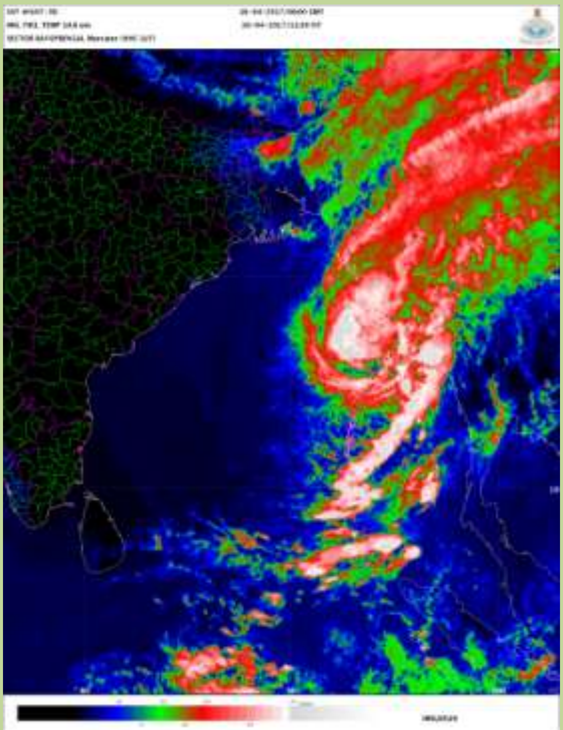
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Cyclonic Storm,'Maarutha' over the Bay of Bengal (15-17April 2017): A Report



INSAT-3D typical satellite imagery 0600 UTC of 16th April

Cyclone Warning Division

India Meteorological Department

New Delhi

May 2017

Cyclonic Storm "Maarutha" over the Bay of Bengal
(15-17 April 2017)

1. Introduction:

A depression (D) developed over southeast Bay of Bengal (BOB) in the morning (0000 UTC) of 15th April. Moving northeastwards, it intensified into a deep depression (DD) over eastcentral BOB in the afternoon of 15th and into a cyclonic storm (CS) "MAARUTHA" over eastcentral BOB in the midnight of 15th. Further moving northeastwards, it reached its peak intensity in the early hours of 16th. The system maintained its peak intensity till evening of 16th. Moving nearly northeastwards, it crossed Myanmar coast near Sandoway (Thandwe) in the midnight. After landfall, the system weakened into a DD in early hours of 17th, into a D in the morning and well marked low pressure area over central Myanmar and neighbourhood in the forenoon of 17th. The salient features of the system were as follows:

i. Climatologically, in the satellite era (1961 onwards), there had been three cyclones developing over north Indian Ocean (NIO) during 1-15th April, including 1 over Arabian Sea (AS) and 2 over BOB. Both the cyclones over BOB had recurving tracks. The cyclone in 2009 crossed Bangladesh coast as DD near Chittagong and the other (in 1972) weakened over eastcentral BOB. The cyclone over AS also had recurving track and weakened over sea. CS Maarutha was the first ever landfalling cyclone over Myanmar developing during the period 1-15 April in satellite era.

ii. The peak maximum sustained surface wind speed (MSW) of the cyclone was 70-80 kmph gusting to 90 kmph (40 knots) and the system crossed Myanmar coast with this peak MSW between 1800-1900 UTC of 16th April. The lowest estimated central pressure was 996 hPa (from 0000 UTC of 16th to 1800 UTC of 16th).

iii. The life period of cyclone was 51 hours (2.13 days).

iv. The track length of the cyclone was about 1170 km.

v. The system moved very fast under the influence of mid-latitude trough in westerlies lying over India in the middle and upper tropospheric levels. In addition an anticyclonic circulation lay to the southeast of system centre which further accentuated the northeasterly winds over the cyclone field. Also the upper tropospheric ridge ran along 10-11^{0}N throughout the life period of the system. As a result, since the genesis stage itself, the system lay to the north of ridge. Under this scenario, Maarutha moved northeastwards very fast with a 12 hrly average speed of 22.8 kmph.

vi. The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were $1.95X10^2$ knots, $0.76 X 10^4$ $knots^2$ and $0.299 X10^6$ $knots^3$ respectively.

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 and Prediction of CS, Maarutha

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) since its inception over southeast BOB on 15th April. At the genesis stage, the system was monitored mainly with satellite observations from INSAT 3D, 3DR and Kalpana along with available ships & buoy observations. On 16th Department of Meteorology and Hydrology, Myanmar provided hourly coastal observations till landfall. Various national and international 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 were 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 Bangladesh, Myanmar and Thailand, National & State Disaster Management Agencies, general public and media since inception of the system over BOB.

3. Brief life history

3.1. Genesis

An upper air cyclonic circulation developed over south Andaman Sea & neighbourhood extending upto 3.1 km above mean sea level on 11th. Moving nearly northeastwards, it concentrated into a trough of low over Andaman & Nicobar Islands and neighbourhood on 12th. It lay as a low pressure area over southeast BOB and neighbourhood with upper air cyclonic circulation extending upto 5.8 km above mean sea level in the evening of 13th. It became a well marked low pressure area in the early hours of 14th over the same region. It concentrated into a depression in the early hours of 15th over southeast BOB. At 0000 UTC of 15th the sea surface temperature (SST) around the region of depression was 30-32^{0}C. The ocean thermal energy was about 100 KJ/cm^2. The vertical wind shear was about 10-20 knots (moderate) around the system centre. The low level relative vorticity and convergence were about $150 \times 10^{-6} s^{-1}$ and $30 \times 10^{-5} s^{-1}$ respectively. There was favourable poleward outflow in association with the anti-cyclonic circulation lying to the souheast of the system centre. The upper level divergence was about $40 \times 10^{-5} s^{-1}$. The upper tropospheric ridge at 200 hpa level ran along 10^{0}N. Madden Julain Oscillation (MJO) was in Phase 7 with amplitude less than 1. Hence the environmental conditions were favourable for genesis, except MJO.

3.2 Intensification

Moving northeastwards, it intensified into a deep depression (DD) over eastcentral Bay of Bengal in the afternoon of 15th and into a cyclonic storm (CS) "MAARUTHA" over eastcentral in the Bay of Bengal midnight of 15th. On 15th, similar thermodynamical features continued. Under the favourable lower level convergence & vorticity, upper level divergence enhanced by poleward outflow due to an anticyclonic circulation in the southeast of system centre and a trough in mid latitude westerlies around 80^0E and incursion of warm moist air from southeast towards the system centre, the system gradually intenisfied into a CS. However, strong vertical wind shear and unfavourable MJO inhibited rapid intensification or further intensification of the system. Moving northeastwards, it reached its peak intensity in the early hours of 16th. The system maintained its peak intensity till landfall near Sandoway (Thandwe) in the midnight. After landfall, the system weakened into a Deep Depression in early hours of 17th, into a Depression in the morning and well marked low pressure area over central Myanmar and neighbourhood in the forenoon of 17th.

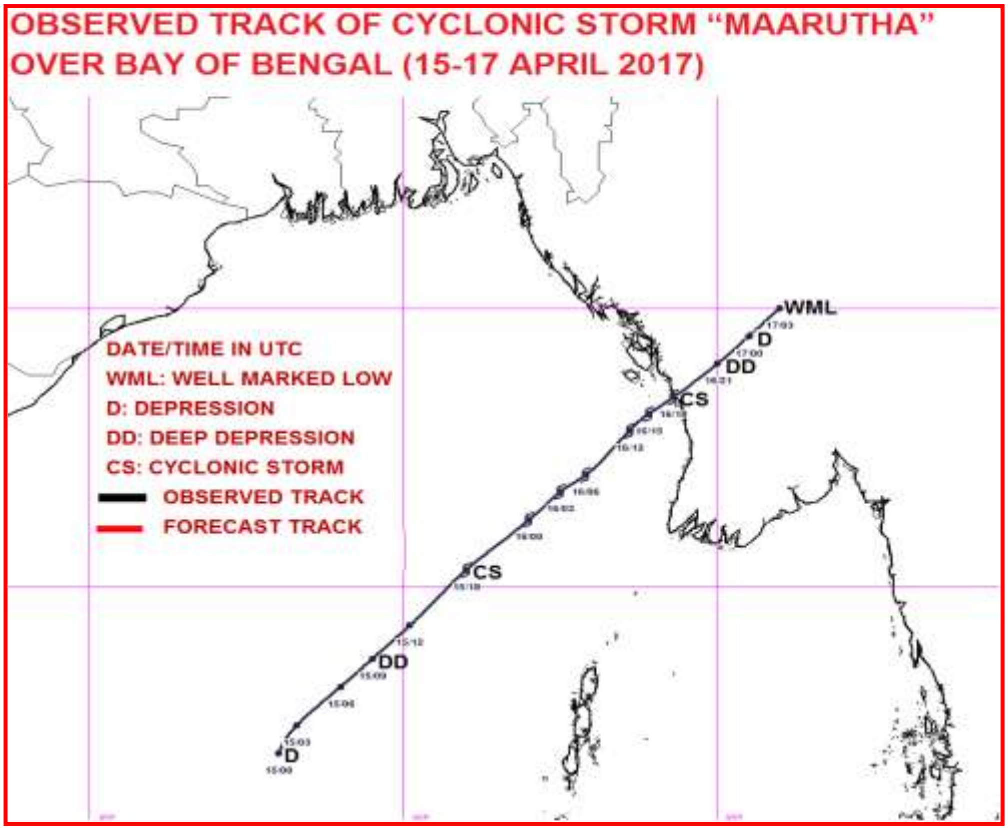


Fig.1 : Observed track of cyclonic storm Maarutha (15-17 April, 2017) over Bay of Bengal

Table 1: Best track positions and other parameters of Cyclonic Storm, 'Maarutha' over the Bay of Bengal during 15-17 April, 2017

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
	0000	12.0/88.0	1.5	1001	25	3	**D**
	0300	12.5/88.3	1.5	1001	25	3	D
	0600	13.2/89.0	1.5	1000	25	4	D
15/04/2017	0900	13.7/89.5	2.0	999	30	5	**DD**
	1200	14.3/90.1	2.0	999	30	5	DD
	1800	15.3/91.0	2.5	998	35	6	**CS**
	2100	15.5/91.2	2.5	996	40	8	CS
	0000	16.2/92.0	2.5	996	40	8	CS
	0300	16.7/92.5	2.5	996	40	8	CS
	0600	17.0/92.9	2.5	996	40	8	CS
	0900	17.5/93.2	2.5	996	40	8	CS
16/04/2017	1200	17.8/93.6	2.5	996	40	8	CS
	1500	18.1/93.9	2.5	996	40	8	CS
	1800	18.4/94.3	2.5	996	40	8	CS
	Crossed Myanmar coast near Sandoway (Thandwe) during 1800-1900 UTC						
	2100	19.0/95.0	-	1000	30	5	**DD**
	0000	19.5/95.5	-	1002	20	3	**D**
17/04/2017	0300	**Well Marked Low Pressure Area over central Myanmar and neighbourhood**					

The lowest estimated central pressure and the maximum sustained wind speed are presented in Fig.2.

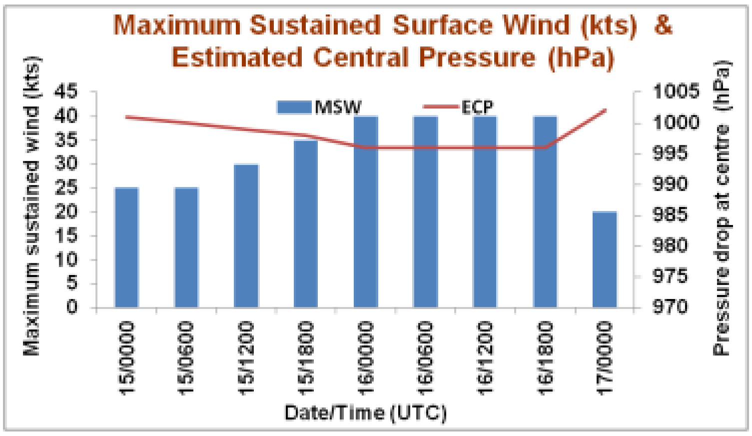


Fig.2: Lowest estimated central pressure and the maximum sustained wind speed

The lowest estimated central pressure had been 996 hPa. The estimated maximum sustained surface wind speed (MSW) was 40 knots during 2100 UTC of 15th to 1800 UTC of 16th April. At the time of landfall, the ECP was 996 hPa and MSW was 40 knots (cyclonic storm). The ECP and Vmax graph also indicates that the system intensified gradually till 0000 UTC of 16th April and maintained its intensity till landfall at 1800 UTC of 16th April and then weakened rapidly into a well marked low pressure area at 0300 UTC of 17th April. There was no rapid intensification and rapid weakening of the system throughout its life cycle.

The total precipitable water imageries (TPW) during 15h to 17nd April are presented in Fig.3.

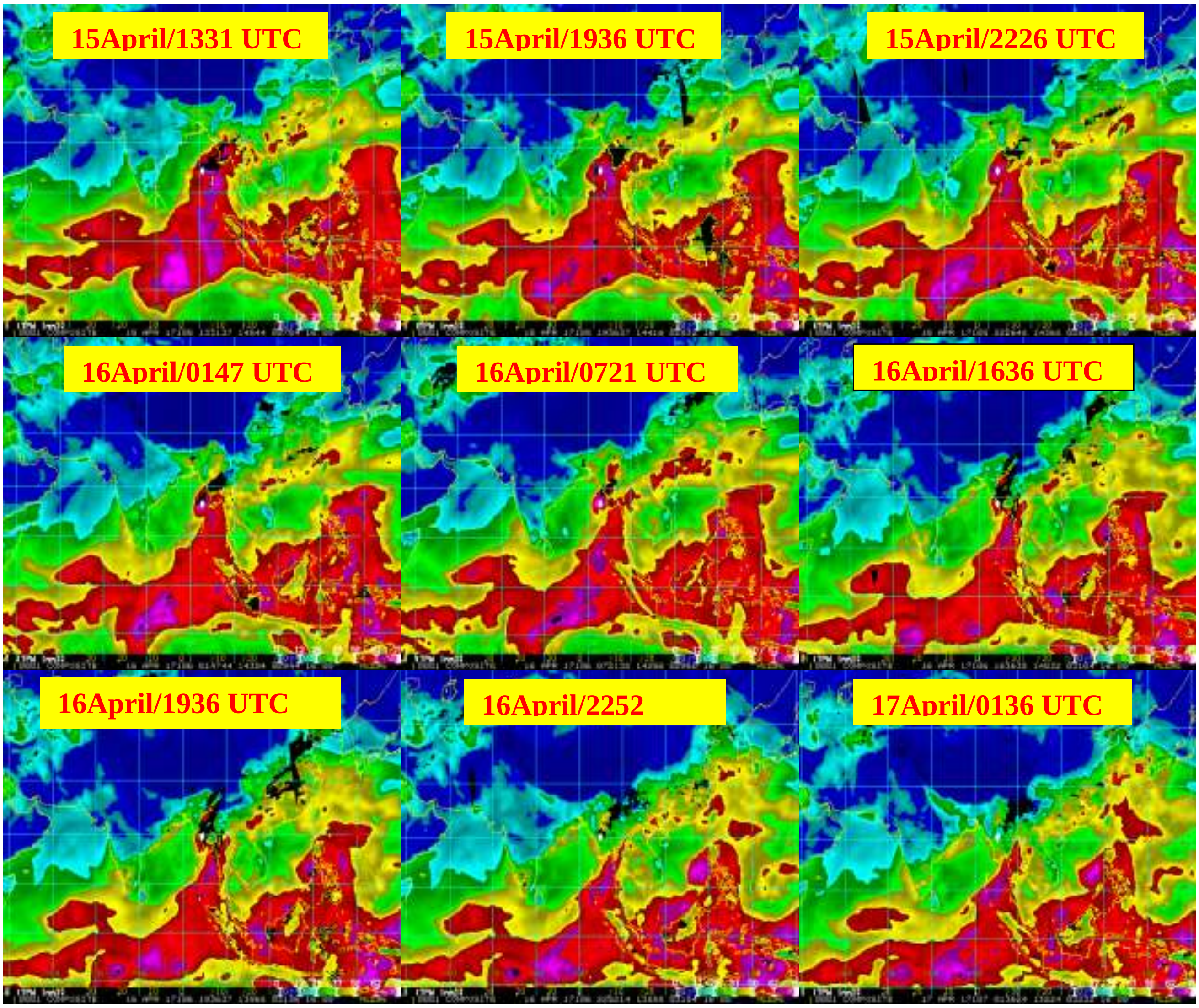


Fig.3 : Total precipitable water imageries during 15th to 17th April 2017

It indicates that due to cross equatorial flow, warm and moist air continued to converge around the system centre till 0600 UTC of 16th. It resulted in intensification of depression into cyclonic stotrm on 15th night. Futher, it maintained its intensity till landfall on 16th midnight. There was poleward outflow throughout the life period of the system in association with an anticyclonic circulation lying to the southeast of the system centre and an upper tropospheric trough lying over India roughly along 85^{0}E as seen from. It helped in increasing the upper level divergence and hence favouring the intensification. The SST was high 30-32^{0}C over central Bay of Bengal and adjoining areas. Also the Ocean thermal energy was high over this region. The vertical wind shear of horizontal wind was high (> 20 knots) during most part of the life period, which was not favourable for intensification. The high vertical wind shear was due to the upper tropospheric trough lying to the west of the system. The favourable upper level divergence coupled with lower level relative vorticity was being countered by the unfavourable vertical wind shear. As a result, the system maintained its intensity as a cyclonic storm only. The large scale feature like Madden Julian Oscillation was not favourable for intensification, as MJO index lay over phase-7 with amplitude greater than 1. The system moved very fast with a 12 hrly average speed of 25 kmph, which was not favourable for intensification, as it limited its life period and stay over the sea.

3.3. Movement

CS Maarutha moved nearly northeastwards throughout its life period, under the influence of anticyclonic circulation located to the southeast of the system centre. There was a trough in middle and upper tropospheric levels lying to the west of system centre roughly along 85^{0}E which further helped in northeastwards movement of the system and higher translational speed. At the genesis stage the translational speed was maximum and was about 27 kmph. It then gradually decreased to minimum of about 16 kmph prior to landfall. After the landfall it increased sharply to about 30 kmph over Myanmar. The six hourly average translational speed of CS Maarutha is presented in Fig.4.

The wind speed in middle and deep layer around the system centre is presented in Fig.5. It indicates that the mean wind speed in deep and middle layer decreased slightly from 2000 UTC of 15^{th} to 0000 UTC of 16^{th} and then increased gradually from 0000 UTC of 16^{th} to 2000 UTC of 16^{th}. The mean wind direction in deep and middle layer also indicates northeast/ north-northeastward movement. The southerly shear prevailed over the centre and to the left of the cyclone.

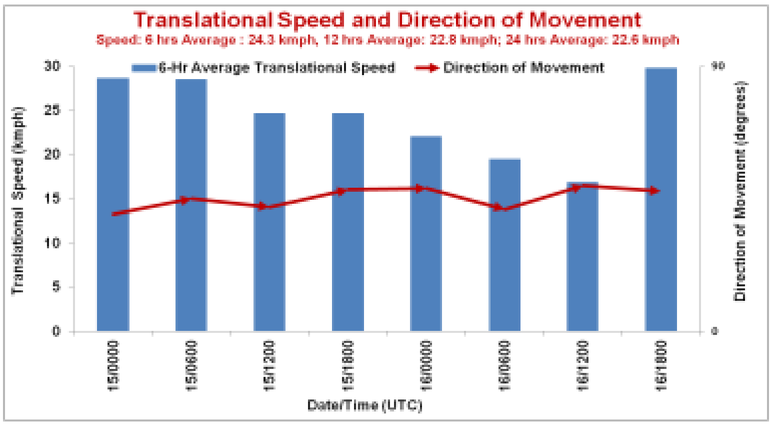


Fig.4 Six hourly average translational speed (kmph) and direction of movement in association with CS Maarutha

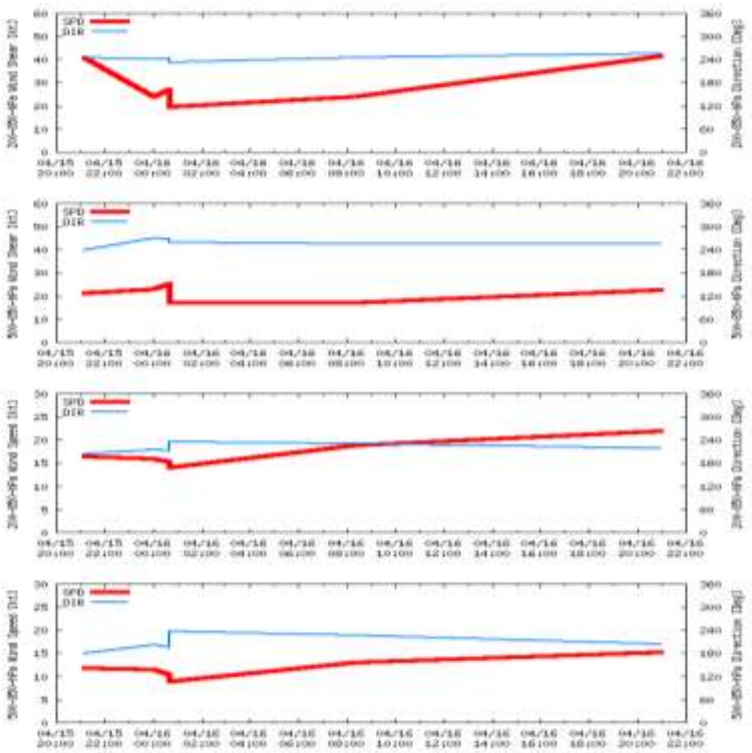


Fig.5 Wind shear and wind speed in the middle and deep layer around the system during 15th to 16th April 2017.

3.4. Structure:

SCATSAT surface winds from SAC, ISRO (Fig.6a) indicated that the winds were observed around system centre with maxima in northeast and southeast sector. It also agrees with best track estimates of CS Maarutha. The multisat imageries from CIRA (Fig.6b) also indicated similar distribution of winds. The average size of 34 kts winds was 59 nm.

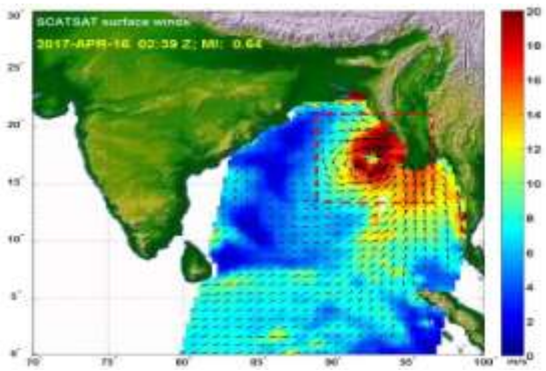


Fig.6a: Typical SCAT SAT surface wind imagery based on 0239 UTC of

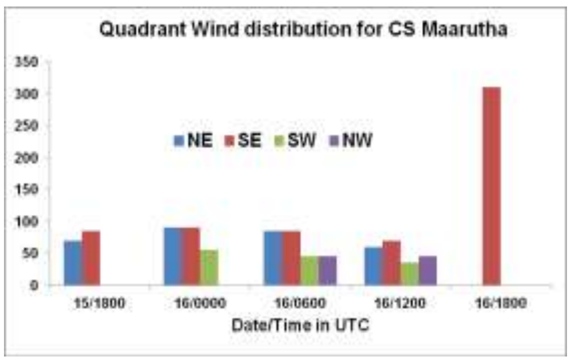


Fig.6b:Quadrant wind distribution during life cycle of CS Maarutha from CIRA

3.4. Landfall Point and Time:

The plot of hourly synoptic observations during 0600-1800 UTC of 16th April is presented in Fig. 7.

Observation Time ➡ / Stations ⬇	0600	0700	0800	0900	1000	1100
48062 (Sittwe)	064 -3.7	061 -2.1	058 -1.9	047 -1.9	037 -3.0	029 -3.0
48071 (Kyaykpyu)	078 -2.1	061 3.3	053 -4.0	041 -3.2	023 -5.3	023 -4.8
48080 (Sandoway)	039 -5.7	030 -6.3	013 -6.3	003 -3.2	992 -9.5	984 -8.9
48085 (Gwa)	036 -6.2	030 -7.2	018 -5.8	011 -7.2	992 -7.7	005 -6.4
48094 (Pathein)	039 -5.6	029 -6.2	026 -5.0	023 -4.2	020 -3.7	024 -3.1

Observation Time ➡ / Stations ⬇	1200	1300	1400	1500	1600	1700	1800
48062 (Sittwe)	025 -3.2	024 -3.8	030 -3.4	044 -3.5	050 -3.6	054 -3.5	054 -3.1
48071 (Kyaykpyu)	018 -5.8	023 -5.5	033 -4.0	041 -5.2	045 -5.3	060 -4.0	060 -3.0
48080 (Sandoway)	984 -8.7	991 -7.9	997 -7.7	010 -9.0	016 -8.4	020 -7.3	021 -5.3
48085 (Gwa)	016 -4.9	027 -4.3	032 -4.8	043 -4.5	053 -3.3	056 -2.5	058 -1.9

Fig.7: The plot of hourly synoptic observations during 0600-1800 UTC of 16th April

4. Climatological aspects

Considering the area of genesis (+/- 2^0 around the genesis point), the cliamtological tracks of the TCs during 1961-2015 are presented in Fig.7.

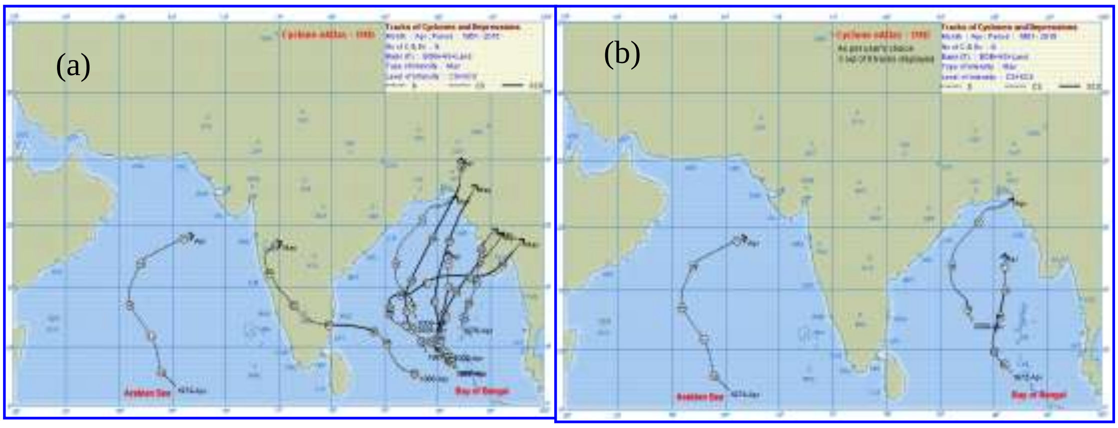


Fig 8: Climatological tracks of TCs forming over north Indian Ocean region during 1961-2015 in the (a) month of April and (b) during 1-15 April.

Occurrence of cyclone in the month of April is very rare. Climatologically, in the satellite era (1961 onwards), there had been three cyclones developing over north Indian Ocean (NIO) during 1-15th April, including 1 over Arabian Sea (AS) and 2 over BOB. Both the cyclones over BOB had recurving tracks. The cyclone in 2009 crossed Bangladesh coast as DD near Chittagong and the other (in 1972) weakened over eastcentral BOB. The cyclone over AS also had recurving track and weakened over sea. The CS Maarutha was the first ever landfalling cyclone over Myanmar developing during the period 1-15 April during satellite era.

5. Features observed through satellite and Radar

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.

5.1 INSAT-3D features

Typical INSAT-3D enhanced coloured imageries, cloud top brightness temperature, visible and IR imageries are presented in Fig.9.

According to available satellite imageries, the system attained intensity of T 1.5 at 0000 UTC of 15th April. The convection showed curved band pattern with well defined wrapping from eastern sector. Associated broken low and medium clouds with embedded intense to very intense convection lay over south and adjoining eastcentral BOB between latitude 6.5^0 N to 16.0^{0}N and longitude 83.0^0 E to 93.0^0 E. The lowest cloud top temperature was minus 70^{0}Celcius. At 0900 UTC of 15th the system intensified into a DD and attained intensity of T 2.0. The convection showed curved band pattern with well defined wrapping from eastern sector. Associated broken low and medium clouds with embedded intense to very intense convection lay over south and adjoining eastcentral BOB between latitude 10.5^0 N to 17.0^0 N and longitude 87.5^0 E to 95.5^0 E. The lowest cloud top temperature was minus 85^0 celcius. At 1800 UTC of 15th, the system attained the intensity of T 2.5. The convection showed curved band pattern. Associated broken low and medium clouds with embedded intense to very intense convection lay over south and adjoining eastcentral BOB between latitude 13.5^0 N to 18.5^0 N and longitude 88.8^0 E to 93.0^0 E. The lowest cloud top temperature was minus 90^0 celcius. Majority of the convective cloud mass lay to the east of the system centre. The curved band was wrapping towards the centre from the southeast.

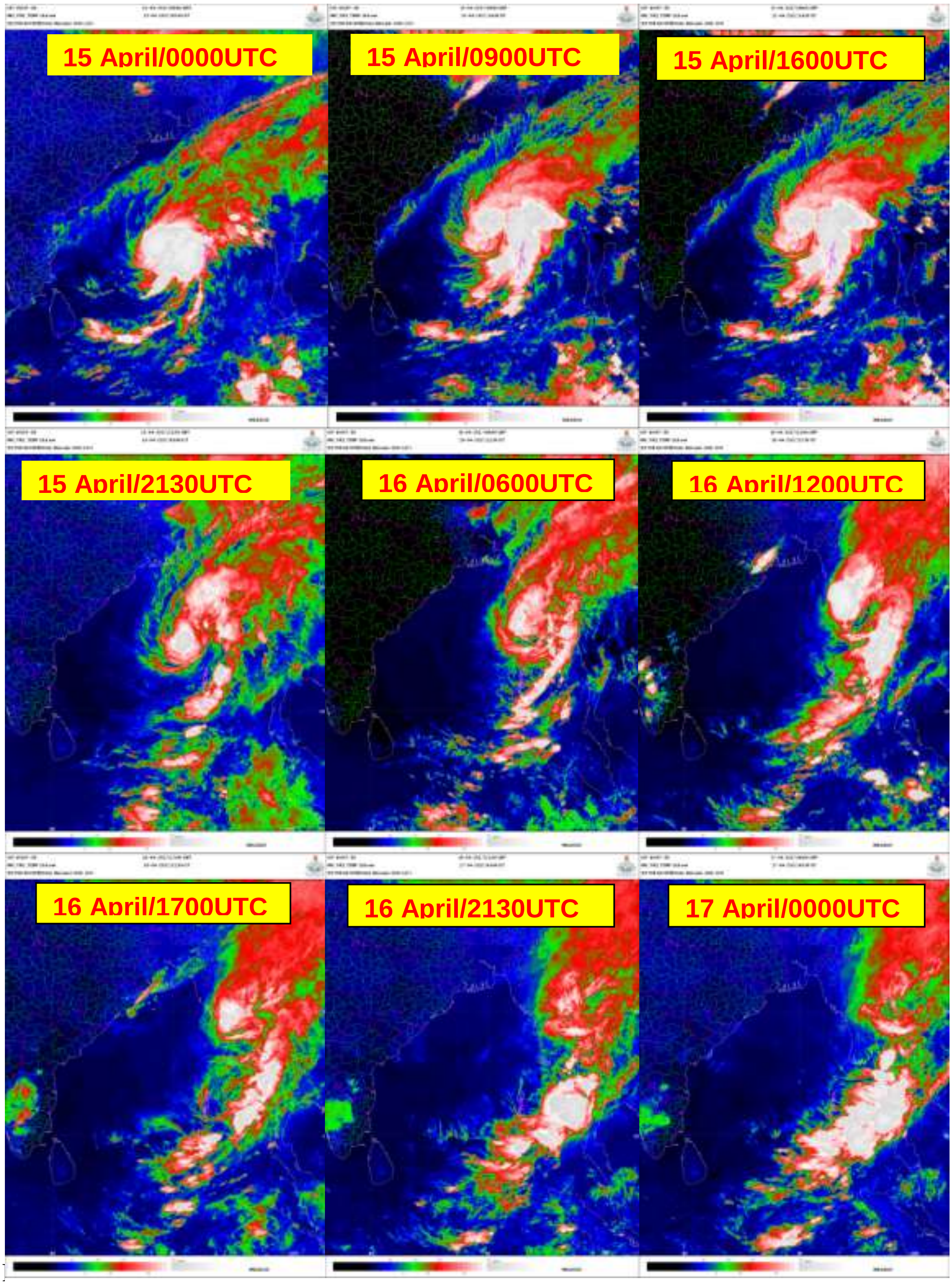


Fig.9(a) INSAT-3D enhanced colored imageries during 15-17 April 2017

At 0000 UTC of 16th, the intensity was T 2.5. The convection showed curved band pattern, however it also showed signs of weakening with tendency of disorganisation. Associated broken low and medium clouds with embedded intense to very intense convection lay over south and adjoining eastcentral BOB between latitude 13.5^{0} N to 17.5^{0} N and longitude 89.0^{0} E to 93.5^{0} E. The lowest cloud top temperature was minus 85^{0} celcius. At 1200 UTC of 16th, intensity of the system was T 2.5. The convection showed curved band pattern. Associated broken low and medium clouds with embedded intense to very intense convection lay over eastcentral BOB between latitude 14.0^{0} N to 20.0^{0} N and east of longitude 91.0^{0} & Arakan coast, Gulf of Martaban adjoining south Myanmar. The lowest cloud top temperature was minus 90^{0} celcius. At 1800 UTC of 16th, the intensity was T2.5. Associated broken low and medium clouds with embedded intense to very intense convection lay over Arakan coast and south Myanmar. The system showed interactions with land surface, major parts of the convection were lying over the land and showed sign of disorganisation.

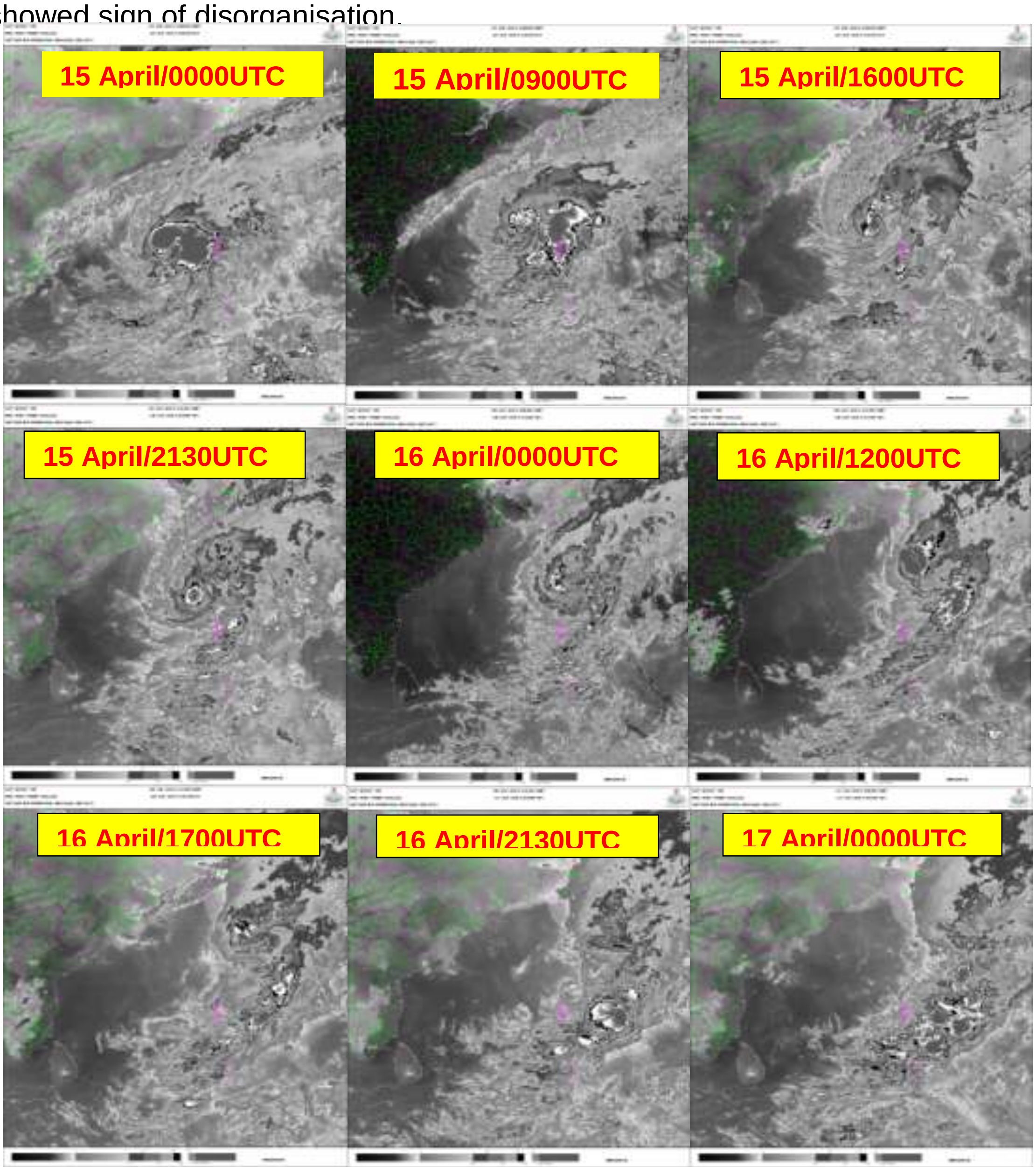


Fig.9(b) INSAT-3D enhanced colored imageries during 15-17 April 2017

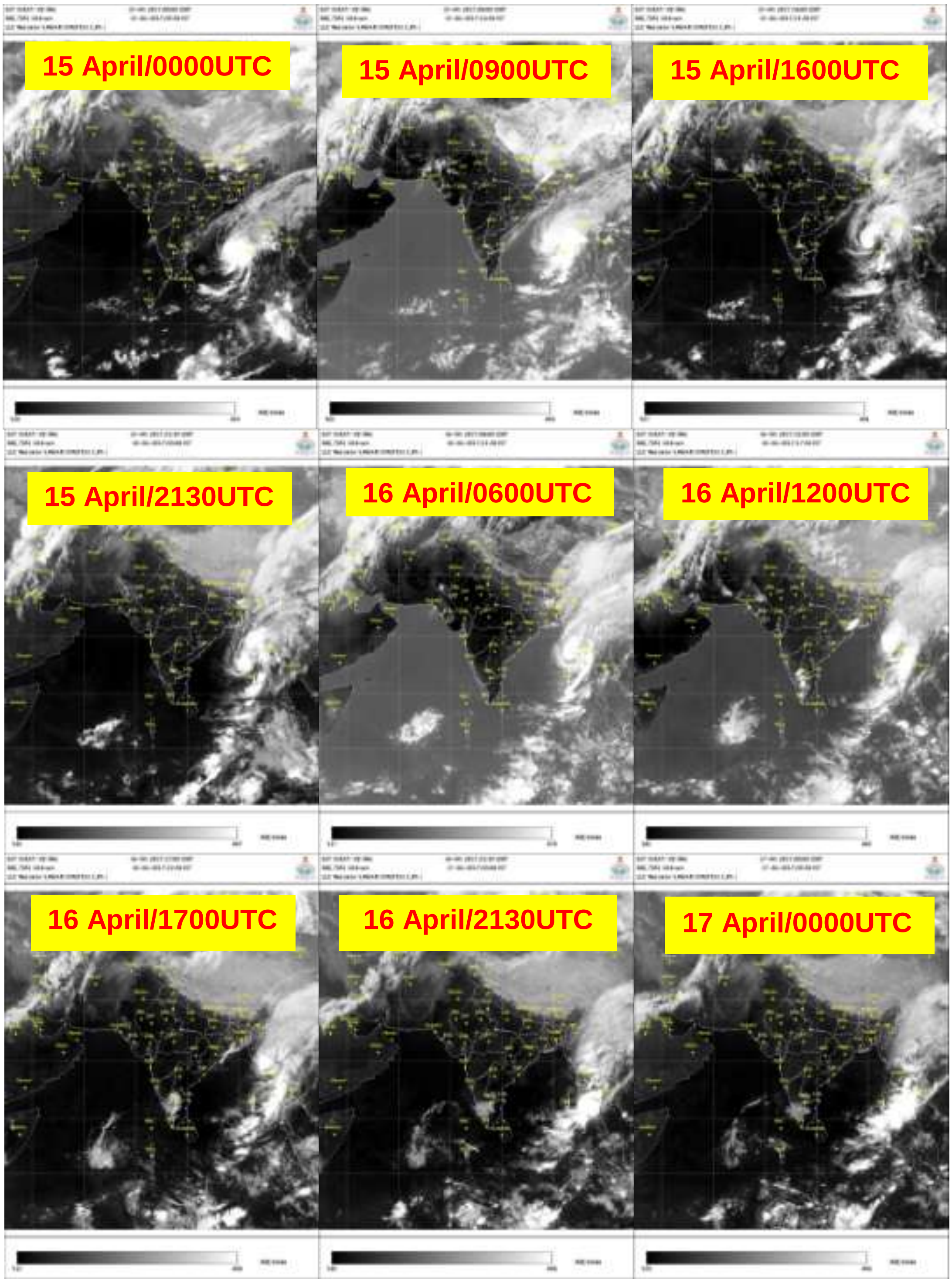


Fig. 9(c): INSAT-3D IR imageries during 15-17 April 2017

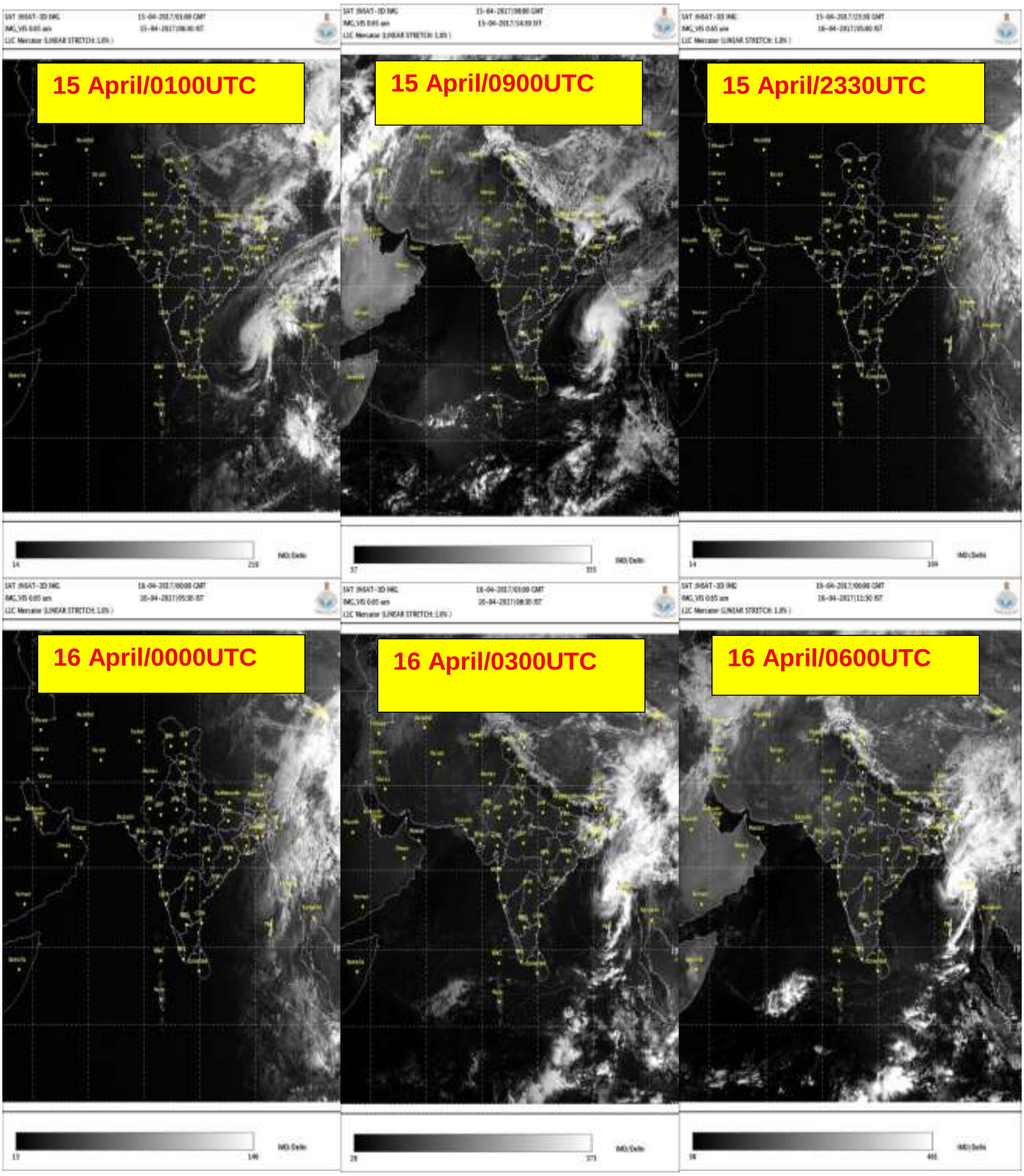


Fig. 9(d): INSAT-3D Visible imageries during 15-17 April 2017

5.2 Microwave features

F-15, F-16, F-17 microwave imageries of the CS Maarutha covering its life period from 15th to 17th April 2017 are presented in Fig.10. These imageries helped in understanding the internal structure of the system and better estimation of location of the system. It could indicate the region of intense convection and hence the rainfall. On 15th, the major region of intense convection lay over northeast sector of system with feeding from southeast. However, there was also intense convection in the western sector close to the system centre. On 16th, however the convection area lay entirely in the northeast.

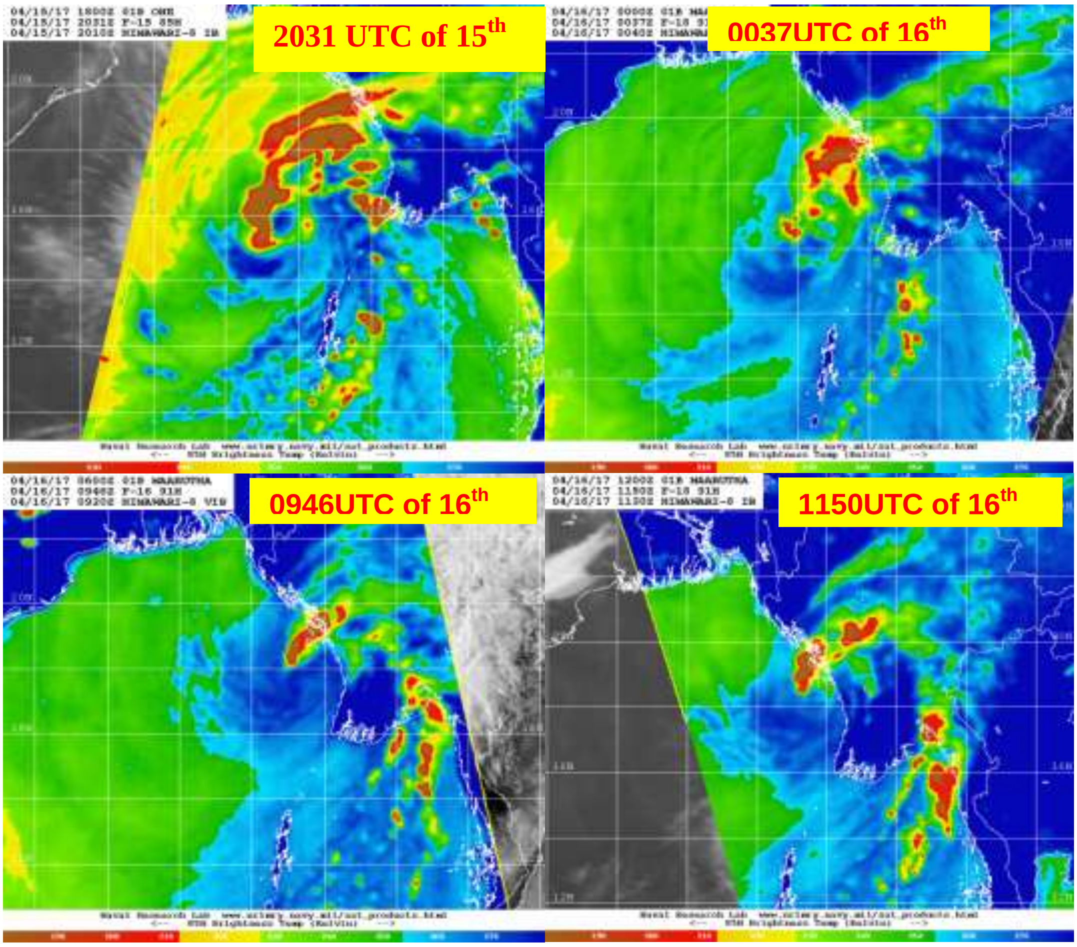


Fig.10: Typical microwave imageries during 15-17 April 2017

6. Dynamical features

IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels are presented in Fig.11. GFS (T574) could simulate the genesis of the system and the associated circulation features during the life period of Maarutha. However, the deep trough in westerlies over India was seen as a feeble trough.

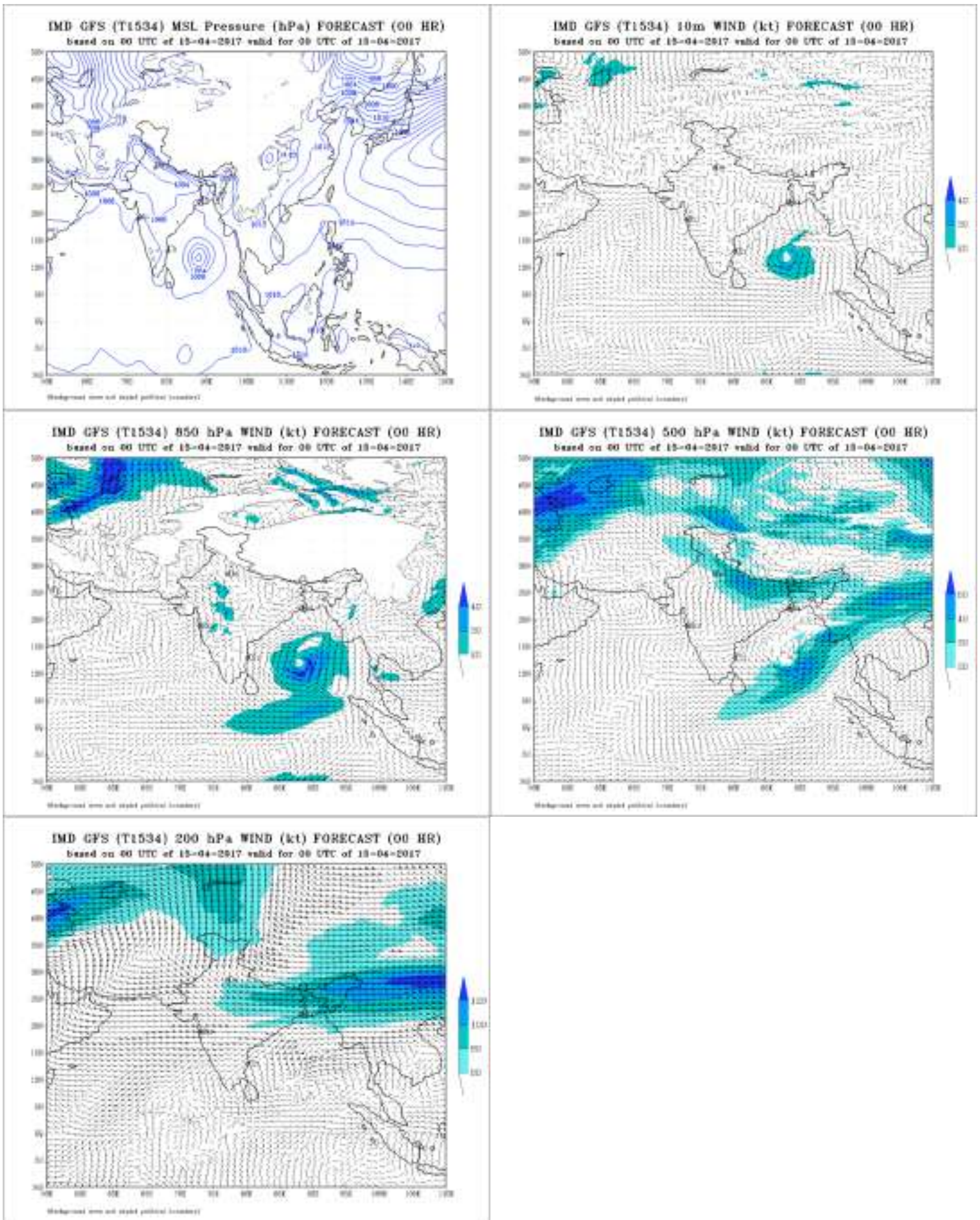


Fig. 11 (a): IMD GFS analysis of MSLP, 10 m wind, winds at 850, 500 and 250 hPa based on 0000 UTC of 15th April 2017.

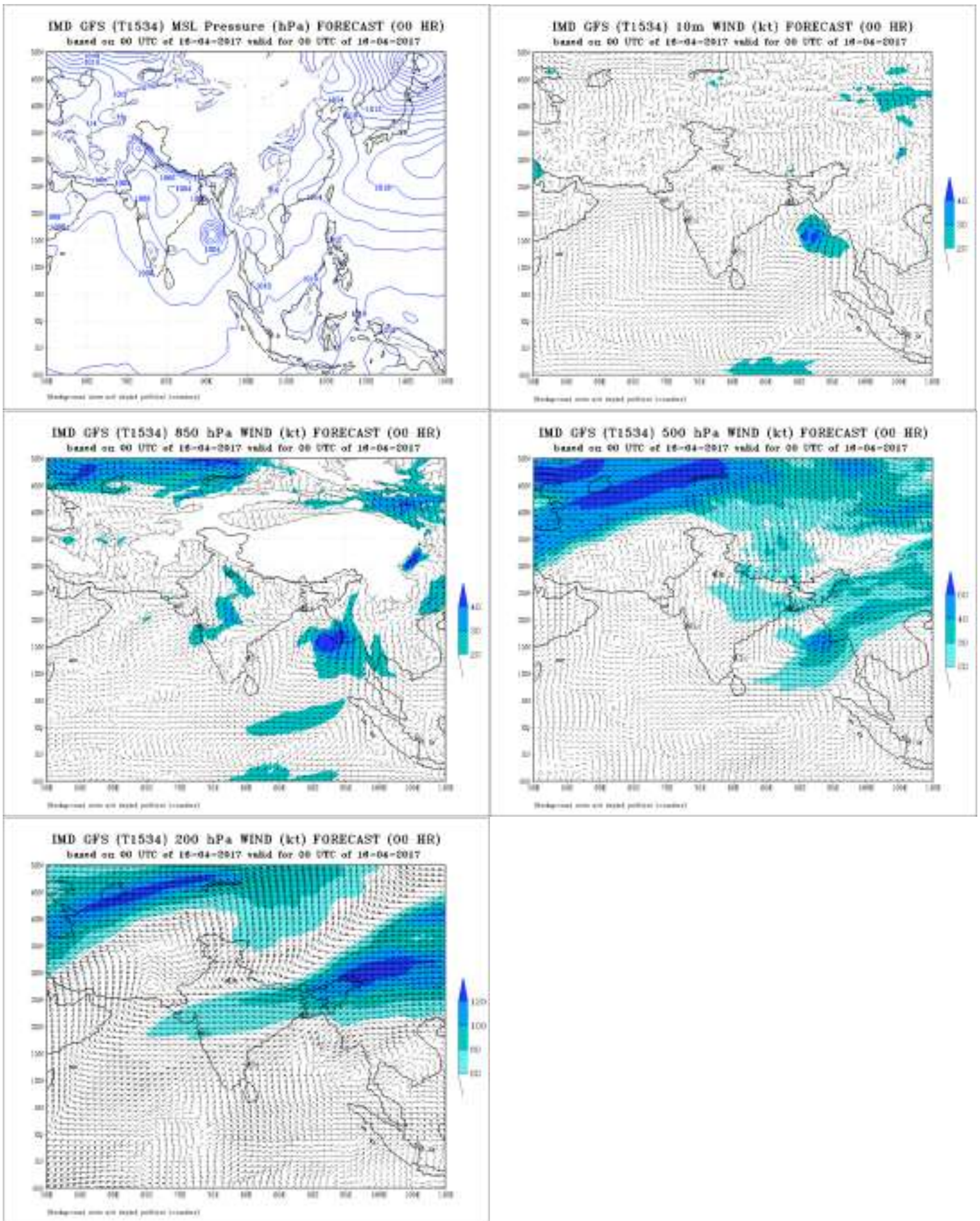


Fig. 11 (b): IMD GFS analysis of MSLP, 10 m wind, winds at 850, 500 and 250 hPa based on 0000 UTC of 15th April 2017.

7. Realized Weather:

IMD-NCMRWF GPM merged gauge rainfall data is presented in Fig 12. It indicates that the system caused heavy to very heavy rainfall in southeast and adjoining eastcentral BOB on 15th and heavy to very heavy rainfall over eastcentral BOB on16th. The rainfall was higher in eastern sector, especially northeast sector. The rainfall decreased significantly at the time of landfall and thereafter.

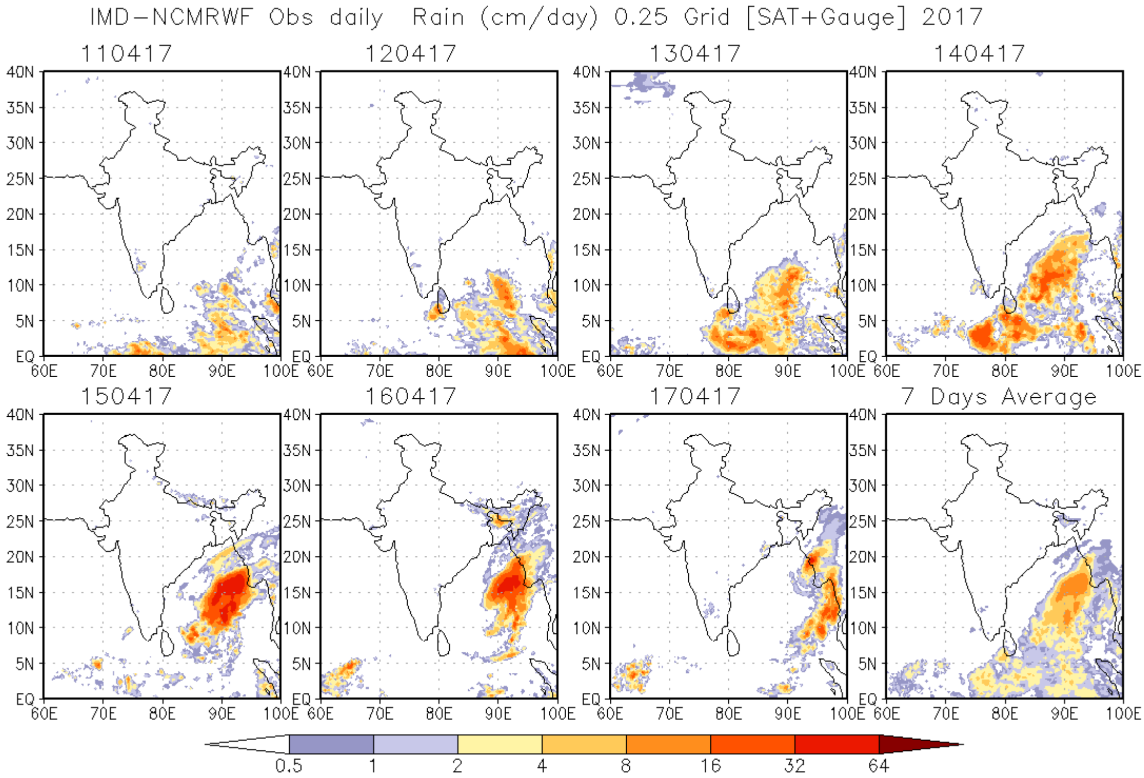


Fig.12: Realised rainfall during 15-17 April, 2017

7. Bulletins issued by IMD

7.1. 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 upto 48 hrs or till the system weakened into a low pressure area. The above forecasts were issued from the stage of deep depression onwards along with the cone of uncertainty in the track forecast. (Fig.13)
- **Cyclone structure forecast for shipping and coastal hazard management** The radius of maximum wind and radii of MSW ≥28 knots, ≥34 knots, ≥50 knots and ≥64 knots wind in four quadrants of cyclone was issued every six hourly giving forecast for +06, +12, +18, +24, +36 and +48 hrs lead period.
- **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 deep 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.
- **Tropical cyclone forecasts and adverse weather warning bulletins:** The tropical cyclone forecasts alongwith expected adverse weather like heavy rain, gale wind and storm surge were issued with every three hourly update

during cyclone period to the central, state and district level disaster management agencies including MHA NDRF, NDM for Andaman & Nicobar Islands. The bulletin also contained the suggested action for disaster managers and general public. 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 bulletins were issued by the cyclone warning division at New Delhi and cyclone warning centres of IMD at Chennai, Kolkata, Visakhapatnam and Bhubaneswar to ports, fishermen, coastal and high sea shipping community
- **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.

Statistics of bulletins issued by Cyclone Warning services of IMD in association with the cyclone Maarutha are given in Table 2a.

Table-2a: Bulletins issued by Cyclone Warning Division, New Delhi

S.N	Bulletin	No. of Bulletin	Issued to
1	National Bulletin	15	1. IMD's website 2. FAX and e-mail to Control Room NDM, Cabinet Secretariat, Minister of Sc. & Tech, Secretary MoES, DST, HQ Integrated Defence Staff, DG Doordarshan, All India Radio, DG-NDRF, Director Indian Railways, Indian Navy, IAF, Chief Secretary- Andaman & Nicobar Islands.
2	RSMC Bulletin for WMO/ ESCAP Panel countries	16	1. IMD's website 2. All WMO/ESCAP member countries through GTS and E-mail. 3. Indian Navy, IAF by E-mail
3	Tropical	7	1. Met Watch offices in Asia Pacific regions

	Cyclone Advisory Centre Bulletin (Text & Graphics)		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
4	Tropical Cyclone Vital Statistics (Coded and Textual)	7	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.
5	Cyclone Warnings through SMS	40	SMS through (i) IMD network for disaster managers at national level and and Andaman & Nicobar Islands daily
6	Cyclone Warnings by Social Media	6	Cyclone Warnings were uploaded on Social networking sites like Face book and Tweeter since inception to weakening of system (when there was change in intensity).

Bulletins issued by Cyclone Warning services of IMD in association with the system are given in Table 2 (a-b)

Table-2b: Bulletins issued by ACWC Chennai/ACWC Kolkata/CWC Bhubaneswar/ CWC VZK

S.No	Type of Bulletin	No. of Bulletins issued by		
		ACWC Chennai	ACWC Kolkata	CWC Vishakhapatnam
1.	Sea Area Bulletins	6	10	NIL
2.	Coastal Weather Bulletins	6	13	*6*
3.	Fishermen Warnings issued	NIL	17	NIL
4.	Port Warnings	4	12	6
5.	Heavy Rainfall Warning	NIL	02	NIL
6.	Gale Wind Warning	NIL	NIL.	NIL
7.	Information & Warning issued to State Government and other Agencies	NIL	05	NIL
8.	SMS	NIL	NIL	60

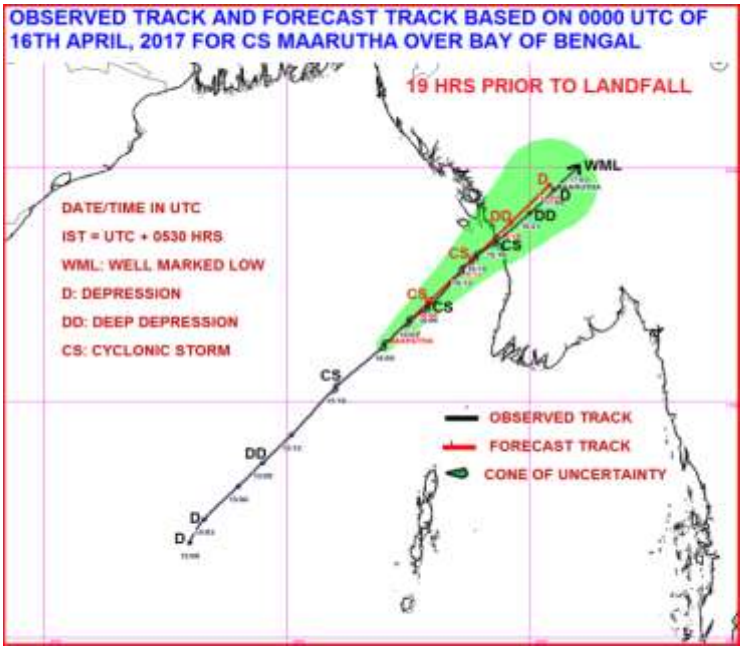


Fig.13: Observed track and forecast based on 0000 UTC of 16th April, 2017 alongwith cone of uncertainty.

9. Damage due to CS Maarutha over Myanmar

Three people were killed in Irrawaddy Division. A total of 81 houses were damaged by the storm. Some damage photographs from Myanmar are presented in Fig. 14.

Fig.14: Damage photographs from Myanmar

10. Performance of operational NWP models

IMD operationally runs a regional models, WRF for short-range prediction and one Global model T574L64 for medium range prediction (7 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^{o} S to 45^{o} N long 40^{o} E to 120^{o} E. Initial and boundary conditions are obtained from the IMD Global Forecast System (IMD-GFS) at the resolution of 23 km. The boundary conditions are updated at every six hours interval.

Global models are also run at NCMRWF. These include unified model adapted from UK Meteorological Office. Apart from the observations that are used in the earlier system, the new observations assimilated at NCMRWF include (i) Precipitation rates from SSM/I and TRMM (ii) GPSRO occultation (iii) AIRS and AMSRE radiances (iv) MODIS winds. Additionally ASCAT ocean surface winds and INSAT-3D AMVs are also assimilated. 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. It has semi-implicit time integration with 3D semi-Lagrangian advection, terrain following height coordinates and high order advection. It features mass-flux for shallow convection with convective momentum transport, non-local mixing and entrainment for boundary layer. NCMRWF Ensemble Prediction System (NEPS) is a global medium range probabilistic forecasting system adapted from UK MET Office. The configuration consists of 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 (Bishop et al., 2001). An important component common to both the deterministic and ensemble model is that they do not use any TC relocation in the analysis.

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), JMA (Japan Meteorological Agency). Hurricane WRF (HWRF) model and Ensemble prediction system (EPS) has been implemented at the NWP Division of the IMD HQ for operational forecasting of cyclones.

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. In this report performance of the individual models, MME forecasts, SCIP, GPP, RII and Decay model for cyclone Maarutha are presented and discussed in following sections:

10.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for Maarutha

Figure 15 shows the predicted zone of cyclogenesis. Grid point analysis and forecasts of GPP correctly predicted the cyclogenesis zone over south west Bay of Bengal 96 hrs before its formation. Fig. 16 presents the area average analysis and GPP forecasts.

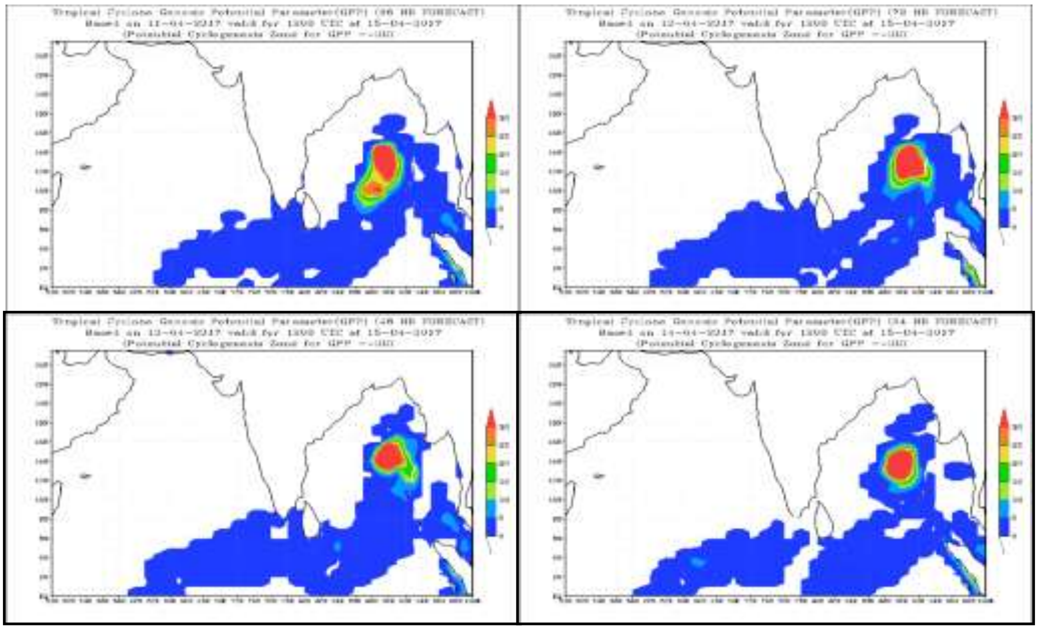


Fig.15: Predicted zone of cyclogenesis based on 1200 UTC of 11th - 14th April.

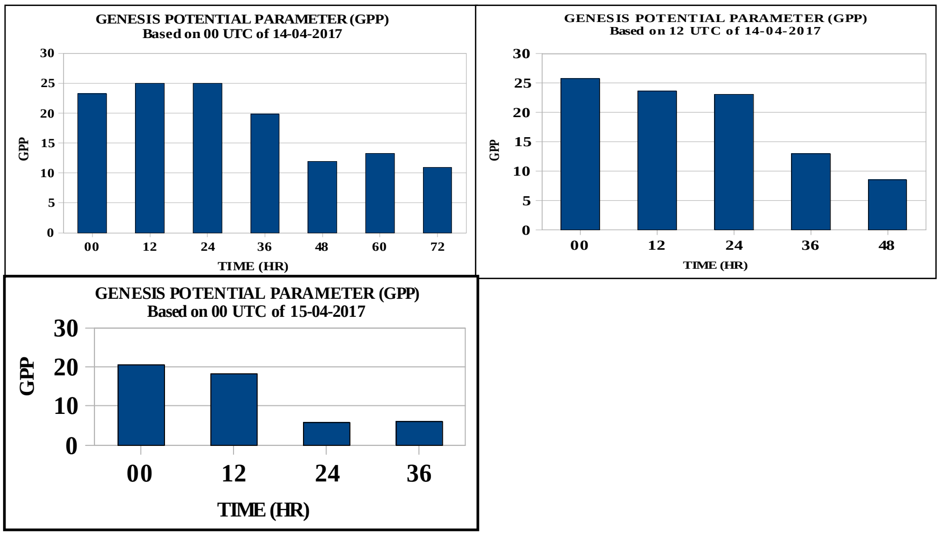


Fig. 16: Area average analysis and forecasts of GPP based on 0000 & 1200 UTC of 14th and 15th April.

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. From Fig.16, GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0).

10.2 Track prediction by NWP models

Based on initial conditions of 0000 UTC of 15th, most of the models except JMA, IMD GFS and NCUM suggested landfall over Myanmar between Thandwe and Kyaukpyu. Many models like JMA, IMD GFS and NCUM predicted no landfall. However, only NCEP GFS and HWRF predicted landfall time around 1800 UTC around 42 hours prior to landfall. Most of the models (ECMWF, UKMO, JMA, IMD GFS, WRF and MME) were predicting landfall between 0000 to 1200 UTC of 17th. The tracks forecast by different models based on 0000 UTC of 15th April are presented in Fig. 17(a).

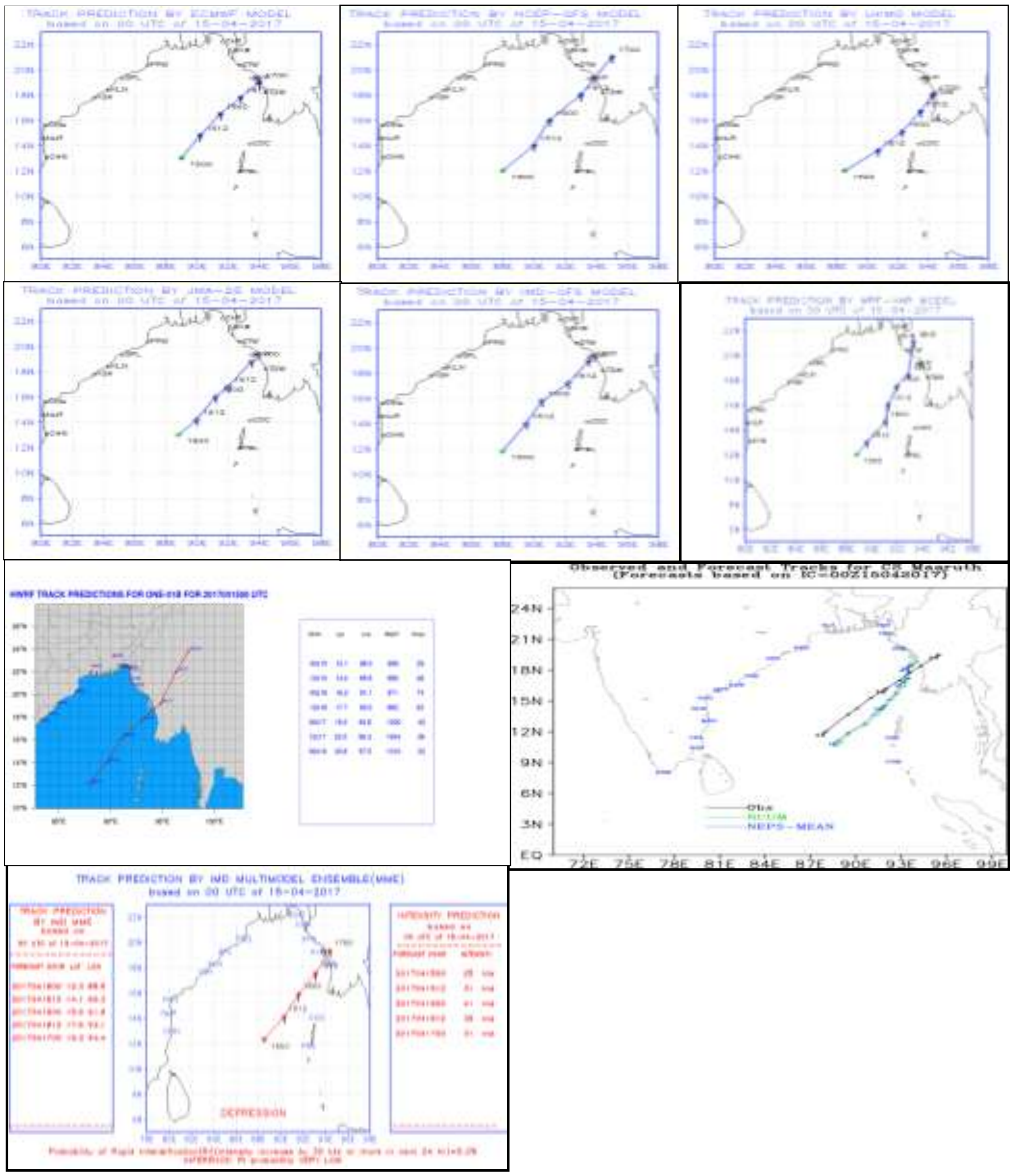


Fig.17 (a): Track prediction by NWP models based on 0000 UTC of 15th April, 2017

Based on initial conditions of 0000 UTC of 16th, ECMWF, NCEP GFS, UKMO, HWRF and MME predicted landfall close to Thandwe. Models like JMA and WRF predicted no landfall. However, only UKMO and HWRF predicted landfall time around 1800 UTC. Even 18 hours prior to landfall many models (ECMWF, NCEP and MME) predicted early rainfall. IMD GFS and JMA could not capture fast movement and predicted delayed landfall time. The track forecasts by different models based on 0000 UTC of 16th April are presented in Fig. 17(b).

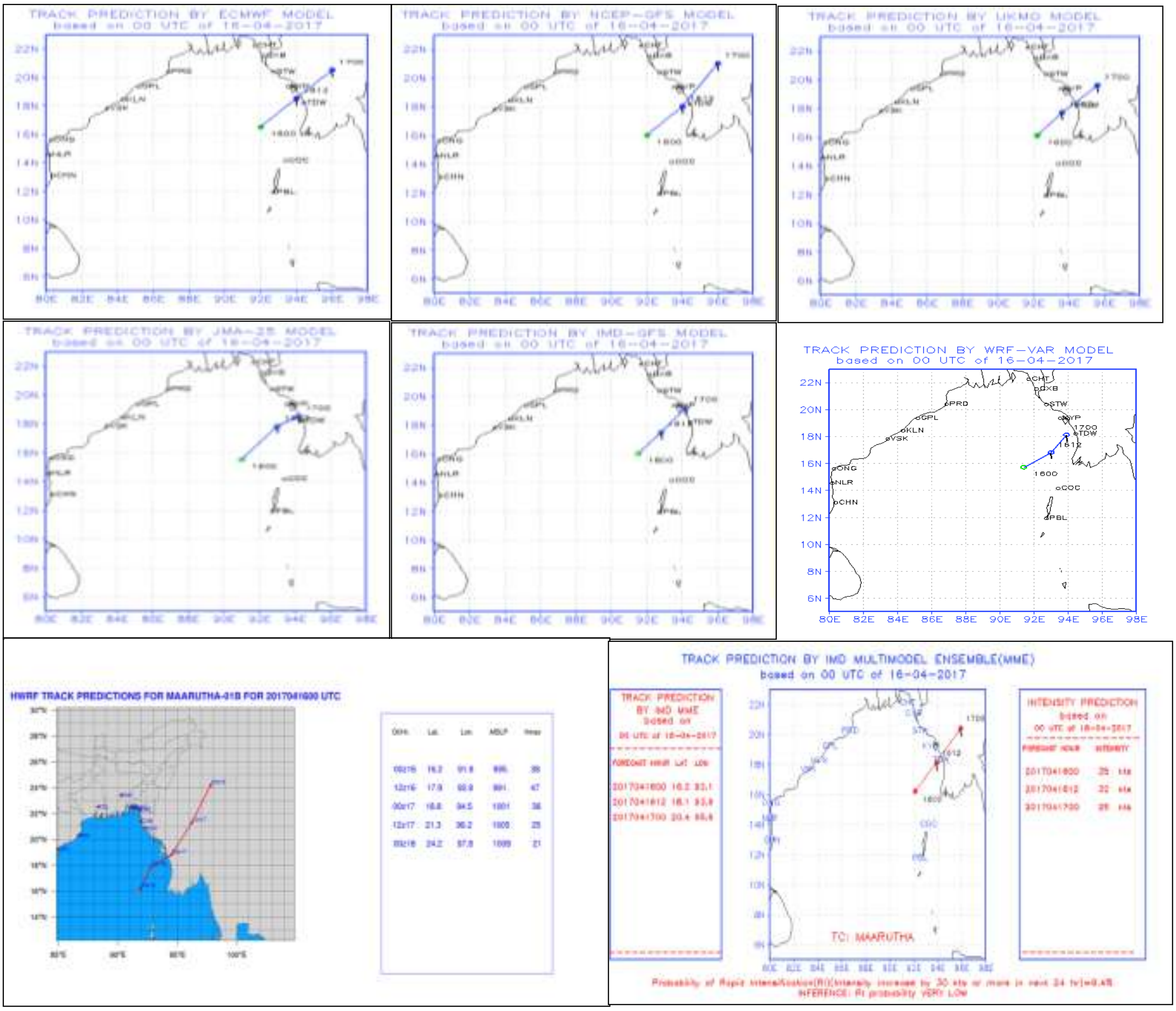


Fig.17 (b): Track prediction by NWP models based on 0000 UTC of 16th April, 2017

Hence to conclude, even 18 hours prior to landfall, most of models failed to capture landfall time correctly as Maarutha was a fast moving system. The landfall and track forecast errors as compared to operational forecast have been exceptionally higher for all lead periods as discussed in following sections.

10.3: Track and intensity forecast errors by various Models

The average track forecast errors (Direct Position Error) in km at different lead period (hr) of various models are presented in Table 3. The average cross track errors (CTE) and along track errors (ATE) are presented in Table 4 (a-b). From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of MME were significantly less for all lead periods. The track frecast errors for HWRF were the least for 36 and 48 hours lead period. Table 4(a) and (b) indicate show that DPE was largely contributed by ATE, that is errors in speed of movement of the storm, whereas CTE shows that forecast tracks were close to the observed track.

Table-3: Average track forecast errors (Direct Position Error (DPE)) in km

Models	Lead time →			
	12 hr	24 hr	36 hr	48 hr
IMD-GFS	100(3)	160(3)	186(2)	217(1)
IMD-WRF	112(3)	176(3)	310(2)	431(1)
JMA	65(3)	133(3)	168(2)	224(1)
NCEP	64(3)	117(3)	117(2)	175(1)
UKMO	78(3)	101(3)	151(2)	209(1)
ECMWF	55(3)	84(3)	119(2)	167(1)
IMD-HWRF	114(4)	115(3)	111(2)	81(1)
IMD-MME	46(3)	75(3)	110(2)	117(1)
NCUM	220	215	240	233
NCEP	190	228	230	271
Operational Error	**3**	**41**	**60**	

Table-4 (a). Average cross-track forecast errors (CTE) in km

Models	Lead time →			
	12 hr	24 hr	36 hr	48 hr
IMD-GFS	42	68	54	110
IMD-WRF	32	17	69	108
JMA	18	33	38	95
NCEP	30	69	66	155
UKMO	67	62	53	28
ECMWF	23	55	66	73

IMD-HWRF	58	42	51	28
IMD-MME	11	22	28	66
NCUM	140	120	160	122
NCEP	105	80	110	105

Table-4(b). Average along-track forecast errors (ATE) in km

Models	Lead time →			
	12 hr	24 hr	36 hr	48 hr
IMD-GFS	91	143	178	187
IMD-WRF	107	175	301	417
JMA	58	126	164	203
NCEP	56	90	89	81
UKMO	34	74	136	207
ECMWF	50	52	97	150
IMD-HWRF	92	103	98	75
IMD-MME	37	71	106	97
NCUM	165	170	215	198
NCEP	142	242	178	272

Landfall point and time forecast errors are presented in Table 5 and 6. For lead period of 18hrs, landfall point forecast error was the least by HWRF and ECMWF followed by JMA. For lead period of 42 hrs, the landfall point forecast error was the least by UKMO followed by IMD MME and HWRF.

Table-5: Landfall point forecast errors (km) of NWP Models at different lead time (hr)

Model	Forecast Lead Time (hour) →			
	06:30 hr	18:30 hr	30:30 hr	42:30 hr
	16April/12z	16April/00z	15April/12z	15April/00z
IMD-GFS	***	65	NLF	NLF
IMD-WRF	***	NLF	85	221
JMA	***	18	21	NLF
NCEP	***	25	69	109
UKMO	***	25	31	31
ECMWF	***	16	75	69
IMD-HWRF	40	16	65	40
IMD-MME	***	25	40	40

**** - No landfall

Table-5: Landfall time forecast errors (hour) at different lead time (hr)
('+' indicates delay landfall, '-' indicates early landfall; '***'-No landfall)

Forecast Lead Time (hour) →	06:30 hr	18:30 hr	30:30 hr	42:30 hr
Based on	16April/12z	16April/00z	15April/12z	15April/00z
IMD-GFS	***	+03:30	NLF	NLF
IMD-WRF	***	NLF	+11:30	+25:30
JMA	***	+05:30	-01:30	NLF
NCEP	***	-04:30	+05:30	-01:30
UKMO	***	-01:30	-01:30	+15:30
ECMWF	***	-05:30	+05:30	-01:30
IMD-HWRF	-00:30	+02:30	+05:30	+01:30
IMD-MME	***	-03:30	+05:30	+02:30

Intensity prediction:

The intensity forecasts of IMD-SCIP model and HWRF model are presented in Table 6. The errors were SCIP model were the least. The probability of rapid intensification (RI) index of IMD is shown in Table 7. It correctly predicted no RI for cyclone, Maarutha.

Table-6: Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of SCIP model

Lead time →	12 hr	24 hr	36 hr	48 hr
IMD-SCIP (AAE)	3.7(3)	6.5(2)	5.0(1)	-
IMD-SCIP (RMSE)	4.8	8.5	5.0	-
IMD-HWRF (AAE)	10.8(4)	19.0(3)	20.0(2)	23.0(1)
IMD-HWRF (RMSE)	12.6	22.1	20.1	23.0

The figure in paranthesis represents the No. of observations verified.

Table 7: Probability of Rapid intensification

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes(kt) occurred in 24h
00/15.04.2017	5.2 %	VERY LOW	15
12/15.04.2017	9.4 %	VERY LOW	10
00/16.04.2017	9.4 %	VERY LOW	-20

Intensity prediction by SCIP model is presented in Fig. 18. The SCIP model underpredicted the intensity of the system.

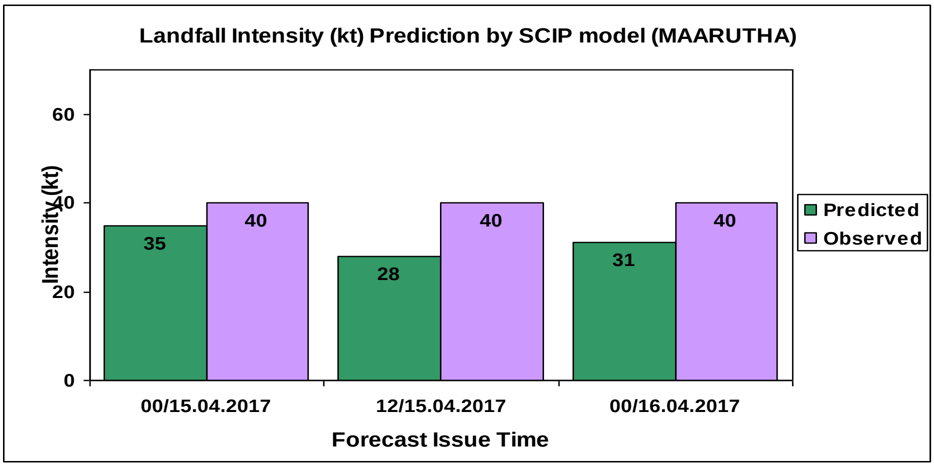


Fig.18: Intensity prediction by SCIP Model

10.4. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model is presented in fig.19. Rainfall associated with the system decreased near landfall. The system caused more rainfall during initial stages.

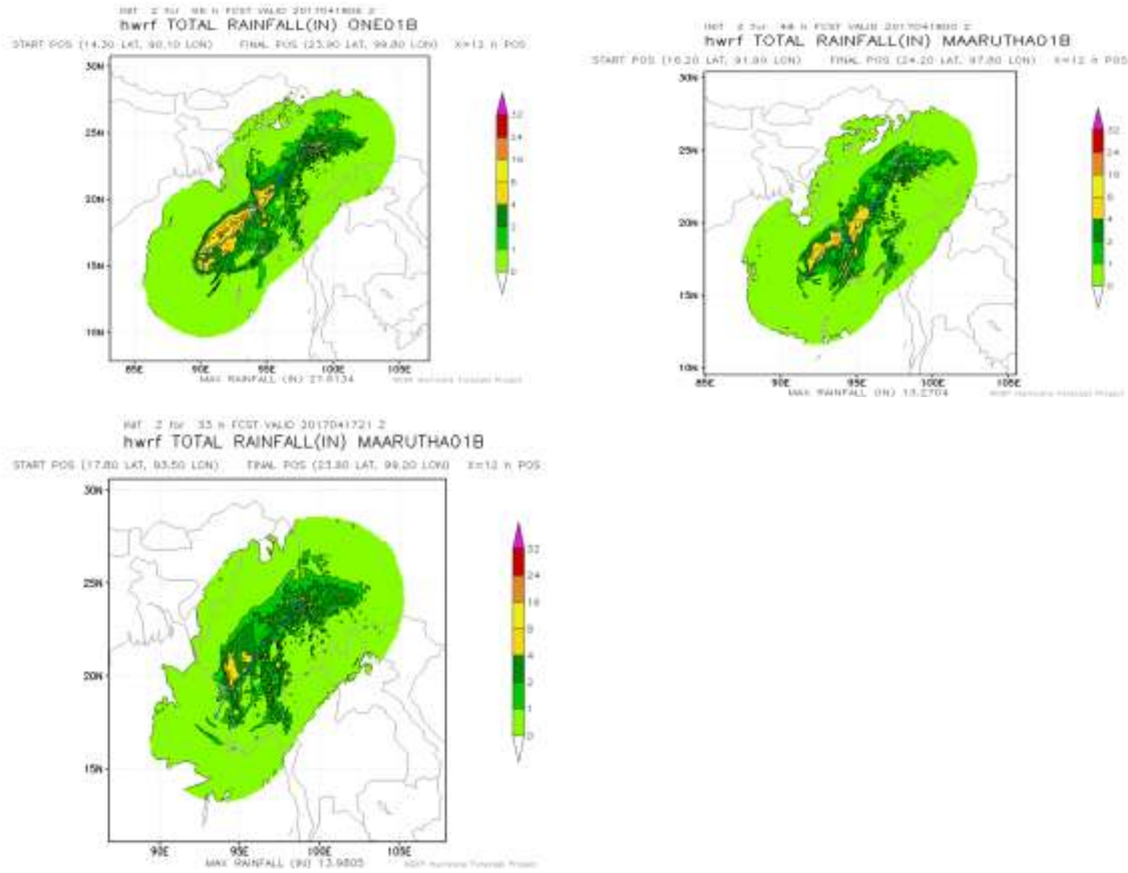


Fig.19: HWRF rain swath (inch) based on 15/1200, 16/0000 and 16/1200 UTC initial conditions.

11. Operational Forecast Performance

11.1. Genesis Forecast:

i. The first information regarding formation of a low pressure area over southeast & adjoining eastcentral Bay of Bengal around 14th April was issued in the morning of 12th April and low pressure area developed over southeast BOB and neighbourhood in the evening of 13th (about 36 hrs in advance of formation of low pressure area).

ii. The first information regarding formation of depression over southeast BOB on 15th April was issued by IMD on 13th morning and depression formed over southeast BOB in the morning of 15th (48 hours in advance of formation of depression).

10.2. Operational landfall forecast error and skill

i. In it's first bulletin based on 0000 UTC of 15th April, RSMC New Delhi indicated the nearly northeastward movement of system towards Myanmar coast (42 hours prior to landfall).

ii. The first bulletin indicating movement of cyclone north-northeastwards and landfall over Myanmar coast between Sittwe and Sandoway (Thandwe), Myanmar by forenoon of 17th April was given on 0300 UTC of 15th (39 hours prior to landfall).

iii. The first bulletin indicating landfall near Sandoway (Thandwe), Myanmar around midnight of 16th April was given on 0000 UTC of 17th and system crossed Myanmar coast near Sandoway (Thandwe) between 1800 and 1900 UTC of 17th (18 hours prior to landfall).

iv. There was almost zero error in landfall point forecast issued 12 hrs before landfall and about 41 km and 60 km respectively in the forecast issued 24 and 36 hrs before landfall.

The operational landfall forecast errors and skill are presented in Table 8. The landfall point error (LPE) has been about 3, 41 and 60 km against long period average (LPA) based on 2012-16 of 27, 36 and 57 km for 12, 24 and 36 hours lead period respectively. For 12 hour lead period, the landfall point error was almost zero. The landfall time error (LTE) has been 2.0, 0.5 and 6.5 hours against the LPA of 2.4, 4.2 and 4.3 hours for 12, 24 and 36 hours lead period respectively.

Table 8: Landfall Point and Time Error in association with CS Maarutha

Lead Period (hrs)	Base Time	Landfall Point ($^0N/^0E$)		Landfall Time (hours)		Operational Error		LPA error (2012-16)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	16/0600	18.47/94.30	18.44/94.31	16/1630	16/1830	3	2.0	27.2	2.4
24	15/1800	18.79/94.17	18.44/94.31	16/1900	16/1830	41	0.5	35.8	4.2
36	15/0600	18.92/94.06	18.44/94.31	17/0100	16/1830	60	6.5	56.9	4.3

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

The landfall point and time could not be predicted beyond 36 hours as the life of the system from DD to landfall was about 33 hours.

11.3 Operational track forecast error and skill

The operational average track forecast errors and skills (compared to climatological and persistence (CLIPER) forecasts) are shown in Table 9. The track forecast errors for 12, 24 and 36 hours lead period have been 32, 33.5 and 110.5 km against the long period average (LPA) of 59.7, 97.2 and 119.4 km respectively. The track forecast errors have been significantly lower than the LPA for all lead periods. The skill in operational track forecast compared to CLIPER forecast has also been higher than long period average for all lead periods. The track forecast skill was about 56%, 82% and 59% for 12, 24 and 48 hrs lead period respectively, which are higher than the long period average (LPA) during 2012-16 for 12 and 24 hrs lead period.

Table 9: Average Track forecast error in association with CS Maarutha

Lead Period (hrs)	N	Average track forecast error (km)	Skill (%)	LPA (2012-16)	
				Track forecast error (km)	Skill (%)
12	5	32.0	56.0	59.7	43.7
24	3	33.5	82.3	97.2	53.6
36	1	110.5	59.3	119.4	63.4

11.4 Operational Intensity forecast error and skill

The operational intensity forecast errors and skill compared to persistence forecast in terms of absolute error (AE) and root mean square error (RMSE) are presented in Table 10. The operational AE in intensity forecast has been significantly less than LPA as it was about 3.6, 2.3 and 15.1 knots against the LPA (2012-16) of 6.5, 10.7 and 13.8 knots respectively for 12, 24 and 36 hrs lead period. Similarly, operational RMSE in intensity forecast has been about 5.0, 2.4 and 15.1 knots against LPA of 9.0, 14.4 and 18.5 knots for 12, 24 and 36 hours lead period respectively.

Table 10: Average Intensity forecast error in association with CS Maarutha

Lead Period (hrs)	N	Average Intensity Error (kts)		Skill (%) in intensity forecast		LPA Intensity forecast Error (kts) (2012-16)	
		AE	RMSE	AE	RMSE	AE	RMSE
12	5	3.6	5.0	60.4	53.5	6.5	9.0
24	3	2.3	2.4	87.2	90.1	10.7	14.4
36	1	15.1	15.1	39.5	39.5	13.8	18.5

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

11.5. Adverse weather forecast verification

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Table 11-14. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table 11: Verification of Heavy Rainfall Forecast

Date & Time	Heavy rainfall warning issued	24-hour Heavy rainfall realised ending at 0300 UTC of date
15.04.2017 0300 UTC	Rainfall at most places with heavy rainfall at isolated places very likely to occur over Andaman Islands during next 24 hrs and isolated heavy rainfalls during subsequent 24 hours.	Andaman & Nicobar Islands: Maya Bandar-4, Port Blair-2
16.04.2017 0300 UTC	Light to moderate (upto 3 cm) rainfall at many places very likely to occur over Andaman Islands during next 12 hrs.	Andaman & Nicobar Islands:: Long Island-5, Hut Bay-4, Port Blair-4, Maya Bandar-4, IAF Carnicobar-2

Table 12 (a): Verification of Gale Wind Forecast

Date/ Time(IST)	Sqall/ Gale wind Forecast	Recorded wind speed (knots)
15.04.2017 0300 UTC	Squally winds speed reaching 50-60 kmph gusting to 70 kmph would prevail over Andaman Islands and adjoining Sea areas during next 48 hours.	40-50 kmph
16.04.2017 0300 UTC	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would prevail over Andaman Islands and adjoining Sea areas during next 12 hours.	

Table 12 (b): Gale Wind Frecast verfication at the time of landfall over Myanmar:

S.No.	Lead Period	Forecast Wind	Estimated Wind	Error(Estimated-Forecast)
1.	**12**	**35 kts**	**40 kts**	**+5 kts**
2.	**24**	**43 kts**	**40 kts**	**-3 kts**
3.	**36**	**38 kts**	**40 kts**	**+2 kts**

Sandoway reported maximum sustained wind (MSW) of 35 knots at the time of landfall.

Table 13: Verification of Storm Surge Forecast issued by IMD

Forecast Storm surge above astronomical tide and area to be affected	Actual Storm Surge
0300 UTC of 16 April The storm surge of about one meter height above the astronomical tide is very likely to inundate the low lying areas of Myanmar coast near landfall point at the time of landfall. **1200 UTC of 16 April** The storm surge of about one to two meter height above the astronomical tide is very likely to inundate the low lying areas of Myanmar coast near landfall point at the time of landfall.	Not reported

12. Summary and Conclusion:

The CS Maarutha formed from a well marked low pressure area over southeast BOB concentrated into a depression at 0000UTC of 15th April. The depression over eastcentral and adjoining southeast BOB moved northeastwards, intensified into a deep depression at 0900 UTC of the 15th and gradually intensified into a cyclonic storm, Maarutha at 1800 UTC of 15th over eastcentral Bay of Bengal. It further moved northeastwards and crossed Myanmar coast near Sandoway (Thandwe) during 1800UTC and 1900UTC of 16th and while continuing its northeastwards movement, weakened into a deep depression at 2100 UTC of 16th over Myanmar.

IMD utilised all its resources to monitor and predict the genesis, track and intensification of CS Maarutha. The forecast of its genesis (formation of Depression), its track, intensity, point & time of landfall, were predicted well with sufficient lead time. The track forecast errors for 12, 24 and 36 hours lead period have been 32, 33.5 and 110.5 km against the long period average (LPA) of 59.7, 97.2 and 119.4 km respectively. The landfall point error (LPE) has been about 3, 41 and 60 km against long period average (LPA) based on 2012-16 of 27, 36 and 57 km for 12, 24 and 36 hours lead period respectively. The operational AE in intensity forecast has been significantly less than LPA as it was about 3.6, 2.3 and 15.1 knots against the LPA (2012-16) of 6.5, 10.7 and 13.8 knots respectively for 12, 24 and 36 hrs lead period.

13. Acknowledgement:

India Meteorological Department (IMD) duly acknowledges the contribution from Department of Meteorology and Hydrology, Myanmar for their valuable support especially for the hourly observations on the day of landfall. We also thank contribution from all the stake holders who contributed to the successful monitoring, prediction and early warning service of CS Maarutha by IMD. We acknowledge the contribution of all sister organisations of Ministry of Earth Sciences including National Centre for Medium Range Weather Forecasting Centre (NCMRWF), IIT Bhubaneswar, INCOIS & NIOT Chennai and Space Application Centre, Indian Space Research Organisation (SAC-ISRO) for their valuable support. The support from various Divisions/Sections of IMD including Area Cyclone Warning Centre (ACWC) Chennai & Kolkata, M.O. Port Blair, Cyclone Warning Centre (CWC) Vishakhapatnam & Bhubaneswar, Agrimeteorology Division, Pune, Numerical Weather Prediction Division, Satellite Division and Information System and Services Division at IMD, New Delhi is also acknowledged.