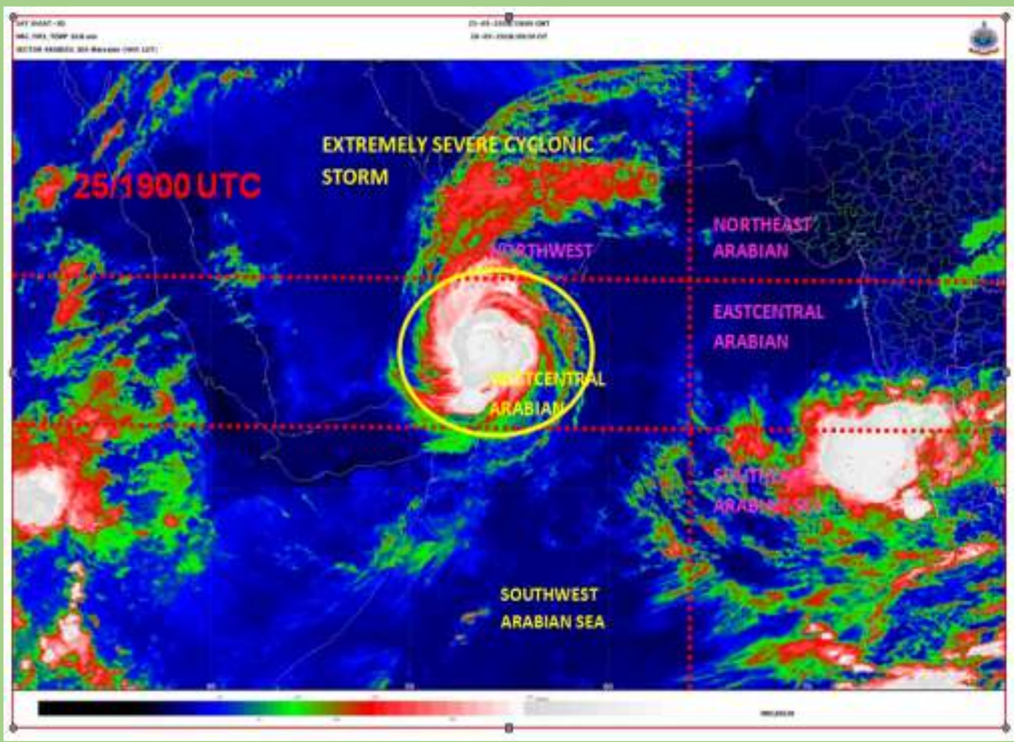
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Extremely Severe Cyclonic Storm, 'MEKUNU' over the Arabian Sea (21 – 27 May 2018): A Report



INSAT-3D enhanced colored IR imagery of 25th May, 2018

Cyclone Warning Division

India Meteorological Department

New Delhi

JUNE 2018

Extremely Severe Cyclonic Storm, 'MEKUNU' over the Arabian Sea (21 – 27 May 2018)

1. Introduction

Extremely Severe Cyclonic Storm (ESCS) Mekunu originated from a low pressure area which formed over southeast Arabian Sea (AS) in the morning (0300 UTC) of 20th May. It became a well marked low pressure area over southwest & adjoining southeast AS in the early morning (0000 UTC) of 21st May.

Under favourable environmental conditions, it concentrated into a Depression (D) over southwest AS in the evening (1200 UTC) of 21st May. Moving west-northwestwards it intensified into a deep depression (DD) in the morning (0300 UTC) of 22nd May. It then moved north-northwestwards and intensified into a cyclonic storm (CS) **"Mekunu**" in the evening (1200 UTC) of same day over southwest AS. It further continued to move north-northwestwards, intensified into a Severe Cyclonic Storm (SCS) in the morning (0300 UTC) and into a Very Severe Cyclonic Storm (VSCS) in the afternoon (0900 UTC) of 23rd May over Westcentral AS. Moving further north-northwestwards, it intensified into an Extremely Severe Cyclonic Storm (ESCS) in the morning (0300 UTC) of 25th and crossed south Oman coast near 16.85^0N/53.75^0E around midnight (between 1830-1930 UTC) of 25th May as an ESCS with an estimated wind speed of 170-180 kmph gusting to 200 kmph. It moved north-northwestwards and weakened into a VSCS over Oman in the early hours of 26th May (2100 UTC of 25th May). Continuing to move north-northwestwards, it weakened into an SCS in the early morning (0000 UTC), into a CS in the afternoon (0900 UTC) and into a DD around midnight (1800 UTC) of 26th May. It further weakened into a D in the early morning (0000 UTC) and into a well marked low pressure area over Saudi Arabia and adjoining Oman & Yemen in the morning (0300 UTC) of 27th May.

The salient features of the system are as follows.

i. ESCS Mekunu was the second cyclonic storm over AS during the year 2018.
ii. Mekunu had a straight north-northwestward moving track.
iii. It formed (at 1200 UTC of 21st May) just 5 days after the formation of CS Sagar (at 1200 UTC of 16th May) over Arabian Sea. Such cylogenesis in quick succession within a week last occurred over AS in post-monsoon season of 2015 (ESCS Chapala followed by ESCS Megh).
iv. It attained its peak intensity on the day of landfall while lying close to coast.
v. It maintained the peak maximum sustained surface wind speed (MSW) of 170-180 kmph gusting to 200 kmph (95 knots) for 6 hours during 1200 UTC to 1800 UTC of 25th May.
vi. The lowest estimated central pressure was 960 hPa during 1200 UTC to 1800 UTC of 25th May.

vii. The life period of cyclone was 135 hours (5.6 days) against long period average (LPA) (1990-2013) of 6.6 days for very severe cyclonic storm over Arabian Sea in pre-monsoon season.
viii. The track length of the cyclone was 1385 km.
ix. The 12 hour average translational speed of the cyclone was 10.4 kmph against LPA (1990-2013) of 14.3 kmph over AS.
x. The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were 11.6 $X10^2$ knots, 8.4 X 10^4 $knots^2$ and 6.5 $X10^6$ $knots^3$ 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. The observed track of the system during 21st-27th May is presented in **Fig.1**. Typical satellite imagery is presented in **Fig.2**. The best track parameters of the system are presented in Table 1.

2. Monitoring of ESCS, 'MEKUNU'

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) prior to it's genesis as low pressure area over AS from 21st 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 (NWP) 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

Under the influence of a cyclonic circulation that developed over Lakshadweep and neighbourhood on 18th May, a low pressure area formed over southeast AS in the morning (0300 UTC) of 20th May. It lay as a well marked low pressure area over southwest & adjoining southeast AS in the early morning (0000 UTC) of 21st May.

At 0300 UTC of 21st May, the Madden Julian Oscillation (MJO) index lay over phase 2 with amplitude more than 1. The MJO phase was favouring cyclogenesis over the AS and its further intensification. The sea surface temperature (SST) was 29-31^{0}C over southwest and adjoining westcentral AS. The tropical cyclone heat potential (TCHP) was more than 100 KJ/cm^2 over the above region. The low level relative vorticity was about $100x10^{-6}sec^{-1}$ to the southwest of system centre. The lower level convergence was about 20 $x10^{-5}sec^{-1}$ to the southwest of system centre. The upper level divergence was about 40 $x10^{-5}$ sec^{-1} over the system centre. The vertical wind shear (VWS) was low to moderate (10-15 knots) over the system centre. VWS was also low to moderate over westcentral AS near Oman and Yemen coast. All these conditions indicated favourable environment for further intensification of the system.

At 1200 UTC of 21st, similar environmental features continued. The low level relative vorticity increased significantly and was about $150x10^{-6}sec^{-1}$ to the southwest of system centre. The lower level convergence was about 20 $x10^{-5}sec^{-1}$ to the south and southwest of system centre. The upper level divergence was about 30 $x10^{-5}$ sec^{-1} over the system centre. The vertical wind shear is low to moderate (10-15 knots) over the system. Hence the environmental conditions are favourable for further intensification of the system. Under these conditions the WML southwest & adjoining southeast AS concentrated into depression (**D**) at 1200 UTC over the same region.

3.2. Intensification and movement

At 0300 UTC of 22nd, the MJO was in Phase 2 with amplitude more than 1. The SST was 29-31^{0}C over southwest and adjoining westcentral AS. There was positive SST anomaly over westcentral AS. The TCHP was more than 60-80 KJ/cm^2 over the region. The low level relative vorticity increased significantly and was about $150x10^{-6}sec^{-1}$ to the south of system centre. The lower level convergence was about 20 $x10^{-5}sec^{-1}$ to the southwest of system centre. The upper level divergence was about 30 $x10^{-5}$ sec^{-1} to the west of the system centre. The vertical wind shear was low to moderate (05-15 knots) near the system centre. The total precipitable water (TPW) imagery indicated continous warm and moist air incursion into the core of the system. All these environmental conditions favoured the intensification of system into **DD** at 0300 UTC over southwest AS near latitude 9.2^{0}N and longitude 57.2^{0}E.

At 1200 UTC of 22nd, MJO was in Phase 2. Similar sea conditions prevailed. The low level relative vorticity increased significantly and was about $250x10^{-6}sec^{-1}$ over the system centre. The lower level convergence also increased and was about 50 $x10^{-5}sec^{-1}$ around the system centre. The upper level divergence remained unchanged and was about 30 $x10^{-5}$ sec^{-1} over the system area. The vertical wind shear was low to moderate (05-15 knots) near the system centre. The TPW imagery indicated continous warm and moist air incursion into the core of the system. All these conditions led to the intensification of system into **CS "Mekunu"** at 1200 over southwest AS near latitude 10.2^{0}N and longitude 56.8^{0}E.

At 0300 UTC of 23rd, MJO was in Phase 2 with amplitude greater than 1. The SST was 29-31^{0}C over southwest and adjoining westcentral AS. There was positive SST anomaly over westcentral AS. The tropical cyclone heat potential was about 80-100 KJ/cm^2 over the region. The low level relative vorticity was about $250x10^{-6}sec^{-1}$ close to east of the system centre. The lower level convergence decreased and was about 40 $x10^{-5}sec^{-1}$ close to west of the system centre. The upper level divergence was about 30 $x10^{-5}$ sec^{-1} close to west of the system centre. The TPW imagery indicated continuous warm and moist air incursion into the core of the system. Under these conditions, the system intensified into an **SCS** at 0300 UTC over southwest AS near latitude 11.2^{0}N and longitude 55.9^{0}E.

At 0900 UTC of 23rd, MJO was in Phase 2 with amplitude greater than 1. Similar sea conditions prevailed. The low level relative vorticity remained same and was about $250x10^{-6}$ sec^{-1} close to south of the system centre. The lower level convergence increased and was about 50 $x10^{-5}$ sec^{-1} close to southwest of the system centre. The upper level divergence was about 40 $x10^{-5}$ sec^{-1} close to west of the system centre. The vertical wind shear was moderate to high (15-25 knots) near the system centre. The TPW imagery indicated continuous warm and moist air incursion into the core of the system. The steering winds indicated that the system would move nearly northwards for next 12 to 24 hours and thereafter north-northwestwards towards south Oman–south east Yemen coasts under the influence of anticyclonic circulation at middle and upper troposhperic levels located to the northeast of the system centre. Under these conditions, the system intensified into a **VSCS** at 0900 UTC over southwest and adjoining westcentral AS near latitude 11.8^0N and longitude 55.9^0E.

At 0300 of 24^{th}, the MJO was in Phase 2. The SST was 29-31^0C over southwest and adjoining westcentral AS. There was positive SST anomaly over westcentral AS. The tropical cyclone heat potential was about 80-100 KJ/cm^2 over the core region. However, it was relatively low along the predicted track. The low level relative vorticity was about $250x10^{-6}$ sec^{-1} to the south of system centre. The low level convergence increased and was about 60 $x10^{-5}$ sec^{-1} to the southwest of the system centre. The upper level divergence was about 40 $x10^{-5}$ sec^{-1} to the south of the system centre. The vertical wind shear was moderate to high (15-25 knots) near the system centre. The TPW imagery indicated continuous warm and moist air incursion into the core of the system. However, the rate of incursion showed decreasing trend. The environmental conditions predicted gradual intensification of the system during next 24 hours, as there was relatively lower tropical cyclone heat potential along the predicted track, moderate to high vertical wind shear and gradual decrease in rate of warm moist air incursion. An anticyclonic circulation at middle and upper troposhperic levels was located to the northeast of the system centre. Under it's influence, the system was expected to move nearly northwards for next 12 to 24 hours and thereafter north-northwestwards towards south Oman–south east Yemen coasts. Under these conditions, the system gradually intensified and lay over westcentral & adjoining southwest AS near latitude 13.3^0 N and longitude 55.4^0E as a **VSCS**.

At 0300 UTC of 25^{th}, MJO was in Phase 2 with amplitude greater than 1. The SST was 30-31^0 C over westcentral AS with positive SST anomaly over the region. The TCHP was about 70-90 KJ/cm^2 to the left forward sector of the predicted track and around 60-70 KJ/cm^2 to the right of the predicted track. The low level relative vorticity increased and was about $300x10^{-6}$ sec^{-1} to the southeast of the system centre. The lower level convergence was about 60 $x10^{-5}$ sec^{-1} to the south-southwest of the system centre. The upper level divergence was about 20 $x10^{-5}$ sec^{-1} to the southwest of the system centre. The vertical wind shear was low to moderate (10-15 knots) over the system area. Under these conditions the system gradually intensified into **ESCS.** The upper level ridge ran along 20^0N and an anticyclonic circulation was located at middle and upper troposhperic level to the northeast of the system center.
The system was in the periphery of the anticyclone. The steering winds indicated that the system would move north-northwestwards towards south Oman–southeast Yemen coasts. Under these conditions the system moved north-northwestwards and lay over westcentral AS near latitude 15.4°N and longitude 54.5°E.

At 1200 UTC of 25^{th}, similar sea conditions and MJO Phase continued. The low level vorticity decreased gradually and was about $300x10^{-6}$ sec^{-1} to the south of system centre. The lower level convergence decreased slightly and was about 50 $x10^{-5}$ sec^{-1} to the south of the system centre. The upper level divergence increased and was about 30 $x10^{-5}$ sec^{-1} to the south of the system centre. The vertical wind shear decreased and became low (5-10 knot) over the system area. Though there was decrease in warm moist air incursion into the core of system and decrease in lower level vorticity and convergence, the decreased wind shear and increased upper level divergence led to gradual intensification and the system reached it's **peak intensity of 95 knot**. Under the influence of anticyclonic circulation to the northeast of system centre, it moved north-northwestwards and lay over westcentral AS near latitude 16.4^{0}N and longitude 54.1^{0}E.

At 2100 UTC of 25th, similar sea conditions and MJO Phase continued. The low level relative vorticity was about 300x10^{-6} sec^{-1} to the southeast of the system centre. The lower level convergence was about 50 x10^{-5} sec^{-1} to the southeast of the system centre. The upper level divergence increased and about 40 x10^{-5} sec^{-1} to the southwest of the system centre. The vertical wind shear was low (5-10 knots) around system center. As a result, despite land interactions and decrease in warm & moist air incursion into the system, the strength of the system decreased gradually to 90 kt (ESCS) after landfall. As the system lay in the periphery of ridge at 20^{0}N and anticyclone to it's northeast, it moved northwestwards and lay over Oman near latitude 17.1^{0}N and longitude 53.5^{0}E at 2100 UTC of 25th.

Under the influence of anticyclonic circulation at middle and upper troposhperic level lying to the northeast of the system centre, it moved northwestwards after landfall. As the vertical wind shear was low (5-10 kt), the rate of weakening was restricted and the system gradually weakened over Oman into a **VSCS** at 0000 UTC of 26th near 17.2^{0}N and longitude 53.5^{0}E, into an **SCS** at 0300 UTC near 17.4^{0}N and longitude 53.2^{0}E, into a **CS** at 0900 UTC near 18.1^{0}N and longitude 53.1^{0}E, into a **DD** at 1800 UTC near 18.6^{0}N and longitude 52.8^{0}E, **D** at 0000 UTC of 27th near 19.0^{0}N and longitude 52.6^{0}E and **WML** at 0300 UTC over Saudi Arabia and adjoining areas of Oman & Yemen.

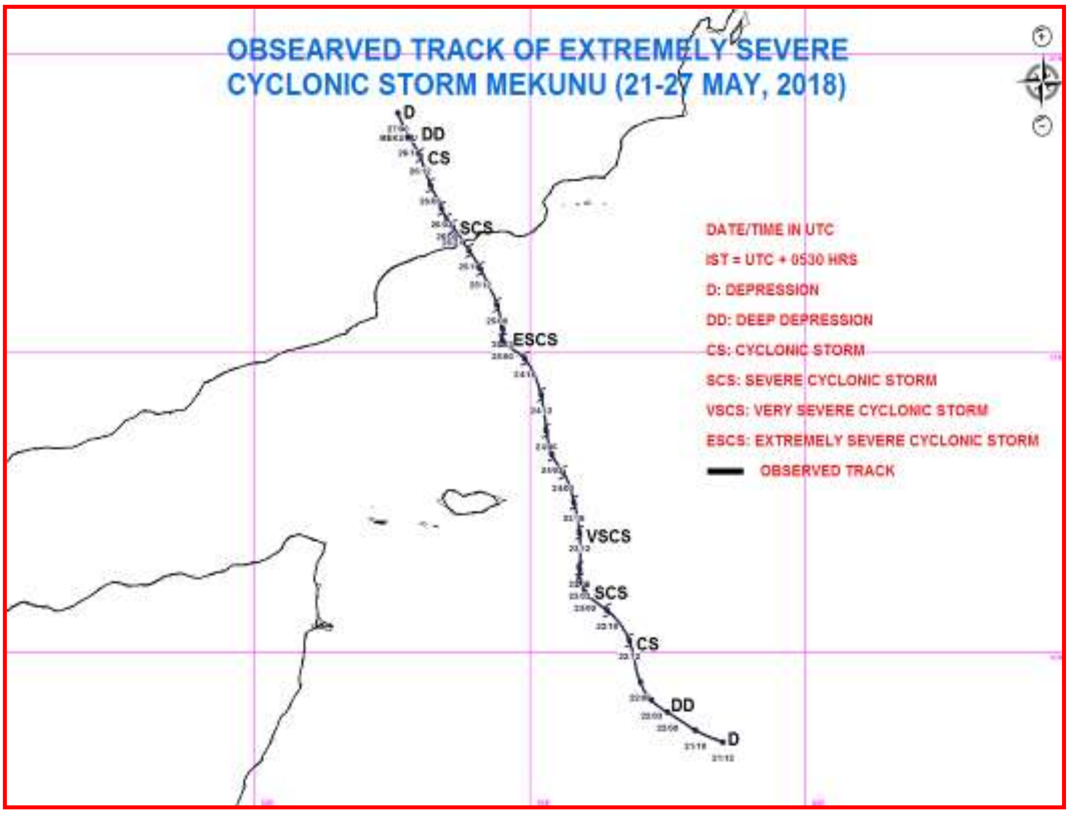


Fig.1 Observed track of ESCS Mekunu (21- 27 May, 2018) over Arabian Sea

Table 1: Best track positions and other parameters of the Extremely Severe Cyclonic Storm, 'Mekunu' over the Arabian Sea during 21 May-27 May, 2018

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
21/05/2018	1200	8.5	58.5	1.5	1004	25	3	**D**
	1800	8.7	58.0	1.5	1003	25	4	D
22/05/2018	0000	9.0	57.5	1.5	1002	25	4	D
	0300	9.2	57.2	2.0	1001	30	5	**DD**
	0600	9.5	57.0	2.0	1000	30	6	DD
	1200	10.2	56.8	2.5	998	35	7	**CS**
	1500	10.5	56.7	2.5	998	35	7	CS
	1800	10.7	56.4	2.5	996	40	8	CS
	2100	10.8	56.2	2.5	996	40	9	CS
23/05/2018	0000	11.0	56.0	3.0	994	45	10	CS
	0300	11.2	55.9	3.5	984	55	15	**SCS**
	0600	11.4	55.9	3.5	980	60	18	SCS
	0900	11.8	55.9	3.5	978	65	20	**VSCS**
	1200	12.0	55.9	4.0	978	65	22	VSCS
	1500	12.3	55.9	4.0	976	70	24	VSCS
	1800	12.5	55.8	4.0	976	70	24	VSCS
	2100	12.8	55.7	4.0	976	70	24	VSCS
24/05/2018	0000	13.0	55.6	4.0	974	70	24	VSCS
	0300	13.3	55.4	4.5	972	75	28	VSCS
	0600	13.7	55.3	4.5	970	80	32	VSCS
	0900	14.0	55.2	4.5	970	80	32	VSCS
	1200	14.3	55.2	4.5	970	80	32	VSCS
	1500	14.6	55.1	4.5	970	80	32	VSCS
	1800	14.9	54.9	4.5	970	80	32	VSCS
	2100	15.1	54.7	4.5	970	80	32	VSCS
25/05/2018	0000	15.2	54.5	4.5	968	85	36	VSCS
	0300	15.4	54.5	4.5	964	90	40	**ESCS**
	0600	15.8	54.4	4.5	964	90	40	ESCS
	0900	16.2	54.2	4.5	962	90	42	ESCS
	1200	16.4	54.1	5.0	960	95	45	ESCS
	1500	16.5	54.0	5.0	960	95	45	ESCS
	1800	16.7	53.9	5.0	960	95	45	ESCS
	Crossed south Oman coast near Latitude 16.85^0 N and longitude 53.75^0 E during 1830 UTC and 1930UTC of 25th May 2018.							
	2100	17.1	53.6	-	964	90	40	ESCS
26/05/2018	0000	17.2	53.5	-	976	75	28	**VSCS**
	0300	17.4	53.4	-	986	60	18	**SCS**
	0600	17.8	53.2	-	988	50	12	SCS
	0900	18.1	53.1	-	990	45	10	**CS**
	1200	18.3	53.0	-	992	40	8	CS
	1500	18.5	52.9	-	994	35	7	CS
	1800	18.6	52.8	-	996	30	5	**DD**

27/05/2018	0000	19.0	52.6	-	1000	25	3	**D**
	0300	**Weakened into a well marked low pressure area over Saudi Arabia and adjoining areas of Oman & Yemen at 0300 UTC of 27th May 2018.**						

The total precipitable water imageries (TPW) during 22-27 May are presented in **Fig.2**. These imageries indicate continuous warm and moist air advection from the southeast sector into the system during 22nd to 24th. From 25th afternoon, the warm moist air advection into the core decreased significantly.

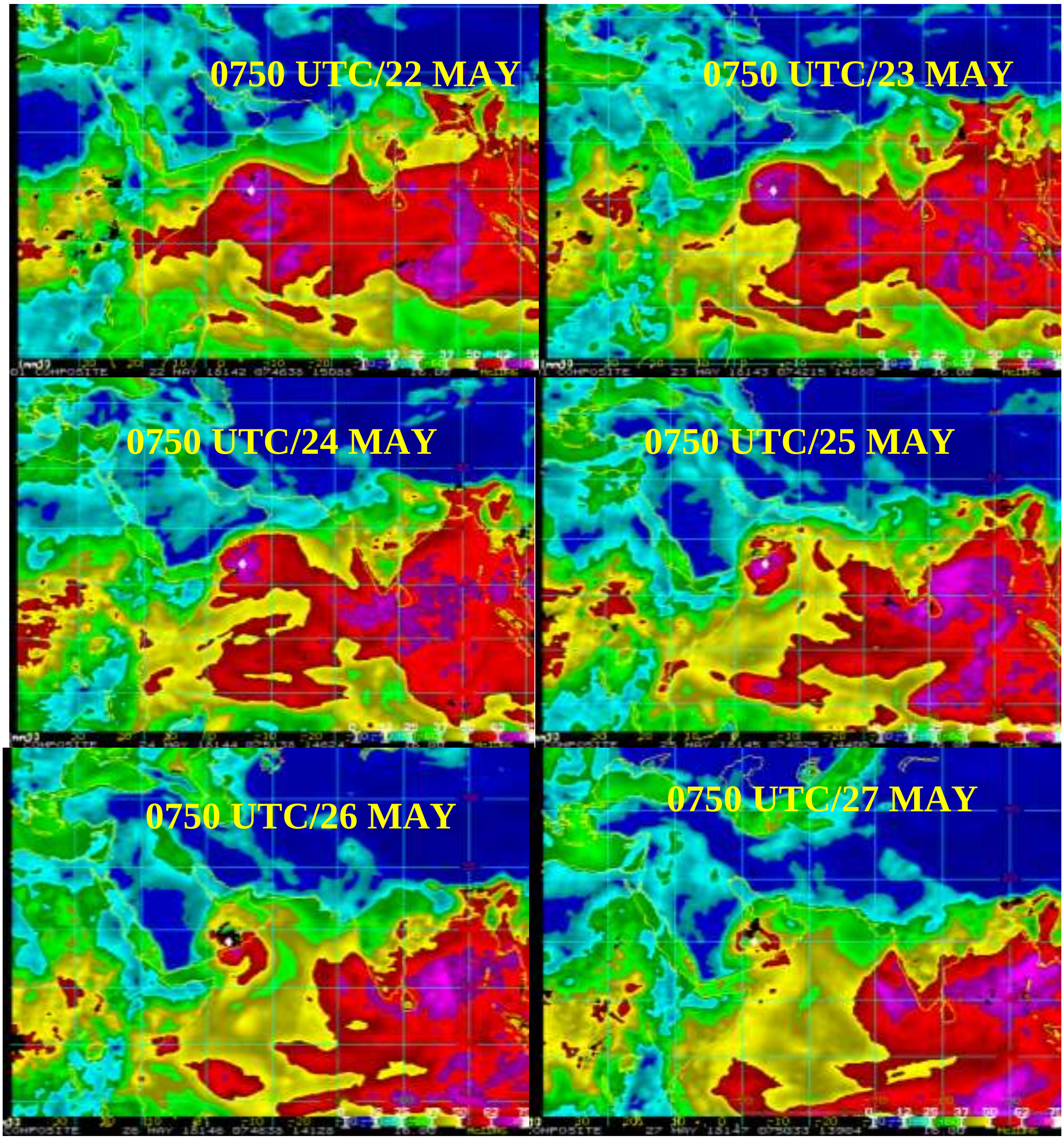


Fig. 2: Total Precipitable Water Imageries during 22-27 May, 2018

The mean wind speed in middle and deep layer around the system centre is presented in **Fig.3**. The wind shear between lower to upper tropospheric levels around the system centre increased from 12 to 22 kt from 0000 UTC of 22nd to 0000

UTC of 23rd. It then decreased gradually to almost less than 2 kt during 1200 UTC of 25th to 0000 UTC of 26th. Thereafter, it increased gradually. The direction of wind shear between lower to upper tropospheric levels was nearly east-northeasterly upto 1200 UTC of 24th, it then became east-southeasterly till 1200 UTC of 25th and then east-northeasterly till 0000 UTC of 26th. It then became south-southeasterly. The wind shear between lower to middle tropospheric levels around the system was about 10 kt upto 0000 UTC of 24th, increased to 20 kt around 0300 UTC of 24th, thereafter it decreased gradually becoming less than 10 kt from 0000 UTC of 25th onwards. The direction of wind shear was south-southeasterly during genesis phase, becoming nearly easterly from 0000 UTC of 23rd to 1200 UTC of 25th. It became northerly at 0000 UTC of 26th. Thereafter, it gradually changed to northeasterly, easterly and then southerly around 0300 UTC of 27th. Hence the direction as well as the speed of shear was favourable for intensification of the system.

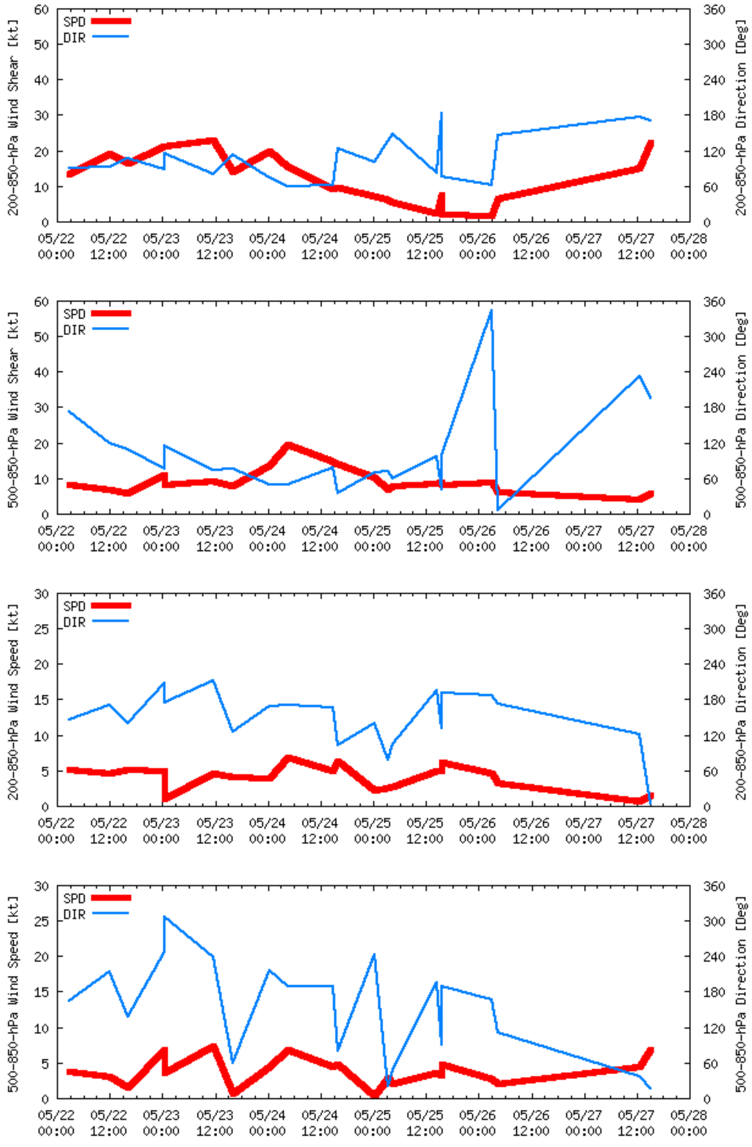


Fig.3 Wind shear and wind speed in the middle and deep layer around the system during 22nd to 28th May 2018.

3.3 Movement

From **Fig.3**, the mean deep layer winds between 200-850 hPa levels steered the system north-northwestwards with a speed of 10 knots or less throughout the life period. The six hourly movement of ESCS Mekunu is presented in **Fig.4 (a)**. The six hourly average translational speed of the cyclone was about 10.5 kmph and hence was slow moving in nature. The system had a track length of about 1385 km during its life period.

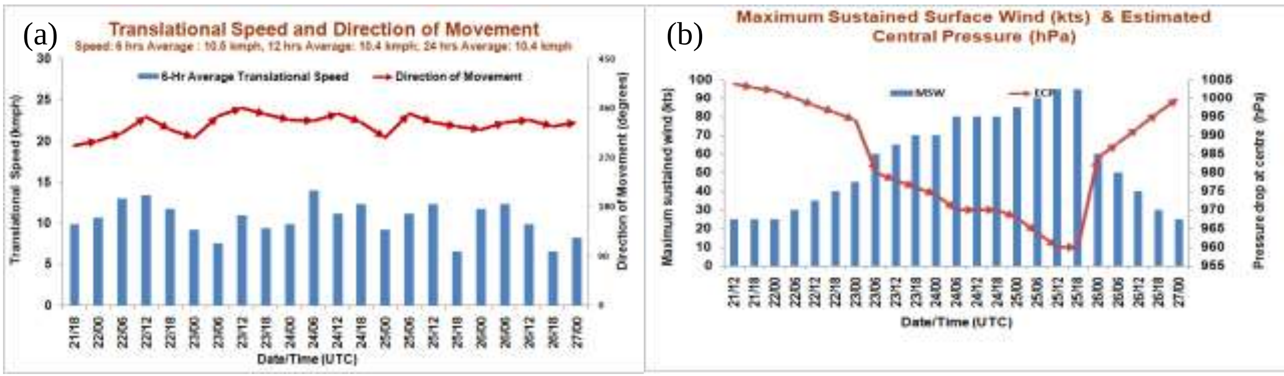


Fig.4 (a) Twelve hourly average translational speed (kmph) and direction of movement in association with ESCS Mekunu and (b) Lowest estimated central pressure and the maximum sustained wind speed

3.4. Maximum Sustained Surface Wind speed and estimated central pressure:

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig.4 (b)**. The lowest estimated central pressure (ECP) had been 960 hPa during 1200 to 1800 UTC of 25th to 0300 UTC of 30th. The ECP gradually decreased from 1004 hPa at 1200 UTC of 21st to 994 hPa at 0000 UTC of 23rd. Thereafter, there was a sudden fall in pressure from 994 hPa to 990 hPa (14 hPa) during 0000 UTC of 23rd to 0600 UTC of 23rd. it then gradually decreased becoming minimum 960 hPa during 1200 to 1800 UTC of 25th. Thereafter, there was sudden rise in ECP from 960 hPa (at 1800 UTC of 25th) to 976 hPa at 0000 UTC of 26th. Thereafter it increased gradually to 1000 hPa at 0000 UTC of 27th. Similarly, in the wind field it is seen that there was gradual increase in maximum sustained wind speed (MSW) during 1200 UTC of 21st (25kt) to 0000 UTC of 23rd (45 kt), sudden rise of 15 kt during 0000 to 0600 UTC of 23rd, gradual increase in intensity of system reaching maximum of 95 kt at 1200 UTC of 25th. The system maintained its intensity upto 1800 UTC of 25th, thereafter there was sudden fall in MSW to 75 kt at 0000 UTC of 26th. The system then weakened gradually. Fig. 6 clearly indicates that there was sudden rise in intensity of system by 15 kt on 23rd during 0000 to 0600 UTC and another sudden peak was observed after landfall when the intensity sharply decreased by 20 kt during 1800 UTC of 25th to 0000 UTC of 26th. On all other occasions during the life cycle of system, there was gradual strengthening and weakening of system.

There was rapid intensification during 1200 UTC of 22nd to 1800 UTC of 23rd, when the wind speed increased from 35 knots to 70 knots.

5. Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7 & MTSAT, microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops and SCAT SAT imageries were considered for monitoring the system.

5.1 INSAT-3D features

Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig.5 (a-d)**.

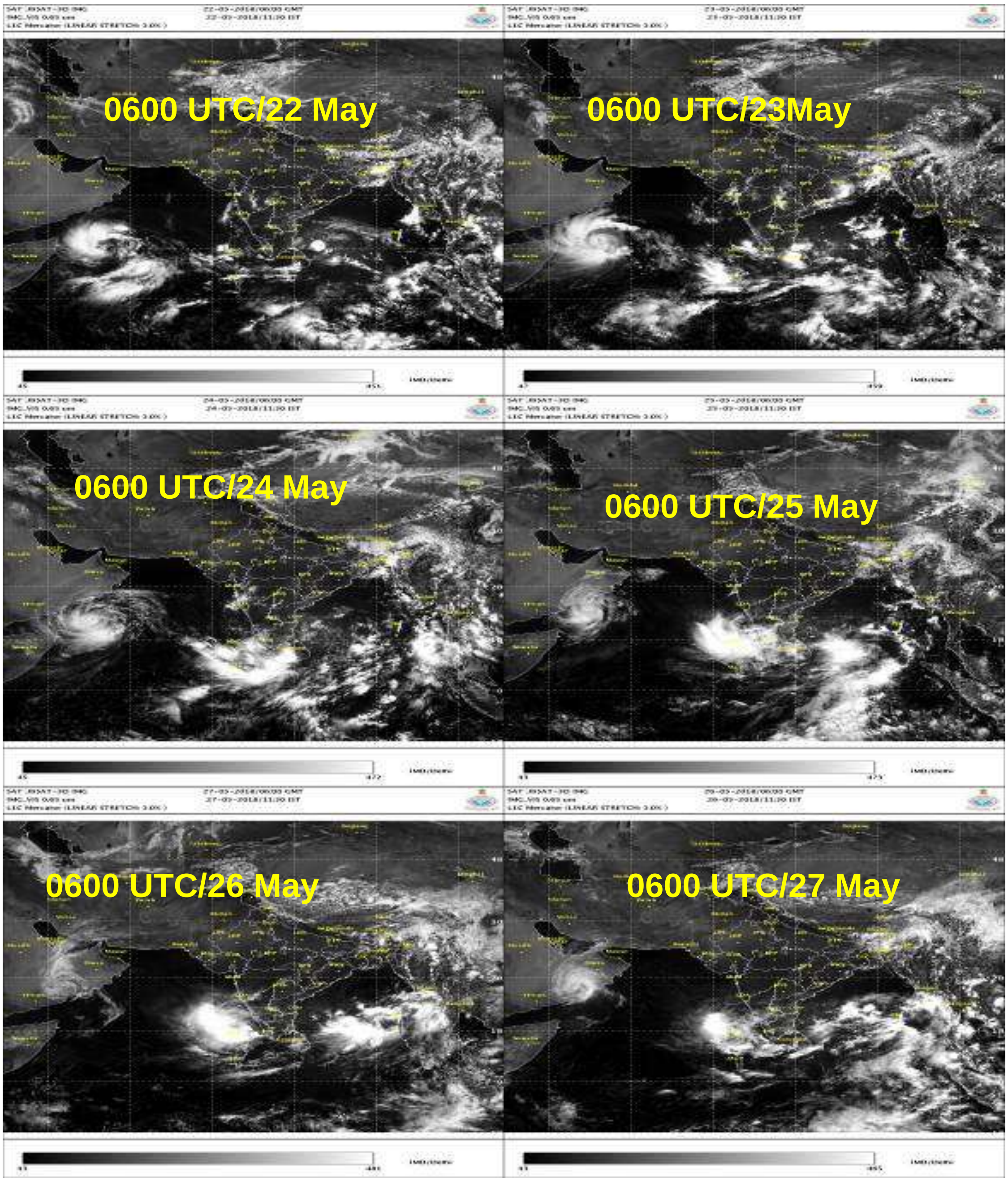


Fig. 5a: INSAT-3D visible imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

Intensity estimation using Dvorak's technique suggested that the system attained the intensity of **T 1.5** at 1200 UTC of 21st. The convection over south AS further organised and indicated curved banding features from northwest to southeast sector across southwest sector. Minimum cloud top temperature was -93^{0}C. At 0300 UTC of 22nd, the convection further organized and the system attained the intensity of **T2.0**. The convection showed curved banding features from northeast to southwest sector across northwest sector. Minimum CTT was -93^{0}C.

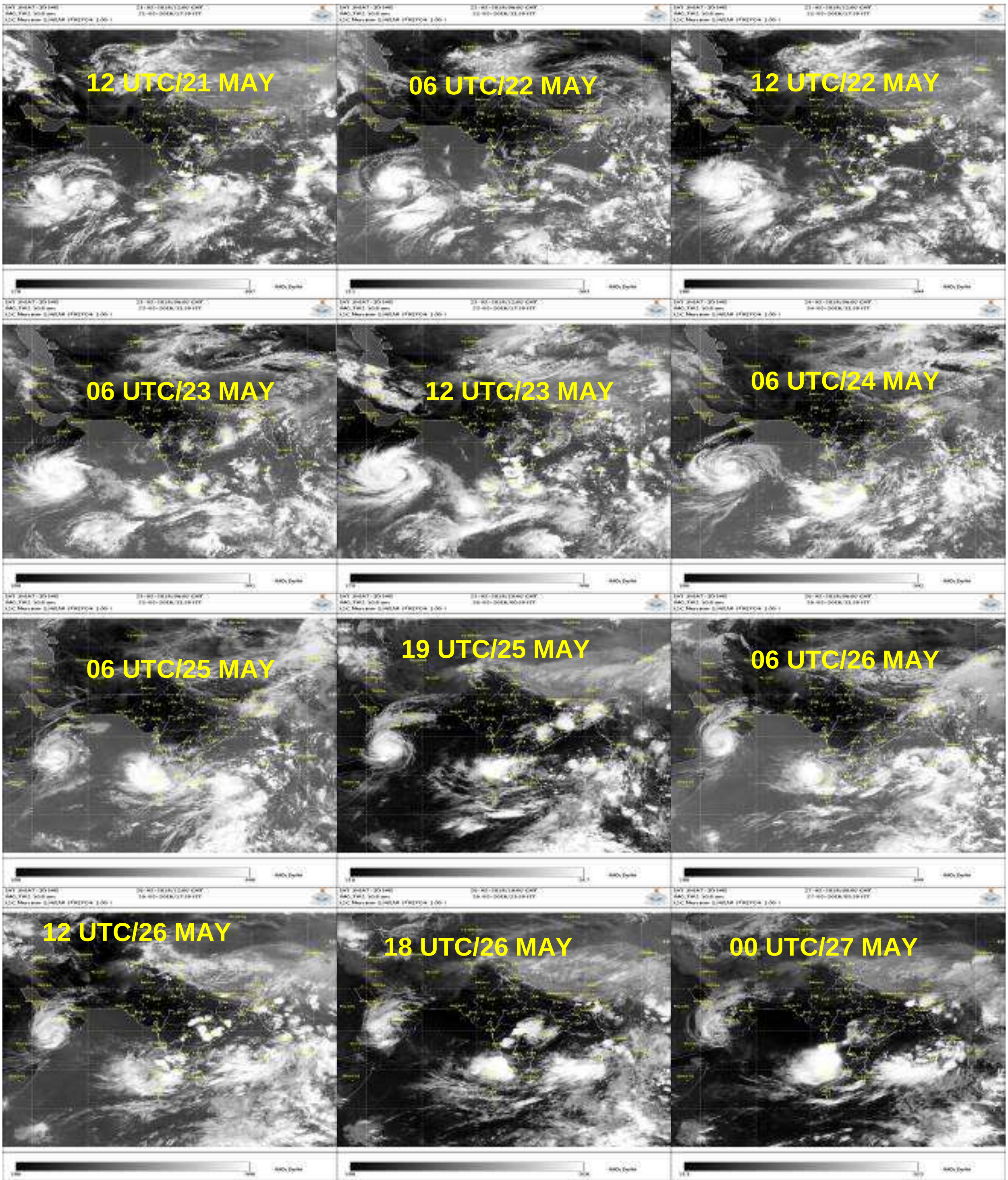


Fig. 5b: INSAT-3D IR imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

At 1200 UTC of 22nd, the system attained the intensity **T 2.5**. The cloud pattern indicated banding features from northeast to southwest sector across northwest sector. The intensity of the system was **T3.5**. The convection showed curved banding features from northeast to southwest sector across northwest sector. At 0900 UTC of 23rd, the system attained the intensity **T 4.0**. The convection increased over western and southern sector. With the consolidation of central dense overcast, satellite imagery indicated appearance of eye. It indicated intensification of the system. Minimum CTT was -93^{0}C. At 0300 UTC of 24th, the system further intensified and attained the intensity **T4.5**. The convection showed central dense overcast pattern with well defined spiral bands. Minimum CTT was -93^{0}C.

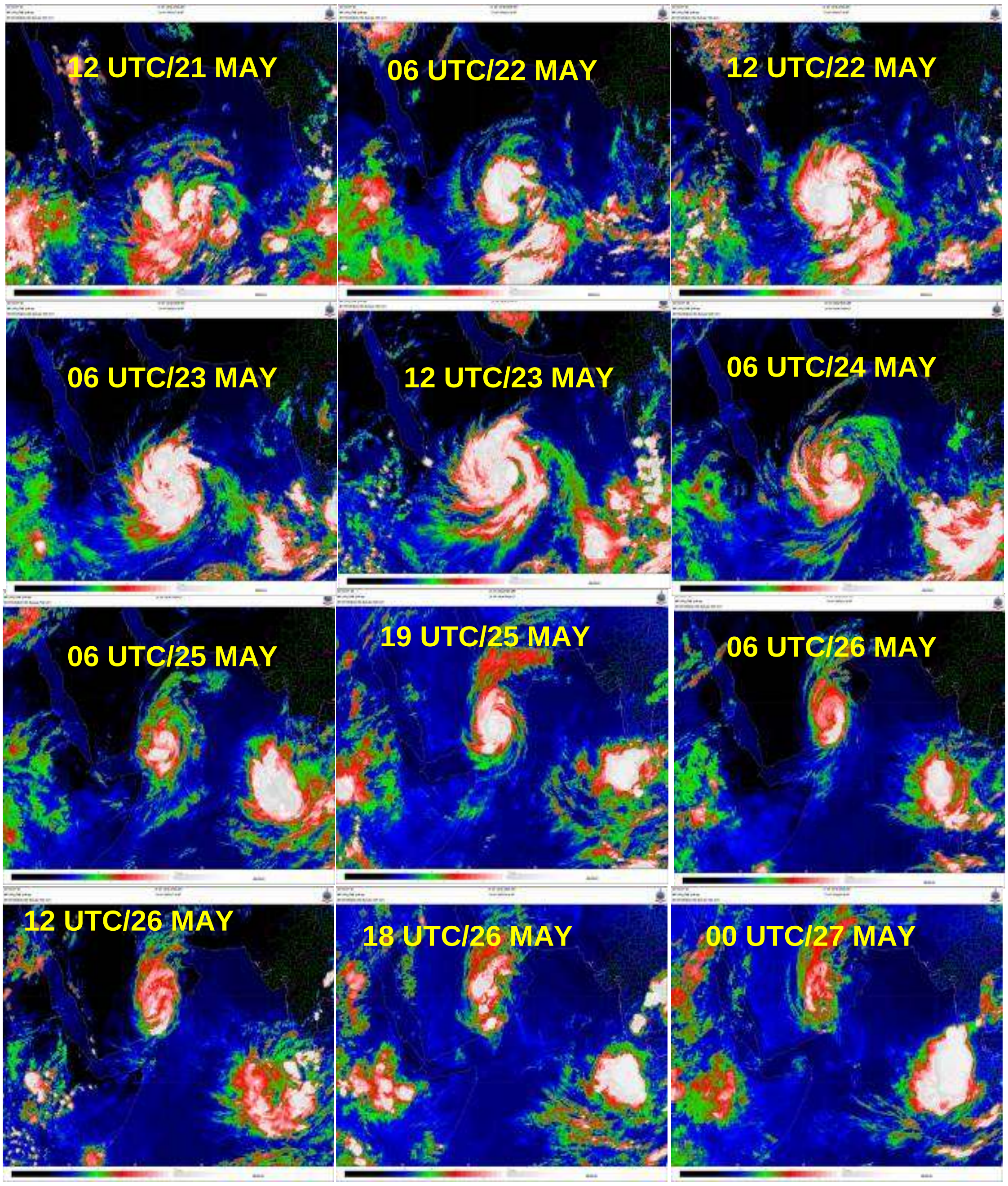


Fig. 5c: INSAT-3D enhanced colored imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

At 0300 UTC of 25th, the intensity of the system was **T 5.0**. The convection showed central dense overcast pattern with spiral bands. Associated broken low and medium clouds with embedded intense to very intense convection lay over westcentral and adjoining southwest AS between latitude 10.5^{0}N & 18.5^{0}N and longitude 51.0^{0}E to 58.0^{0}E. At 1800 UTC of 25th, the intensity of the system was **T 5.5**. The clouds got organized further and showed eye pattern. At 1800 UTC of 25th, the intensity of the system was T 5.5. The clouds got organized further and showed eye pattern. The system crossed Oman coast close to Salalah around 1900 UTC of 25th.

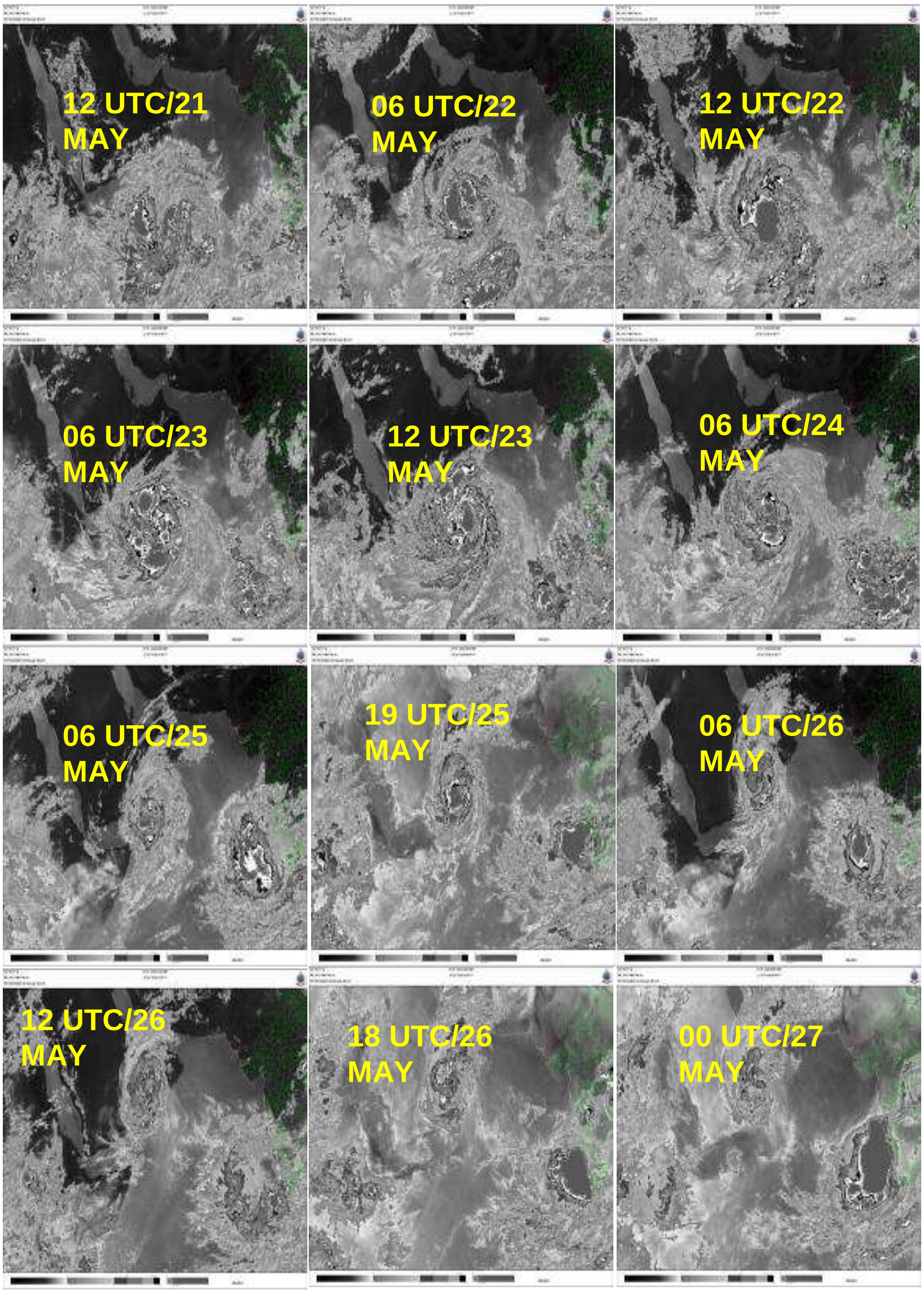


Fig. 5d: INSAT-3D cloud top brightness imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

5.2. Microwave Imageries:

Microwave imageries from polar orbiting satellites F-15, F-16, F-18, GCOM W1, GPM 89, NOAA-19 were utilised for determining the centre and area of intense convection. Typical microwave imageries during the life cycle of ESCS Mekunu are presented in **Fig. 5(e).**

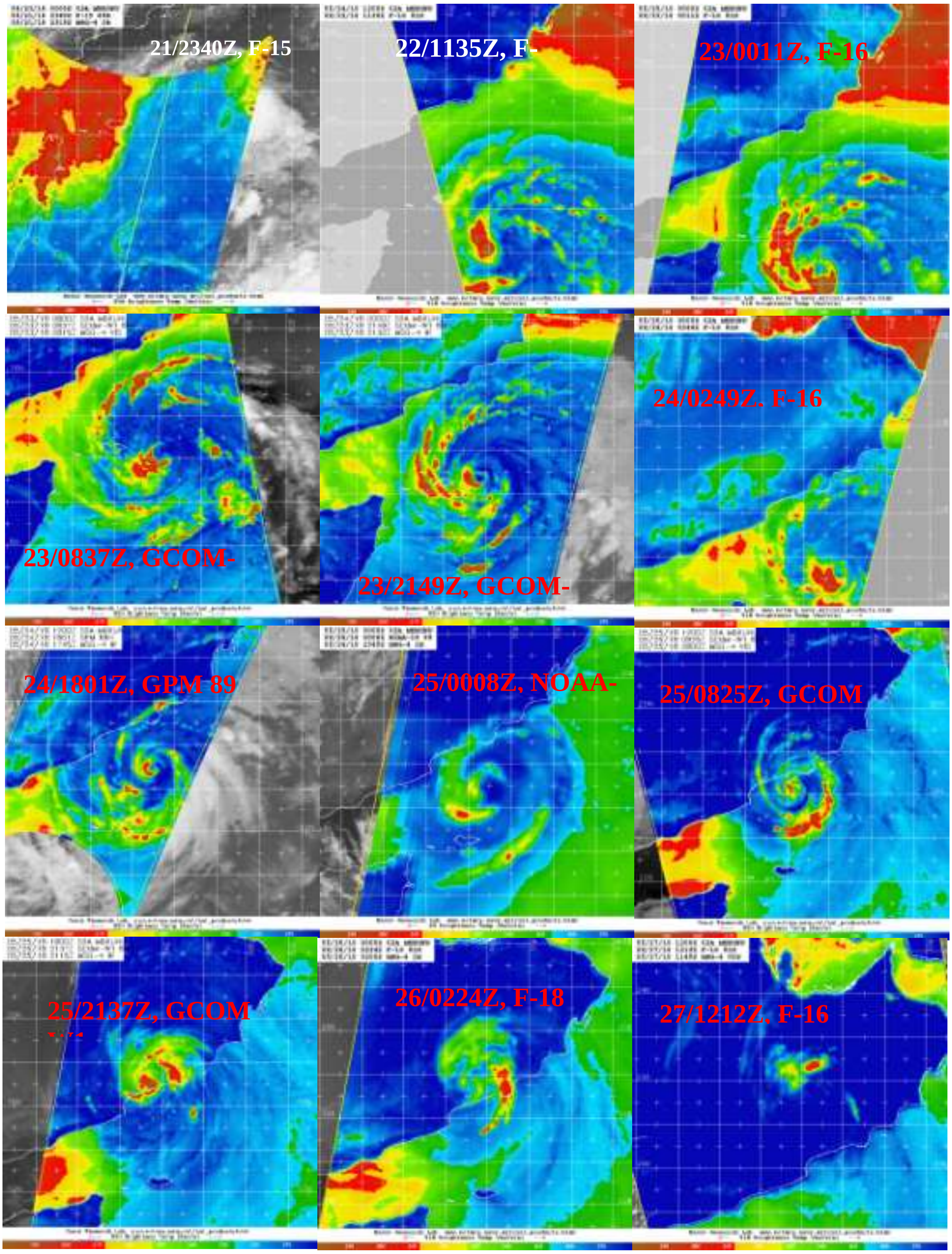


Fig. 5e: Microwave imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

When the system was over sea, imageries from ASCAT were also utilized for determination of centre, intensity and wind distribution around the centre of the system. Typical ASCAT imageries from Metop-B are presented in Fig. 5(f).

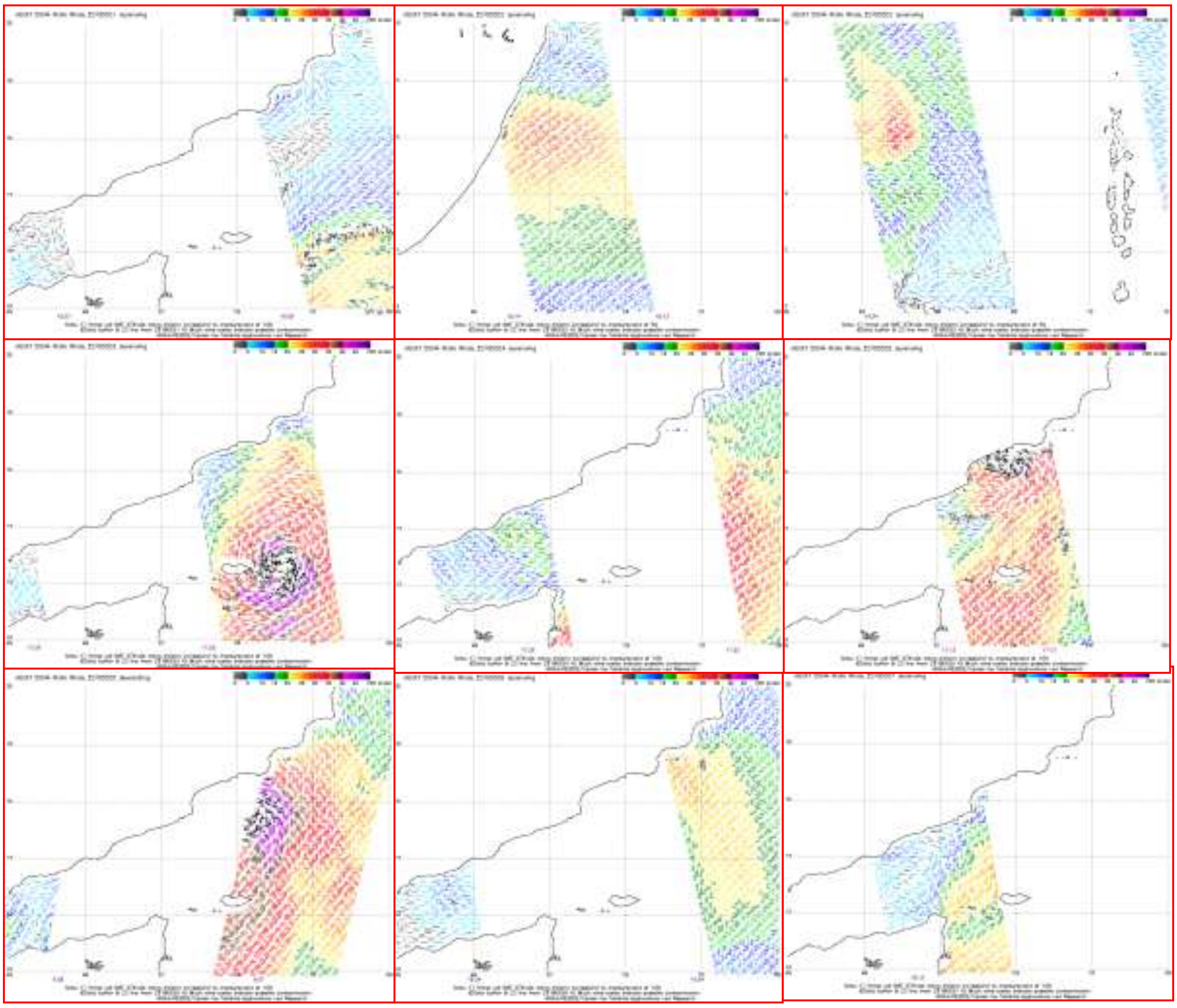


Fig. 5(f): ASCAT (Met-Op B) imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

Typical imageries from polar satellite, SCATSAT are presented in Fig.9 (b). SCATSAT passes are available twice a day at 0454 UTC and 1636 UTC at http://mosdac.gov.in/scorpio/SCATSAT_Data. The observations based on 1636 UTC of 21st indicated cyclonic circulation over southwest Arabian Sea. Stronger winds were seen in northern sector. The imagery also indicated large scale cross equatorial flow, inflow of warm and moist air into the system centre from southeast sector. At 0454 UTC of 22nd May, the area of strong winds extended to southwest sector. At 1636 UTC of 23rd, stronger winds were seen in the northwest sector. At 0454 UTC of 24th, the centre was seen near 13.5N/56E, warm and moist air advection from southwest to northwest sector was seen. The estimated intensity was more than 60 kts. The maximum size in the southern sector was also due to higher southwesterly winds in the region. On 25th and 26th stronger winds were seen in the northeast sector. SCAT Sat imageries helped in determination of centre to a good extent. Intensity estimates beyond 60 kts cannot be done with the help of these imageries.

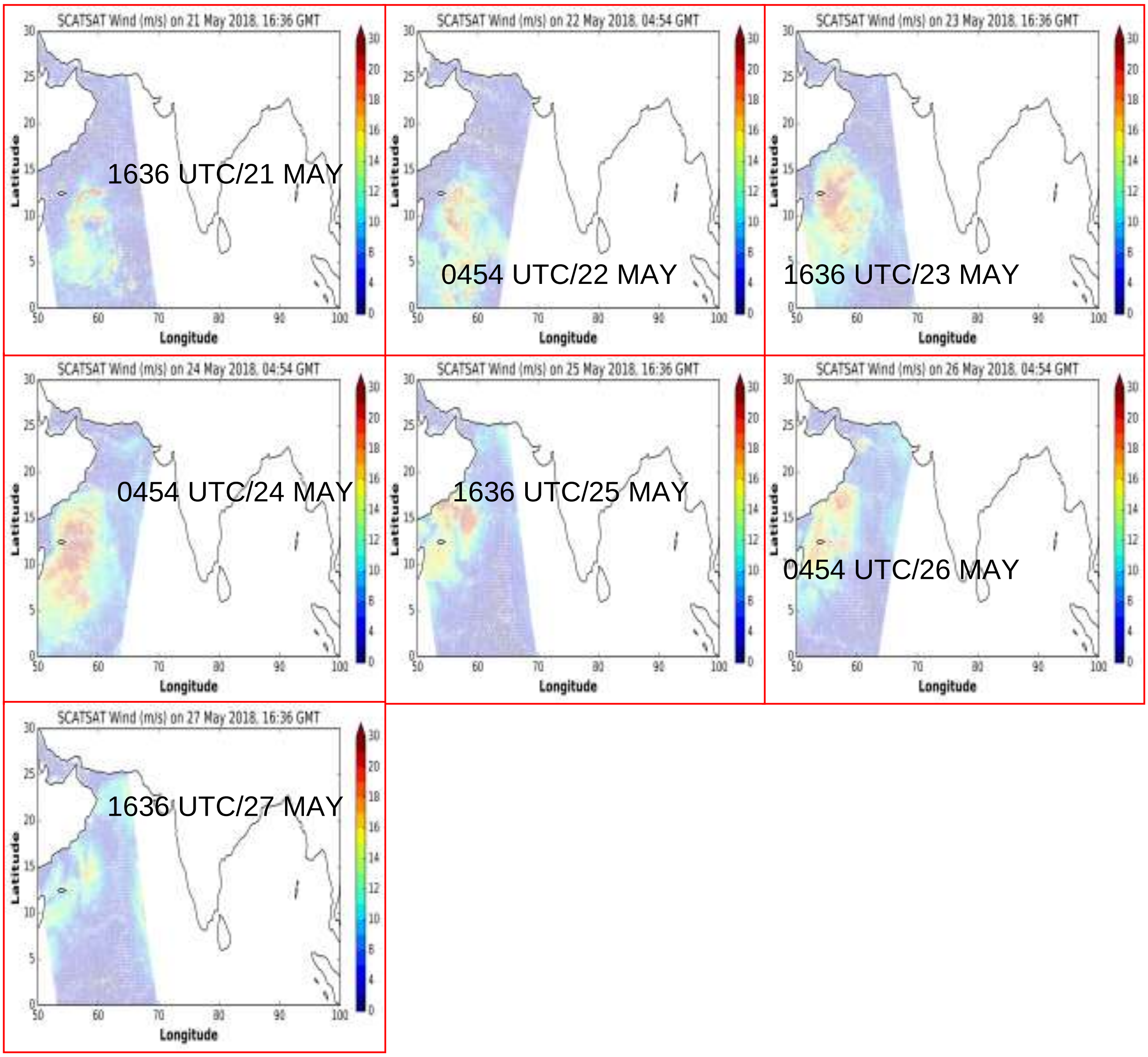


Fig. 5(f): SCAT SAT imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

6. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 21st to 27th May are presented in Fig.6. GFS (T1534). Based on 0000 UTC observations of 21st, the model predicted a low pressure area over southeast and adjoining southwest AS. It indicated a cyclonic circulation over southeast AS extending upto 500 hPa level.

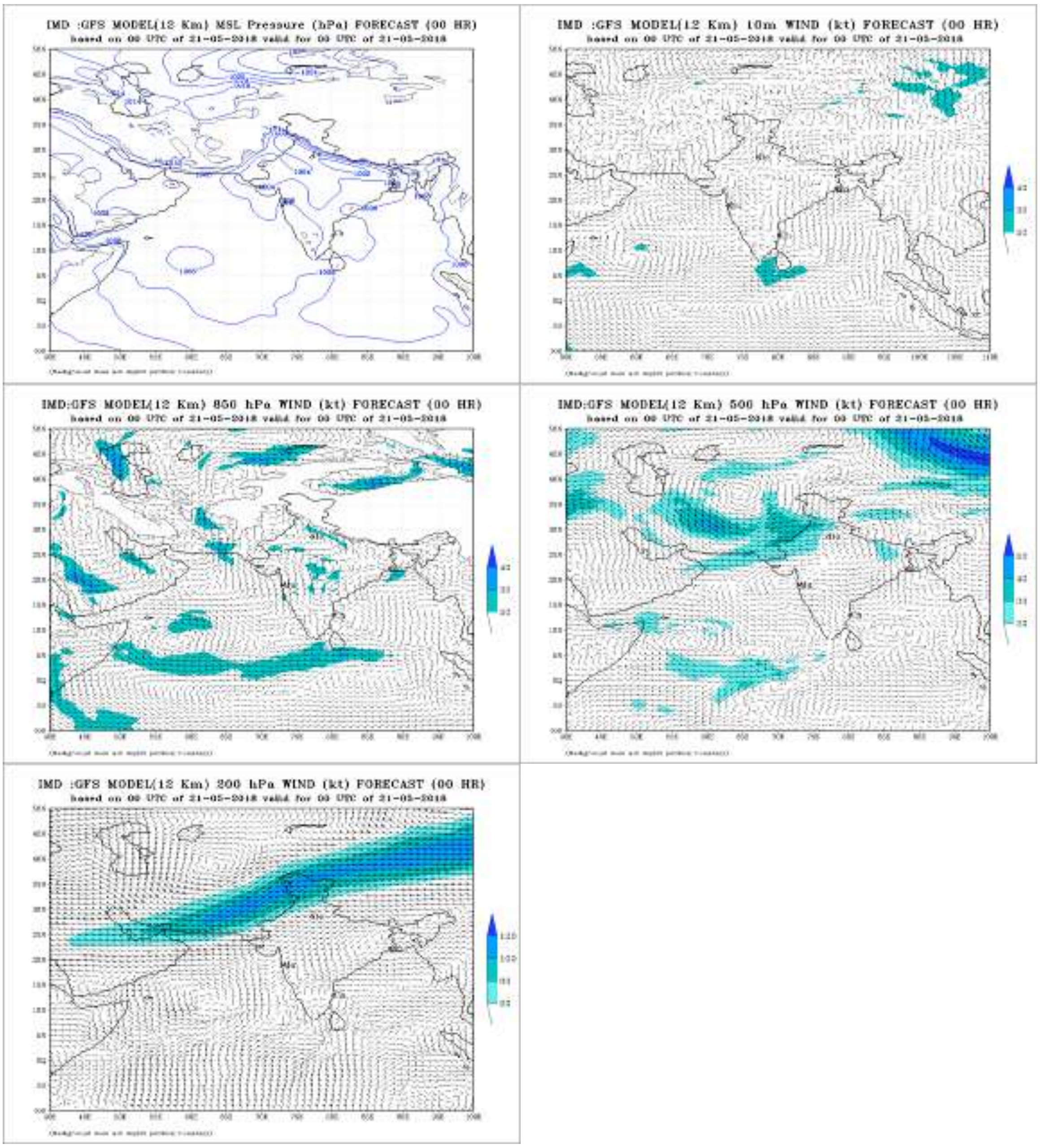


Fig. 6 (a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 21st May

Analysis based on 0000 UTC of 22nd May, predicted intensification of system into a deep depression over southeast AS. Vertically the system extended upto 500 hPa levels.

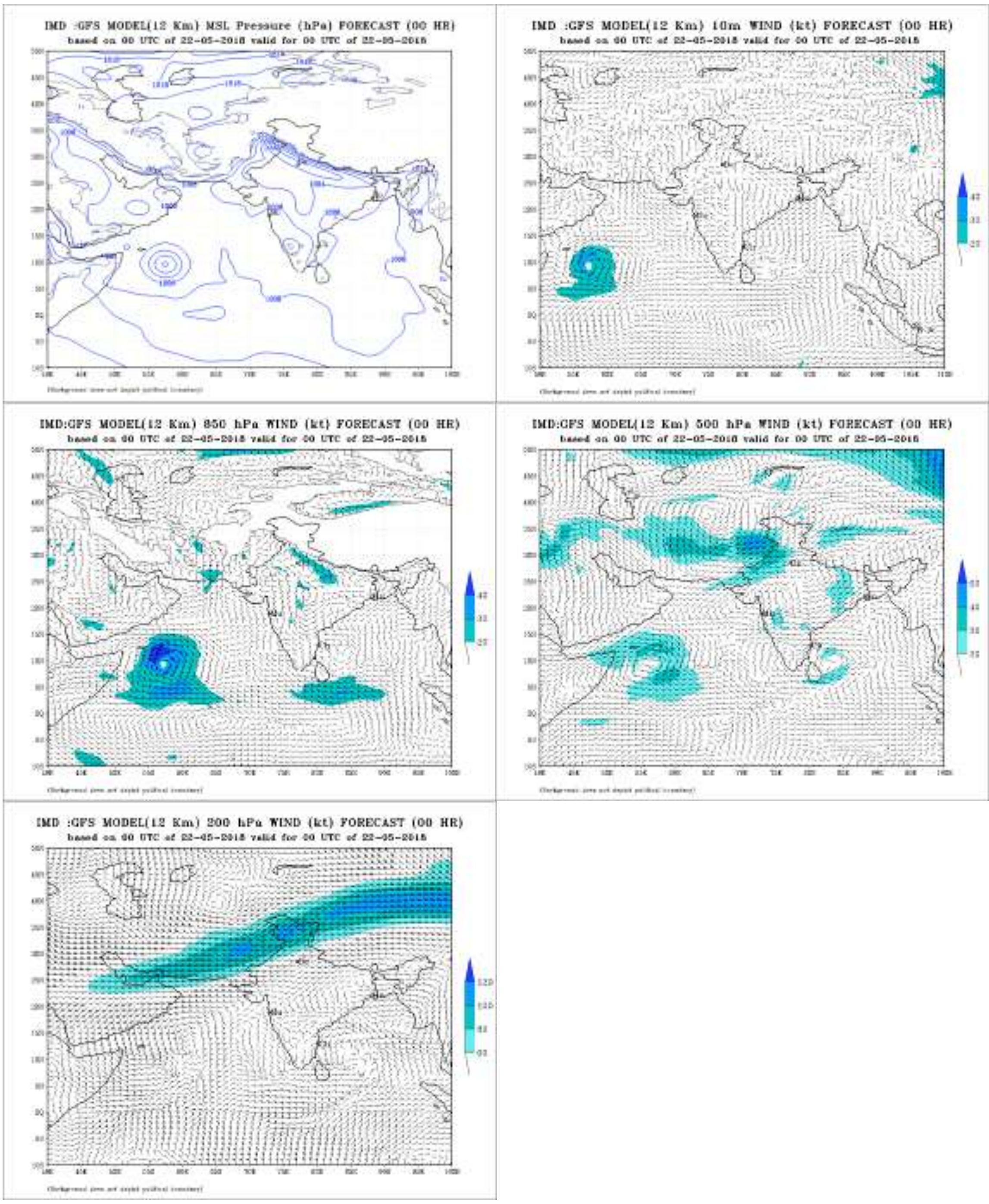


Fig. 6 (b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 22nd May

Analysis based on 0000 UTC of 23rd May predicted northwards movement and further intensification of system into a severe cylonic storm over southeast AS. The circulation extended upto 500 hpa levels.

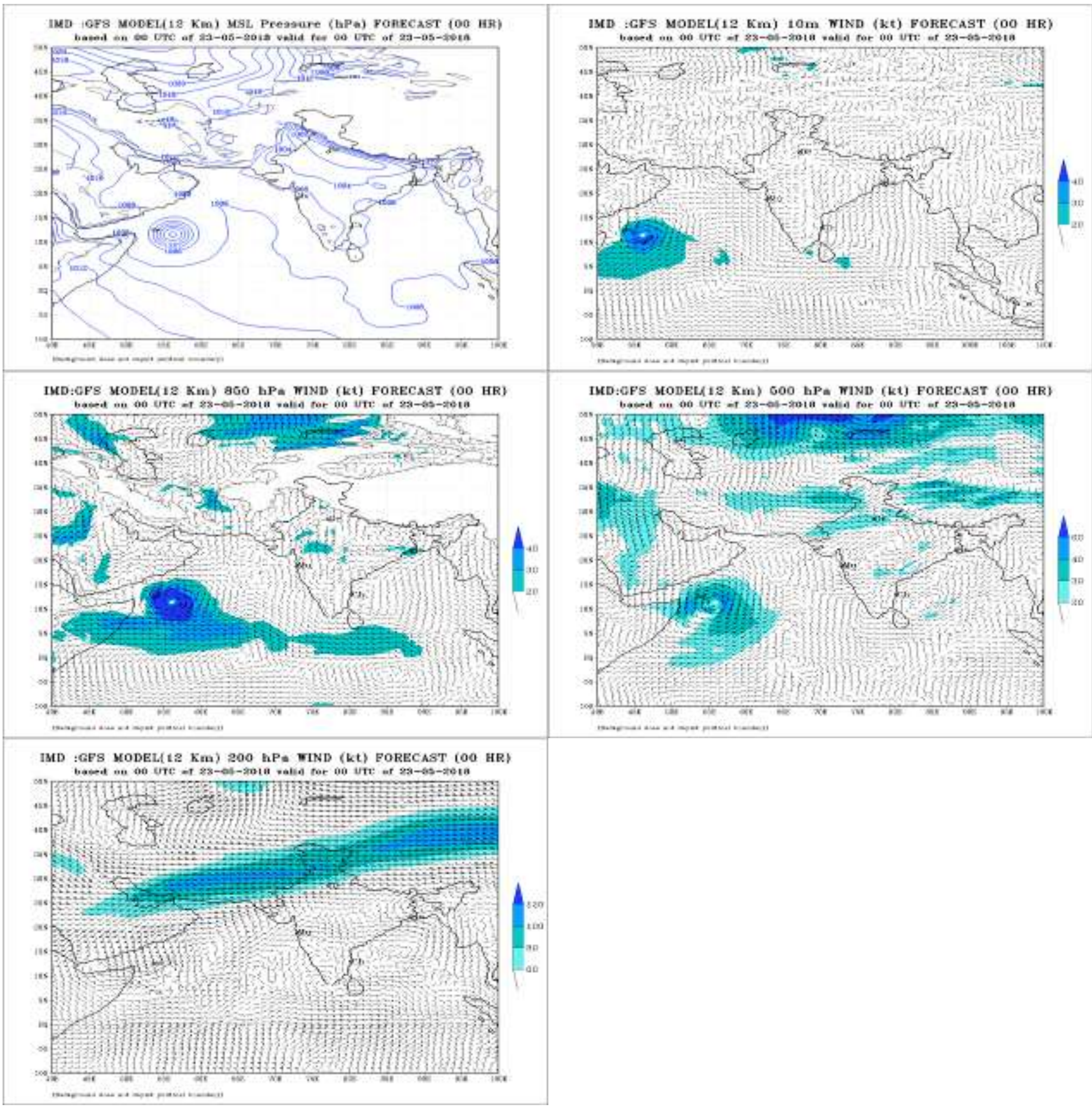


Fig. 6 (c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 23rd May

Initial conditions based on 0000 UTC of 24th May indicated further intensification of the system to the east of Socotra Islands.

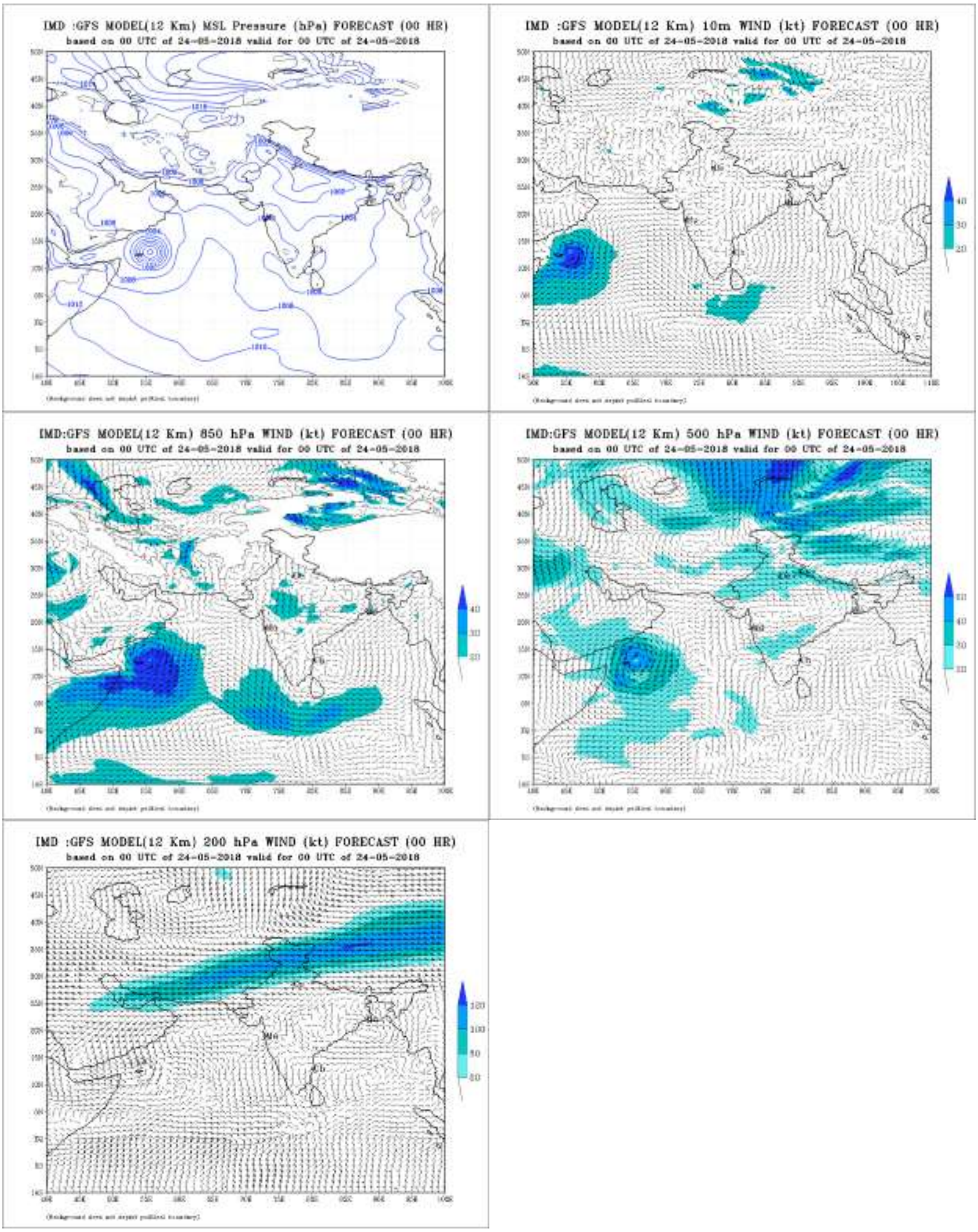


Fig. 6 (d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 24th May

Analysis based on 0000 UTC of 25th May indicated the northwards movement of system towards Salalah (Oman).

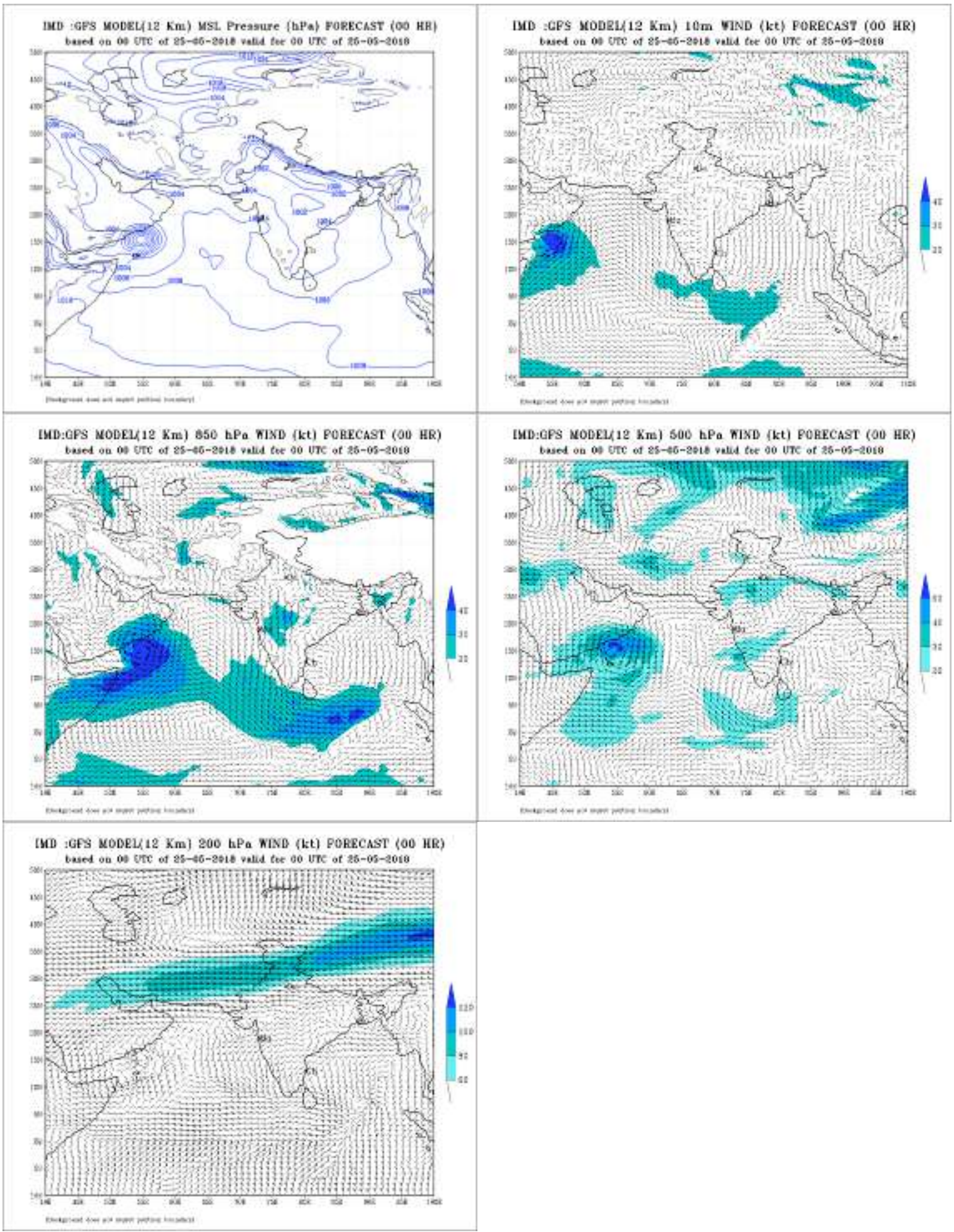


Fig. 6 (e): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 25th May

The initial conditions based on 0000 UTC of 26th indicated the system crossing the Oman coast close to Salalah as a cyclonic storm.

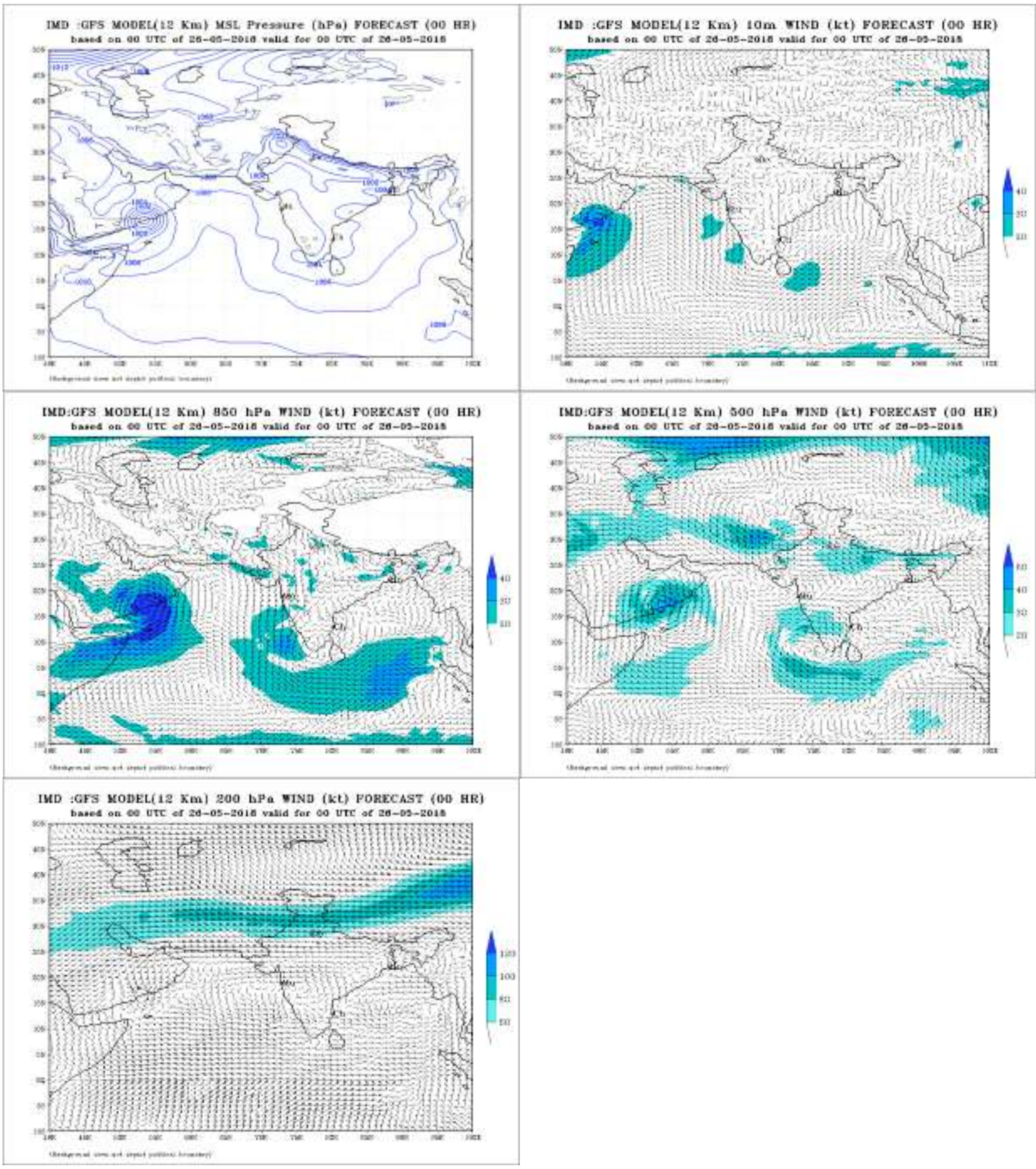


Fig. 6 (f): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 26th May

Hence to conclude, to a large extent IMD GFS could simulate the genesis, intensification, movement and landfall characteristics of the system. However, during landfall it predicted weakening of the system. Actually system crossed Oman coast with peak intensity as an ESCS.

7. Realized Weather:

7.1 Rainfall:

Rainfall associated with ESCS Mekunu based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig 7**. It indicates the occurrence of extremely heavy rainfall over Oman and adjoining Yemen due to this cyclone.

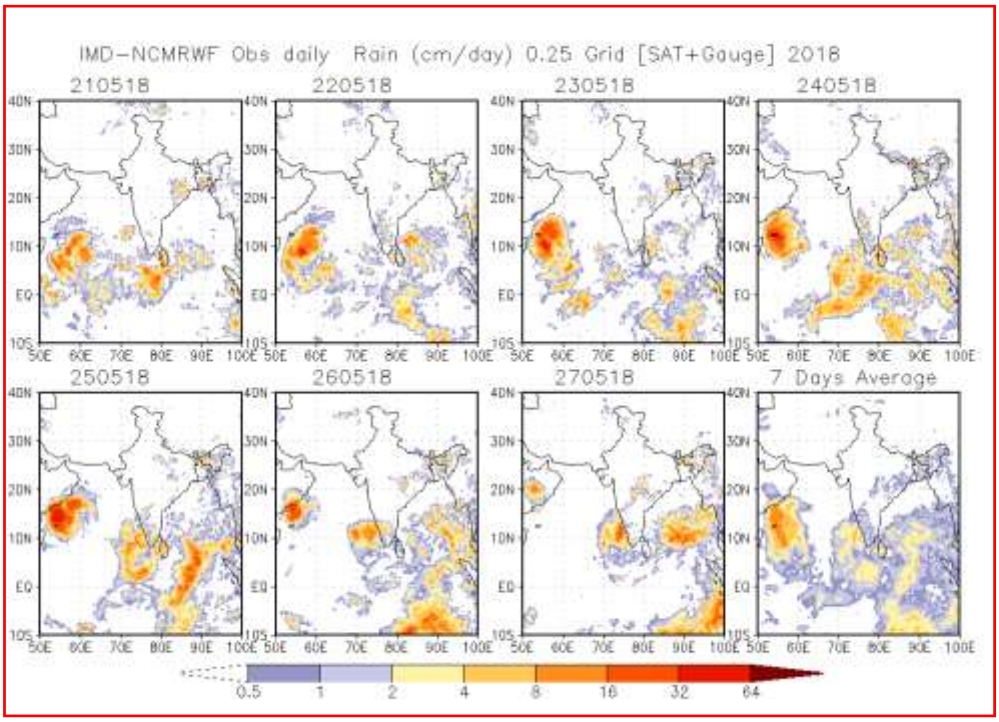


Fig.7: IMD-NCMRWF GPM merged gauge rainfall during 21st May– 27th May and 7 days average rainfall (cm/day)

8. Damage due to ESCS Mekunu

Damage over India:

No casualties were reported from any Indian state due to ESCS, Mekunu.

Damage over Socotra Islands: Socotra received widespread rainfall leading to flash flooding and downed power lines (Fig. 8(a)). About 20 persons lost their lives because of heavy rains and strong winds caused by cyclone Mekunu.

Fig.8 (a): People walking through floods (Source Middle East Eye, Screengrab/AFP)

Damage over Oman:

According to Oman's Public Authority for Civil Aviation (PACA), Salalah received 278.2 millimeters (10.95 inches) of rain in just 24 hours ending around 10:30 a.m. on May 26. This was over double the city's average yearly rainfall of about five inches in just 24 hours. In addition, Salalah reported 617 millimeters of rainfall during 23-27 May. As per media reports (Times News Service), Taqah recorded 275 mm, Mirbat received 221 mm, Rakhyoot had 214 mm, Thumrait recorded 196 mm, and Sadah received 180 mm. Moreover, the Sahalnoot Dam collected 6.4 million cubic metres of water. As per official records six persons lost their lives in Oman. Typical damage photographs are presented in Fig. 8(b).

Fig.8 (b): Flooding in Salalah in southwest Oman on 26th May

Fig.8 (c): Destructive winds lashed western Oman during 25th – 26th May

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 27 km, 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. IMD also runs operationally, the cyclone specific Hurricane Weather Research & Forecast (HWRF) model (resolution 18 km, 6 km and 2 km) for cyclone track & intensity prediction in case of cyclone situation in the north Indian Ocean.

Global models are also run at NCMRWF. These include GFS and unified model adapted from UK Meteorological Office. NCUM (N768/L70) model features a horizontal resolution of 17km and 70 vertical levels. It uses 4D-Var assimilation and features no cyclone initialization/relocation. NCUM is a grid point model which has a Non-hydrostatic dynamics with a deep atmosphere suitable for all scales. NCMRWF Ensemble Prediction System (NEPS) is a global medium range probabilistic forecasting system adapted from UK MET Office. The configuration consists of 220 four cycles of assimilation corresponding to 00Z, 06Z, 12Z 18Z and 10-day forecasts are made using the 00Z initial condition. The N400L70 forecast model consists of 800x600 grid points on the horizontal surface and has 70 vertical levels. Horizontal resolution of the model is approximately 33 km in the mid-latitudes. The 10 day control forecast run starts with N768L70 analysis of the deterministic assimilation forecast system and 44 ensemble members start from different perturbed initial conditions consistent with the uncertainty in initial conditions. The initial perturbations are generated using Ensemble Transform Kalman Filter (ETKF) method.

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 I 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.

IMD also makes use of NWP products prepared by some other operational NWP Centres like, ECMWF (European Centre for Medium Range Weather Forecasting), GFS (NCEP), UKMO (UKMet), JMA (Japan Meteorological Agency). Ensemble prediction system (EPS) has been implemented at the NWP Division of the IMD HQ for operational forecasting of cyclones.

In this report performance of the individual models, MME forecasts, SCIP, GPP, RII and Decay model for cyclone MEKUNU are presented and discussed.

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

Fig. 9 shows the predicted zone of cyclogenesis based on 0000 UTC of 15th August upto 144 hours lead period.

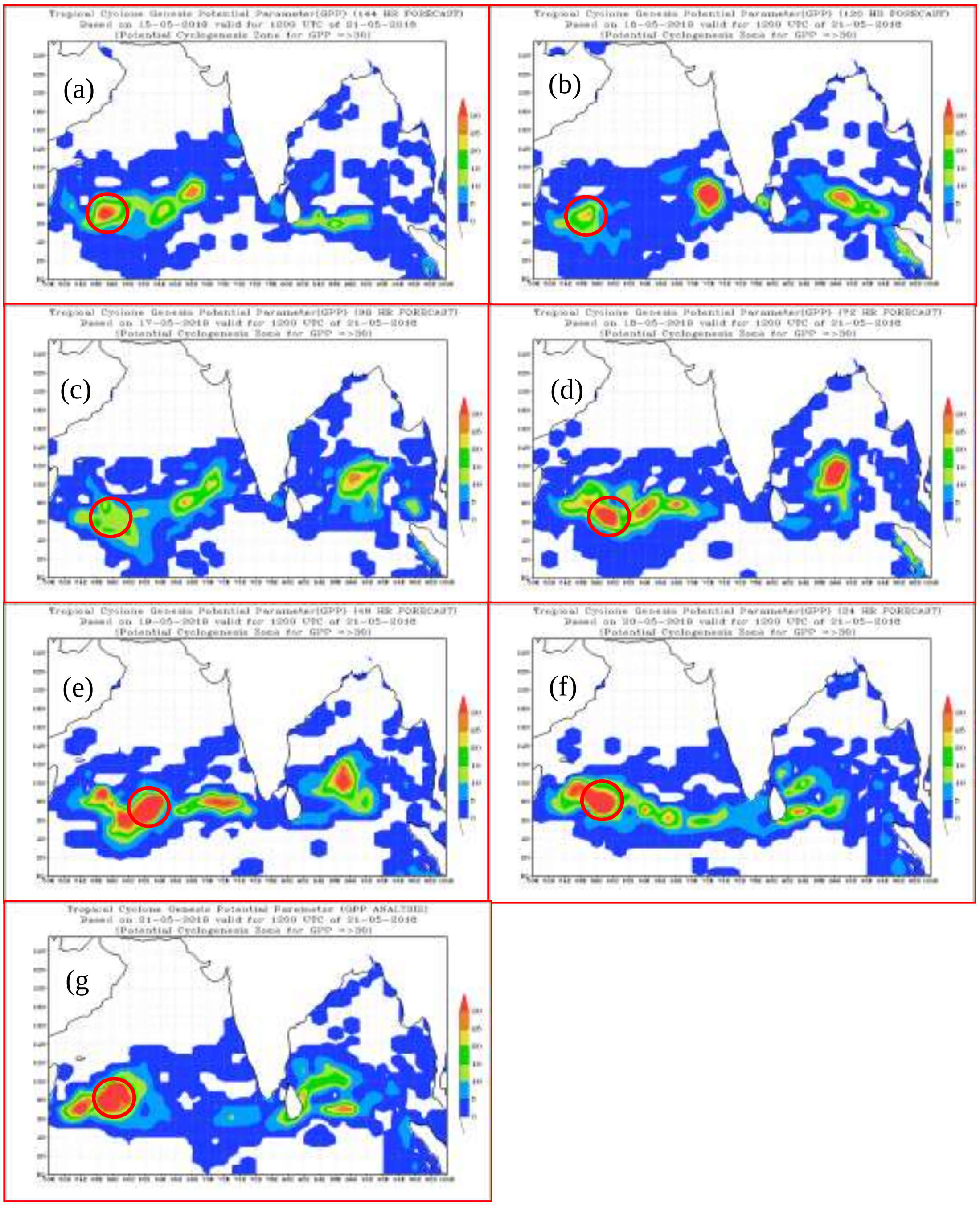


Fig. 9 (a-g): Predicted zone of cyclogenesis based on 0000 UTC of 15th (144 hours in advance) to 21st May (12 hours in advance) 2018.

The model could predict cyclogenesis zone correctly and consistently about 72 hours in advance. At the same time it was indicating a false potential zone for cyclogenesis over south BoB 48 & 72 hours in advance.

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 was also predicted. Conditions for (i) Developed system: Threshold value of average GPP ≥ 8.0 and (ii) Non-developed system: Threshold value of GPP < 8.0. The forecasts of GPP (Fig. 10) showed potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0). However, based on 0000 & 1200 UTC analysis of 21st, the model predicted weakening trend after 24 hours. It also indicated intensification after 72 hours. Similar trends were seen based on 0000 UTC analysis of 22nd. Actually the system didn't weaken at anytime till landfall.

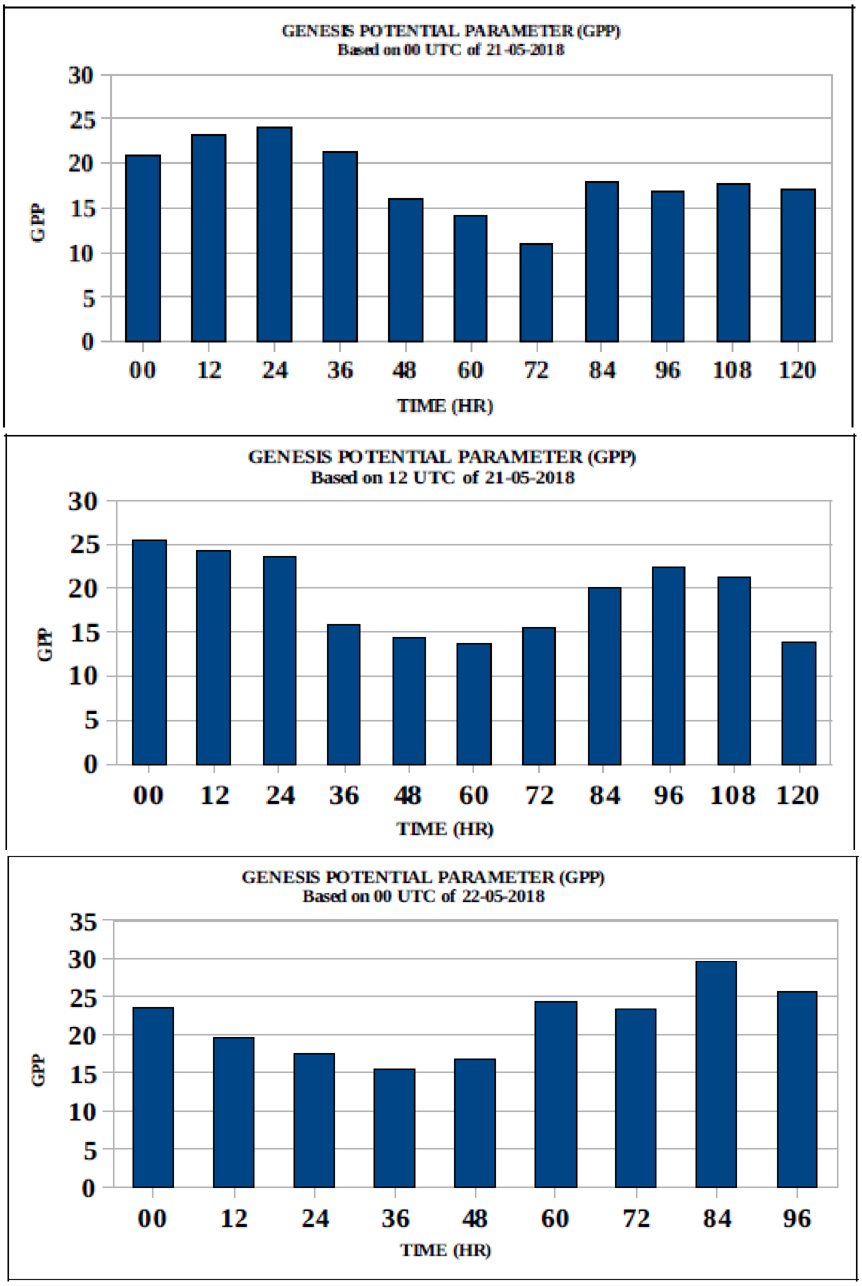


Fig. 10: Area average analysis and forecasts of GPP based on 0000 & 1200 UTC of 21st and 0000 UTC of 22nd May, 2018

9.2 Track prediction by NWP models

Track prediction by various NWP models is presented in Fig.11. Based on initial conditions of 1200 UTC of 21st May, ECMWF & IMD GFS predicted landfall close to Salalah around 1200 UTC of 26th. UKMO, NCEP GFS and MME predicted landfall to the east of Salalah around 0000 UTC of 26th. JMA and WRF-VAR predicted weakening over sea and eastwards movement. The SCIP model predicted maximum intensification of system upto VSCS stage (81 kt) at the time of landfall. Probability of rapid intensification during next 24 hours was predicted as Low (21%). It also predicted rapid weakening of system after landfall (intensity falling to 53 kt (-28 kt) in next 12 hours). Many models on 21st could predict movement towards Oman coast close to Salalah but there was a delay in prediction of landfall time.

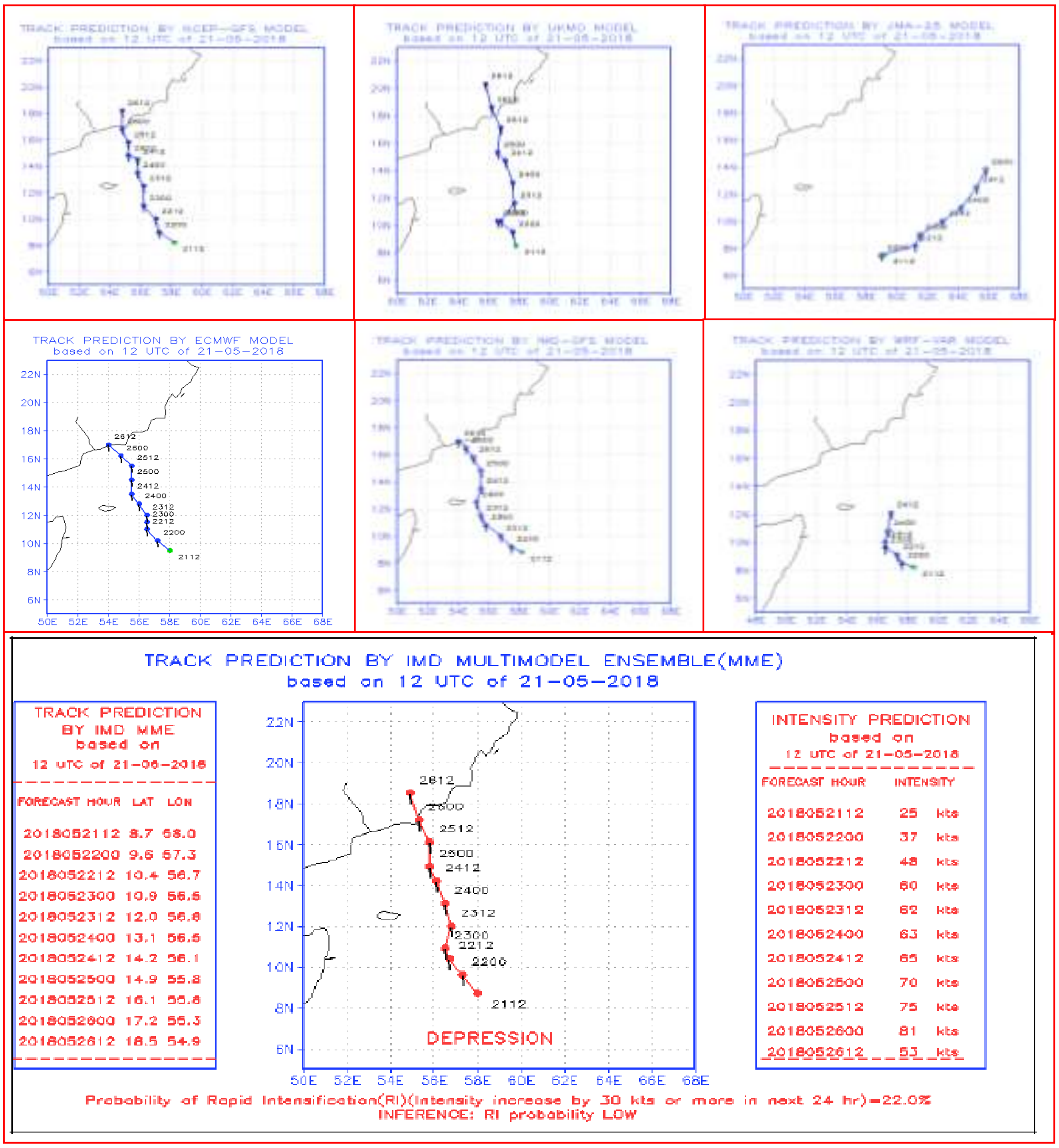


Fig. 11 (a): NWP model track forecast based on 1200 UTC of 21st May

Based on initial conditions of 0000 UTC of 22nd May, ECMWF & IMD GFS predicted landfall to the west of Salalah around 0000 UTC of 26th. NCEP GFS predicted landfall over Yemen around 0600 UTC of 26th. UKMO predicted landfall to the east of Salalah around 0000 UTC of 26th. MME predicted landfall close to Salalah around 0000 UTC of 26th. JMA and WRF-VAR predicted weakening over sea and movement off the actual track. The SCIP model predicted maximum intensification of system upto VSCS stage (87 kt) at the time of landfall. Probability of rapid intensification during next 24 hours was predicted as Low (9%). It also predicted rapid weakening of system after landfall (intensity falling to 51 kt (-36 kt) in next 12 hours). However, system didn't weaken rapidly after landfall. Most of the models on 22nd predicted movement towards Oman coast close to Salalah but there was a delay in predction of landfall time. But MME predicted landfall over Salalah around 0000 UTC of 26th.

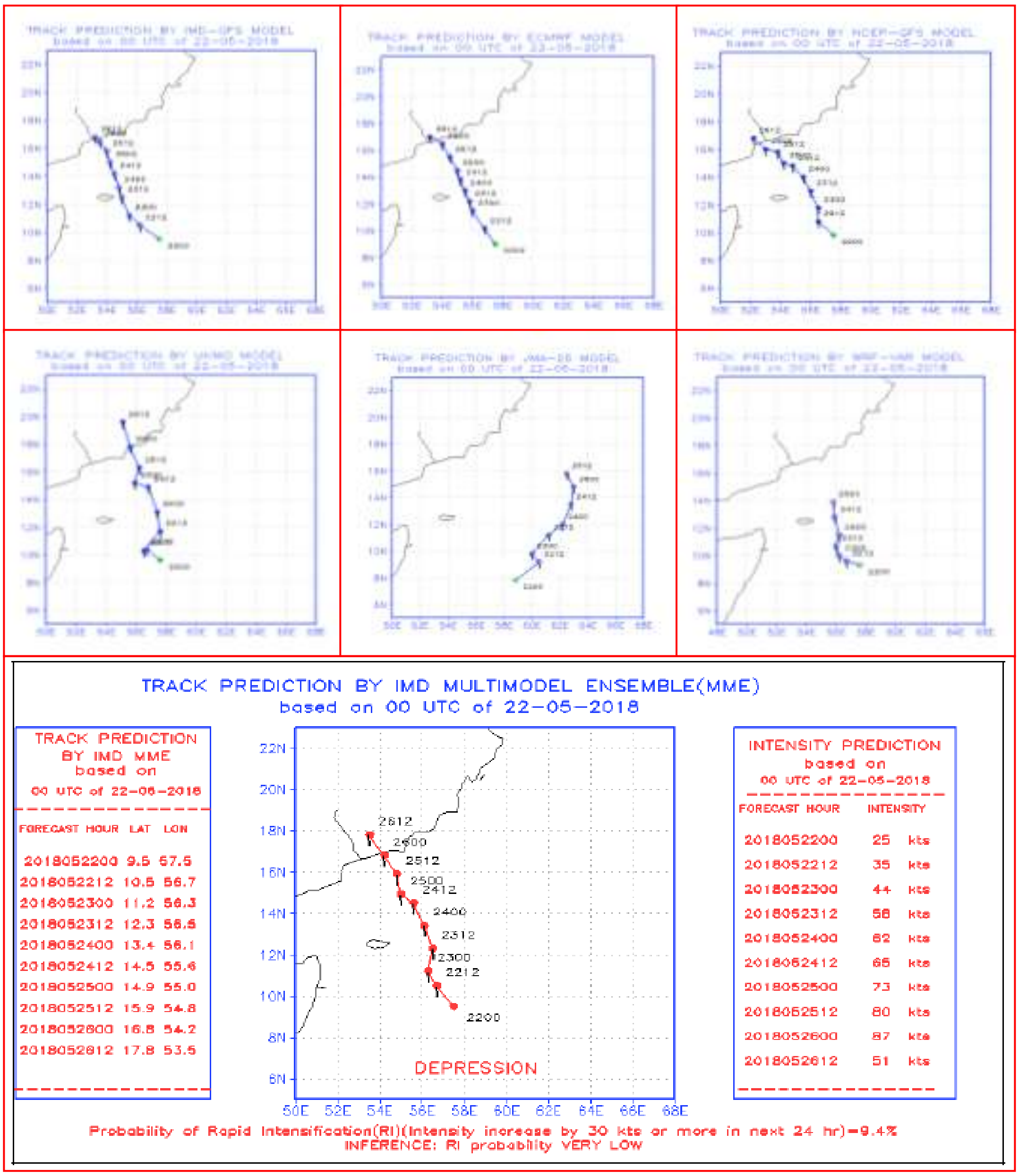


Fig. 11 (b): NWP model track forecast based on 0000 UTC of 22nd May 2018

Based on initial conditions of 0000 UTC of 23rd May, ECMWF & IMD GFS predicted landfall over Yemen around 0000 UTC of 26th. NCEP GFS predicted landfall over Yemen around 0600 UTC of 26th. UKMO predicted landfall to the east of Salalah around 0000 UTC of 26th. MME & NCEP GFS predicted landfall close to Salalah around 0000 & 1200 UTC of 26th respectively. HWRF predicted landfall close to Salalah around 1500 UTC of 26th. JMA and WRF-VAR predicted weakening over sea and movement off the actual track. The SCIP model also predicted maximum intensification of system upto VSCS stage (87 kt) after landfall. Probability of rapid intensification during next 24 hours was predicted as moderate (32%). HWRF predicted maximum intensification upto VSCS stage (73 kt) and gradual weakening of system.

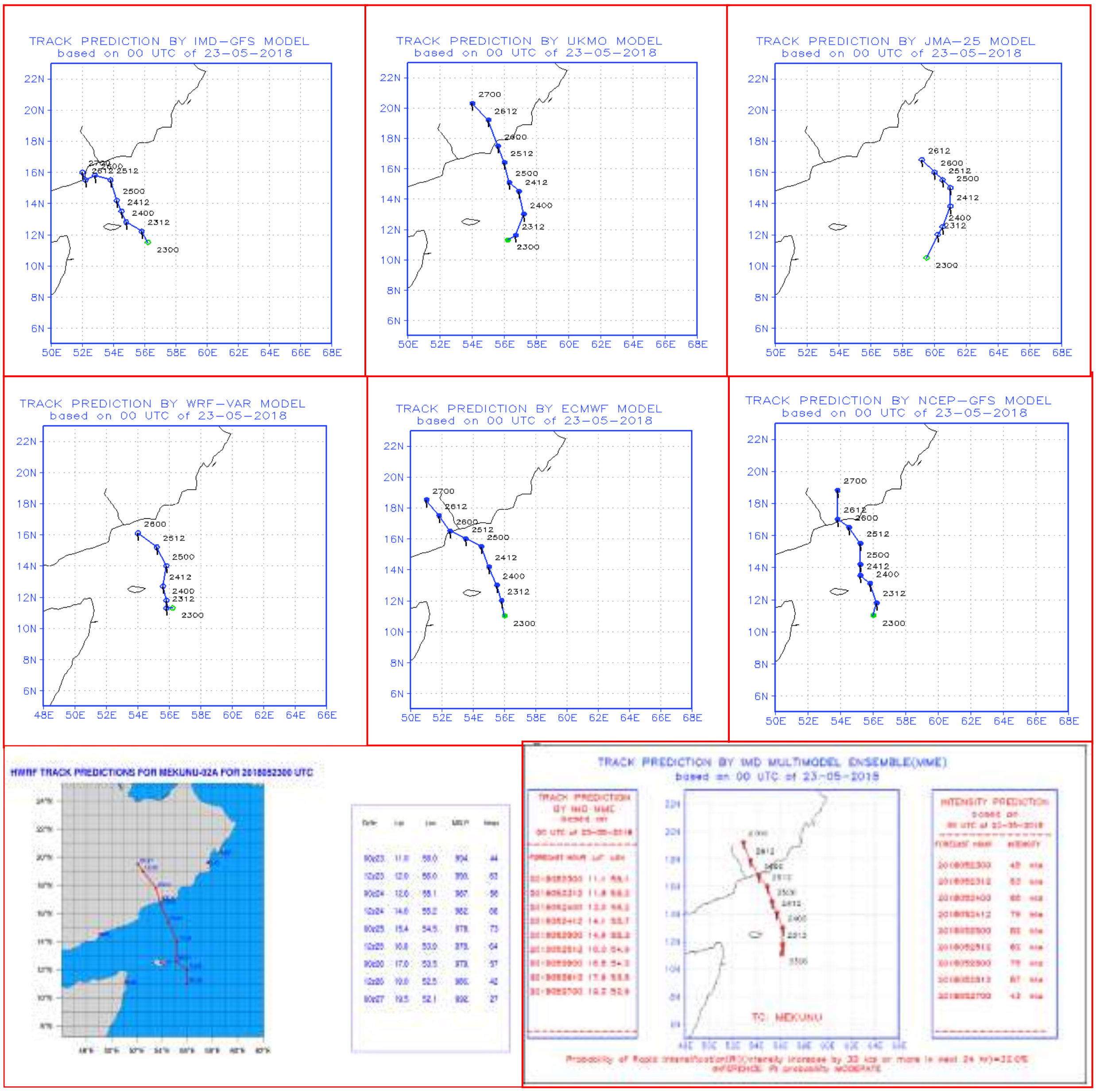


Fig. 11 (c): NWP model track forecast based on 0000 UTC of 23rd May

Based on initial conditions of 0000 UTC of 24th May, ECMWF, IMD GFS, UKMO, HWRF & MME predicted landfall close to Salalah between 1800 UTC of 25th to 0000 UTC of 26th. WRF-VAR & NCEP GFS predicted landfall over Oman-Yemen border between 0000 to 0600 UTC of 26th. JMA predicted landfall to the east of Salalah (about 200 km) around 1200 UTC of 26th. The SCIP model predicted maximum intensification of system upto VSCS stage (87 kt) prior to landfall around 1200 UTC of 25th with landfall at this intensity. Probability of rapid intensification during next 24 hours was predicted as moderate (32%). HWRF predicted maximum intensification upto VSCS stage (88 kt) around 0000 UTC of 25th and weakening of system prior to landfall (61 kt).

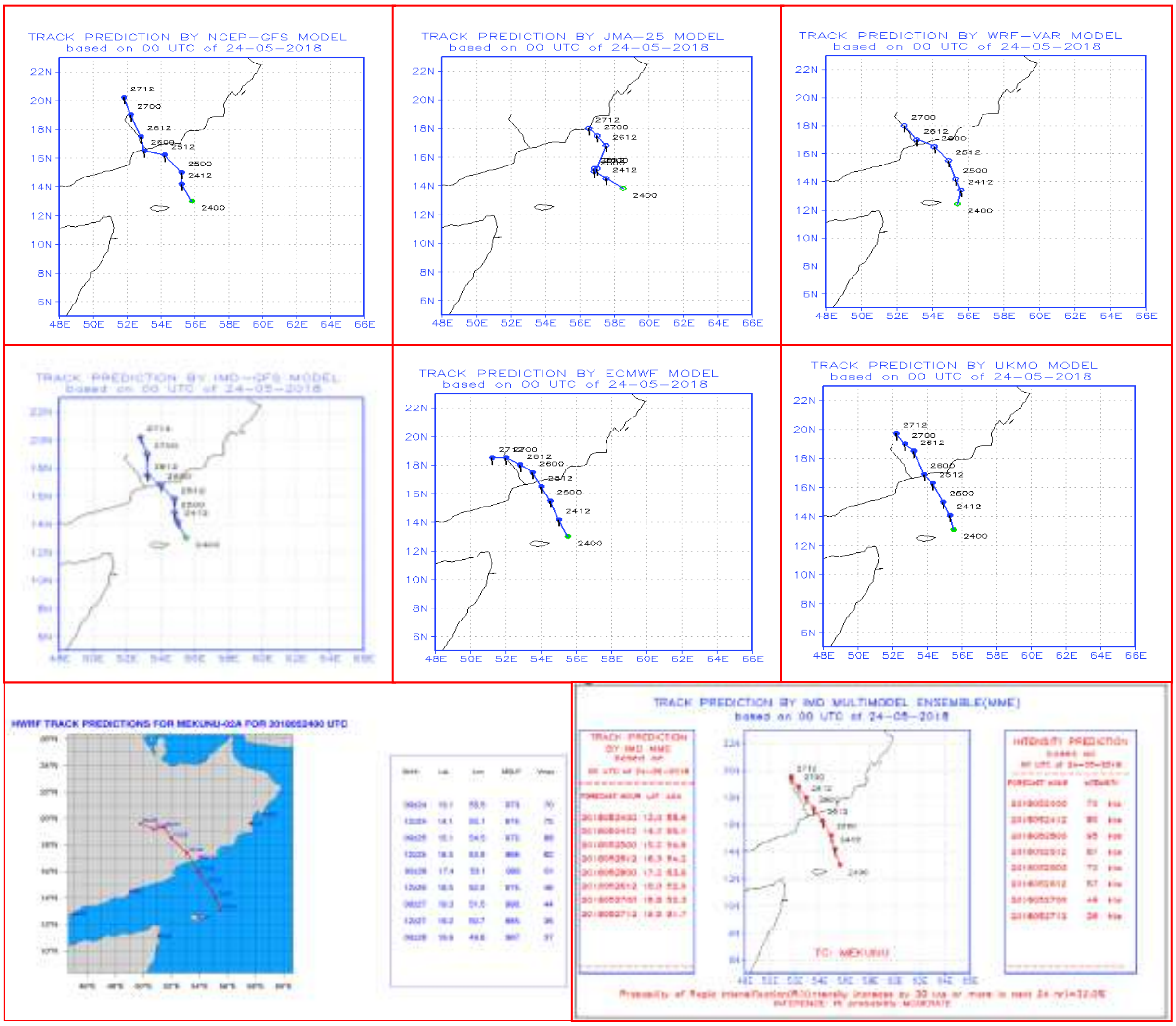


Fig. 11 (d): NWP model track forecast based on 0000 UTC of 24th May

Based on initial conditions of 0000 UTC of 25th May, ECMWF, UKMO, HWRF & MME predicted landfall close to Salalah between 1800 UTC & 2000 UTC of 25th. IMD GFS & NCEP GFS predicted landfall over Oman-Yemen border around 0000 to of 26th & 1800 UTC of 25th respectively. JMA predicted landfall to the east of Salalah (about 100 km) around 0000 UTC of 26th. WRF-VAR predicted landfall over Yemen around 0900 UTC of 26th. The SCIP model also predicted maximum intensification of system upto VSCS stage (88 kt) prior to landfall around 1200 UTC of 25th with landfall at this intensity. Probability of rapid intensification during next 24 hours was predicted as low (22%). HWRF predicted maximum intensification upto VSCS stage (83 kt) around 0000 UTC of 25th and landfall with this peak intensity.

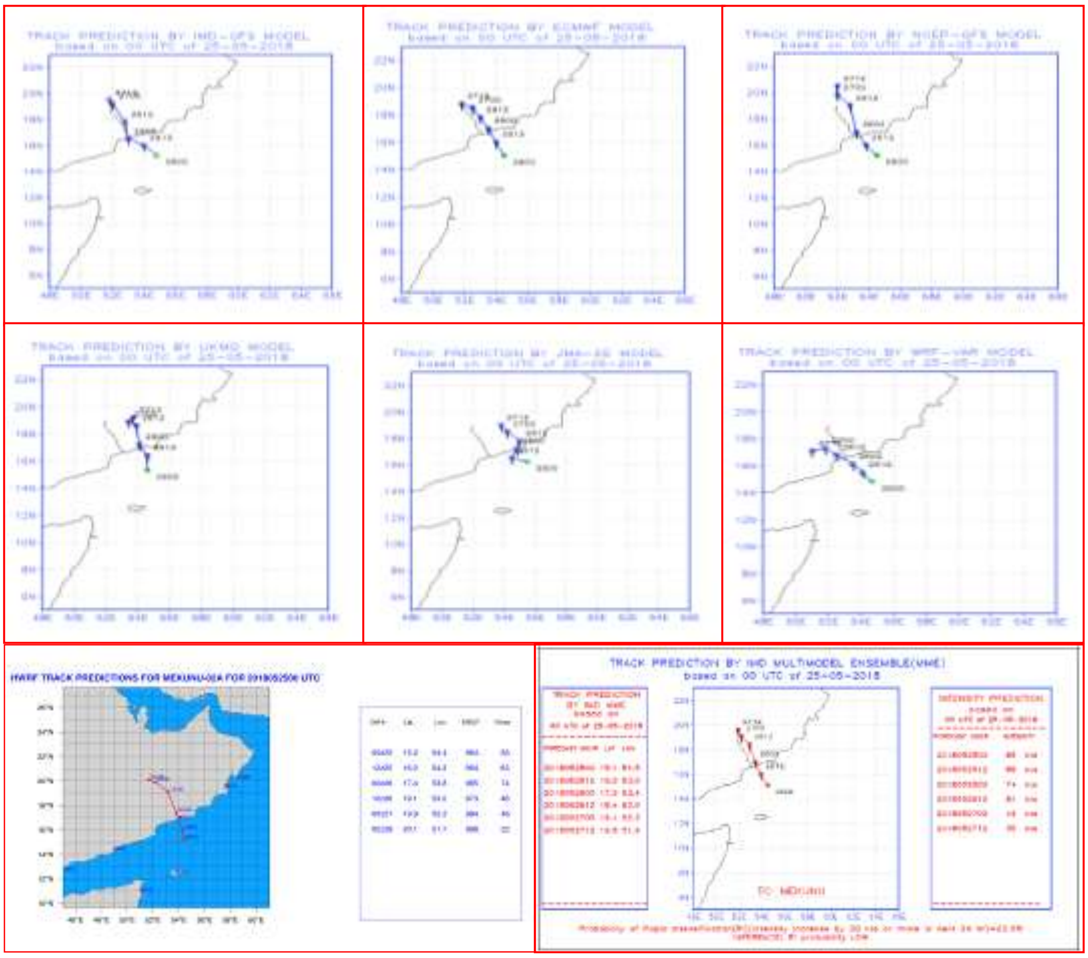


Fig. 11 (e): NWP model track forecast based on 0000 UTC of 25th May

Composite picture of forecast tracks based on initial conditions of 0000, 0600 & 1200 UTC during 21st -25th May alongwith observed track is presented in Fig. 12. It indicates that till 1200 UTC of 22nd, HWRF predicted landfall to the east of Salalah. Thereafter, the model predicted landfall close to Salalah.

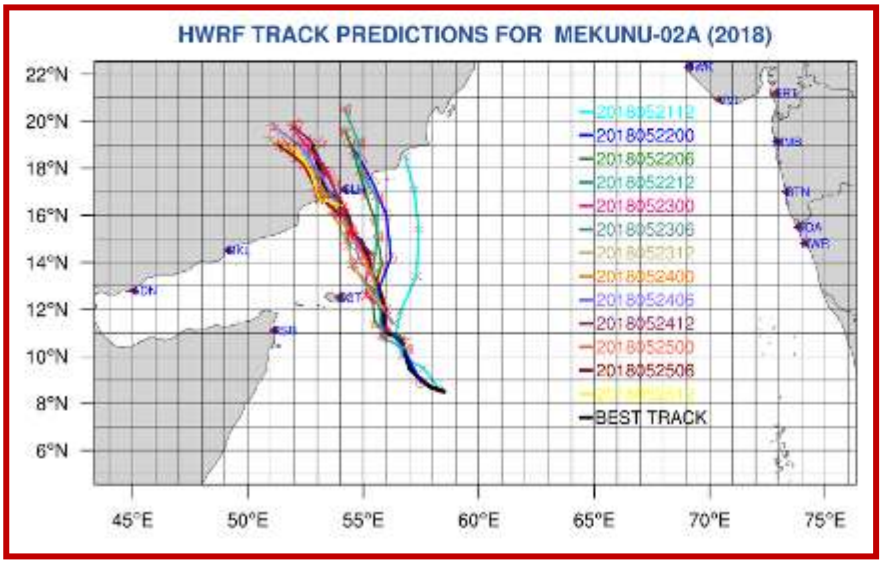


Fig. 12: Observed track and forecast tracks by HWRF based on initial conditions during 0000 UTC of 21st to 25th May

9.3 Track and intensity forecast errors by various NWP Models

The average track forecast errors (Direct Position Error) in km at different lead period (hr) of various models are presented in Table 2. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of HWRF, MME & ECMWF were the least for 24 hours lead period. For 48 hours lead period, the errors were the least by ECMWF followed by MME and IMD HWRF. For 72 hours lead period, the errors were the least by MME followed by ECMWF. For 120 hours lead period errors were the least by ECMWF and IMD GFS followed by NCEP GFS and MME. Overall the errors were the least by MME followed by ECMWF for various lead periods. The average cross track errors (CTE) and along track errors (ATE) are presented in Table 3 (a-b). The CTE was relatively higher than ATE in respect of MME. In case of ECMWF model it was opposite for most of the lead periods.

Table 2: Average track forecast errors (Direct Position Error (DPE)) in km

Lead time →	**12H**	**24H**	**36H**	**48H**	**60H**	**72H**	**84H**	**96H**	**108H**	**120H**
IMD-GFS	43(9)	69(9)	79(9)	74(8)	76(7)	103(6)	132(5)	198(4)	204(2)	179(1)
IMD-WRF	89(9)	143(9)	154(9)	194(8)	212(7)	174(6)	-	-	-	-
JMA	272(9)	349(9)	430(9)	543(8)	658(7)	756(6)	835(5)	-	-	-
NCEP-GFS	49(9)	61(9)	78(9)	94(8)	89(7)	86(6)	108(5)	144(4)	166(2)	190(1)
UKMO	60(9)	92(9)	130(9)	149(8)	159(7)	168(6)	218(5)	272(4)	294(2)	368(1)
ECMWF	53(9)	52(9)	43(9)	46(8)	57(7)	92(6)	116(5)	135(4)	162(2)	179(1)
IMD-HWRF	44(18)	51(18)	60(17)	86(15)	126(13)	163(11)	221(9)	239(8)	-	-
IMD-MME	46(9)	51(9)	56(9)	62(8)	68(7)	75(6)	82(5)	95(4)	134(2)	202(1)

( ): Number of forecasts verified;   -: No forecast issued

Table 3 (a): Average cross-track forecast errors (CTE) in km

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	23	45	53	55	56	79	111	175	190	178
IMD-WRF	81	137	139	174	194	161	-	-	-	-
JMA	128	203	247	317	379	430	472	-	-	-
NCEP-GFS	23	40	62	70	73	59	89	110	110	102
UKMO	29	42	63	61	48	52	62	58	20	52
ECMWF	21	25	20	28	30	56	74	87	152	178
IMD-HWRF	19	30	21	15	42	93	137	173	-	-
IMD-MME	23	17	27	30	36	54	67	67	84	78

Table 3(b). Average along-track forecast errors (ATE) in km

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	32	44	50	45	41	53	63	91	74	22
IMD-WRF	30	36	59	70	69	54	-	-	-	-
JMA	213	263	332	423	526	615	683	-	-	-
NCEP-GFS	36	40	36	52	45	55	45	84	123	161
UKMO	48	73	101	129	149	160	206	264	293	364
ECMWF	45	38	32	32	45	59	70	78	54	22
IMD-HWRF	64	60	75	113	115	122	149	151	-	-
IMD-MME	36	46	44	53	55	49	46	59	95	186

Landfall point and time forecast errors are presented in Table 4 and 5. The landfall point error was the minimum for ECMWF model for 19, 31 and 43 hour forecast period as well as for 91 and 103 hours lead period. It was the minimum in case of MME for 55, 67 and 79 hours lead period. The landfall time error was the least in case of IMD-MME for most of the lead periods.

Table 4: Landfall point forecast errors (km) of NWP Models at different lead time

Forecast Lead Time (hour) →	7 hr	19 hr	31 hr	43 hr	55 hr	67 hr	79 hr	91 hr	103 hr
Based on	**25 /12z**	**25/ 00z**	**24 / 12z**	**24 / 00z**	**23/ 12z**	**23/ 00z**	**22/ 12z**	**22/ 00z**	**21 /12z**
IMD-GFS	85	108	85	17	48	224	-	65	31
IMD-WRF	85	105	209	27	59	-	-	-	-

JMA	-	113	159	318	-	-	-	-	-
NCEP	27	48	55	108	51	17	41	162	112
UKMO	31	51	41	17	102	208	342	210	309
ECMWF	48	31	8	8	59	142	41	38	31
IMD-MME	27	41	8	31	41	48	38	48	169

Landfall Point Error: Landfall Forecast Point- Actual Landfall Point, **: No forecast issued

Table-5. Landfall time forecast errors (hour) at different lead time (hr) ('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	**7 hr**	**19 hr**	**31 hr**	**43 hr**	**55 hr**	**67 hr**	**79 hr**	**91 hr**	**103 hr**
Based on	**25 May 12z**	**25 May 00z**	**24 May 12z**	**24 May 00z**	**23 May 12z**	**23 May 00z**	**22 May 12z**	**22 May 00z**	**21 May 12z**
IMD-GFS	+5	+5	+5	+6	+5	+18	-	+17	+17
IMD-WRF	+23	+15	+5	+11	+17	-	-	-	-
JMA	-	+3	+17	+41	-	-	-	-	-
NCEP	+1	+2	+2	+5	+5	+16	+15	+12	+6
UKMO	+5	+3	+3	+5	0	+7	+9	+5	+1
ECMWF	0	+3	-1	-3	+3	+5	+5	+11	+17
IMD-MME	+1	+2	0	0	+3	+5	+5	+5	+5

Landfall Time Error: Landfall Forecast Time- Actual Landfall Time
- : No forecast issued

The composite intensity track prediction by IMD SCIP model based on initial conditions of 0000 & 1200 UTC during 21^{st} - 25^{th} May is presented in Fig. 20. Overall, SCIP underestimated intensity of the system including the peak intensity.

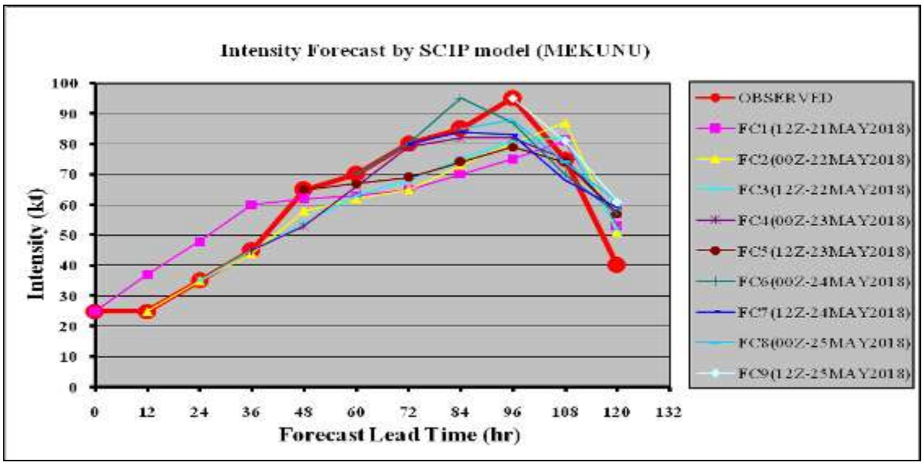


Fig.20: Intensity prediction by SCIP Model

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

Lead time → (hrs)	12	24	36	48	60	72	84	96	108	120
IMD-SCIP (AAE)	4.6 (9)	9.3 (9)	9.6 (8)	9.4 (7)	10.5 (6)	11.6 (5)	13.5 (4)	14.7 (3)	8.5 (2)	13.0 (1)
IMD-HWRF (AAE)	7.2 (21)	9.2 (20)	7.8 (18)	16.8 (16)	13.0 (14)	11.3 (12)	12.9 (10)	8.3 (8)		
IMD-SCIP (RMSE)	6.5	11.1	11.2	11.1	11.8	13.1	14.0	15.1	8.9	13.0
IMD-HWRF (RMSE)	9.3 (21)	10.7 (20)	10.2 (18)	19.8 (16)	17.6 (14)	14.4 (12)	15.8 (10)	11.6 (8)		

The intensity forecast errors by HWRF were significantly higher than IMD SCIP for 48 hours lead period. For other lead periods, the errors were comparable. For 72 and 96 hours lead period, the HWRF errors were less than the SCIP errors.

The probability of rapid intensification (RI) index by MME is shown in Table 6. Rapid intensification occurred at 1200 UTC of 23rd (65 kt at 23/1200 UTC & 35 kt at 22/1200 UTC). However, the RI index couldn't predict RI of the system.

Table 6: Probability of Rapid intensification (RI) by RI Model

Forecast based on	**Probability of RI predicted**	**Chances of occurrence predicted**	**Intensity changes(kt) occurred in 24h**
12/21.05.2018	22 %	LOW	+10
00/22.05.2018	9.4 %	VERY LOW	+20
12/22.05.2018	22 %	LOW	+30
00/23.05.2018	32 %	MODERATE	+25
12/23.05.2018	32 %	MODERATE	+15
00/24.05.2018	32 %	MODERATE	+15
12/24.05.2018	32 %	MODERATE	+15

9.4. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model are presented in **Fig.20**. HWRF could successfully predict occurrence of rainfall along the predicted track even after the landfall of system. Based on 1200 UTC of 24th, the expected rainfall during 1200 UTC of 24th to 1200 UTC of 28th May is about 8-16 inches (20-40cm) over coastal areas of south Oman and southeast Yemen. It may be 20-25 inches (50-60 cm) at some places in south coastal Oman. Over interior areas of Oman, it may be around 8-10 inches (20-25 cm) during 1200 UTC of 24th to 1200 UTC of 28th May. As per the available rainfall reports from media at Oman, extremely heavy rainfall of the order of 30 cm was recorded on the day of landfall over Salalah.

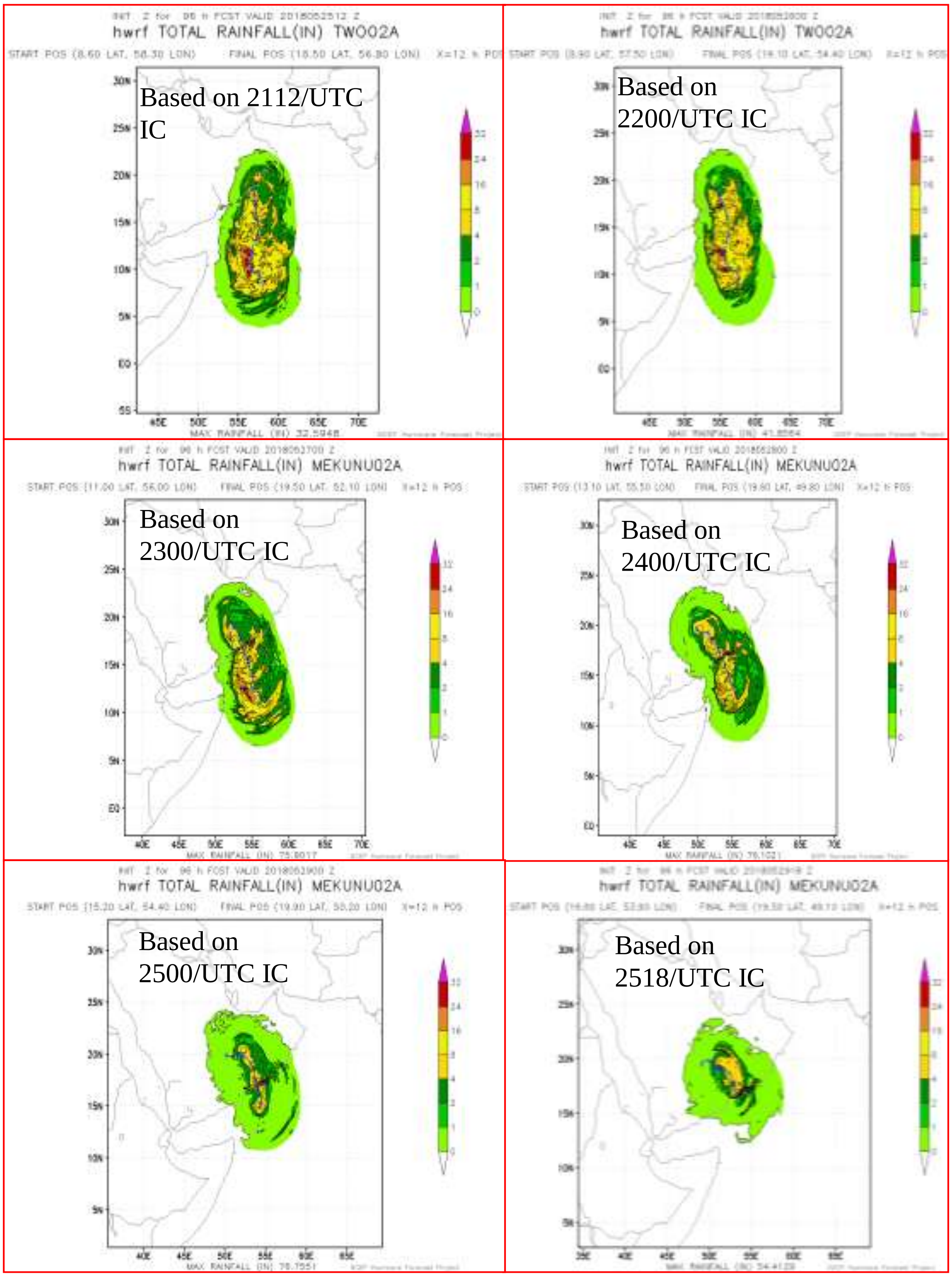


Fig.20: Heavy rainfall forecast by HWRF based on initial conditions of 0000 UTC of 21th-25th May, 2018.

10.5 Storm surge forecast

IMD predicts storm surge forecast based on guidance from Advance Circulation (ADCIRC) model and Indian Institute of Delhi Model. IMD predicted expected storm surge of 1.5 metre to 2 metre above astronomical tide during 1800 UTC of 25th to 0300 UTC of 26th. The maximum storm surge was expected over Salalah. Storm surge forecast by ADCIRC Model based on 0600 UTC observations of 23rd May is presented in **Fig.21**.

Fig. 21: Storm Surge Forecast issued by ADCIRC Model based on 0600 UTC of 23rd May, 2018

10. Operational Forecast Performance

10.1. Genesis Forecast

- First information regarding formation of a low pressure area over southeast AS was given in Tropical Weather Outlook issued in the morning (0600 UTC) of 20th May with moderate probability (51-75%) of it's intensification into a D during next 24-48 hours (36 hours in advance of formation of D). D formed over southwest AS at 1200 UTC of 21st.

10.2. Landfall Forecast

- First bulletin issued around noon (0600 UTC) of 20th May indicated that the system would move towards south Oman-southeast Yemen coasts (about 138 hours in advance of actual landfall).
- First information regarding landfall of cyclone near south Oman-southeast Yemen coast close to Salalah around morning of 26th May was issued at 0300 UTC of 22nd May (88 hours in advance of actual landfall). The system crossed south Oman coast near 16.85^{0}N/53.75^{0}E around midnight (between 1830 & 1930 UTC) of 25th May.

- The landfall point forecast errors for 24, 48 and 72 hrs lead period were 17.2, 12.5 and 29.0 km respectively and the landfall time forecast errors for 24, 48 and 72 hrs lead period were 7.0, 8.0, and 7.0 hrs respectively (Fig. 22 and Table 7).

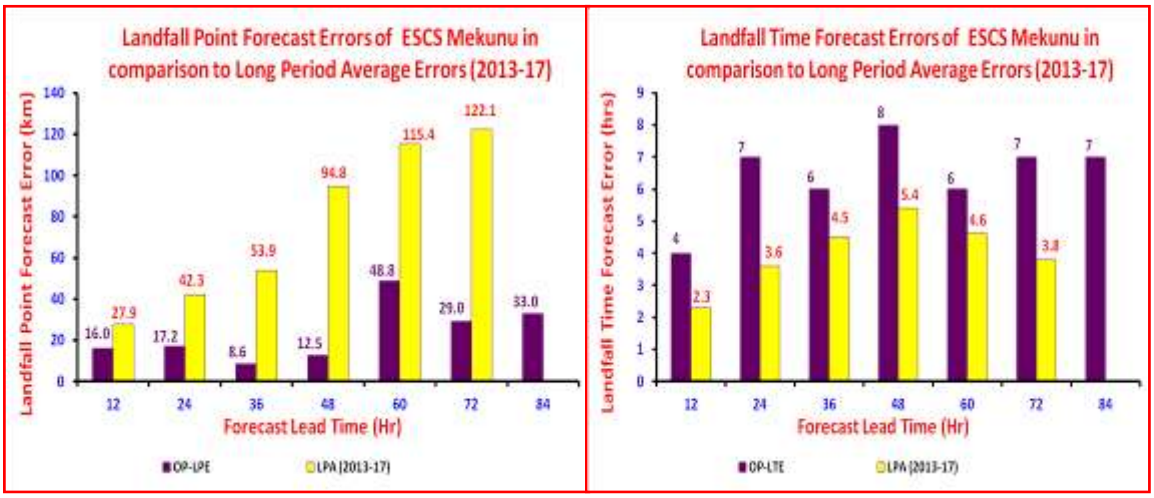


Fig.22: Landfall Point Forecast Error (LPE) and Landfall Time Forecast Errors (LTE) of ESCS Mekunu

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	25/06	16.8/53.6	16.9/53.8	25/2300	25/1900	16.0	4	27.9	2.3
24	24/18	16.9/53.9	16.9/53.8	26/0200	25/1900	17.2	7	42.3	3.6
36	24/06	16.9/53.8	16.9/53.8	26/0100	25/1900	8.6	6	53.9	4.5
48	23/18	16.9/53.8	16.9/53.8	26/0300	25/1900	12.5	8	94.8	5.4
60	23/06	16.7/53.3	16.9/53.8	26/0100	25/1900	48.8	6	115.4	4.6
72	22/18	17.0/54.0	16.9/53.8	26/0200	25/1900	29.0	7	122.1	3.8
84	22/00	17.0/54.0	16.9/53.8	26/0200	25/1901	33.0	7		

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

- The track based on 0000 UTC of 22nd **(Fig.22)** shows that the system moved north-northwestwards towards south Oman-southeast Yemen coast.
- Typical graphics showing observed and forecast tracks for different lead periods is presented in **Fig.23.** It indicates that for all lead periods track was well

predicted. The observed and a typical forecast track with cone of uncertainty based 0000 UTC of 23rd is presented in **Fig.24.**

The track forecast error for 24, 48, and 72 hrs lead period were 48.8, 63.3, and 79.4 km respectively, which is significantly less than the average track forecast errors of 93, 144 and 201 km during last five years (2013-17). The track forecast skill was about 54.9%, 68.3%, and 71.6% against the long period average (LPA) of 45%, 55%, and 68% during 2013-17 for 24, 48 and 72 hrs lead period respectively. (**Fig. 25 and Table 8**).

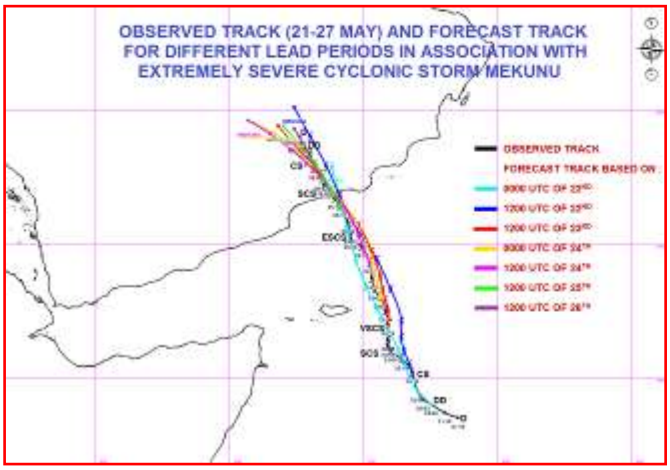


Fig.23: Observed track and forecast tracks for different lead periods

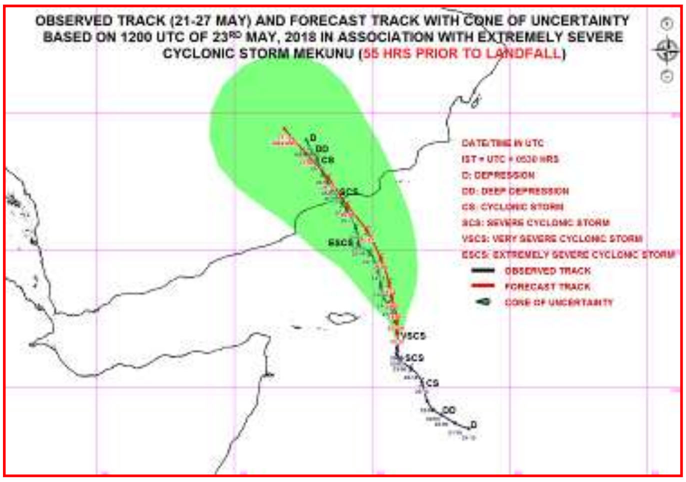


Fig.24: Observed and forecast track with cone of uncertainty based on 1200 UTC of 23rd May, 2018 in association with ESCS Mekunu

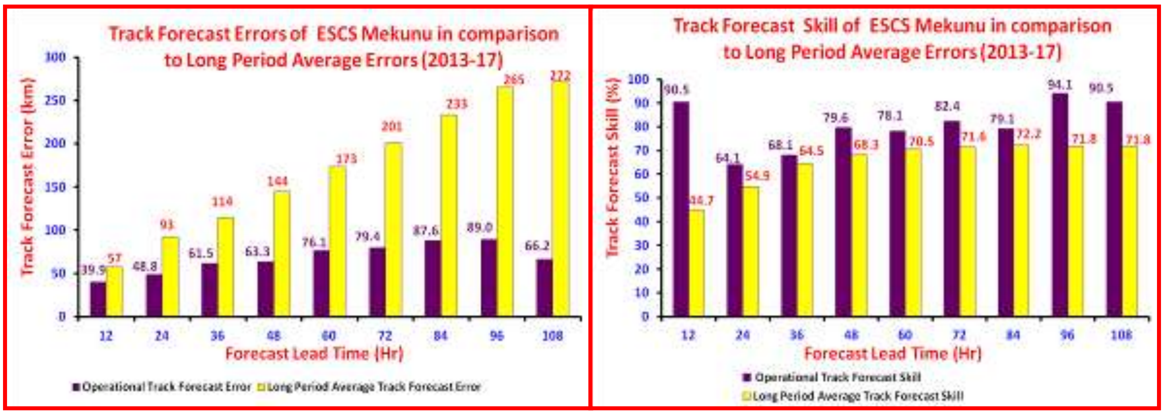


Fig.25: Track Forecast Errors and Skill for ESCS Mekunu

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	20	39.9	90.5	57	44.7
24	17	48.8	64.1	93	54.9
36	16	61.5	68.1	114	64.5
48	14	63.3	79.6	144	68.3
60	12	76.1	78.1	173	70.5
72	10	79.4	82.4	201	71.6
84	7	87.6	79.1	233	72.2
96	5	89.0	94.1	265	71.8
108	3	66.2	90.5	272	71.8

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

10.4. Intensity Forecast

- First information regarding intensification of system into a cyclonic storm was issued in Tropical Weather Outlook issued around noon (0600 UTC) of 20th May.
- First information that the system would cross south Oman-southeast Yemen coasts near Salalah as a VSCS with MSW of 150-160 kmph was issued in the morning(0300 UTC) of 22nd May (about 88 hours in advance of landfall).
- The wind warning was further updated in the morning (0300 UTC) of 24th May to 160-170 kmph (about 39 hours in advance of landfall) and in the evening (1200 UTC) of 25th May to 170-180 kmph (about 7 hours in advance of landfall). The system crossed south Oman-southeast Yemen coasts as an ESCS with MSW of 170-180 kmph.
- Typical graphical product giving wind distribution around the cyclone based on 1200 UTC of 23rd May 2018 is presented in **Fig. 26.**
- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 5.5, 14.1 and 14.7 knots against the LPA of 10.4, 15.5 and 15.4 knots respectively. The skill based on AE of intensity (wind) forecast for 24, 48 and 72 hrs lead period was 74.9, 56.7 and 71.7% against the LPA of 37.1, 56.8 and 69.3% respectively. (**Fig.27 and Table 9**)
- The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 6.9, 16.1 and 16.2 knots against the LPA of 14.0, 20.6 and 20.6 knots respectively. The skill based on RMSE of intensity (wind) forecast for

24, 48 and 72 hrs lead period was 77.9%, 60.9% and 76.7% against the LPA of 40.1, 60.0 and 73% respectively. (**Fig.28**)

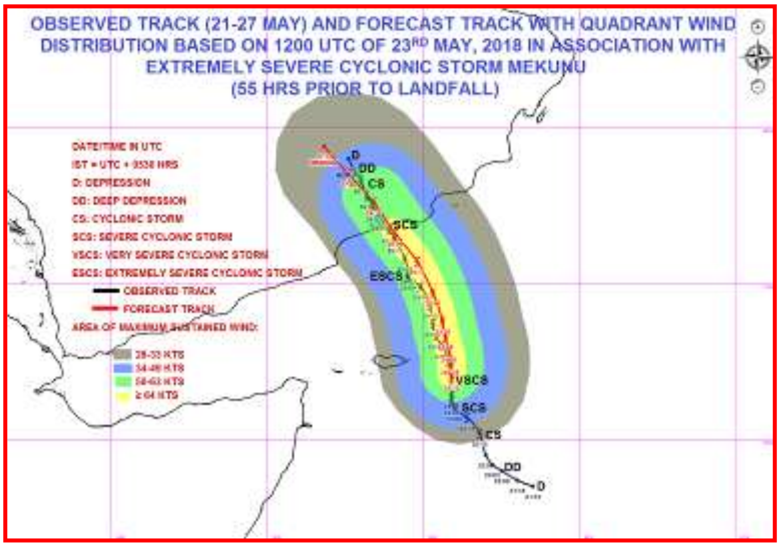


Fig.26: Observed and forecast track with quadrant wind distribution based on 1200 UTC of 23rd May, 2018 in association with ESCS Mekunu

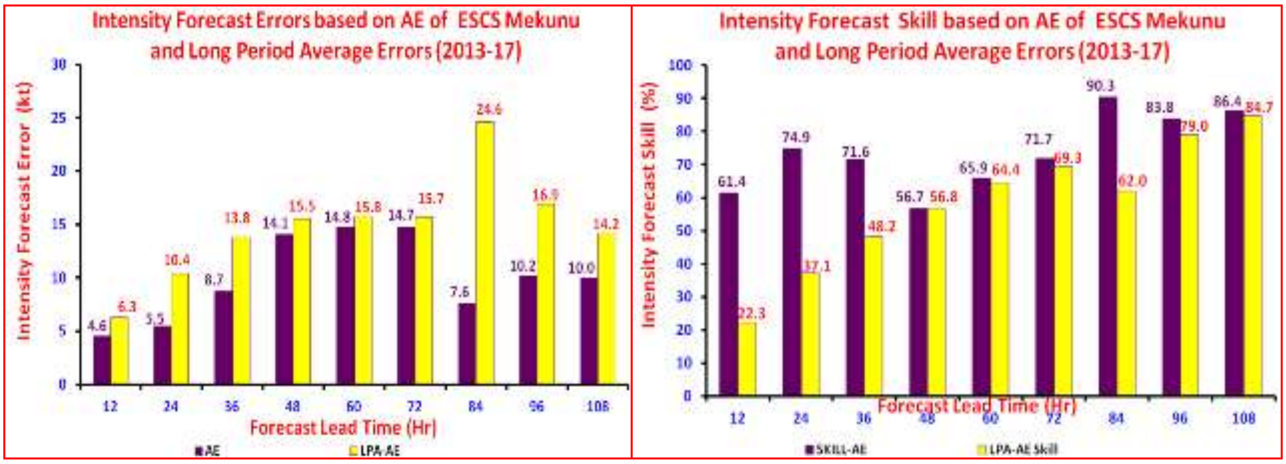


Fig. 27: Absolute errors (AE) of intensity forecast and skill for ESCS Mekunu

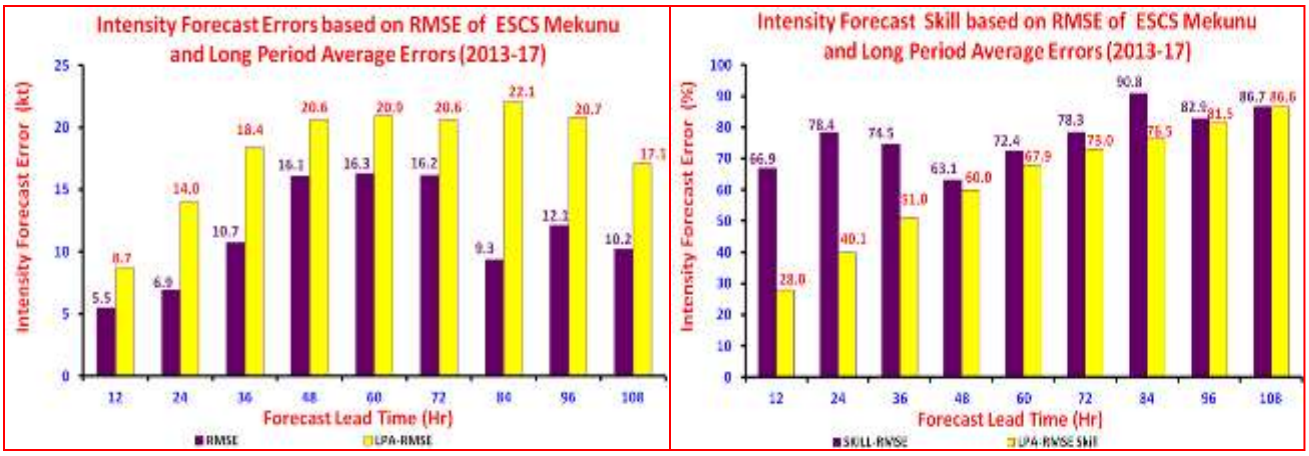


Fig. 28: Root mean square errors (RMSE) of intensity forecast and skill for ESCS Mekunu

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	20	4.6	5.5	61.4	66.9	6.3	8.7	22.3	28.0
24	17	5.5	6.9	74.9	78.4	10.4	14.0	37.1	40.1
36	16	8.7	10.7	71.6	74.5	13.8	18.4	48.2	51.0
48	14	14.1	16.1	56.7	63.1	15.5	20.6	56.8	60.0
60	12	14.8	16.3	65.9	72.4	15.8	20.9	64.4	67.9
72	10	14.7	16.2	71.7	78.3	15.7	20.6	69.3	73.0
84	7	7.6	9.3	90.3	90.8	24.6	22.1	62.0	76.5
96	5	10.2	12.1	83.8	82.9	16.9	20.7	79.0	81.5
108	3	10.0	10.2	86.4	86.7	14.2	17.1	84.7	86.6

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

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 etc. upto 120 hours 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, ≥34, ≥50 and ≥64 knots wind in four geographical quadrants (NE, NW, SW, SE) of cyclone was issued every six hour giving forecast for +06, +12, +18, +24, +36 … upto 120 hours lead period.
- **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..

- **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 agencies including MHA, NDRF, NDMA and State level disaster management agencies of all the states along west coast of India including Tamil Nadu, Andhra Pradesh, Kerala, Karnataka, Goa, Maharashtra, Gujarat, Lakshadweep Islands, Daman & Diu and Dadra & 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 authorities including Indian Navy & Indian Air Force.
- **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. Similarly, Sea Area and Coastal Weather bulletins, Port Warnings and Fishermen warnings were issued by 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 and Dadra & Nagar Haveli not to venture into southwest AS during 21st-23rd May and into westcentral AS during 23rd-26th May was issued in the afternoon (0800 UTC) of 20th May.
- **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.
- **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 and middle east 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 system were described in the RSMC bulletins.
- **TC Vital:** Tropical cyclone vital parameters were prepared every six hour 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 ESCS Mekunu are given in **Table 10.**

Table 10: Bulletins issued by RSMC New Delhi

S.N	Bulletin	No. of Bulletins	Issued to
1	(a) Informatory Message (b) National Bulletin	2 43	1. IMD's website 2. FAX and e-mail to Control Room MHA, NDMA, Cabinet Secretariat, Secretary MoES, DST, HQ Integrated Defence Staff, DG Doordarshan, All India Radio, DG-NDRF, Director Indian Railways, Chief Secretary- Tamil Nadu, Kerala, Karnataka, Goa, Maharashtra and Gujarat, Lakhshadweep, Daman & Diu and Dadra & Nagar Haveli.
2	RSMC Bulletin	43	1. IMD's website 2. WMO/ESCAP member countries through Global Telecommunication System (GTS) and E-mail.
3	GMDSS Bulletin	43	1. IMD website, RSMC New Delhi website 2. Transmitted through WMO Information System (WIS) to Joint WMO/IOC Technical Commission for Ocean and Marine Meteorology (JCOMM)
4	Tropical Cyclone Advisory Centre Bulletin (Text & Graphics)	20	1. Met Watch offices in Asia Pacific regions and Middle East though GTS to issue Significant Meteorological information for International Civil Aviation 2. WMO's Aviation Disaster Risk Reduction (ADRR), Hong Kong through ftp 3. RSMC website
5	Tropical Cyclone Vital Statistics	20	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 and whenever intensity changed	SMS for disaster managers at national level and concerned states (Total of 1495 messages were sent).
7	Warnings through Social Media	Daily	Cyclone Warnings were uploaded on Social networking sites like Face book and Tweeter since inception to weakening of system
8	Press Release	Daily once (Total 8)	Disaster Managers, Media persons by email and uploaded on website
9	Press Briefings	Daily	Regular briefing daily

12. Summary and Conclusion:

Extremely Severe Cyclonic Storm (ESCS) Mekunu originated from a low pressure area which formed over southeast Arabian Sea (AS) in the morning (0300 UTC) of 20th May. It became a well marked low pressure area over southwest & adjoining southeast AS in the early morning (0000 UTC) of 21st May. Under favourable environmental conditions, it concentrated into a Depression (D) over southwest AS in the evening (1200 UTC) of 21st May. Moving west-northwestwards it intensified into a deep depression (DD) in the morning (0300 UTC) of 22nd May. It then moved north-northwestwards and intensified into a cyclonic storm (CS) **"Mekunu**" in the evening (1200 UTC) of same day over southwest AS. It further continued to move north-northwestwards, intensified into a Severe Cyclonic Storm (SCS) in the morning (0300 UTC) and into a Very Severe Cyclonic Storm (VSCS) in the afternoon (0900 UTC) of 23rd May over westcentral AS. Moving further north-northwestwards, it intensified into an Extremely Severe Cyclonic Storm (ESCS) in the morning (0300 UTC) of 25th and crossed south Oman coast near 16.85^{0}N/53.75^{0}E around midnight (between 1830-1930 UTC) of 25th May as an ESCS with an estimated wind speed of 170-180 kmph gusting to 200 kmph. It moved north-northwestwards and weakened into a VSCS over Oman in the early hours of 26th May (2100 UTC of 25th May). Continuing to move north-northwestwards, it weakened into an SCS in the early morning (0000 UTC), into a CS in the afternoon (0900 UTC) and into a DD around midnight (1800 UTC) of 26th May. It further weakened into a D in the early morning (0000 UTC) and into a well marked low pressure area over Saudi Arabia and adjoining Oman & Yemen in the morning (0300 UTC) of 27th May.

IMD utilised all its resources to monitor and predict the genesis, track and intensification of ESCS Mekunu. The landfall point forecast errors for 24, 48 and 72 hrs lead period were 17.2, 12.5 and 29.0 km respectively and the landfall time forecast errors for 24, 48 and 72 hrs lead period were 7.0, 8.0, and 7.0 hrs respectively. The track forecast error for 24, 48, and 72 hrs lead period were 48.8, 63.3, and 79.4 km respectively, which is significantly less than the average track forecast errors of 93, 144 and 201 km during last five years (2013-17). The track forecast skill was about 54.9%, 68.3%, and 71.6% against the long period average (LPA) of 45%, 55%, and 68% during 2013-17 for 24, 48 and 72 hrs lead period respectively. The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 5.5, 14.1 and 14.7 knots against the LPA of 10.4, 15.5 and 15.4 knots respectively. The skill based on AE of intensity (wind) forecast for 24, 48 and 72 hrs lead period was 74.9, 56.7 and 71.7% against the LPA of 37.1, 56.8 and 69.3% respectively. The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 6.9, 16.1 and 16.2 knots against the LPA of 14.0, 20.6 and 20.6 knots respectively. The skill based on RMSE of intensity (wind) forecast for 24, 48 and 72 hrs lead period was 77.9%, 60.9% and 76.7% against the LPA of 40.1, 60.0 and 73% 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 ESCS Mekunu. RSMC New Delhi acknowledges contribution of World Meteorological Organisation in co-ordinating and helping RSMC in dissemination of warnings to the Government of Oman, Yemen and 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) and other 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.