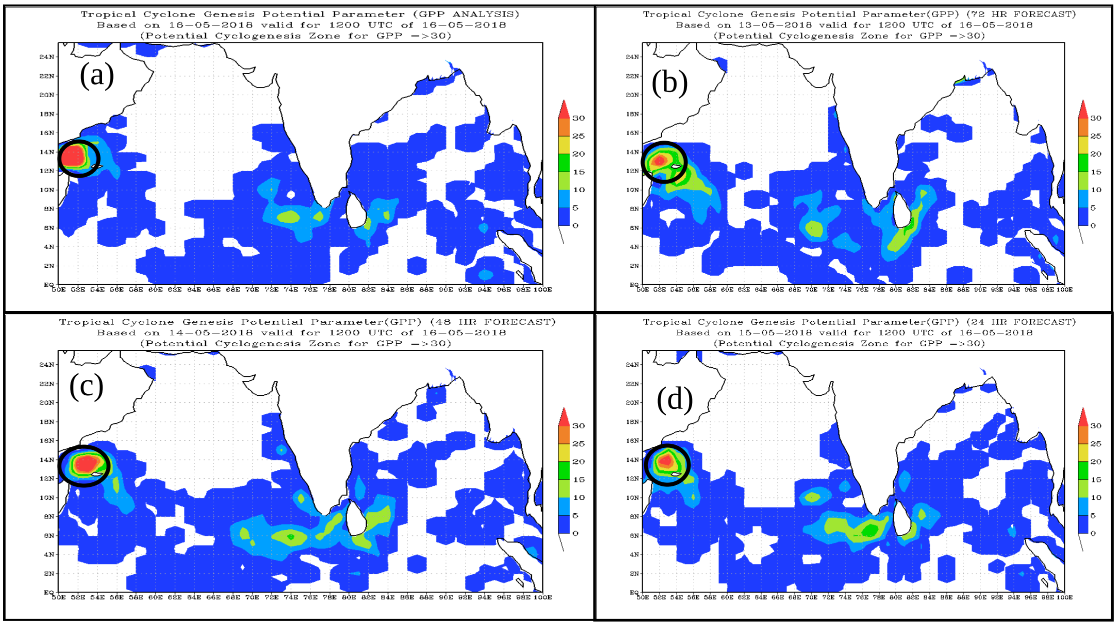


Fig.10(a-f): Predicted zone of cyclogenesis based on 0000 UTC of 13-16th May 2018.

The model could predict cyclogenesis zone correctly about 72 hrs in advance. 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. Based on 0000 UTC of 15th May, the forecasts of GPP (**Fig. 11**) showed potential to intensify into a cyclone at 36 and 60 hrs lead period. Thus the model was not consistent in predicting the cyclogenesis. Similarly the model run at 0000 UTC of 16th may indicated potential for genesis at its 12 hr forecast only. Thus it could not predict the genesis of the system well.

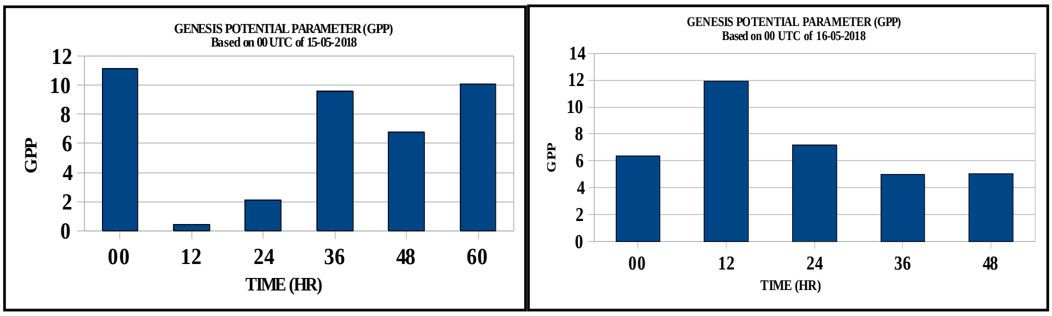


Fig. 11: Area average analysis and forecasts of GPP based on 0000 UTC of 15th and 16th May 2018

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 17th May, most of the models indicated southwestward or west-southwestward movement. However a few models only predicted the landfall and the rest of the models weakened the system over Gulf of Aden.

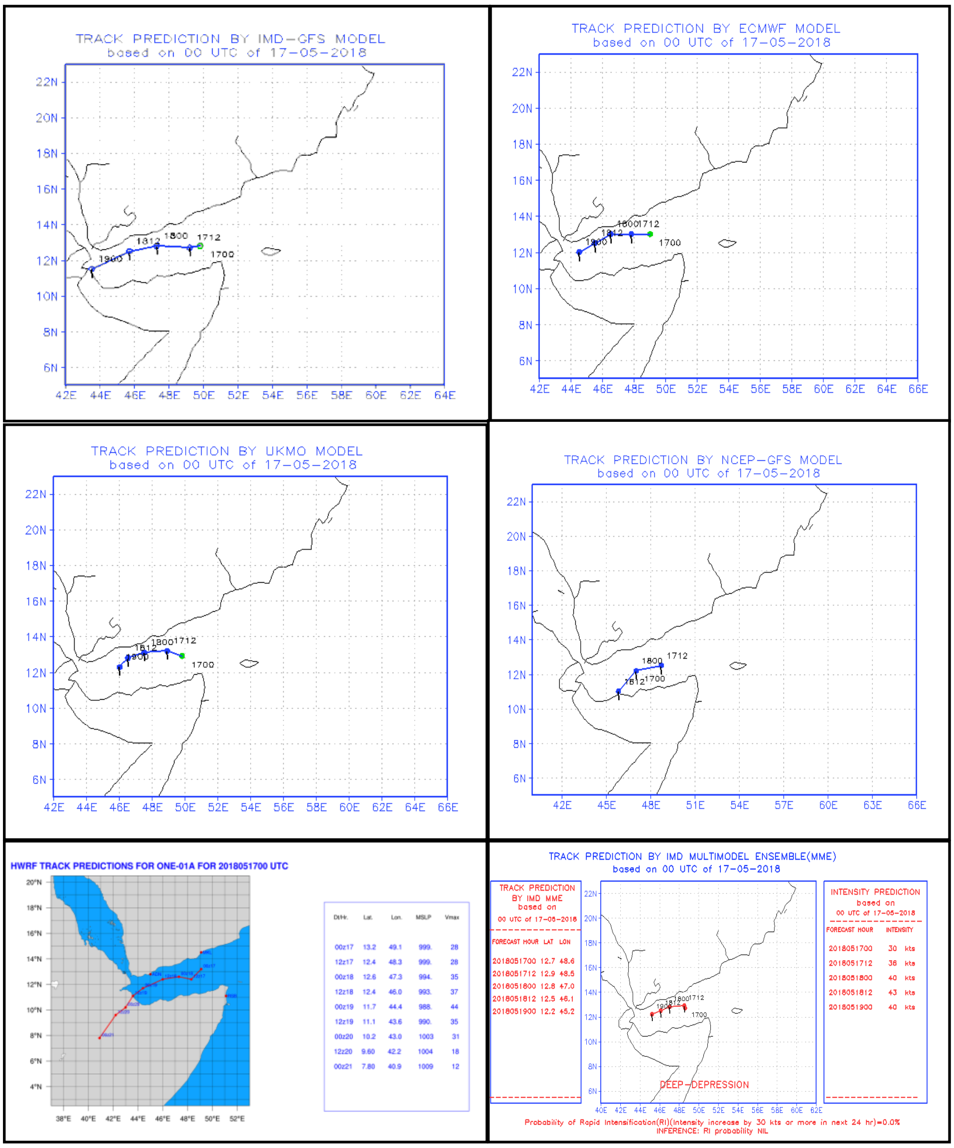


Fig. 12 (a): NWP model track forecast based on 0000 UTC of 17th May

Based on the initial conditions of 0000 UTC of 18th May, the performance of ECMWF model was better than other in predicting the landfall.

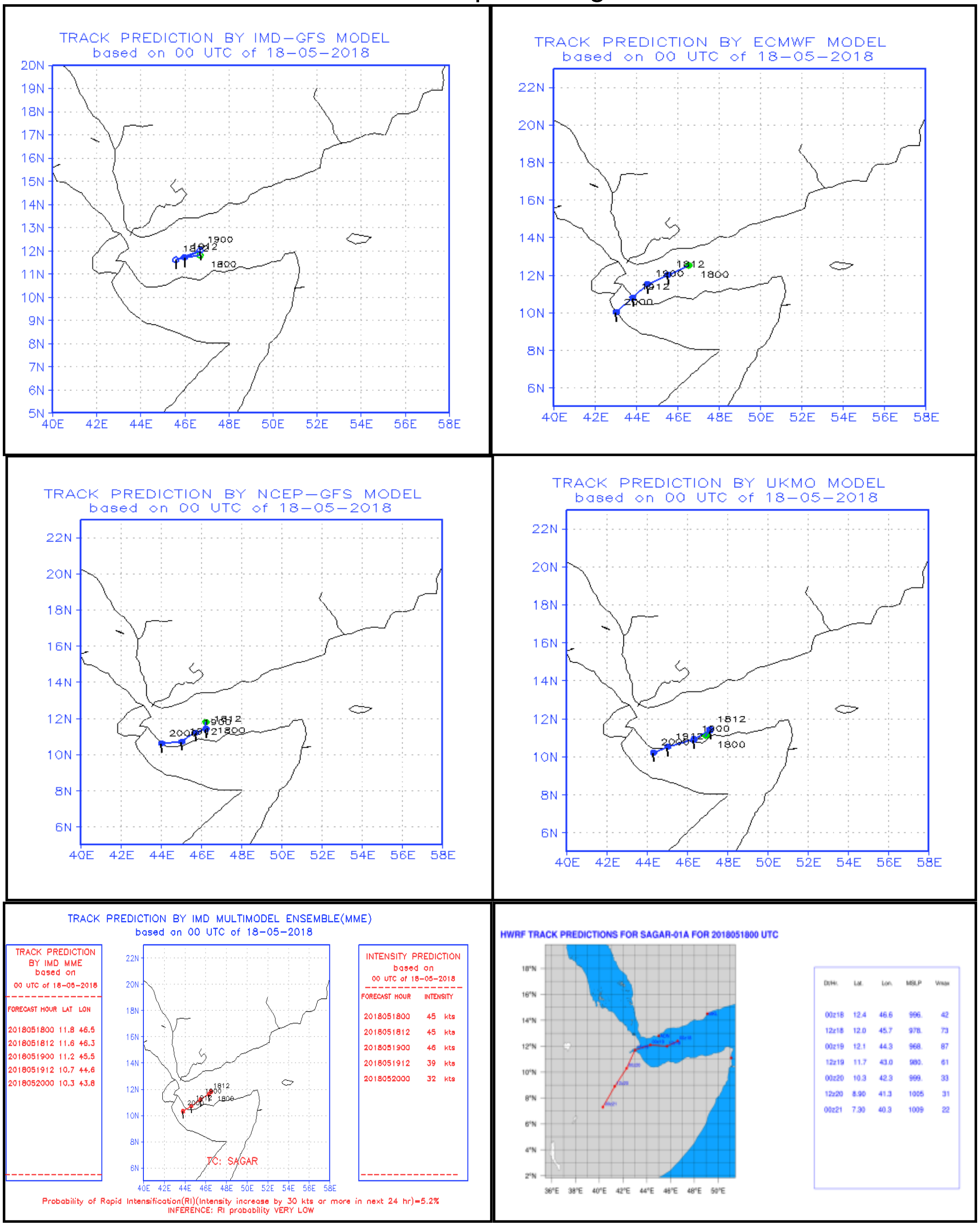


Fig. 12 (b): NWP model track forecast based on 0000 UTC of 18th May

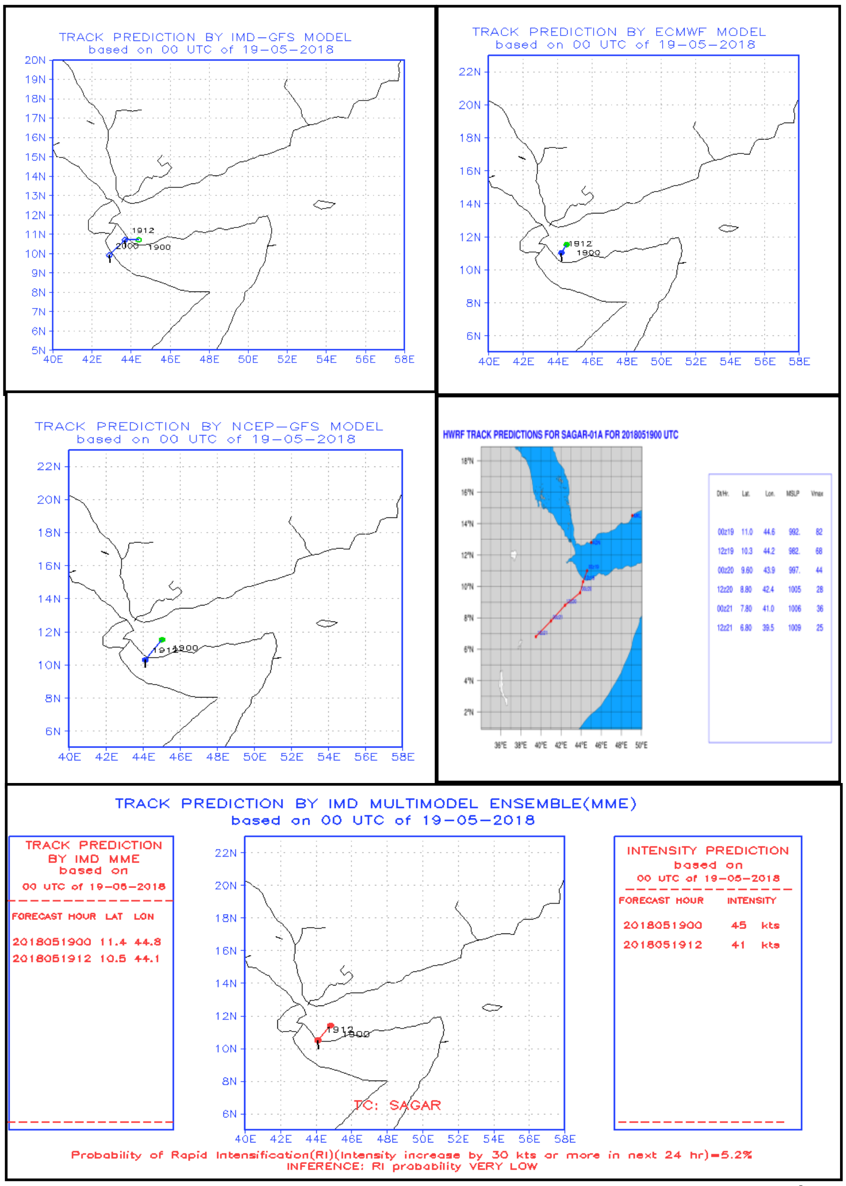


Fig. 12 (c): NWP model track forecast based on 0000 UTC of 19th May

Table 2. Average track forecast errors (Direct Position Error (DPE)) in km (Number of forecasts verified is given in the parentheses) for CS, Sagar

Lead time →	12H	24H	36H	48H	60 H	72 H
IMD-GFS	68(6)	99(5)	154(4)	118(3)	-	-
NCEP-GFS	90(6)	144(5)	212(4)	175(2)	-	-
UKMO	119(4)	127(4)	153(3)	158(3)	-	-
ECMWF	47(6)	59(5)	123(4)	65(3)	-	-
IMD-HWRF	49(5)	106(5)	125(4)	129(3)	136(2)	25(1)
IMD-MME	55(6)	74(5)	170(4)	123(3)	-	-

Table 3(a). Average cross-track forecast errors (CTE) in km for CS, Sagar

Lead time →	12H	24H	36H	48H	60 H	72 H
IMD-GFS	37	37	68	77	-	-
NCEP-GFS	41	45	52	13	-	-
UKMO	65	52	66	46	-	-
ECMWF	26	51	85	48	-	-
IMD-HWRF	38	30	32	96	79	29
IMD-MME	32	29	53	42	-	-

Table 3(b). Average along-track forecast errors (ATE) in km for CS, Sagar

Lead time →	12H	24H	36H	48H	60 H	72 H
IMD-GFS	53	84	122	77	-	-
NCEP-GFS	75	133	189	175	-	-
UKMO	94	112	137	150	-	-
ECMWF	31	18	81	33	-	-
IMD-HWRF	2	32	72	87	57	15
IMD-MME	42	66	160	110	-	-

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**. The average cross track errors (CTE) and along track errors (ATE) are presented in Table **3(a-b).** From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of ECMWF model was minimum for 24 and 48 hr forecasts followed by MME. Above tables show that DPE was largely contributed by ATE, i.e. the errors in speed of movement of the storm.

9.4 Intensity forecast errors by various NWP Models

The intensity forecasts of IMD-SCIP model and HWRF model are shown in Table **4(a-b).** The intensity error was very high with HWRF model upto 36 hr forecasts. The probability of rapid intensification (RI) index of IMD is shown in **Table 5**. The model predicted no RI for CS, Sagar. However the probability of prediction was not in agreement with the actual change in intensity.

Table 4(a). Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of SCIP model (Number of forecasts verified is given in the parentheses) in case of CS, Sagar

Lead time →	12H	24H	36H	48H
IMD-SCIP (AAE)	4.8(5)	8.3(4)	9.0(3)	5.0(1)
IMD-SCIP (RMSE)	5.5(5)	8.7(4)	10.9(3)	5.0(1)

Table 4(b). Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of HWRF model (Number of forecasts verified is given in the parentheses) in case of CS, Sagar

Lead time →	12H	24H	36H	48H	60H	72H
IMD-HWRF (AAE)	31.8(5)	29.0(5)	16.5(4)	6.6(3)	8.0(2)	6.0(1)
IMD-HWRF (RMSE)	33.8(5)	36.7(5)	17.1(4)	7.8(3)	10.3(2)	6.0(1)

Table 5. Probability of Rapid intensification of CS Sagar

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes(kt) occurred in 24h
12/16.05.2018	5.2 %	Very low	+15
00/17.05.2018	0 %	Nil	+15
12/17.05.2018	5.2 %	Very low	+5
00/18.05.2018	5.2 %	Very low	0

9.4. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model are presented in **Fig.13**.

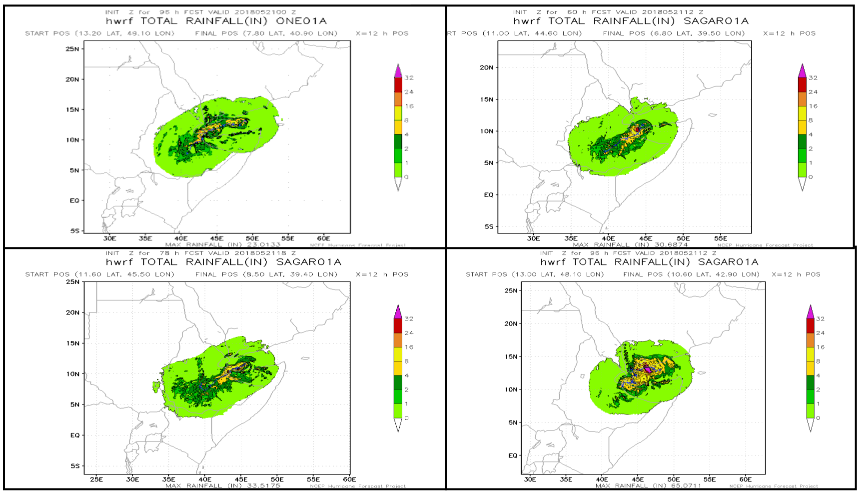


Fig.13: Heavy rainfall forecast by HWRF based on initial conditions of 0000 UTC of 28th-30th May, 2017.

It indicates that HWRF model could capture the occurrence of rainfall over Somalia and adjoining regions, as it predicted the track well.

10. Operational Forecast Performance

10.1. Genesis Forecast

- First information regarding formation of a low pressure area over the central parts of south AS and adjoining central AS around 15th May and it's movement towards Yemen coast with further intensification into D in subsequent 48 hrs was predicted in Tropical Weather Outlook issued at (1130 IST) 0600 UTC of 11th May (72 & 108 hours in advance of formation of low pressure area & D respectively). Low pressure area formed over southwest AS on 14th and D formed over Gulf of Aden at 1200 UTC of 16th.

10.2. Landfall Forecast

- First information regarding landfall of system near northwest Somalia (near 11.3^{0}N/43.1^{0}E) around 0900 UTC of 19th was issued at 1400 UTC of 17th May (42 hours in advance of actual landfall). The system crossed Somalia coast near 10.65^{0}N/44.0^{0}E between 0800-0900 UTC of 19th May.
- The landfall point forecast errors for 12, 24, and 36 hrs lead period were 6.6, 40.4, and 100.5 km respectively and the landfall time forecast errors for 12, 24, and 36 hrs lead period were 1.0, 1.0, and 5.5 hrs respectively **(Fig. 14).**

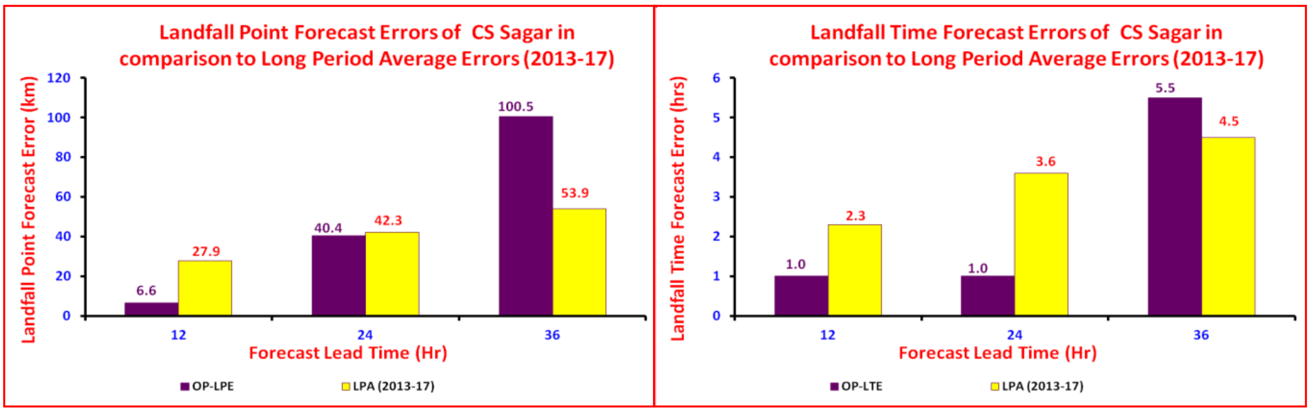


Fig. 14: Landfall Point Errors (LPE) and Landfall Time Errors (LTE) for CS Sagar

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

Lead Period (hrs)	Base Time (UTC)	Landfall Point (^{0}N/^{0}E)		Landfall Time (UTC)		Operational Error		LPA error (2013-17)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	18/18	10.7/44.1	10.7/44.0	19/0830	19/0730	6.6	1.0	53.9	4.5
24	18/06	10.9/43.7	10.7/44.0	19/0630	19/0730	40.4	1.0	94.8	5.4
36	17/18	11.4/43.5	10.7/44.0	19/0200	19/0730	100.5	5.5	115.4	4.6

LPE: Landfall Point Error, LTE: Landfall Time Error, LPA: Long Period Average,
LPE= Forecast Landfall Point-Actual Landfall Point,
LTE= Forecast Landfall Time-Actual Landfall Time

10.3. Track Forecast

- First bulletin issued at 1500 UTC observations of 16th May indicated that the system would move west-northwestwards towards Yemen coast during next 24 hours and then west-southwestwards during subsequent 48 hours. The track (Fig.1) shows that the system moved west-northwestwards upto 0300 UTC of 17th (for 15 hours) and then west-southwestwards till its weakening into a WML at 0300 UTC of 20th May (for subsequent 72 hours). Thus the track of the system including its west-southwestward recurvature was well predicted.
- The typical example of observed and forecast track with cone of uncertainty is presented in **Fig.15.** The graphics showing observed and forecast tracks for different lead periods is presented in **Fig.16.**
- The track forecast error for 12, 24, and 48 hrs lead period were 42.7, 49.6, and 117.2 km respectively, which is significantly less than the average track forecast errors of 57, 93, and 144 km during last five years (2013-17). The track forecast skill was about 18%, 53%, and 64% against the long period average (LPA) of 45%, 55%, and 68% during 2013-17 for 12, 24 and 48 hrs lead period respectively. (**Fig.17**).

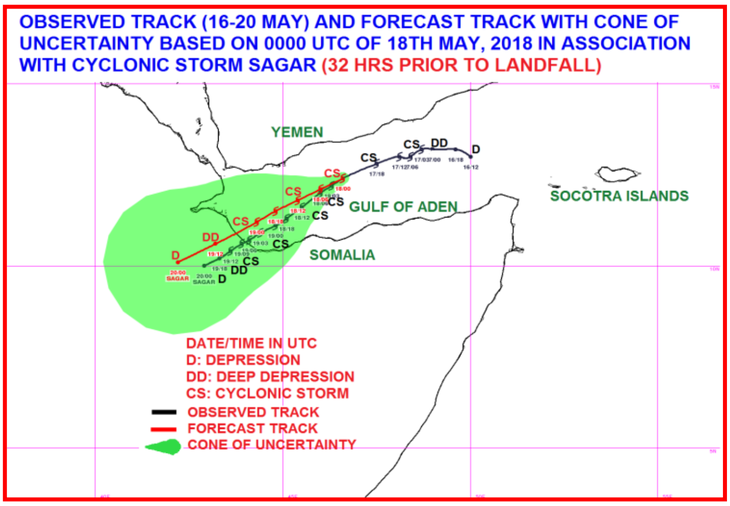


Fig.15: Observed and forecast track with cone of uncertainty based on 0000 UTC of 18th May, 2018 in association with CS Sagar

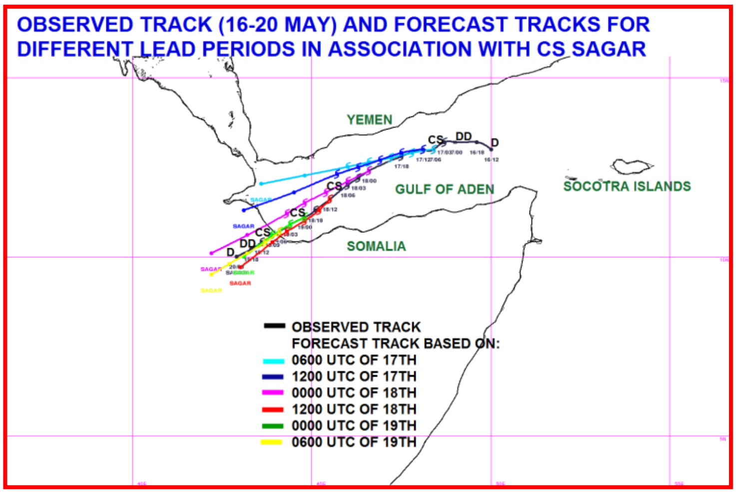


Fig.16: Observed track and forecast tracks for different lead periods

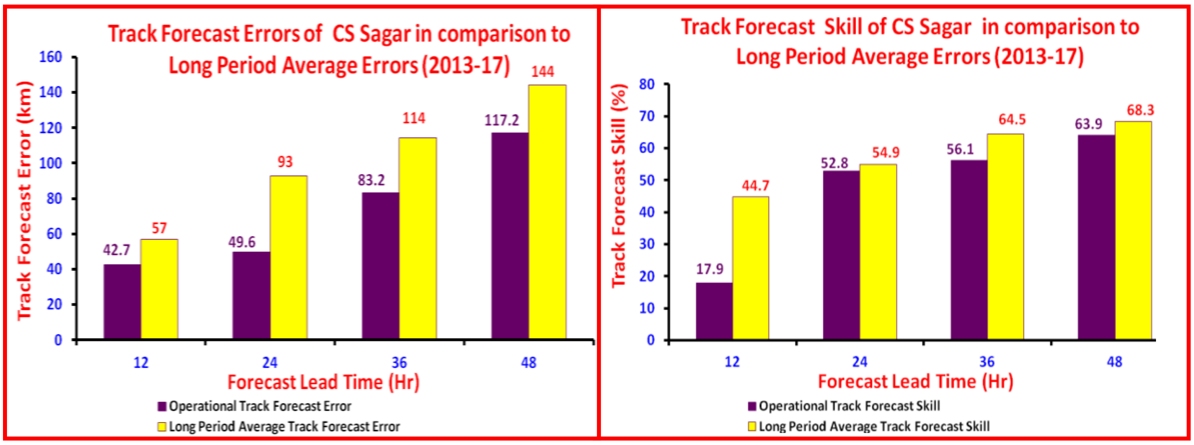


Fig.17: Track Forecast Errors and Skill for CS Sagar

Table 8: Average Track forecast error in association with ESCS Mekunu

Lead Period (hrs)	N	Average track forecast error (km)	Skill (%)	LPA (2013-17)	
				Track forecast error (km)	Skill (%)
12	12	42.7	17.9	57	44.7
24	10	49.6	52.8	93	54.9
36	8	83.2	56.1	114	64.5
48	4	117.2	63.9	144	68.3

N: No. of observations verified, LPA: Long Period Average (2013-17)

4.4. Intensity Forecast

- First wind warning issued at 2000 UTC of 16th indicated that the system would intensify upto a cyclonic storm.
- The warning issued at 0200 UTC of 18th indicated that the system would cross Somalia coast as a CS with MSW of 65-75 kmph (37 knots) (32 hours in advance). The system crossed Somalia coast as a CS with MSW of 40 kts. Typical graphical product giving wind distribution is presented in **Fig. 18.**
- The absolute error (AE) of intensity (wind) forecast for 12, 24 and 48 hrs lead period were 2.2, 7.0 and 10.8 knots against the LPA of 6.3, 10.4, and 15.5 knots respectively. The skill in intensity (wind) forecast based on AE for 12, 24 and 48 hrs lead period was 34.3, 17.6 and 46.3% against the LPA of 22.3, 37.1 and 56.8% respectively. (**Fig.19**)
- The root mean square error (RMSE) of intensity (wind) forecast for 12, 24 and 48 hrs lead period were 2.7, 8.1 and 12.7 knots against the LPA of 8.7, 14.0, and 20.6 knots respectively. The skill based on RMSE of intensity (wind) forecast for 12, 24 and 48 hrs lead period was 53.8, 22.1 and 47.5% against the LPA of 28.0, 40.1 and 60.0% respectively. (**Fig.20**)

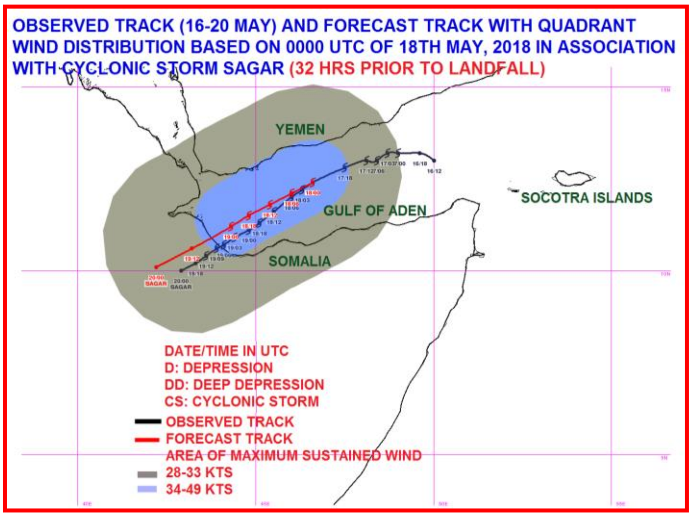


Fig.18: Observed and forecast track with quadrant wind distribution based on 0000 UTC of 18th May, 2018 in association with CS Sagar

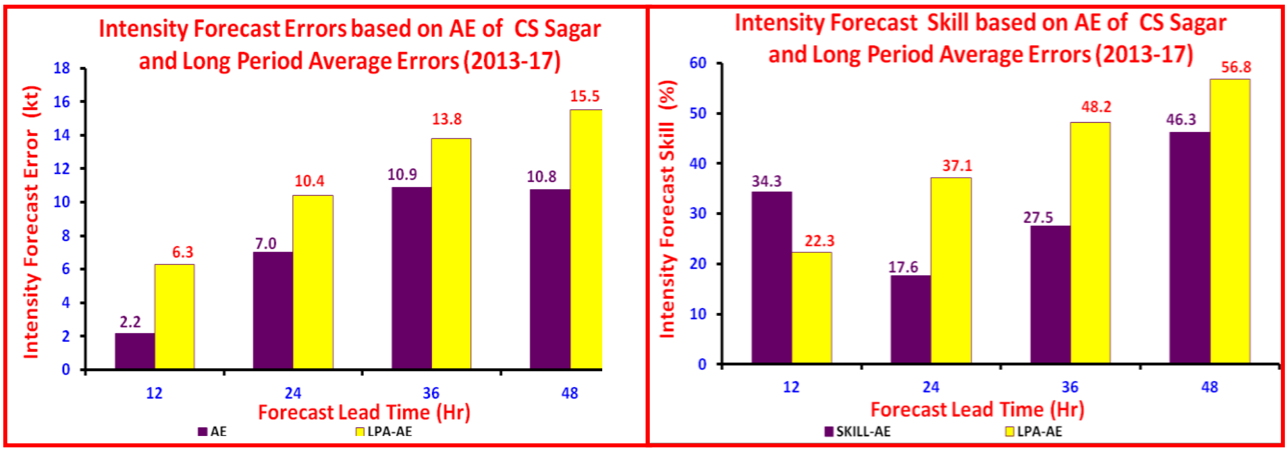


Fig. 19: Absolute errors (AE) of intensity forecast and skill for CS Sagar

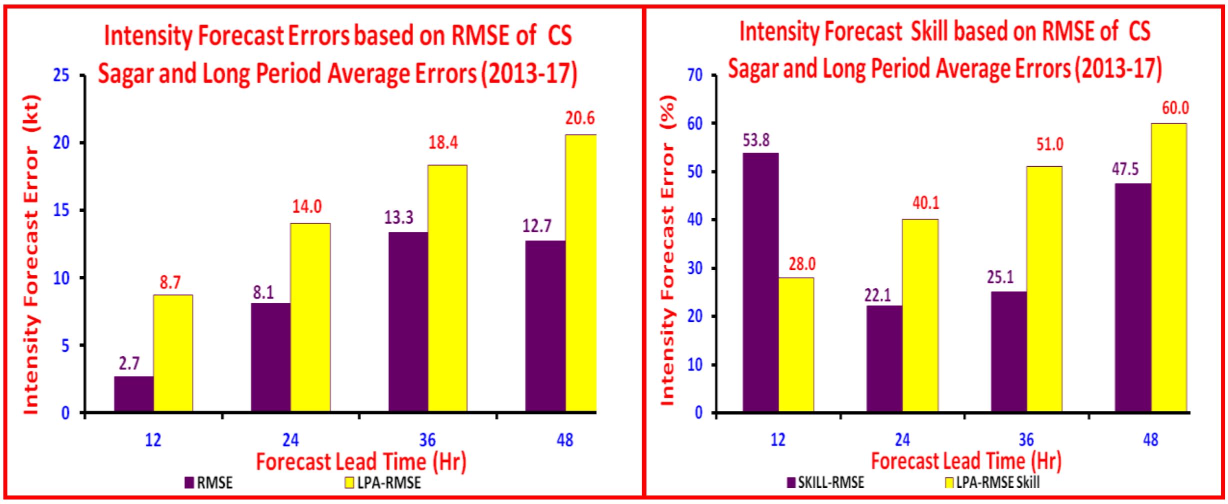


Fig. 20: Root mean square errors (RMSE) of intensity forecast and skill for CS Sagar

Table 9: Average Intensity forecast error in association with ESCS Mekunu

Lead Period (hrs)	N	Average Intensity Error (kts)		Skill (%) in intensity forecast		LPA Intensity forecast Error (kts) (2013-17)		LPA Skill (%) in Intensity forecast (2013-17)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	12	2.2	2.7	34.3	53.8	6.3	8.7	22.3	28.0
24	10	7.0	8.1	17.6	22.1	10.4	14.0	37.1	40.1
36	8	10.9	13.3	27.5	25.1	13.8	18.4	48.2	51.0
48	4	10.8	12.7	46.3	47.5	15.5	20.6	56.8	60.0

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2013-17).

11. Warning Services

11.1. 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 hrs lead period till the system weakened into a low pressure area. The above forecasts were issued from the stage of depression onwards along with the cone of uncertainty in the track forecast.
- **Cyclone structure forecast for shipping and coastal hazard management** The radius of maximum wind and radii of MSW ≥28 knots and ≥34 knots wind in four quadrants of cyclone was issued every six hourly giving forecast for +06, +12, +18, +24, +36 and +48 hrs lead period.
- **Adverse weather warning bulletins:** The tropical cyclone forecasts alongwith expected adverse weather like gale wind was issued with every three hourly update during cyclone period to the central, state and district level disaster management agencies including MHA NDRF, NDMA for all the states along west coast of India, Lakshadweep Islands and Daman & Diu and Dadar Nagar Haveli. The bulletin 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.
- **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.
- **Warning and advisory through social media:** Daily updates were uploaded on facebook and tweeter regularly during the life period of the system.

- **Press release and press briefing:** Press and electronic media were given daily updates since inception of system through press release, e-mail, website and SMS.
- **Warning and advisory for marine community:** The three/six hourly Global Maritime Distress Safety System (GMDSS) bulletins were issued by the cyclone warning division at New Delhi and cyclone warning centres of IMD at Chennai, Meteorological Centre, Thiruvananthapuram, Goa, Area Cyclone Warning Centre Mumbai and Cyclone Warning Centre Ahmedabad to ports, fishermen, coastal and high sea shipping community.
- **Fishermen Warning:** First warning for fishermen of the states of Tamil Nadu, Kerala, Karnataka, Goa, Maharashtra, Gujarat, Lakshadweep, Daman Diu & Dadra Nagar Haveli not to venture into Gulf of Aden and adjoining areas of westcentral and adjoining southwest AS was issued at 1500 UTC of 16th 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 prognostics and diagnostics of the systems were described in the RSMC bulletins and tropical cyclone advisory bulletins.
- **TC Vital:** Tropical cyclone vitals were prepared every six hourly from depression stage onwards and provided to various NWP modeling groups in India for generation/relocation of vortex in the model so as to improve the track and intensity forecast by the numerical models.

Statistics of bulletins issued by RSMC New Delhi in association with the cyclonic storm Sagar are given in **Table 6.**

Table 6 : Bulletins issued by RSMC New Delhi

S.N	Bulletin type	No. of Bulletins	Issued to
1	National 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, Headquarter Integrated Defence Staff, Director General Doordarshan, All India Radio, National Disaster Response Force, Chief Secretary-Tamil Nadu, Kerala, Lakhshadweep, Daman, Diu and Dadra Nagar Haveli, Karnataka, Goa, Maharshtra and Gujarat.
2	RSMC Bulletin	27	1. IMD's website 2. WMO/ESCAP member countries through GTS and E-mail.
3	GMDSS Bulletins	27	1. IMD website, RSMC New Delhi website 2. Transmitted through WMO Information System (WIS) to Joint WMO/IOC Technical Commission for Ocean and Marine Meteorology (JCOMM)
4	Tropical Cyclone Advisory Centre	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

	Bulletin		through ftp 3. RSMC website
5	Tropical Cyclone Vital Statistics	13	Modelling group of IMD, National Centre for Medium Range Weather Forecasting Centre (NCMRWF), Indian National Centre for Ocean Information Services (INCOIS), Indian Institute of Technology (IIT) Delhi, IIT Bhubaneswar etc.
6	Warnings through SMS	Daily	SMS to disaster managers at national level and concerned states (Total 845 messages were sent) (every time when there was change in intensity)
7	Warnings through Social Media	Daily	Cyclone Warnings were uploaded on Social networking sites (Face book and Tweeter) since inception to weakening of system (every time when there was change in intensity).
8	Press Release	4	Disaster Managers, Media persons by email and uploaded on website
9	Press Briefings	Daily	Regular briefing daily

12. Summary and Conclusion:

The Cyclonic Storm (CS) Sagar originated from a low pressure area which formed over southwest Arabian Sea in the morning (0300 UTC) of 14th May. It became a well marked low pressure area in the early morning (0000 UTC) of 15th over the same region. Under favourable environmental conditions, it concentrated into a Depression (D) over Gulf of Aden in the evening (1200 UTC) of 16th May. Moving west-northwestwards it intensified into a deep depression (DD) in the early morning (0000 UTC) and further into a cyclonic storm (CS) **"Sagar"** in the morning (0300 UTC) of 17th May 2018 over Gulf of Aden. Thereafter, it moved west-southwestwards and crossed Somalia coast near latitude 10.65^{0}N and longitude 44.0 ^{0}E as a cyclonic storm with maximum sustained wind speed (MSW) of 70-80 kmph gusting to 90 kmph between 1330 and 1430 IST of 19th May. Moving further west-southwestwards, it weakened into a DD in the mid night (1800 UTC) of 19th, D in the early morning (0000 UTC) of 20th and well marked low pressure area (WML) over Ethiopia and adjoining Somalia in the morning (0300 UTC) of 20th.

IMD utilised all its resources to monitor and predict the genesis, track and intensification of CS Sagar. The track forecast error for 12, 24, and 48 hrs lead period were 42.7, 49.6, and 117.2 km respectively, which is significantly less than the average track forecast errors of 57, 93, and 144 km during last five years (2013-17). The absolute error (AE) of intensity (wind) forecast for 12, 24 and 48 hrs lead period were 2.2, 7.0 and 10.8 knots against the LPA of 6.3, 10.4, and 15.5 knots respectively.

14. Acknowledgements:

India Meteorological Department (IMD) and RSMC New Delhi duly acknowledges the contribution from all the stake holders and disaster management agencies who contributed to the successful monitoring, prediction and early warning service of CS Sagar. RSMC New Delhi acknowledges contribution of World Meteorological Organisation in co-ordinating and helping RSMC in dissemination of warnings to Government of Somalia. 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), research institutes including

IIT Bhubaneswar, IIT Delhi and Space Application Centre, Indian Space Research Organisation (SAC-ISRO) for their valuable support. The support from various Divisions/Sections of IMD including Area Cyclone Warning Centre (ACWC) Chennai & Mumbai, Cyclone Warning Centre (CWC) Ahmedabad, Meteorological Centre (MC) Thiruvananthapuram, MC Goa, MC Bengaluru, Numerical Weather Prediction Division, Satellite Division and Information System and Services Division at IMD, New Delhi is also duly acknowledged.