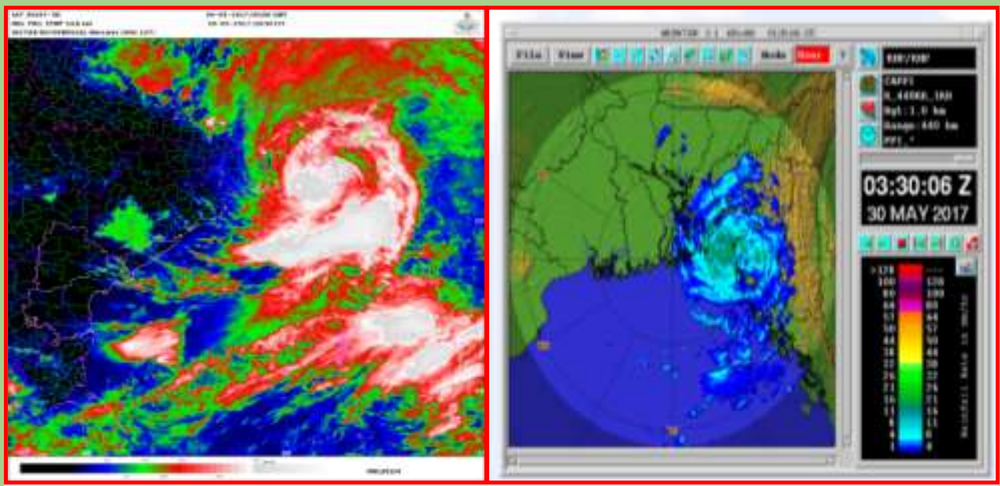
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Severe Cyclonic Storm, 'MORA' over the Bay of Bengal (28-31 May 2017): A Report



INSAT-3D enhanced colored IR imagery & DWR Khepupara imagery of 30th May, 2017

Cyclone Warning Division

India Meteorological Department

New Delhi

JUNE 2017

Severe Cyclonic Storm 'Mora' over the Bay of Bengal (28-31 May 2017)

1. Introduction

A low pressure area formed over southeast Bay of Bengal & adjoining areas of central Bay of Bengal in the morning (0300 UTC) of 25th May, 2017. It persisted over the same region on 26th and seen as a well marked low pressure area in the morning (0300 UTC) of 27th over eastcentral and adjoining westcentral & southeast Bay of Bengal. It moved northeastwards and intensified into a depression (D) over eastcentral Bay of Bengal (BoB) in the early morning (0000 UTC) of 28th May. Continuing its northeastwards movement, it further intensified into a deep depression (DD) in the afternoon (0900 UTC) and into a cyclonic storm (CS) "**MORA**" over eastcentral BoB in the late evening (1800 UTC) of 28th. Thereafter, it moved north-northeastwards and further intensified into a severe cyclonic storm (SCS) in the evening (1200 UTC) of 29th. The system reached its peak intensity in the early hours of 30th (2100 UTC of 29th). It continued to move nearly north-northeastwards and crossed Bangladesh coast close to south of Chittagong in the forenoon (between 0400 and 0500 UTC) of 30th. After landfall, the system weakened into a CS in the afternoon (0900 UTC) of 30th, into a DD in the evening (1200 UTC) and D in the same night (1800 UTC). It further weakened into a well marked low pressure area over Nagaland & neighbourhood in the early morning (0000 UTC) of 31st, into a low pressure area in the forenoon (0300 UTC) and became less marked in the same afternoon (0900 UTC).

The observed track of the SCS Mora is shown in **Fig.1**. The salient features of the system are as follows.

(i) It was the first severe cyclonic storm of the year 2017.

(ii) The severe cyclonic storm, **MORA** developed in the onset phase of southwest monsoon. Its intensification and movement towards north-northeastwards helped in advance of monsoon over the BOB and some parts of northeastern states.

(iii) Like previous cyclone **MAARUTHA** in the pre-monsoon season, it also maintained its peak intensity till landfall.

(iv) The severe cyclonic storm, **MORA** had a north-northeastwards moving track. Considering the area of genesis (± 2^0 around the genesis point), it is seen that about 63% of the cyclones moved north-northeatwards and crossed Bangladesh coast, whereas another 25% moved northeastwards and crossed Myanmar coast and 12% moved westwards towards Andhra Pradesh coast (**Fig.7**). Hence, the direction of the movement of the cyclone was climatological in nature.

(v) The peak maximum sustained surface wind speed (MSW) of the cyclone was 110-120 kmph gusting to 130 kmph (60 knots) and the system crossed Bangladesh coast with this peak MSW between 0400-0500 UTC (0930-1030 hrs IST) of 30th May. The lowest estimated central pressure was 978 hPa (from 2100 UTC of 29th to till landfall around 0430 UTC of 30th).

(vi) The cyclone life period was about 72 hours (3 days).

- **(vii)** The track length of the cyclone was 1086 km.
- **(viii)** The 12 hour average translational speed of the cyclone was about 20.4 kmph and hence was fast moving in nature. The system moved fast under the influence of mid-latitude trough in westerlies lying over India in the middle & upper tropospheric levels and the anti-cyclonic cyclonic circulation lying to the northeast of the system. This trough created strong north-northeasterly steering winds over the cyclone field in middle & upper tropospheric levels, which was further accentuated by the north-northeasterly winds from anticyclonic circulation.
- **(ix)** The Velocity Flux was $3.45X10^2$ knots.
- **(x)** Lowest estimated central pressure (ECP) was 978.0 hPa with a pressure drop of 18 hPa.
- **(xi)** The Accumulated Cyclone Energy (ACE) which is a measure of damage potential was about 1.74×10^4 knot^2.
- **(xii)** The Power Dissipation Index which is a measure of loss due to a cyclone was 0.899×10^6 knot^3.

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

2. Monitoring of SCS, 'MORA'

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

The cyclone was monitored & predicted continuously by IMD since its inception over southeast BoB and adjoining areas of central BoB on 25th May. At the genesis stage, the system was monitored mainly with satellite observations and buoy observations. From 30th May morning, the system was continuously monitored by Doppler Weather Radar at Khepupara. 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 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, National & State Disaster Management Agencies, general public and media since inception of the system over BOB.

3. Brief life history

3.1. Genesis

Under the influence of an upper air cyclonic circulation over southeast BoB, a low pressure area formed over southeast BoB & adjoining central BoB with associated upper air cyclonic circulation extending upto 5.8 km above mean sea level at 0300 UTC of 25th May. Moving northeastwards, it was seen as a well marked low pressure area in the morning of 27th over eastcentral and adjoining westcentral & southeast Bay of Bengal. At 0300 UTC of 27th, the sea surface temperature (SST) was around 29-30˚C. The low level convergence was about $20x10^{-5}$ second^{-1}, the upper level divergence was around $30x10^{-5}$

second^{-1} and the low level relative vorticity was about 50-100x10^{-6} second^{-1} around the system centre. The vertical wind shear of horizontal wind was moderate (10 knots). The Madden Julian Oscillation (MJO) index was in phase 2 with amplitude >1. The upper tropospheric ridge at 200 hPa level was along 17^{0}N in association with anticyclonic circulation to the northeast of the system centre. Under these favourable environmental conditions, the well marked low pressure area over eastcentral and adjoining westcentral & southeast Bay of Bengal moved northeastwards and concentrated into a depression (D) at 0000 UTC of 28th over southeast & adjoining central BoB near latitude 14.0ºN and longitude 88.5ºE.

3.2. Intensification

At 0900 UTC of 28th, SST was around 29-30˚C. The low level convergence was about 20x10^{-5} second^{-1}, the upper level divergence was around 40x10^{-5} second^{-1} and the low level relative vorticity was about 150x10^{-6} second^{-1}. The vertical wind shear of horizontal wind was moderate (10 knots). The MJO index was in phase 2 with amplitude near 1. The upper tropospheric ridge at 200 hPa level lay along 18^{0}N in association with anticyclonic circulation to the northeast of the system centre. A trough in upper and middle tropospheric levels was lying over eastern India near longitude 85.0^{0}E. Under these favourable environmental conditions, the system moved nearly east-northeastwards and concentrated into a deep depression **(DD)** at 0900 UTC of 28th over eastcentral BoB near latitude 15.4ºN and longitude 90.5ºE. At 1500 UTC of 28th, similar environmental conditions prevailed; SST was around 30-31˚C and ocean thermal energy was around 100 KJ/cm^{2}. Moving northeastwards, the system intensified into a cyclonic storm **(CS)** over eastcentral BoB near latitude 16.0ºN and longitude 91.0ºE.

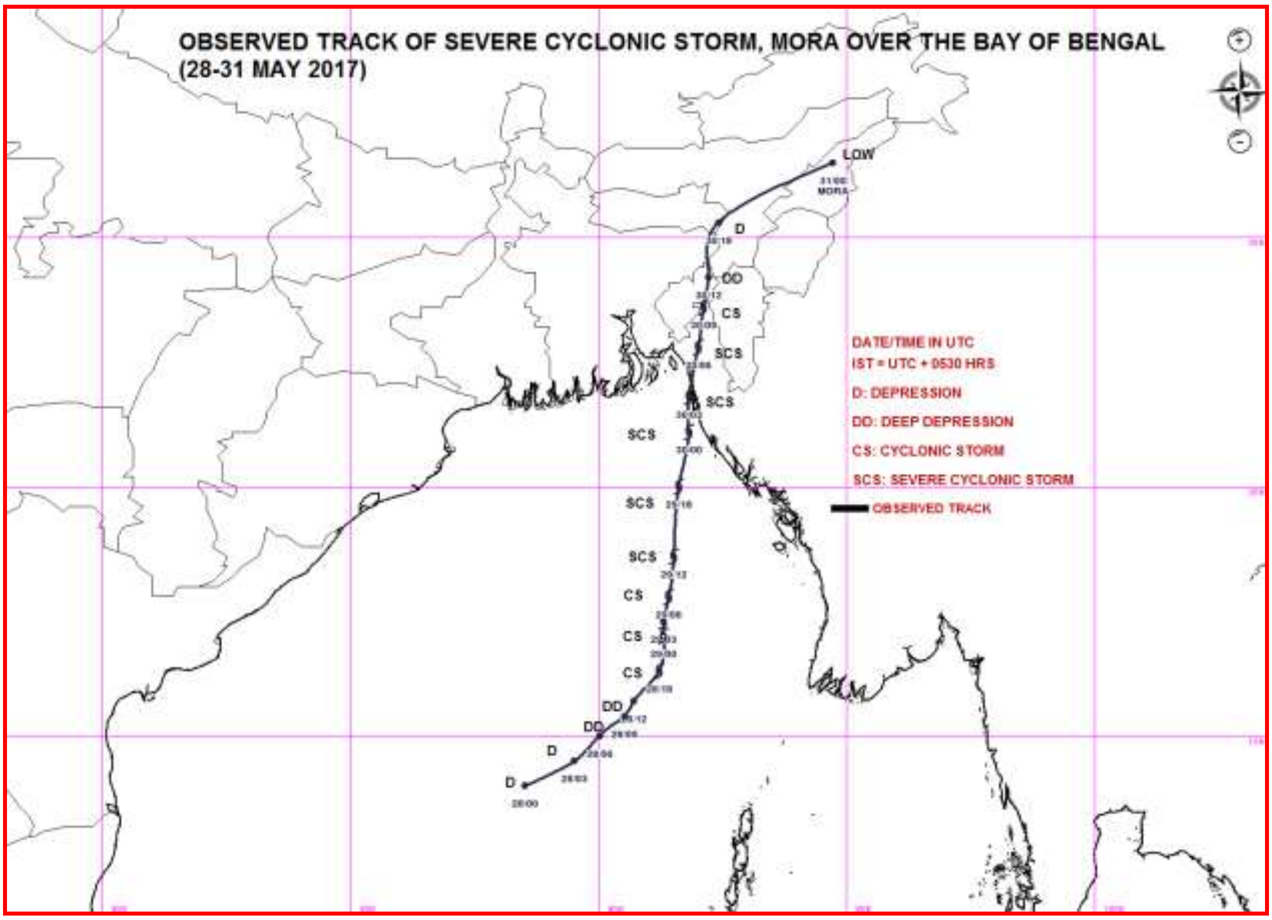


Fig.1 Observed track of SCS,'Mora' over BoB during 28-31 May 2017

At 1200 UTC of 29th, thermal conditions remained the same. The low level convergence was about 40×10^{-5} second^{-1}, the upper level divergence was around 30-40×10^{-5} second^{-1} around the system centre and the low level relative vorticity increased to about 200×10^{-5} second^{-1}. The vertical wind shear of horizontal wind was high (15-20 knots) around the system centre. The MJO index was in phase 3 with amplitude >1. The upper tropospheric ridge at 200 hPa level laid along 18^0N in association with anticyclonic circulation to the northeast of the system centre. The system laid in the western periphery of anticyclonic circulation. Under these environmental parameters, the system moved nearly north-northeastwards, intensified gradually into severe cyclonic storm **(SCS)** and lay centered over northeast and adjoining eastcentral BoB near latitude 18.6ºN and longitude 91.5.4ºE. The advection of warm moist air from southeast sector continued and under similar thermo-environmental conditions the system attained its peak intensity of 60 kts at 2100 UTC of 29th. Moving north-northeastwards, the system crossed Chittagong between 0400 and 0500 UTC of 30th. Due to the interaction of the system with orographically dominated land surface, the system weakened into a **CS** and laid centered over Bangladesh and adjoining Mizoram & Tripura near latitude 23.6ºN and longitude 92.1ºE at 0900 UTC of 30th. Moving further north-northeastwards, the system weakened into **DD** at 1200 UTC over Tripura & neighbourhood and into a **D** at 1800 UTC of 30th over south Meghalaya & neighbourhood. While moving northeastwards, the system weakened into a well marked low pressure area over Nagaland & neighbourhood at 0000 UTC of 31st May.

Table 1: Best track positions and other parameters of the Severe Cyclonic Storm, 'Mora' over the Bay of Bengal during 28-31 May, 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
28/05/2017	0000	14.0/88.5	1.5	998	25	3	**D**
	0300	14.5/89.5	1.5	998	25	3	D
	0600	15.0/90.0	1.5	997	25	3	D
	0900	15.4/90.5	2.0	996	30	4	**DD**
	1200	15.7/90.7	2.0	995	30	5	DD
	1500	16.0/91.0	2.5	994	35	6	**CS**
	1800	16.3/91.2	2.5	994	35	6	CS
	2100	16.6/91.3	2.5	992	40	8	CS
29/05/2017	0000	17.0/91.3	3.0	990	45	10	CS
	0300	17.3/91.3	3.0	990	45	10	CS
	0600	17.8/91.4	3.0	988	45	10	CS
	0900	18.3/91.5	3.0	986	45	11	CS
	1200	18.6/91.5	3.0	984	50	12	**SCS**
	1500	18.8/91.5	3.5	980	55	16	SCS
	1800	20.0/91.6	3.5	980	55	16	SCS
	2100	20.3/91.6	3.5	978	60	18	SCS

30/05/2017	0000	21.1/91.8	3.5	978	60	18	SCS
	0300	21.8/91.9	3.5	978	60	18	SCS
	Crossed Bangladesh coast close to south of Chittagong near 22.0^{0}N/91.9^{0}E during 0400-0500 UTC						
	0600	22.8/91.9	-	982	55	16	**SCS**
	0900	23.6/92.1	-	988	40	10	**CS**
	1200	24.2/92.2	-	990	30	6	**DD**
	1800	25.3/92.4	-	994	20	4	**D**
31/05/2017	0000	**Weakened into a well marked low pressure area over Nagaland & neighbourhood**					

The total precipitable water imageries (TPW) during 27-31 May are presented in **Fig.2**. These imageries indicate continuous warm and moist air advection from the southeast sector into the system. From 30th morning, the system started interacting with land surfaces and moisture supply also reduced from southeast sector.

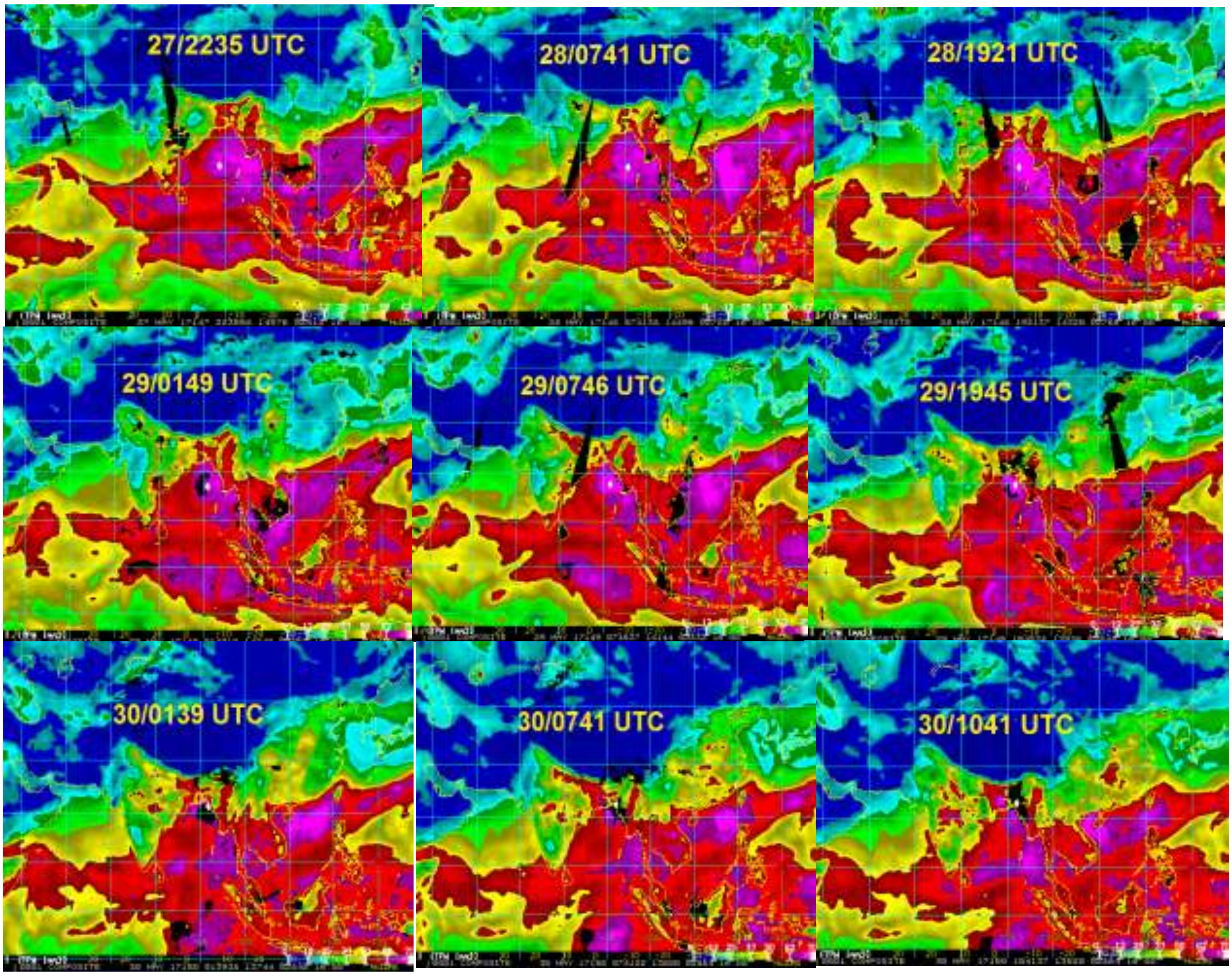


Fig. 2: Total Precipitable Water Imageries during 27-31 May, 2017

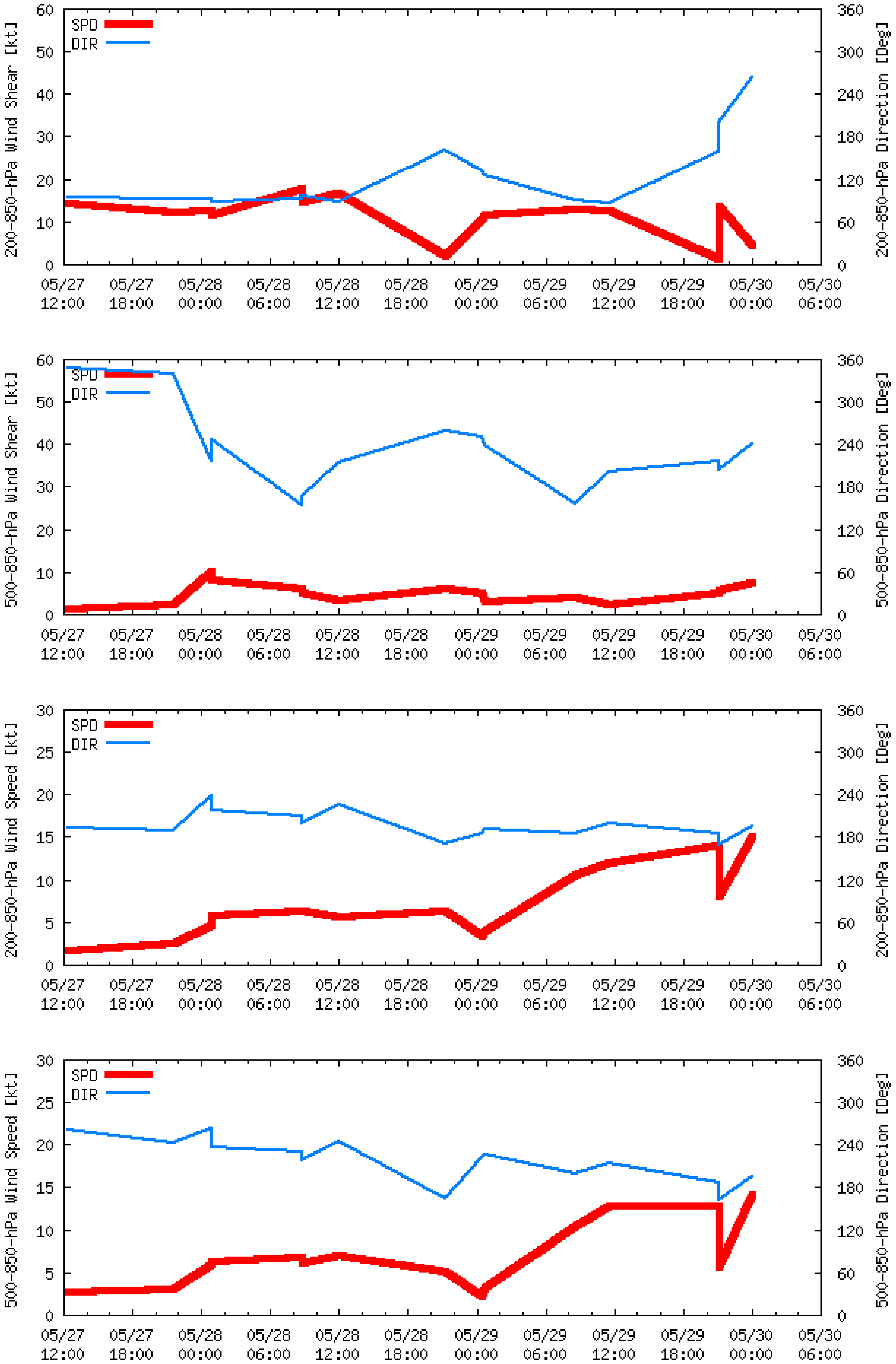


Fig.3 Wind shear and wind speed in the middle and deep layer around the system during 28th to 31st May 2017.

The wind speed in middle and deep layer around the system centre is presented in **Fig.3**. The wind shear around the system between 200 & 850 hPa levels remained steady till 1200 UTC of 28th May. It decreased rapidly from 28th night to 29th morning becoming steady till evening of 29th. Thereafter, it decreased gradually till morning of 30th. The wind shear was 10 knots or less on 29th and 30th, helping the intensification of the system. Further, the anticyclonic wind shear over the region also helped in intensification of the system

As the wind shear was east-southeasterly from 28th evening to night, the convective cloud mass was sheared towards west-northwestwards of the system centre till 28th night. Thereafter, it gradually became northeasterly by 29th night, shearing the cloud mass cloud mass to southwest sector of system. By 30th morning, it gradually became southeasterly, shearing cloud mass to northwest of system centre.

3.3 Movement

From **Fig.3**, it indicates that from 29th onwards, the mean deep layer winds between 200-850 hPa levels steered the near north-northeast movement of the system. The northeasterly movement after the landfall was in association with trough in westerly over eastern India. The initial northeasterly movement of the system was in association with the upper tropospheric ridge lying to the north of the system centre. The SCS, Mora moved initially northeastwards till late evening (1500 UTC) of 28th May. It then moved north-northeastwards till night (1800 UTC) of 30th. Thereafter, it moved east-northeastwards till 0600 UTC of 29th and nearly northwards thereafter. The twelve hourly movement of SCS Mora is presented in **Fig.4**. The 12 hour average translational speed of the cyclone was about 20.4 kmph and hence was fast moving in nature. The system moved fast under the influence of mid-latitude trough in westerlies and the anti-cyclonic cyclonic circulation lying to the northeast of the system. This trough created strong north-northeasterly steering winds over the cyclone field in middle and upper tropospheric levels, which was further accentuated by the north-northeasterly winds from anticyclonic circulation. The system had a track length of about 1086 km during its life period.

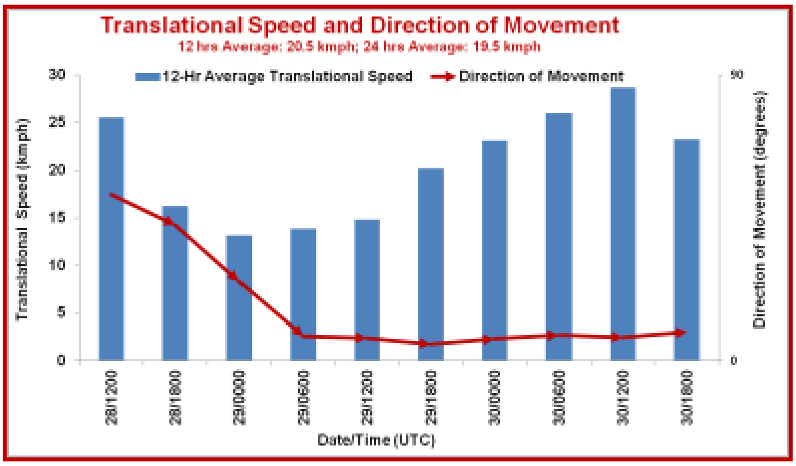


Fig.4 Twelve hourly average translational speed (kmph) and direction of movement in association with SCS Mora

3.4. Landfall point and time:

The observed track during 0300-0600 UTC of 30th May is presented in **Fig.5**. It indicates that system crossed Bangladesh coast close to south of Chittagong around 0400-0500 UTC of 30th May.

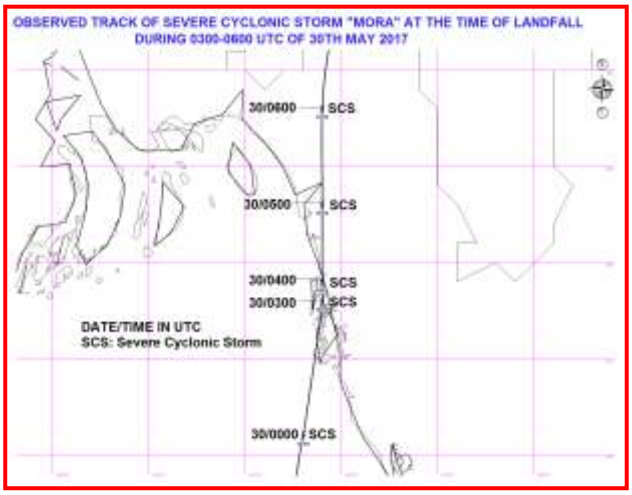


Fig.5: Observed track of SCS Mora during 0300 -0600 UTC of 30th May, 2017

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

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig.6**. The lowest estimated central pressure had been 978 hPa during 2100 UTC of 29th to 0300 UTC of 30th. The estimated maximum sustained surface wind speed (MSW) was 60 knots during the same period. At the time of landfall, the ECP was 978 hPa and MSW was 60 knots (severe cyclonic storm). The ECP and Vmax graph indicate that the system intensified gradually till 2100 UTC of 29th, maintained its intensity till 0300 UTC of 30th and started weakening gradually after landfall.

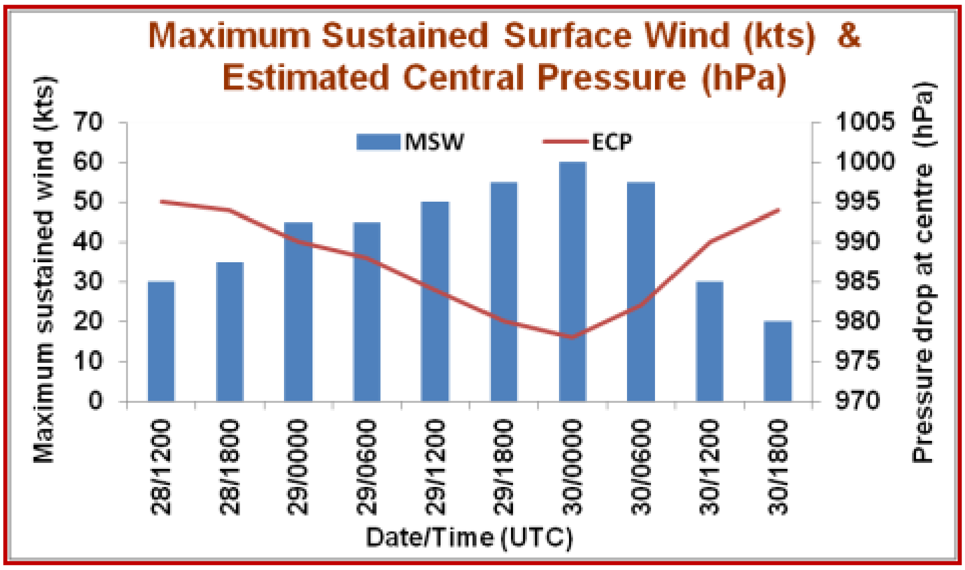


Fig.6 Lowest estimated central pressure and the maximum sustained wind speed

4. Climatological aspects

The severe cyclonic storm, **MORA** had a north-northeastwards moving track. Considering the area of genesis (+/- 2^0 around the genesis point), it is seen that about 63% of the cyclones moved north-northeatwards and crossed Bangladesh coast, whereas another 25% moved northeastwards and crossed Myanmar coast and 12% moved westwards towards Andhra Pradesh coast (Fig.7). Hence, the direction of the movement of the cyclone was climatological in nature.

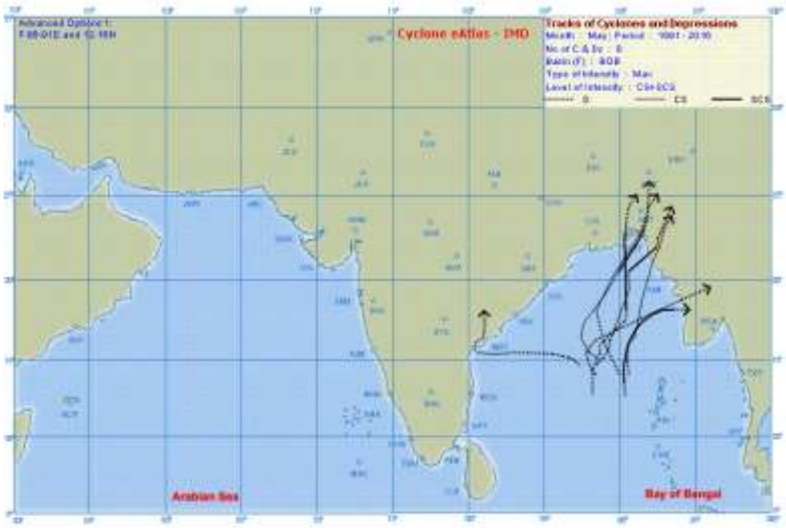


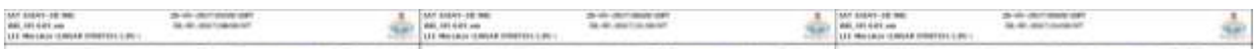
Fig 7. Climatological tracks of TCs (SCS and above) forming within +/- 2^0 around the genesis point during 1891-2016

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 visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig.8**. Intensity estimation using Dvorak's technique suggested that the system attained the intensity of T 1.5 at 0000 UTC of 28th. The cloud pattern was curved band type with well defined wrapping into the centre from eastern sector. Associated broken low and medium clouds with embedded intense to very intense convection laid over BoB between latitude 11.0^0N & 18.0^0N and longitude 85.0^0E & 91.0^0E. At 0900 UTC of 28th, well defined banding features were seen. Banding wrapped 0.35 on 10 degree log spiral. The system attained the intensity of T2.0. Associated broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 10.0^0N & 20.0^0N and longitude 85.0^0E & 93.0^0E. At 1500 UTC of 28th, the system intensified to T2.5. Convection showed curved band pattern with wrap 0.50 in 10 degree log spiral. Associated broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 12.0^0N & 20.0^0N and longitude 85.0^0E & 92.0^0E. At 0000 UTC of 29th, the system



attained the intensity of T 3.0. Convection showed curve band pattern with wrap 0.85 in 10 degree log spiral. Associated broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 12.0^{0}N & 20.0^{0}N and longitude 85.0^{0}E & 92.5^{0}E. Thereafter the system crossed Bangladesh coast to the south of Chittagong between 0400 to 0500 UTC.

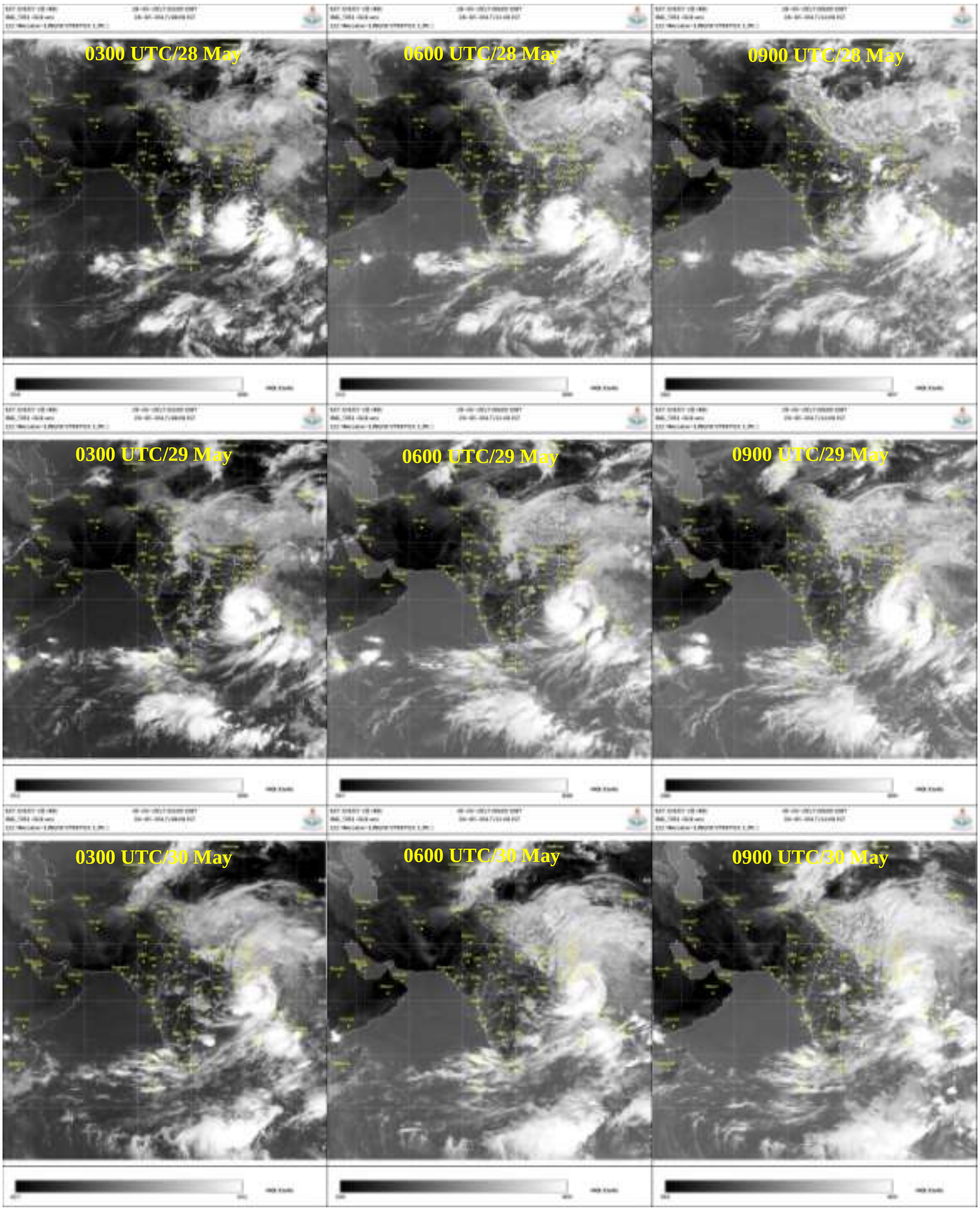


Fig. 8a: INSAT-3D visible imageries during life cycle of SCS Mora (28-31 May, 2017)

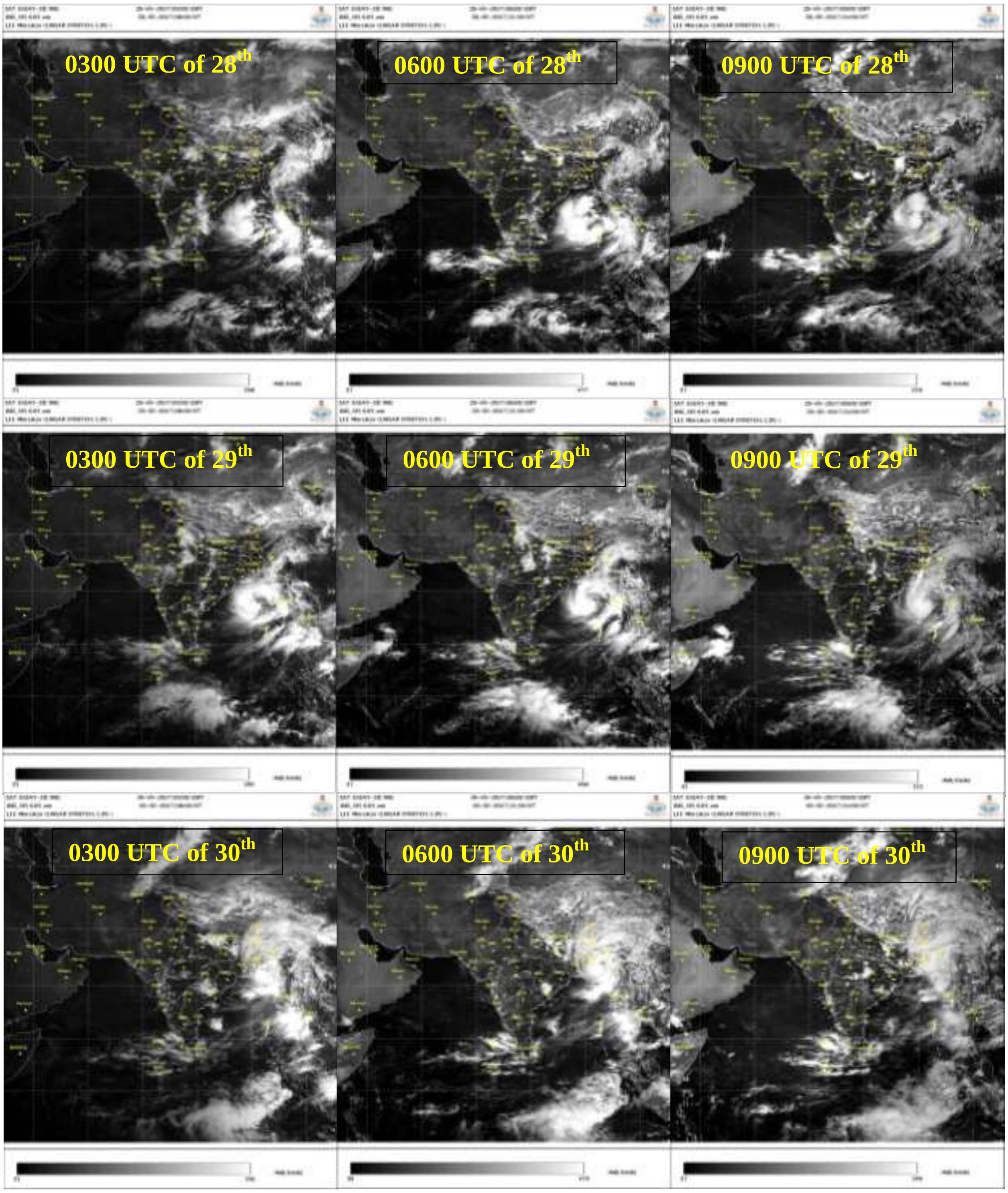


Fig. 8b: INSAT-3D IR imageries during life cycle of SCS Mora (28-31 May, 2017)

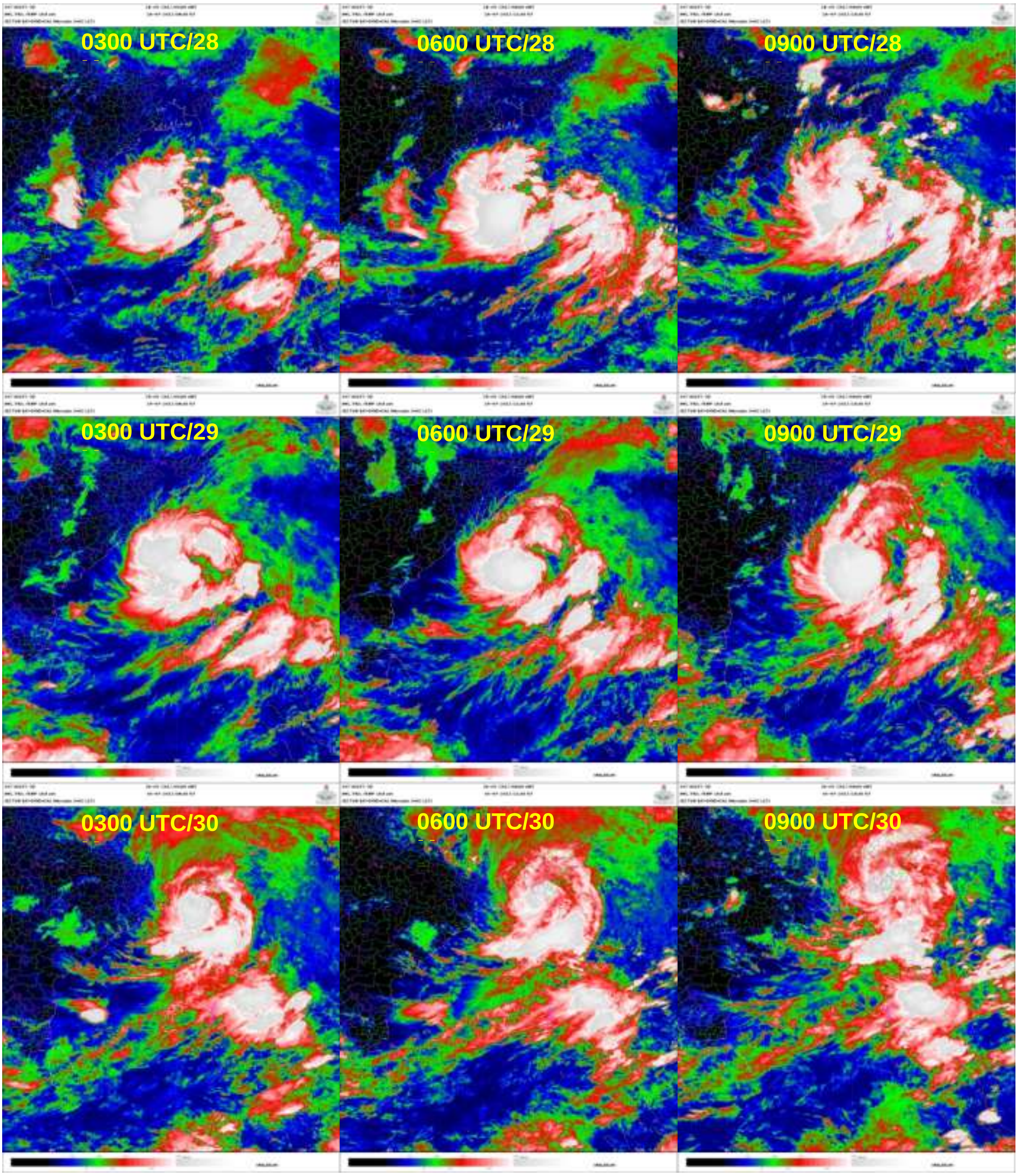


Fig. 8c: INSAT-3D enhanced colored imageries during life cycle of SCS Mora (28-31 May 2017)

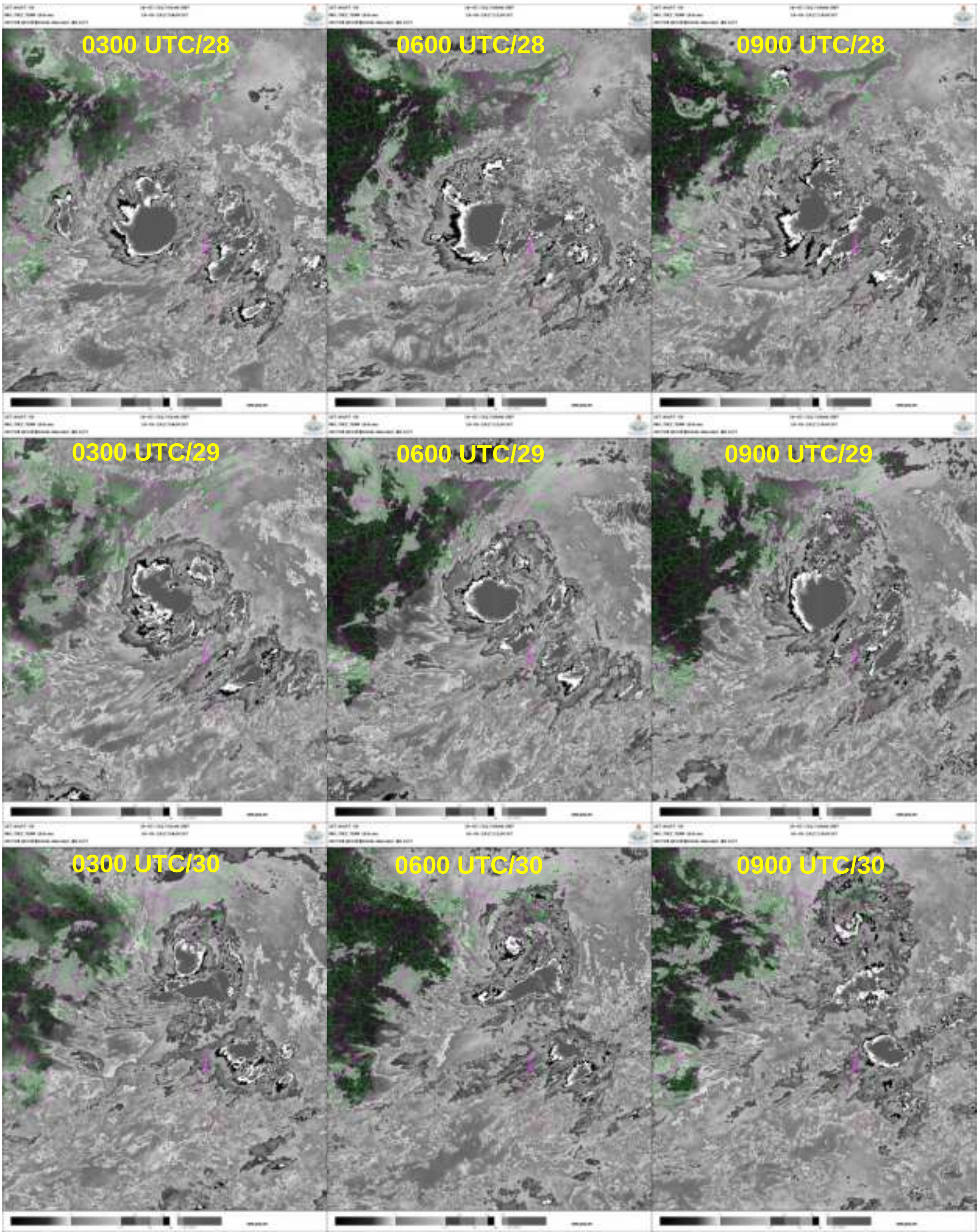


Fig. 8d: INSAT-3D cloud top brightness temperature imageries during life cycle of SCS Mora (28-31 May, 2017)

5.2 Microwave features

F-15, F-16, F-17, GPM and GCOM-W1 microwave imageries of the SCS Mora covering its life period from 27th to 31st May 2017 are presented in **Fig.9 (a).** 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. Area of intense convection was seen in the southwest sector in the night of 28th gradually extending to northwest and then northeast sector by early hours of 29th. From 29th night to early hours of 30th morning, intense convection was observed in southern sector. From afternoon of 30th, region of intense convection shifted to northeast sector.

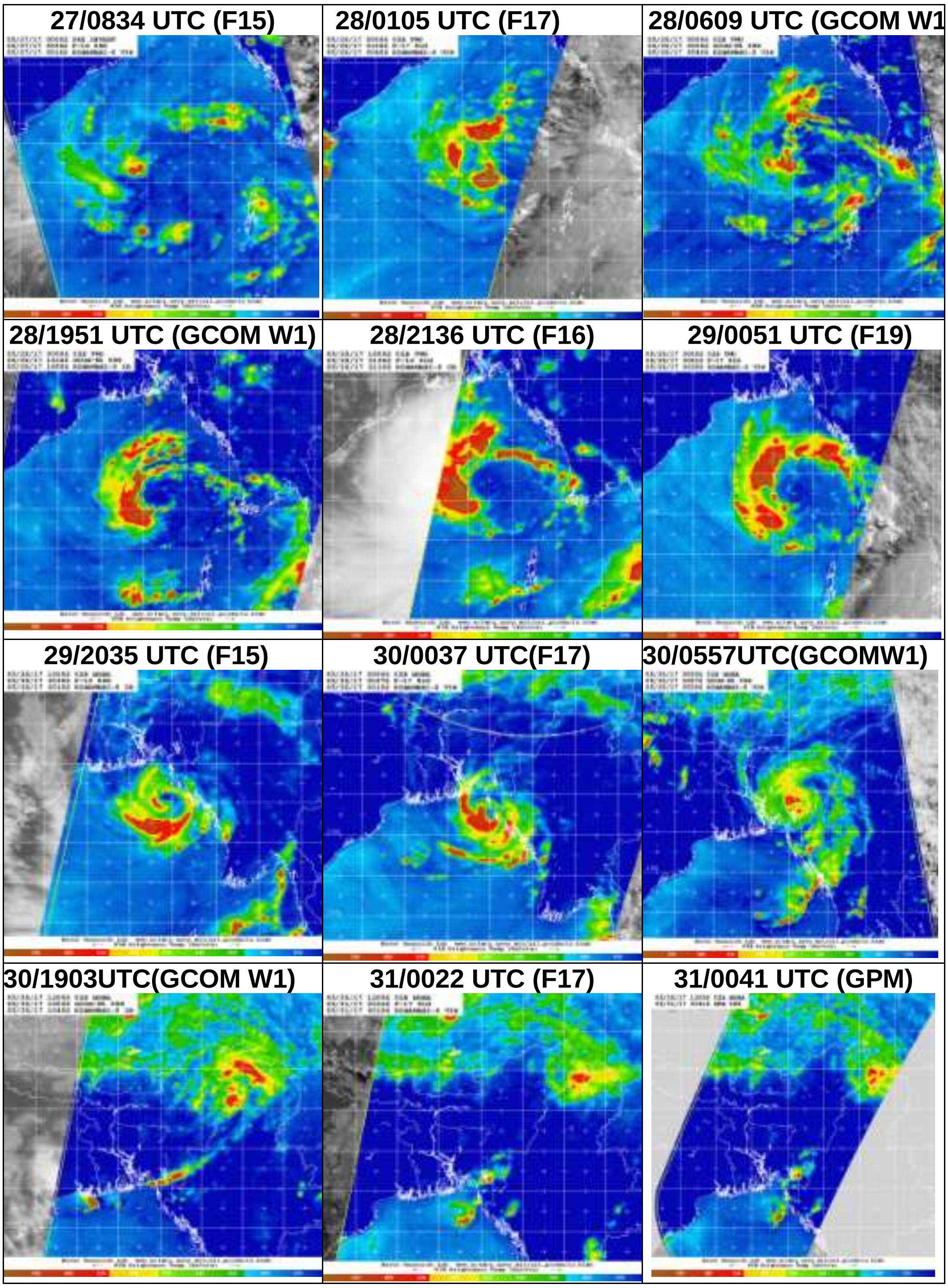


Fig. 9(a): Microwave imageries during life cycle of SCS Mora

5.3: Features observed through SCATSAT imageries

Typical imageries from polar satellite, SCATSAT are presented in **Fig.9 (b).** SCATSAT passes are available twice a day at 0400 UTC and 1700 UTC at http://mosdac.gov.in/scorpio/SCATSAT_Data. The observations based on 1449 UTC of 27th indicated cyclonic circulation over southeast and adjoining eastcentral BoB. Stronger winds were seen in southwest sector. The imagery indicated large scale cross equatorial flow, inflow of warm and moist air into the system centre from southeast. At 0310 UTC, the area of strong winds extended to entire southern sector. At 1400 UTC of 28th, winds became uniform near the core. At 0221 UTC of 29th, the radial extent of 34kts winds was more in the northeast sector followed by southeast sector due to warm and moist air advection in the southeast and northeast sector. The estimated intensity by SCATSAT matched best track estimates. The maximum size in the northeast sector is also due to higher southeasterly wind shear in the region.

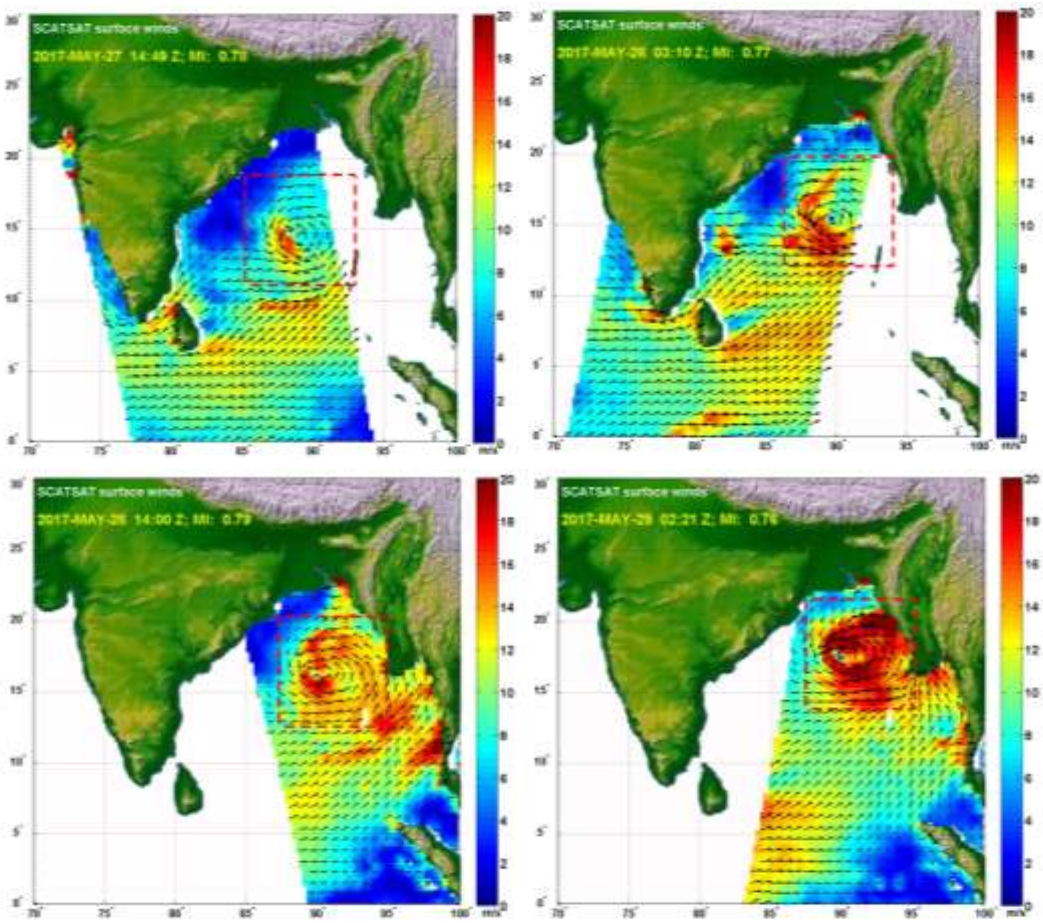


Fig. 9(b): Imageries from SCATSAT during 27th to 29th May 2017.

5.4. Features observed through Radar

As the system was moving towards Bangladesh coast, it was tracked by DWR Khepupara, Cox's Bazar and Molvibazar. Typical Radar imageries from these Radars as received from Bangladesh Meteorological Department on 30th May are presented in **Fig. 10.** These imageries could detect the location of the system correctly. It also helped in estimating the past precipitation and predicting the precipitation in short range.

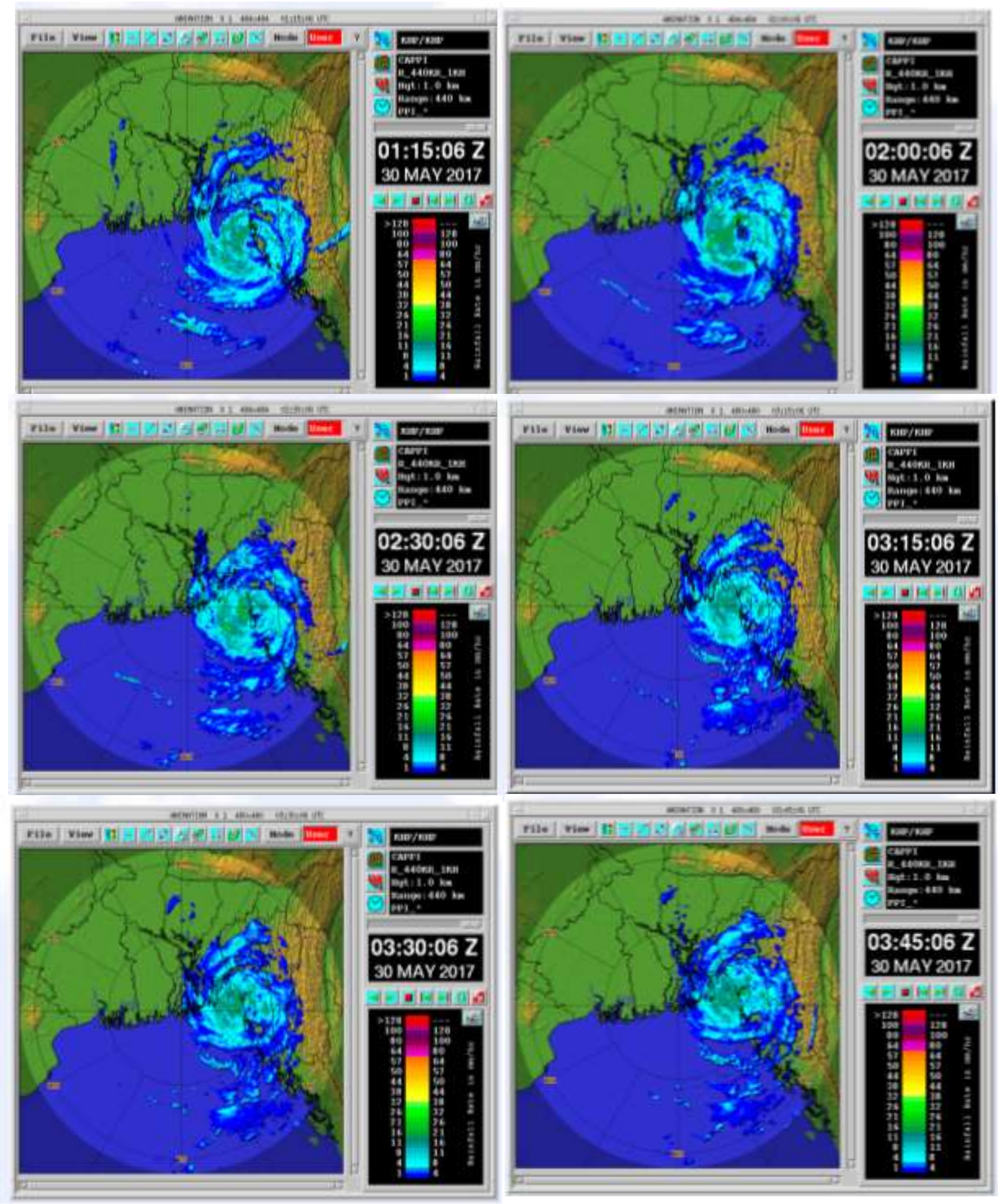


Fig. 10: Imageries from Doppler Weather Radar Khepupara, Bangladesh during 0100 UTC to 0345 UTC of 30th May.

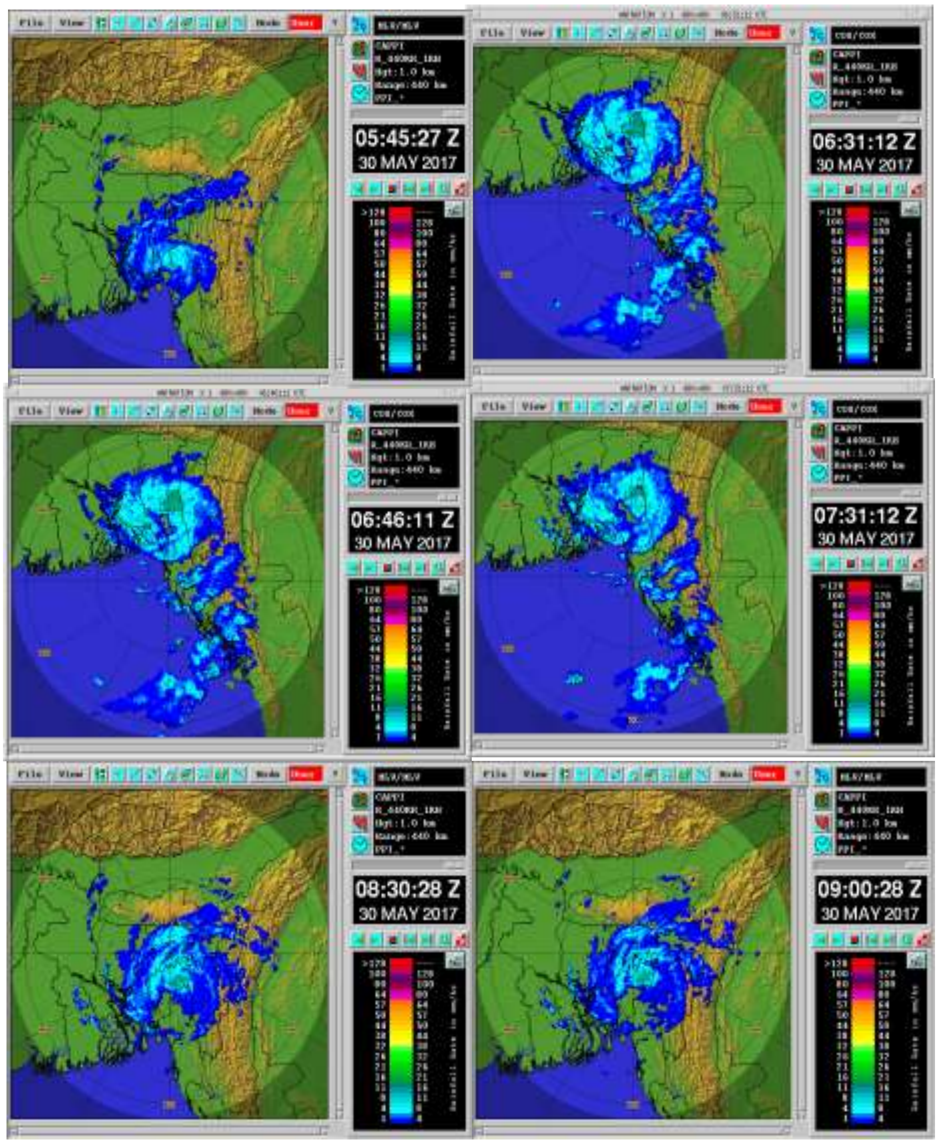


Fig. 10 (contd.): Imageries from Doppler Weather Radar Cox's Bazar and Molvibazar, Bangladesh during 0545 UTC to 0900 UTC of 30th May

6. **Dynamical features**

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 28th-31st May are presented in Fig.11. GFS (T1534). Based on 0000 UTC observations of 28th, the model predicted formation of depression over southeast and adjoining eastcentral BoB extending upto 500 hPa level. At 200 hPa level, it could predict presence of ridge around 18^0N in association with anticyclonic circulation over eastcentral BoB off Myanmar coast and a trough in westerlies over western India around 78^0E.

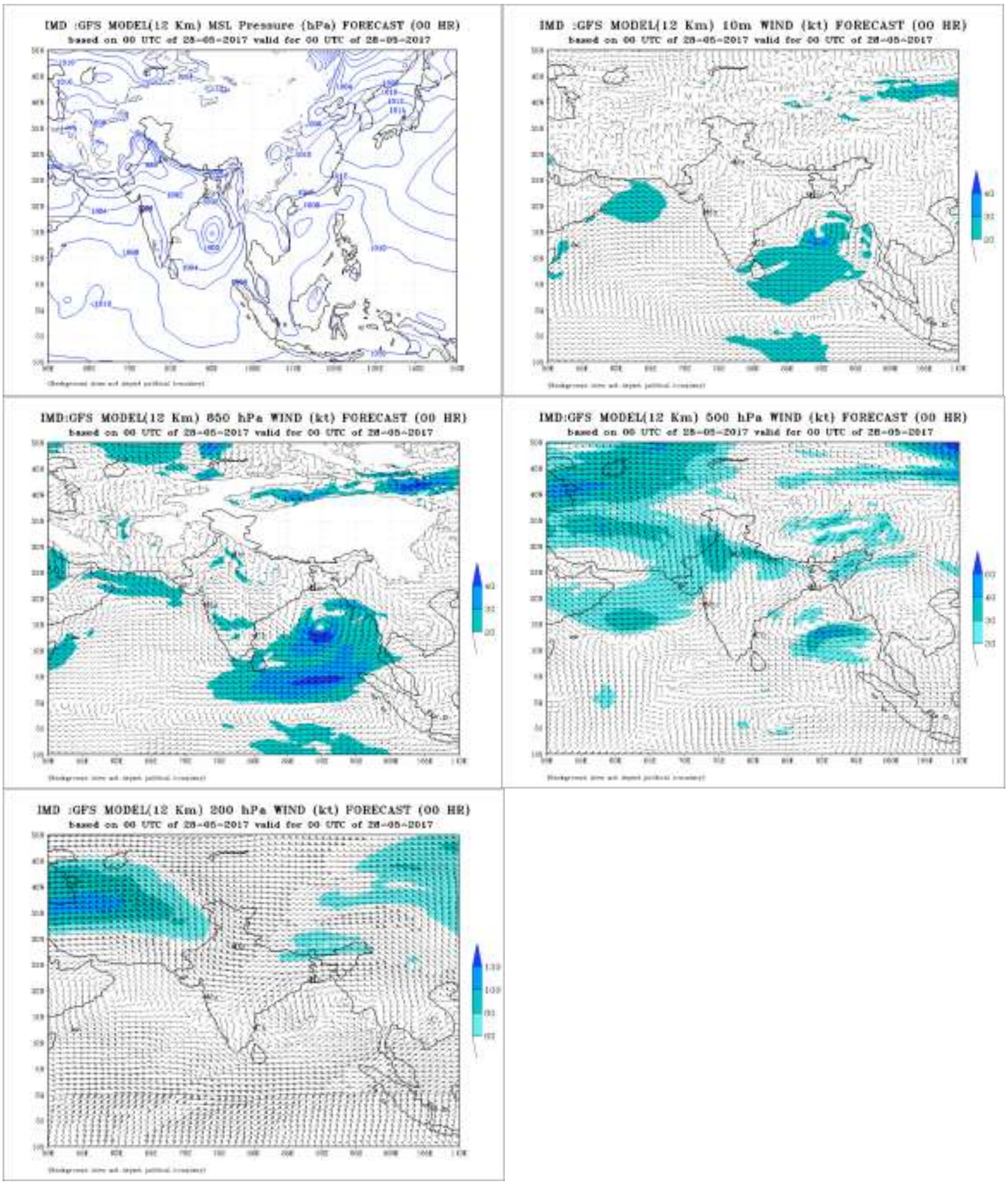


Fig. 11 (a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 28th May

Analysis based on 0000 UTC of 29th May, predicted intensification of system into a cyclonic storm. Vertically the system extended upto 500 hPa levels. At 200 hPa level, it could capture the trough over western India and an anticyclonic circulation to the northeast of system centre.

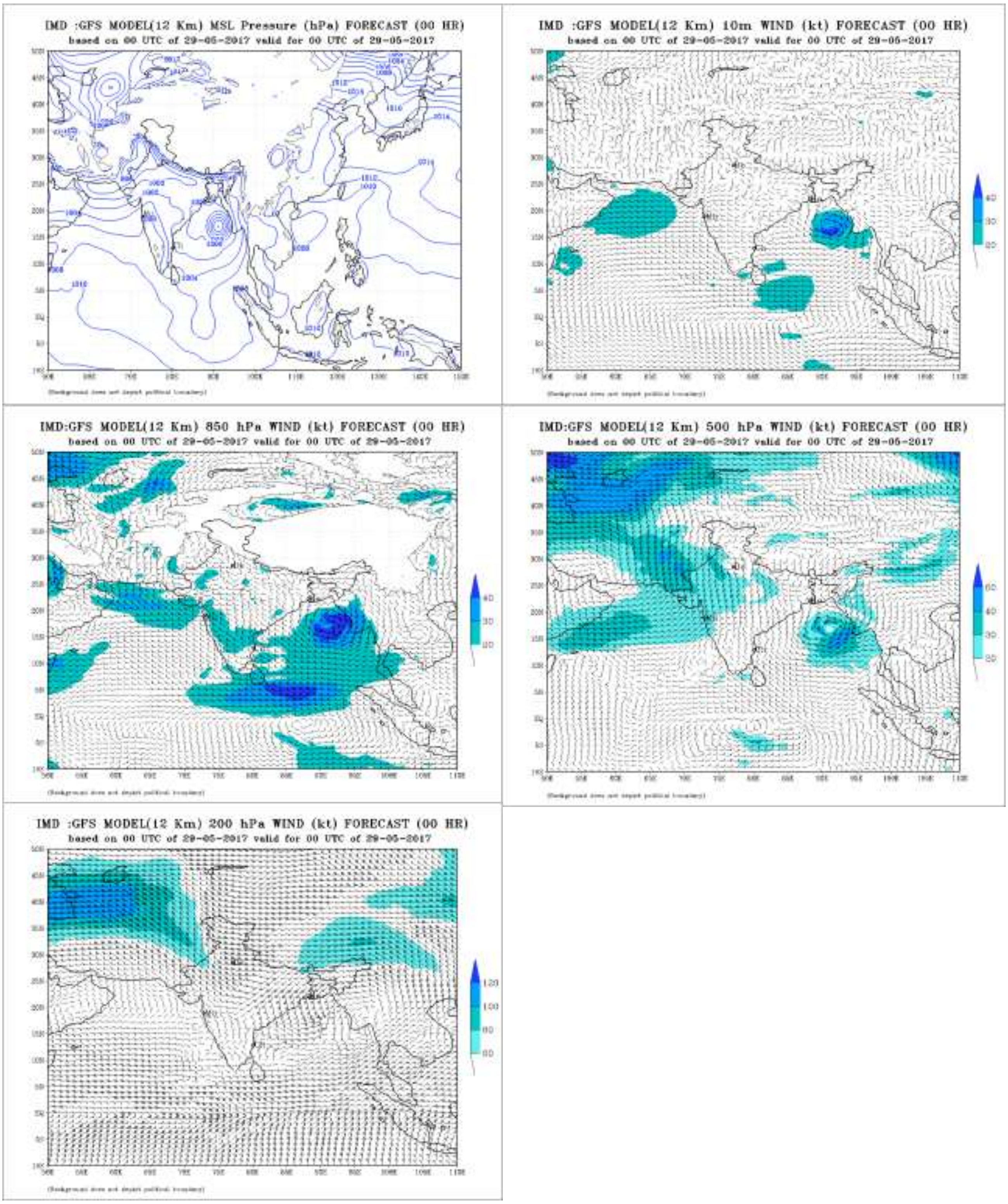


Fig. 11 (b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 29th May

Analysis based on 0000 UTC of 30th May predicted landfall over Bangladesh near 21.5^0N/92.0^0E with severe cyclone intensity.

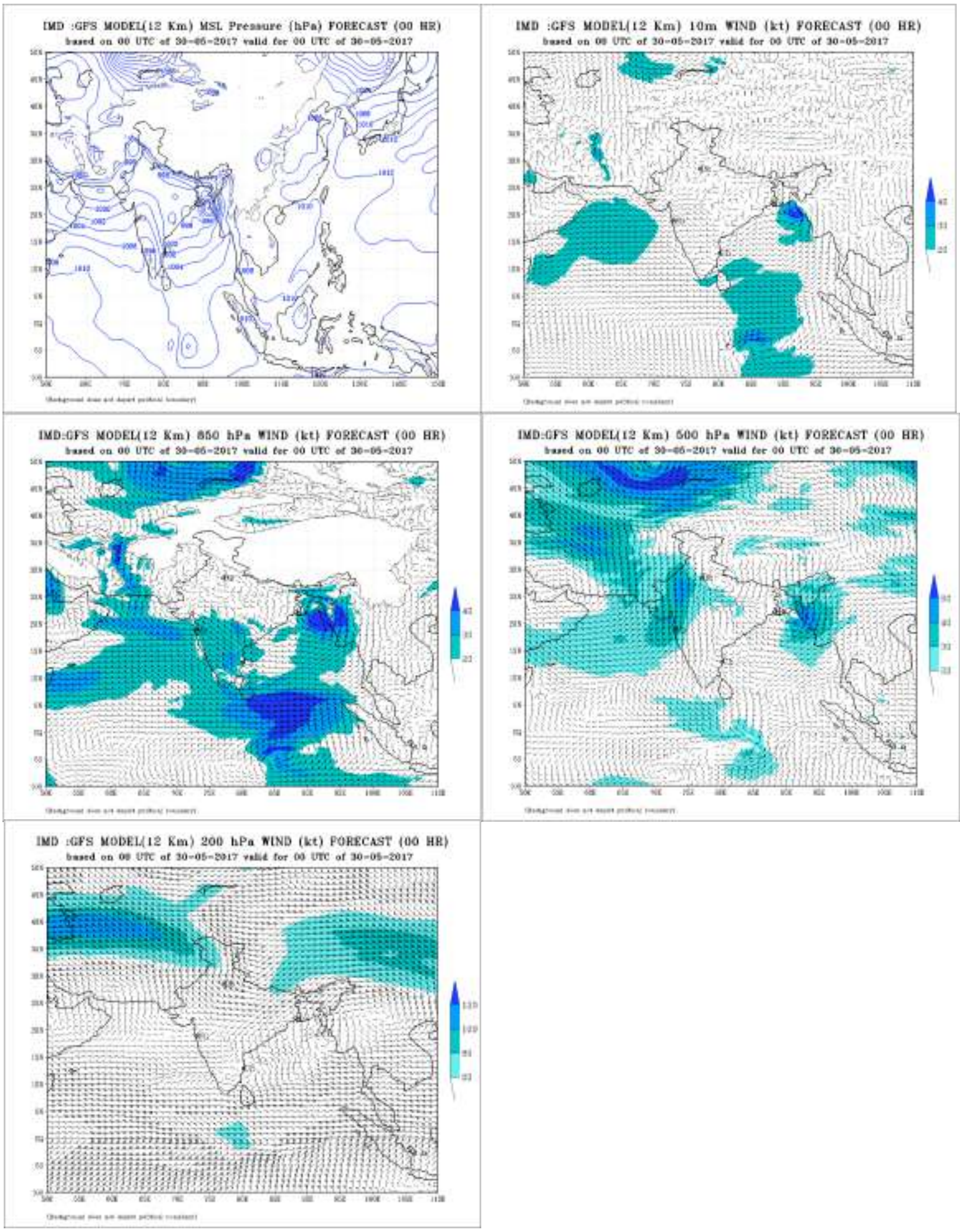


Fig. 11 (c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 30th May

Analysis based on 0000 UTC of 31st May indicated weakening of system and movement towards Tripura.

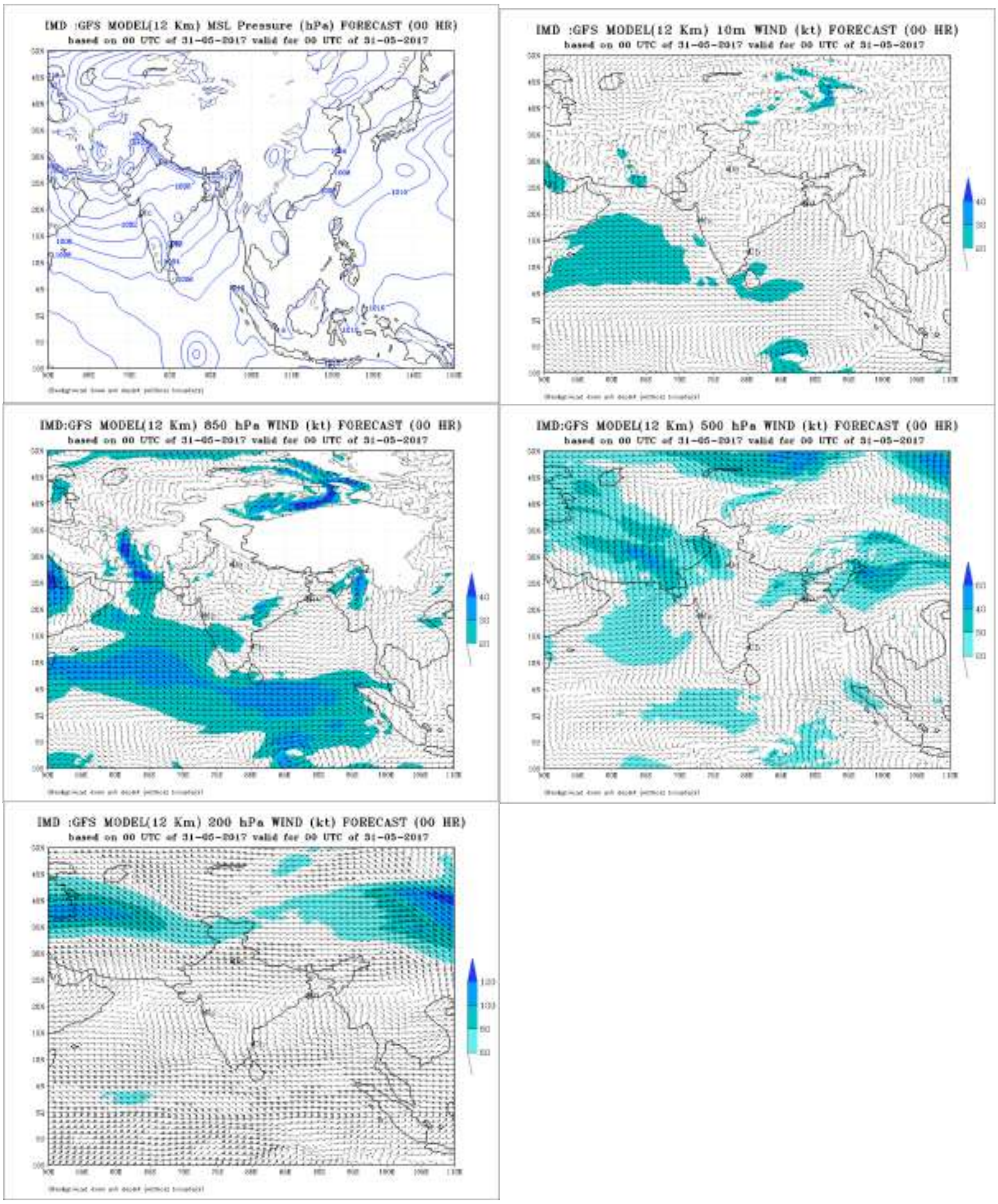


Fig. 11 (d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 31st May

Hence to conclude, to a large extent IMD GFS could simulate the genesis of the system and the associated circulation features during the life period of the system.

7. Realized Weather:

7.1 Rainfall:

(a) Indian States:

Rainfall associated with SCS Mora based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig 12**.

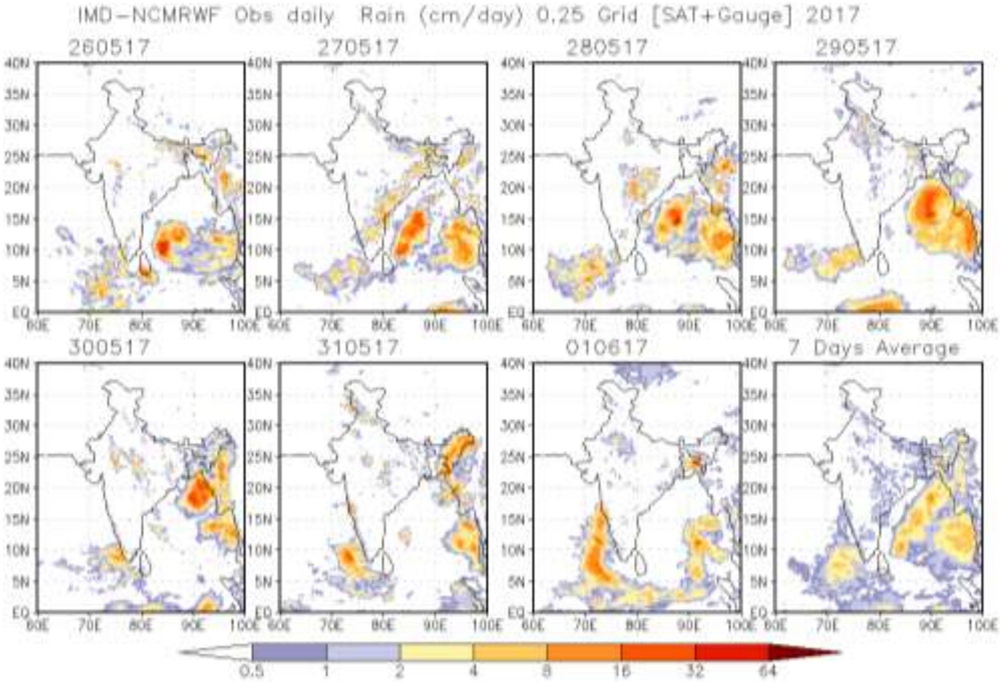


Fig.12: IMD-NCMRWF GPM merged gauge rainfall during 26th May– 1st June and 7 days average rainfall (cm/day)

Realized 24 hrs accumulated rainfall **(≥7cm)** ending at 0830 hrs IST of date due to the cyclone is presented below:

(a) Indian States
31.05.2017
Arunachal Pradesh: Pasighat AERO and Basar-8 each
Assam & Meghalaya: Halflong and B P Ghat-11 each, Lumding-10, Shillong C.S.O.-9, Lakhipur-8 and Karimganj, Chauldhowaghat, Matijuri, Barpathar, Jia Bharali N T Xing and N.Lakhimpur/Lilabari-7 each
Nagaland, Manipur, Mizoram & Tripura: Lunglei and Serchip (Hydro)-10 each and Kohima-7.

(b) Bangladesh
On 30th May, rainfall of 17.7 cm over Chittagong, 17.3 cm over Sandwip, 13.8 cm over Sitakunda, 8.7 cm over Rangamati, 8.3 cm over Hatiya and 11.5 cm over Kutubdia was reported. On 31st May, rainfall of 9.6 cm over Netrokona and 13.9 cm over Hatiya was reported.
(Heavy rain : 64.5 – 115.5 mm, Very heavy rain: 115.6 – 200.4 mm, Extremely heavy rain: 200.5 mm or more).

8. **Damage due to SCS Mora**

(a) **Damage over India:**

No casualties were reported from any Indian state due to SCS Mora. However, rains triggered landslides at many places in Mizoram. It is reported that about 20 houses were damaged in Khawbung village of Champhai district. About 10 houses including a church have been also been damaged in Serchhip district **(Fig 13)**.

Fig 13 (a): Flooded streets in Imphal
The Indian Express, 31st May

Fig. 13 (b): Uprooted trees in Mizoram
The Hindustan Times, 31st May

(b) **Damage over Bangladesh:**

As per preliminary report released by Department Disaster Management, Government of the People's Republic of Bangladesh 7 people lost their lives and 61 got injured due to 'Cyclone Mora'. The damage photographs from Bangladesh Meteorological Department are presented in **Fig. 14**.

Fig. 14 (a): Heavy rains at Cox's Bazar

(b) Rains damaged Rohingya camp in Bangladesh

Fig. 14 (c-d): Damaged shelters and uprooted trees in Cox's Bazar, Bangladesh

Fig. 14 (e): Damaged homes in Cox's Bazar

Fig. 14(f): Strong winds ravaging Dhaka city

Fig. 14(g): Mora making landfall

Fig. 14 (h): Tidal effects of Mora

Fig.14 (i): People moving to cyclone shelters

Fig.14(j): Inundation at Teknaf

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.

Global models are also run at NCMRWF. These include GFS and unified model adapted from UK Meteorological Office. In addition to the above NWP models, IMD also run operationally dynamical statistical models. The dynamical statistical models have been developed for (a) Cyclone Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction, (d) Rapid intensification and 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 MORA are presented and discussed.

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

Fig.15 (a-f) shows the predicted zone of cyclogenesis for SCS Mora.

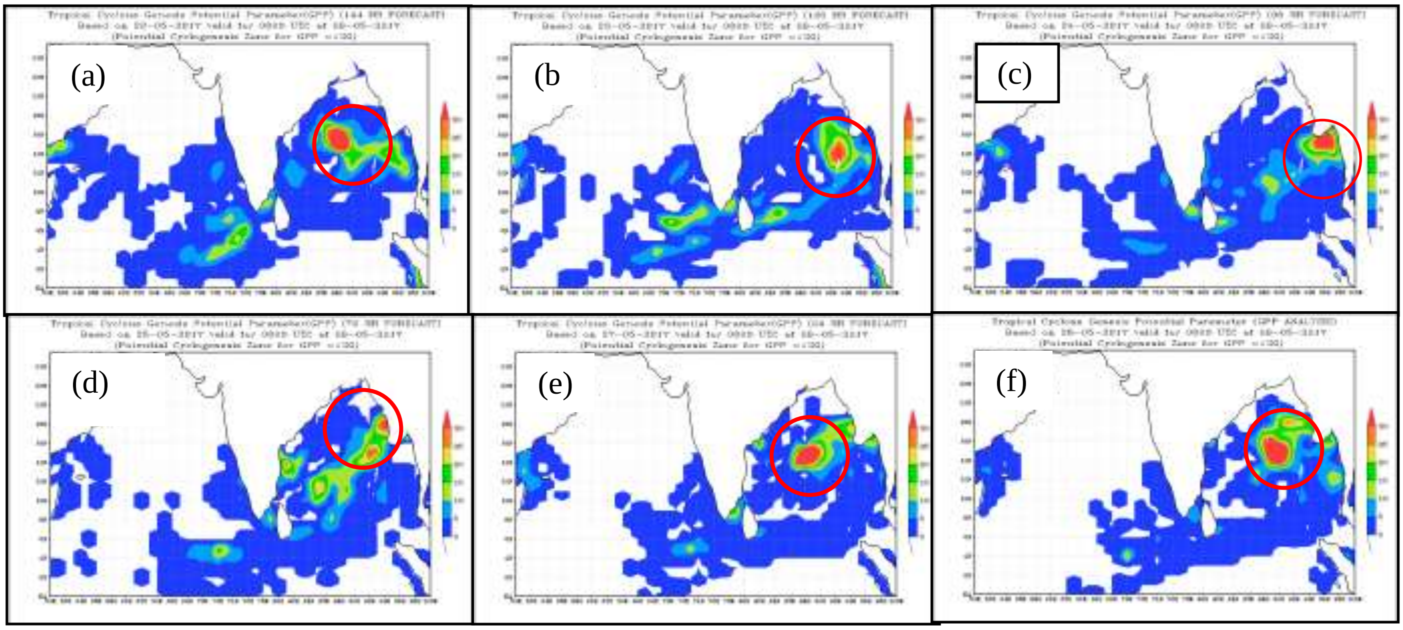


Fig. 15 (a-f): Predicted zone of cyclogenesis based on 0000 UTC of 22nd to 28th May 2017.

The model could predict cyclogenesis zone correctly about 24 and 144 hours in advance. However, for 72, and 120 hours lead period it failed to predict cyclogenesis zone correctly.

Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages (T No. 1.0, 1.5, 2.0) of development. Conditions for (i) Developed system: Threshold value of average GPP ≥ 8.0 and (ii) Non-developed system: Threshold value of GPP < 8.0. The forecasts of GPP (Fig. 18) 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 28th, the model predicted weakening trend after 24 hours. Actually the system didn't weaken till landfall.

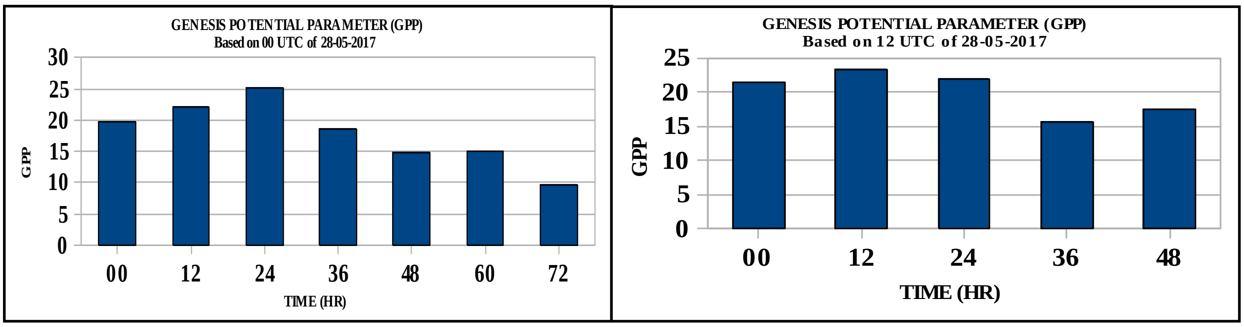


Fig. 16: Area average analysis and forecasts of GPP based on 0000 & 1200 UTC of 28th May, 2017

9.2 Track prediction by NWP models

Track prediction by various NWP models is presented in Fig.19. Based on initial conditions of 0000 UTC of 28th May, ECMWF predicted landfall to the south of Chittagong. WRF-VAR, HWRF and MME predicted landfall to the south of Cox's Bazar. UKMO predicted landfall near Sittwe with overall movement of cyclone similar to observed track. NCEP-GFS, IMD-GFS and JMA were predicting north-northwestward movement and landfall near Dhaka over southwest Bangladesh. Only, WRF-VAR, HWRF, UKMO and MME were predicting landfall in the morning of 30th. ECMWF predicted landfall around night of 29th.

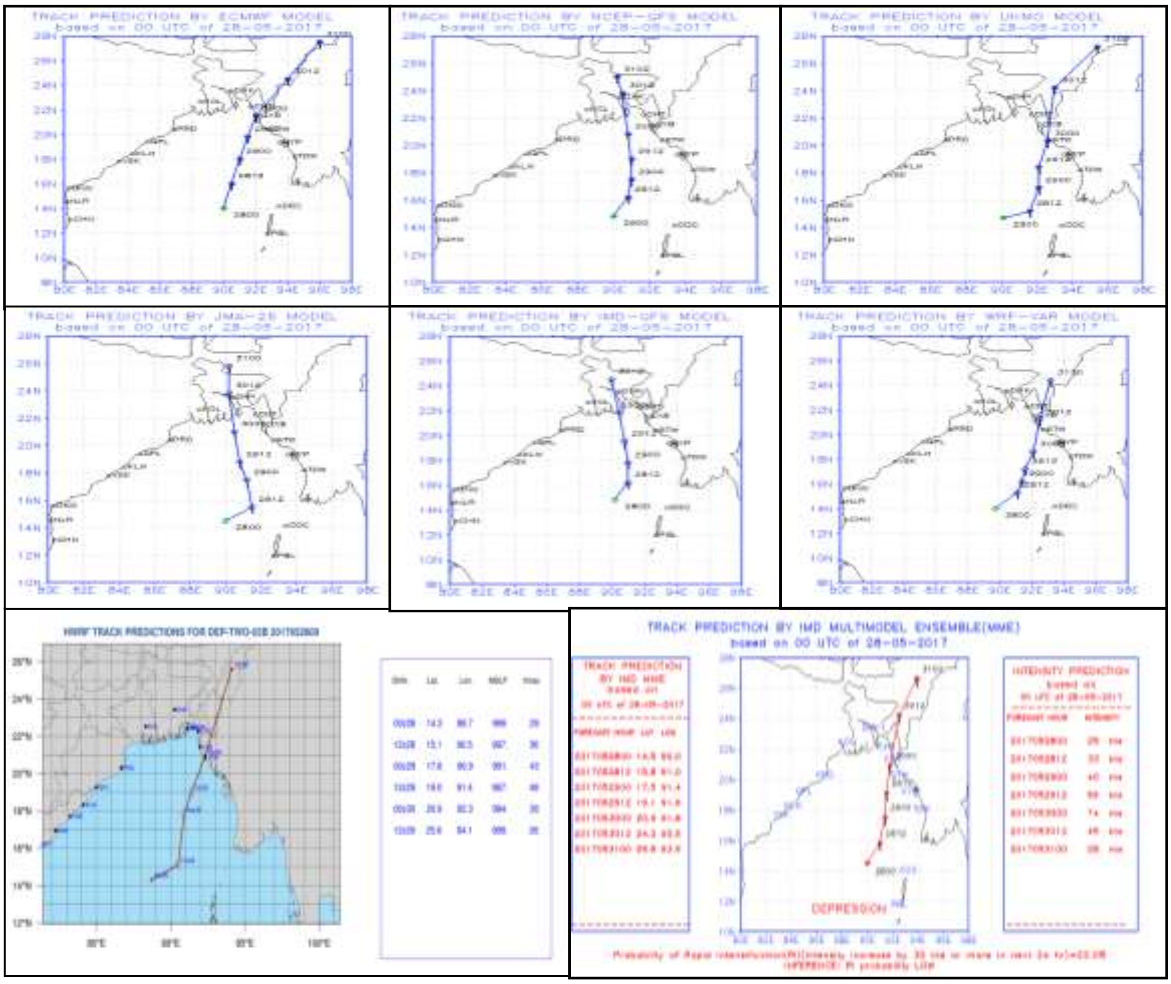


Fig. 17 (a): NWP model track forecast based on 0000 UTC of 28th May

Based on the initial conditions of 0000 UTC of 29th May, ECMWF, UKMO, WRF-VAR, HWRF and MME predicted landfall close to south of Chittagong in the morning of 30th. NCEP-GFS, IMD-GFS and JMA predicted landfall over southeast Bangladesh. But MME predicted probability of Rapid Intensification as HIGH and the system didn't show rapid intensification.

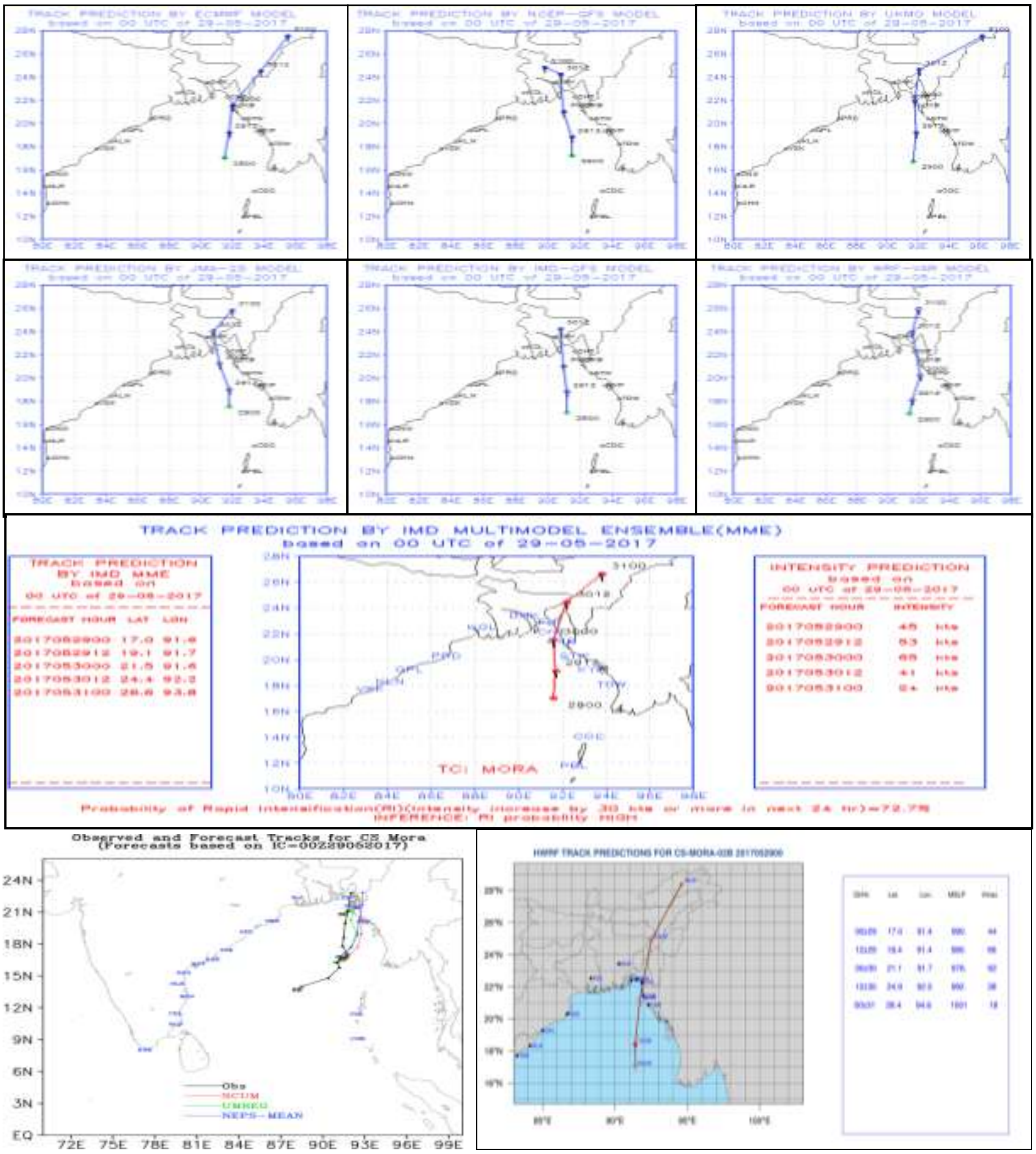


Fig. 17 (b): NWP model track forecast based on 0000 UTC of 29th May

Hence to conclude models like IMD GFS, NCEP GFS and JMA had eastward bias and were predicting landfall over southeast Bangladesh near Dhaka. ECMWF, MME, HWRF and UKMO were unanimous about landfall point and time close to Chittagong. But models were not unanimous about intensity during landfall.

Ensemble Prediction System

The probabilistic and deterministic track forecast by Meteorological Service of Canada (MSC) and National Centre for Environment Prediction (NCEP) and consolidated forecast by these centres based on initial conditions of 0000 UTC of 28th May are presented in **Fig. 18(a**). MSC predicted 20-40% strike probability over southeast Bangladesh and adjoining Myanmar Region. NCEP members showed 60-80% strike probability over southwest Bangladesh and 20-40 % strike probability over southeast coast of Bangladesh. All members ensemble showed 20-40% strike probability over Bangladesh coast. The ensemble forecast was widespread.

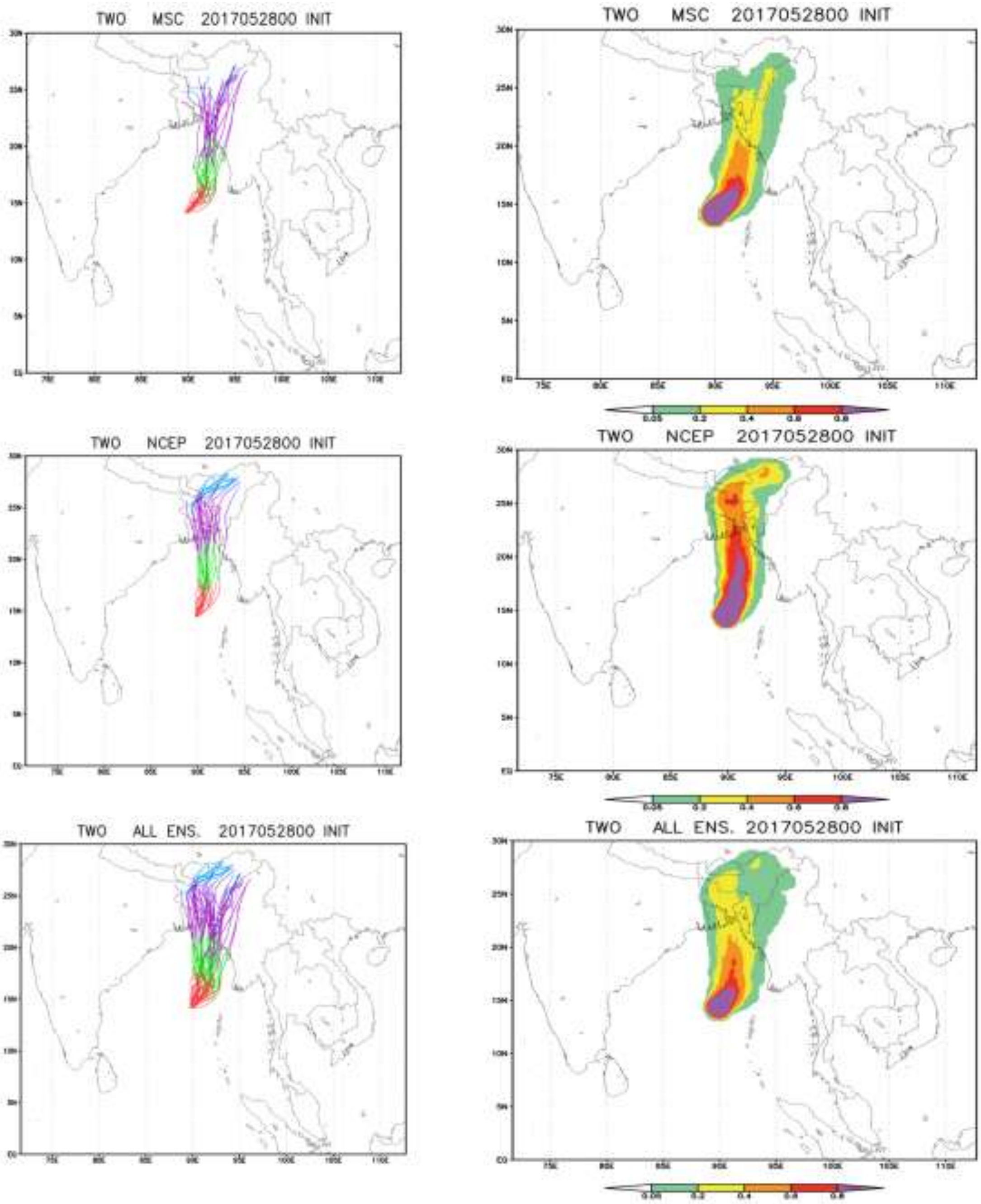


Fig. 18 (a): EPS track and strike probability forecast based on 0000 UTC of 28th May, 2017.

MSC and NCEP probabilistic and deterministic tracks based on 0000 UTC of 29th May are presented in **Fig. 18 (b).** MSC ensemble members predicted 60-80 % strike probability over southeast Bangladesh close to south of Chittagong. However, NCEP ensemble members predicted 80-100 % strike probability to the north of Chittagong. All ensemble members were predicting 60-80 % strike probability over southeast Bangladesh close to south of Chittagong.

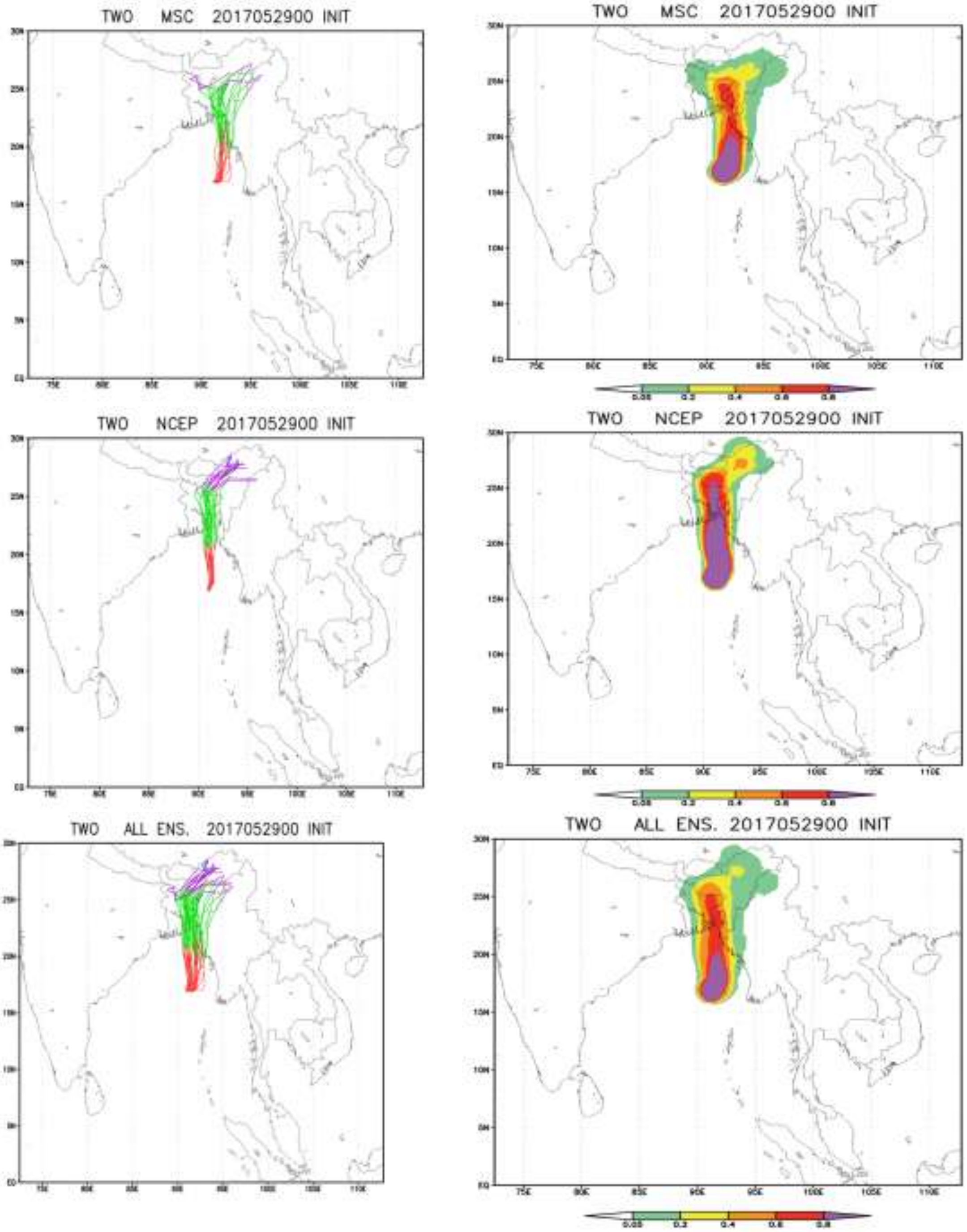


Fig. 18 (b): EPS track and strike probability forecast based on 0000 UTC of 29th May, 2017

UKMO and NCEP probabilistic and deterministic tracks based on 1200 UTC of 29th are presented in **Fig. 18 (c).** Ensembles from UKMO predicted 60-80 % strike probability over southeast Bangladesh. Ensembles from NCEP predicted 80-100 % strike probability over southeast Bangladesh. All ensemble members were predicting 80-100% strike probability over southeast Bangladesh close to south of Chittagong.

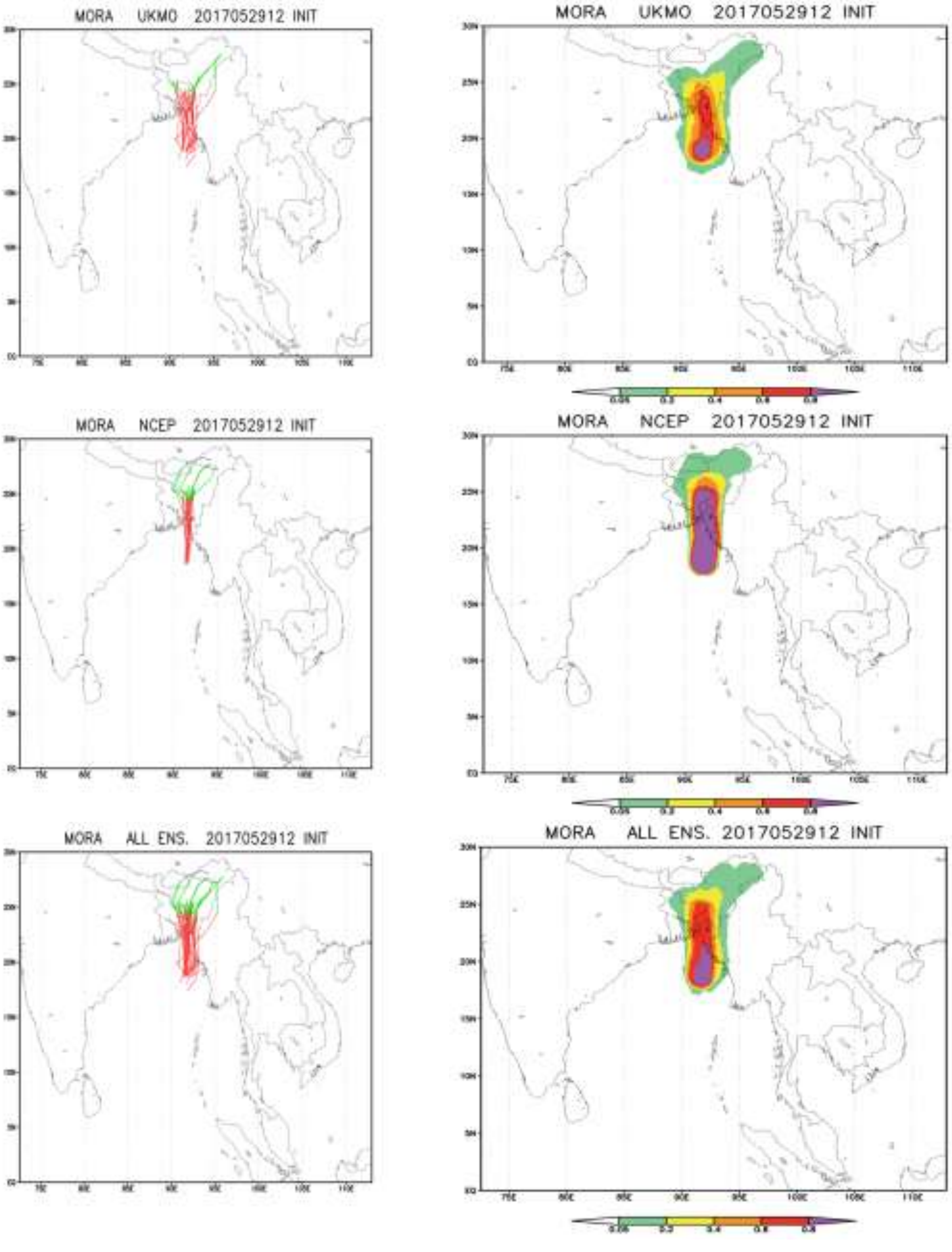


Fig. 18 (c): EPS track and strike probability forecast based on 1200 UTC of 29th May, 2017

12 hours prior to landfall both UKMO and NCEP members were predicting landfall close to south of Chittagong. However, 24 and 48 hours prior to landfall, MSC predicted landfallfall over southeast Bangladesh while NCEP members predicted landfall pver southwest Bangladesh.

Composite forecast track based on various initial conditions by HWRF and observed track is presented in Fig.19. It is seen that HWRF could predict predict landfall over southeast Bangladesh close to Chittagong based on initial conditions of 0600 UTC of 28th to 0000 UTC of 30th. However, based on 0000 UTC initial conditions 960 hours prior to landfall), it predicted landfall near Teknaf.

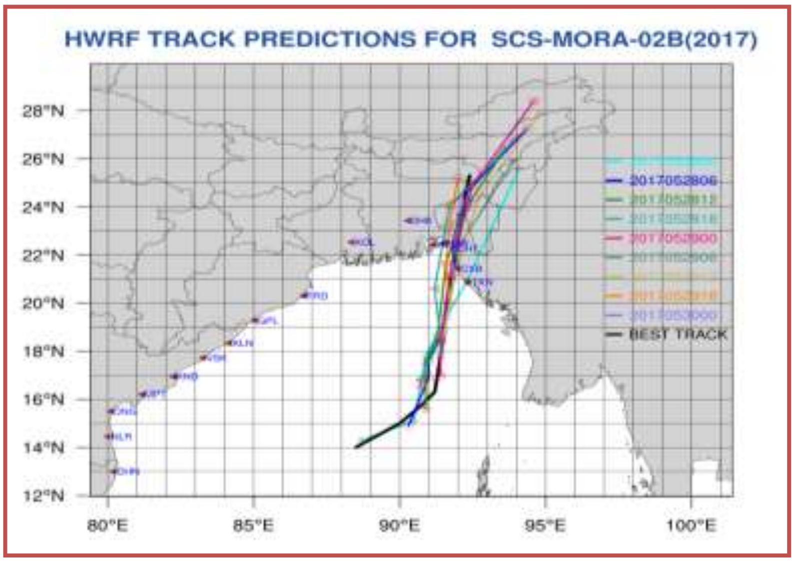


Fig. 19: Observed track and forecast tracks by HWRF based on initial conditions during 0000 UTC of 28th to 30th May

Table 6: Average track forecast errors (Direct Position Error (DPE)) in km

Lead time	12 hr	24 hr	36 hr	48 hr	60 hr
IMD-GFS	58(4)	110(4)	136(3)	189(2)	225(1)
IMD-WRF	79(4)	112(4)	160(3)	290(2)	335(1)
JMA	76(4)	60(4)	111(3)	146(2)	208(1)
NCEP	43(4)	81(4)	120(3)	149(2)	178(1)
UKMO	100(4)	119(4)	55(3)	98(2)	81(1)
ECMWF	68(4)	82(4)	139(3)	81(2)	185(1)
IMD-HWRF	47(9)	49(7)	79(6)	30(4)	114(2)
IMD-MME	53(4)	66(4)	44(3)	43(2)	30(1)
NCUM	127(5)	113(3)	135(2)	214(2)	234(1)
UMERG	124(2)	75(2)	94(2)	175(1)	-
NEPS	93(2)	101(2)	130(2)	151(1)	250(1)
ACCESS	51(3)	66(1)	125(1)	-	

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

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 6. The average cross track errors (CTE) and along track errors (ATE) are presented in Table 7 (a-b). From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of HWRF were the least followed by MME for 12, 24 & 48 hours lead period. Average track errors of IMD-MME were the least followed by UKMO and HWRF for 60 hours lead period.

Table 7 (a). Average cross-track forecast errors (CTE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr
IMD-GFS	39	97	132	187	221
IMD-WRF	24	50	63	92	141
JMA	33	42	103	134	177
NCEP	28	77	110	119	148
UKMO	53	53	44	76	76
ECMWF	36	49	103	42	160
IMD-HWRF	14	11	9	22	72
IMD-MME	20	27	28	36	29
NCUM	85	65	135	170	225
UMERG	60	50	85	145	-
NEPS	58	68	135	148	240
ACCESS	35	65	98	-	-

Table 7(b). Average along-track forecast errors (ATE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr
IMD-GFS	38	49	27	26	42
IMD-WRF	64	97	140	269	304
JMA	64	33	40	54	109
NCEP	28	26	39	89	99
UKMO	77	99	23	55	27
ECMWF	46	57	84	62	93
IMD-HWRF	119	132	177	144	205
IMD-MME	47	60	23	16	10
NCUM	68	78	50	79	60
UMERG	100	58	48	102	-
NEPS	59	68	39	39	80
ACCESS	40	10	79	-	-

Above tables show that DPE was largely contributed by ATE that is the errors in speed of movement of the storm, whereas CTE shows that forecast tracks were close to the observed track.

Landfall point and time forecast errors are presented in Table 8 and 9. Landfall point forecast errors were the least by IMD-MME, WRF-VAR and ECMWF followed by HWRF for various lead periods. Landfall time errors were the least for HWRF for all lead periods except for 60 hours.

Table 8: Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Forecast Lead Time (hour) →	**16:30 hr**	**18:30 hr**	**40:30 hr**	**52:30 hr**
Based on	**29 May/12z**	**29 May/00z**	**28 May/12z**	**28 May/00z**
IMD-GFS	108	144	155	156
IMD-WRF	25	11	59	143
JMA	25	128	158	155
NCEP	108	144	138	138
UKMO	119	11	115	196
ECMWF	25	56	105	56
IMD-MME	25	30	105	25
HWRF	56	73	44	114

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

Table-9. Landfall time forecast errors (hour) at different lead time (hr)
('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	**16:30 hr**	**18:30 hr**	**40:30 hr**	**52:30 hr**
Based on	**29 May/12z**	**29 May/00z**	**28 May/12z**	**28 May/00z**
IMD-GFS	+01:00	+02:30	-02:00	-02:30
IMD-WRF	+02:30	+02:00	+07:30	+05:30
JMA	-01:30	+02:30	+00:30	+01:00
NCEP	+00:30	+02:30	+02:30	+01:30
UKMO	-09:30	-03:30	-05:30	-03:30
ECMWF	-04:30	-04:30	-01:00	-04:30
IMD-MME	-02:30	-00:30	+01:30	-01:30
HWRF	0	0	0	-4:00

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

The intensity forecasts of IMD-SCIP model and HWRF model are shown in Table 10. The errors by IMD-SCIP were the least followed by HWRF. The probability of rapid intensification (RI) index of IMD is shown in Table 11. 24 hours prior to landfall it predicted HIGH probability of rapid intensification. 36 and 48 hours prior to landfall it predicted probability of rapid intensification as LOW. However, the system didn't show any rapid intensification.

Table 10: 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 →	12 hr	24 hr	36 hr	48 hr
IMD-SCIP (AAE)	4.5(4)	7.0(3)	5.5(2)	14.0(1)
IMD-HWRF (AAE)	7.3(9)	7.4(7)	5.8(6)	13.0(4)
IMD-SCIP (RMSE)	5.2(4)	7.5(3)	6.5(2)	14.0(1)
IMD-HWRF (RMSE)	9.5(9)	8.5(7)	6.4(6)	14.5(4)

( ): No of forecasts verified

Table 11: Probability of Rapid intensification

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) occurred in 24h
00/28.05.2017	22 %	LOW	20
12/28.05.2017	22 %	LOW	20
00/29.05.2017	72.7 %	HIGH	15

9.4. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model are presented in **Fig.20**.

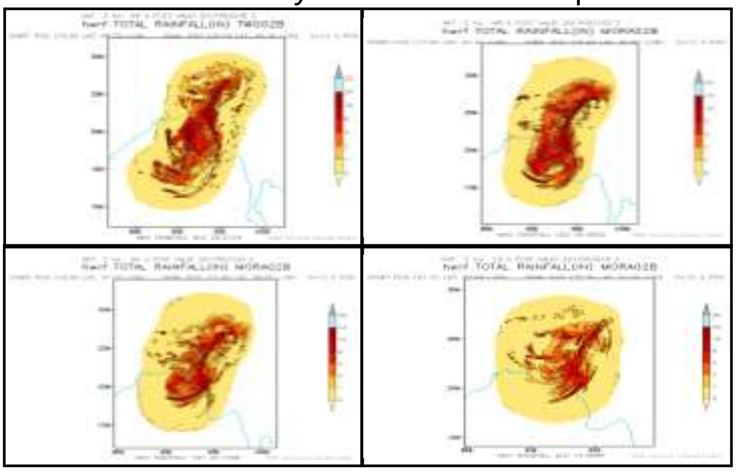


Fig.20: Heavy rainfall forecast by HWRF based on initial conditions of 0000 UTC of 28th-30th May, 2017.

It indicates that HWRF model could capture the occurrence of rainfall over parts of southeast Bangladesh, Myanmar and northeastern states like Assam, Manipur, Nagaland, Mizoram, Arunachal Pradesh based on initial conditions of 0000 UTC of 28th - 30th.

10.5 Storm surge forecast

IMD predicted storm surge forecast based on guidance from Indian National Centre for Ocean Information Services (INCOIS) Advance Circulation (ADCIRC) model and Indian Institute of Delhi. IMD predicted Storm surge of about 1 to 1.5 m height above astronomical tide at the time of landfall over low lying areas of Bangladesh between Sitakund and Uttar Jaldi at the time of landfall. Storm surge forecast by INCOIS is presented in **Fig.21**.

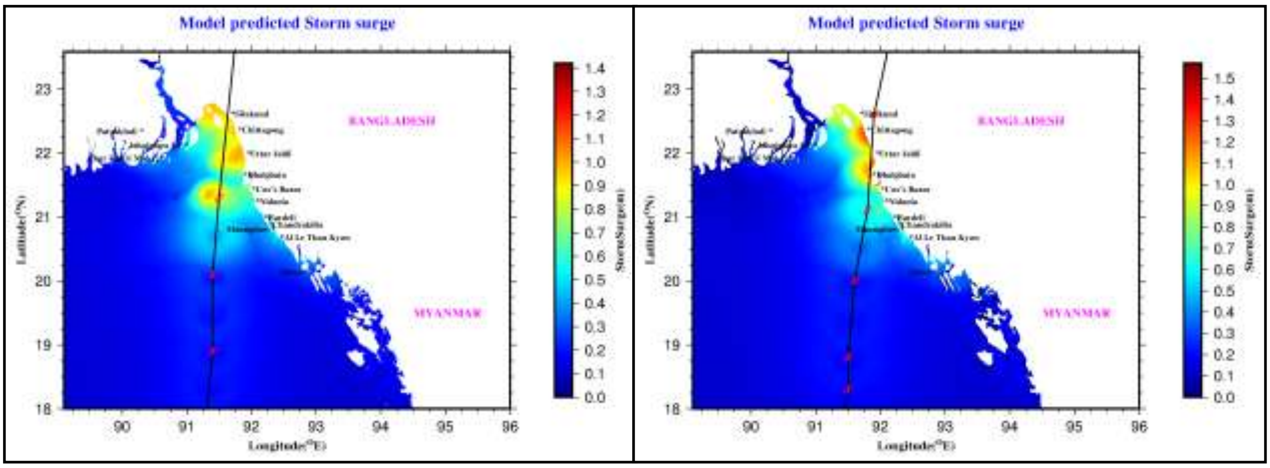


Fig. 21: Storm Surge Forecast issued by INCOIS on 29th and 30th May, 2017.

10. Operational Forecast Performance

Forecast Performance

- **(i)** The first information regarding formation of a low pressure area over southeast & adjoining central Bay of Bengal was issued in the morning of 25th May.
- **(ii)** The first information regarding formation of depression over southeast BOB during next 48 hours (i.e. 28th May) was issued on 26th May and depression formed over southeast BOB in the morning of 28th (48 hours in advance of formation of depression).
- **(iii)** In it's first bulletin based on 0000 UTC of 28th May, RSMC New Delhi indicated the nearly north-northeastward movement of system towards Bangladesh coast with landfall in the forenoon of 30th (52 hours prior to landfall).
- **(iv)** The first bulletin indicating north-northeastwards movement and landfall over Bangladesh coast between longitude 91.0 ºE and 92.0ºE around noon of 30th May was issued on 0300 UTC of 28th (48 hours prior to landfall).
- **(v)** The landfall point forecast error is about 35, 59 and 00 km respectively for 12, 24 and 36 hrs lead period of forecast and landfall time forecast error was almost NIL for all the above forecast times. (Table 12)
- **(vi)** The track forecast error for 12, 24 and 48 hrs lead period are 27, 22 and 73 km respectively against the last five years (2012-2016) average track forecast error of 60, 97 and 149 km. The track forecast skill was about 64%, 87% and 86% for 12, 24 and 48 hrs lead period respectively against the last five years

(2012-2016) average track forecast skill of 44%, 54% and 67% (Table 13). All forecast tracks alongwith observed tracks are shown in Fig.17.

(vii) The absolute intensity (wind) forecast error for 12, 24 and 48 hrs lead period are 2.1, 3.0 and 3.4 knots against the LPA of 6.5, 10.7 and 13.8 knots respectively (Table 14).

(viii) Typical graphical products displaying observed and forecast track with cone of uncertainty and wind distribution forecast are presented in Fig 18.

(ix) It caused heavy rainfall over northeastern states and squally winds over Mizoram and Tripura. Regular bulletins were issued to disaster management agencies of central level and states of West Bengal, Tripura, Manipur, Mizoram, Nagaland, Assam, Meghalaya, Arunachal Pradesh and Andaman & Nicobar Islands during the period.

(x) Every three hourly TC Advisories were issued to central & state level disaster managers, media general public and WMO/ESCAP member countries.

(xi) Every six hourly TCAC Advisories for issued for civil aviation were issued.

(xii) The numerical weather prediction (NWP) and dynamical statistical models provided reasonable guidance with respect to its genesis, track and intensity of the system.

10.1 Operational Genesis forecast

- The first information regarding formation of a low pressure area over southeast & adjoining central Bay of Bengal was issued in the morning of 25th May.
- The first information regarding formation of depression over southeast BOB during next 48 hours (i.e. 28th May) was issued on 26th May and depression formed over southeast BOB in the morning of 28th (48 hours in advance of formation of depression).

10.2. Operational landfall forecast error and skill

The operational landfall forecast errors and skill are presented in Table 12. The landfall point error (LPE) has been about 35, 59 and 00 km against long period average (2012-16) of 36.3, 56.3 and 60.6 km respectively for 12, 24 and 36 hrs lead period of forecast and landfall time forecast error was almost nil for all the above forecast times.

Observed track alongwith forecast tracks based on different lead periods is presented in **Fig.22**. It indicates that for all lead periods, the operational forecast of track was highly consistent and was along the observed track. An example of forecast track along with cone of uncertainty and quadrant wind distribution around the centre of cyclone issued on 0000 UTC of 11th December and observed track is presented in **Fig.23**.

Table 12: Landfall Point and Time Error in association with SCS Mora

Lead Period (hrs)	Base Time (UTC)	Landfall Point ($^0N/^0E$)		Landfall Time (UTC)		Operational Error		LPA error (2012-16)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	29/1500	22.3/91.8	22.0/91.9	30/0430	30/0430	35	0.0	36.5	2.5
24	29/0300	22.5/91.7	22.0/91.9	30/0500	30/0430	59	0.5	56.3	4.2
36	28/1500	22.3/91.8	22.0/91.9	30/0400	30/0430	00	0.5	60.6	4.7
48	28/0300	22.5/91.7	22.0/91.9	30/0900	30/0430	59	4.5	93.5	4.7

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
Forecast is verified upto 48 hrs only due to short life period of the cyclone

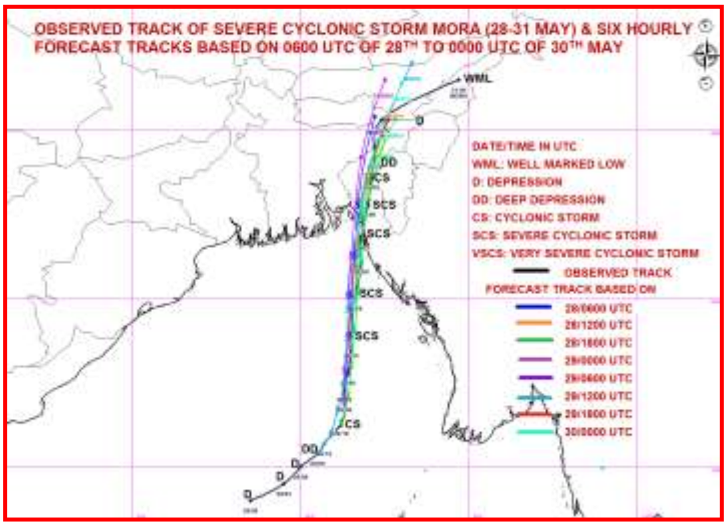


Fig.22: Observed and forecast tracks of SCS, MORA

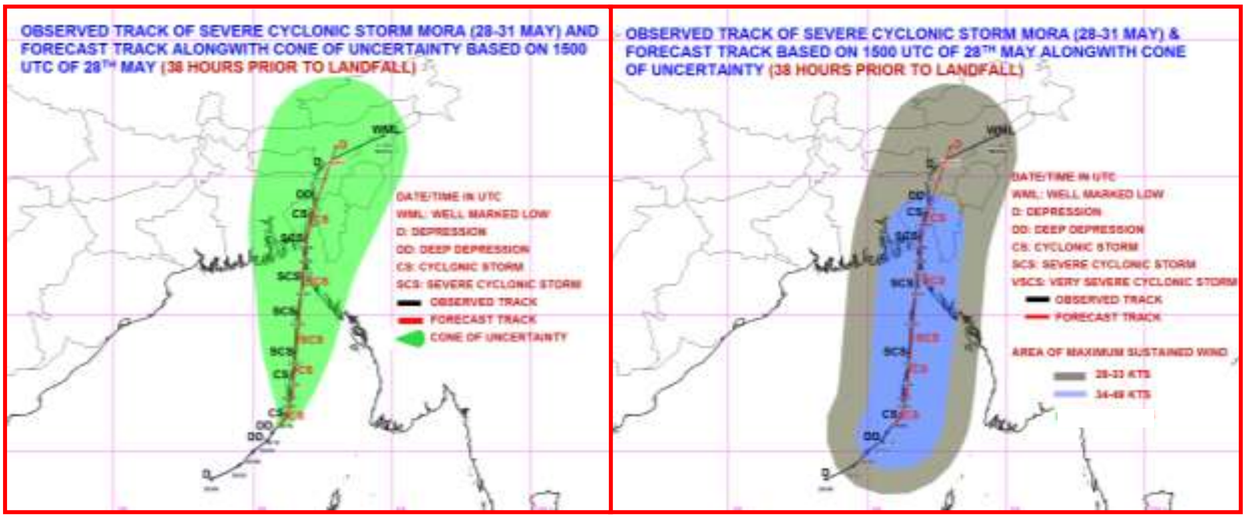


Fig.23: Observed track of SCS Mora (28-31 May, 2017) and forecast track based on 1500 UTC of 18th May alongwith (a) Cone of uncertainty and (b) Quadrant wind distribution

10.3 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 13. The track forecast error for 12, 24 and 48 hrs lead period were 27, 22 and 73 km respectively against the last five years (2012-2016) average (LPA) track forecast error of 60, 97 and 149 km. The track forecast skill was about 64%, 87% and 86% for 12, 24 and 48 hrs lead period respectively against the last five years (2012-2016) average track forecast skill of 44%, 54% and 67% (Table 13). It may be mentioned here that for all lead periods, the errors were significantly less as compared to LPA and skills were exceptionally better.

Table 13: Average Track forecast error in association with SCS Mora

Lead Period (hrs)	N	Average track forecast error (km)	Skill (%)	LPA (2012-16)	
				Track forecast error (km)	Skill (%)
12	8	27.2	63.6	59.7	43.7
24	6	22.5	86.7	97.2	53.6
36	4	34.3	88.2	119.4	63.4
48	2	73.5	86.0	149.1	67.2

N: No. of observations verified, LPA: Long Period Average (2012-16)
Forecast verified upto 48 hours due to short life period of system.

10.4 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 14. The operational AE in intensity forecast has been significantly less than LPA as it was about 2.1, 3.0 and 3.4 knots against LPA of 6.5, 10.7 and 13.8 knots for 12, 24 and 48 hours lead period. Similarly, operational RMSE in intensity forecast has been about 2.3, 3.6 and 3.8 knots against LPA of 9.0, 14.4 and 20.8 knots for 12, 24 and 48 hours lead period respectively. The skill in intensity forecast with reference to AE is about 83.4%, 84.8% and 93.3% for 12, 24 and 48 hours lead period.

Table 14: Average Intensity forecast error in association with SCS Mora

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	8	2.1	2.3	83.4	88.1	6.5	9.0
24	6	3.0	3.6	84.8	87.4	10.7	14.4
36	4	10.8	12.5	64.0	64.7	13.8	18.5
48	2	3.4	3.8	93.3	92.9	15.5	20.8

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2012-16). Forecast verified upto 48 hours due to short life period of system.

10.5. 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 15-17. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table 15. Verification of Heavy Rainfall Forecast

<table>
<tr><th>Date/Time (UTC) of issue</th><th>Heavy rainfall warning for the date</th><th>Realised 24-hour heavy rainfall ending at 0300 UTC of date</th></tr>
<tr><td>28.05.2017
0300</td><td>30th May 2017: Heavy to very heavy rainfall at isolated places over south Assam, Meghalaya, Tripura and Mizoram; and heavy rainfall at isolated places over Arunachal Pradesh and Nagaland.
31st May 2017: Heavy to very heavy rainfall at a few places and isolated extremely heavy rainfall over Assam & Meghalaya. Heavy to very heavy rainfall at isolated places over Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh.</td><td rowspan="4"><u>31.05.2017</u>
Arunachal Pradesh: Pasighat AERO and Basar-8 each
Assam & Meghalaya: Halflong and B P Ghat-11 each, Lumding-10, Shillong C.S.O.-9, Lakhipur-8 and Karimganj, Chauldhowaghat, Matijuri, Barpathar, Jia Bharali N T Xing and N.Lakhimpur/Lilabari-7 each
Nagaland, Manipur, Mizoram & Tripura: Lunglei and Serchip (Hydro)-10 each and Kohima-7.

<u>01.06.2017</u>
Arunachal Pradesh: Roing-11
Assam & Meghalaya: Karimganj-9, A P Ghat-8, Mawsynram, Cherrapunji (RKM),

Cherrapunji & Silchar-7 each
Manipur, Mizoram & Tripura:
Agartala AERO-13
Kailashahar AERO-10</td></tr>
<tr><td>29.05.2017
0300</td><td>29th May 2017: Heavy rainfall at isolated places to commence over Tripura and Mizoram from today evening, the 29th May, 2017.
30th May 2017: Heavy to very heavy rainfall at a few places and isolated extremely heavy rainfall over Assam & Meghalaya. Heavy to very heavy rainfall at isolated places over Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh.
31st May 2017: Heavy to very heavy rainfall at isolated places over Assam & Meghalaya, Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh.</td></tr>
<tr><td>30.05.2017
0300</td><td>30th May 2017: Heavy to very heavy rainfall at a few places and isolated extremely heavy rainfall over Assam & Meghalaya. Heavy to very heavy rainfall at isolated places over Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh.
31st May 2017: Heavy to very heavy rainfall at isolated places over Assam & Meghalaya, Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh.</td></tr>
<tr><td>31.05.2017
0000</td><td>Heavy to very heavy rainfall at isolated places very likely over south and eastern Assam, eastern Meghalaya, Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh during next 24 hours.</td></tr>
</table>

Table 16. Verification of Gale Wind Forecast

Date/ Time(UTC)	Squally wind Forecast	Recorded wind speed
28.05.2017 0300	Squally winds speed reaching 40-50 kmph gusting to 60 kmph would prevail along & off Andaman Islands and adjoining Sea areas during next 48 hours. Squally winds speed reaching 45-55 kmph gusting to 65 kmph would prevail over South Assam, Meghalaya, Mizoram, Manipur and Tripura on 30th May and along & off West Bengal coast on 29th & 30th.	Aizawl/ Lengpui : 35 knots on 30th May 2017
29.05.2017 0300	-do-	
30.05.2017 0300	Squally winds speed reaching 60-70 kmph gusting to 80 kmph would prevail over Mizoram and Tripura during next 24 hours. Squally winds speed reaching 45-55 kmph gusting to 65 kmph would prevail over South Assam, Meghalaya & Manipur and along & off West Bengal coast during next 24 hours.	

Table 17. Verification of Storm Surge Forecast issued by IMD

Date/ Time(UTC)	Storm Surge Forecast	Recorded storm surge
29.05.2017 0300 (21 hours in advance)	The storm surge of height of about 1 to 1.5 meter above astronomical tides is likely to inundate over low lying areas of Bangladesh coast between Sitakund and Uttar Jaldi at the time of landfall.	Not received

11. Bulletins issued by IMD

11.1 Bulletins issued by Cyclone Warning Division, New Delhi

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.
- **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 numerical weather prediction (NWP) modeling groups in India for generation/relocation of vortex in the model so as to improve the track and intensity forecast by the 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, NDMA, chief secretaries Andaman & Nicobar Islands, West Bengal, Assam, Arunachal Pradesh, Meghalaya, Manipur, Nagaland, Mizoram and Tripura. The bulletin also contained the expected damage and suggested action by disaster managers and general public. These bulletins were also issued to Railways, surface transport, Defence including Indian Navy & Indian Air Force, Ministry of Agriculture, Ministry of Information and Broadcasting etc.
  - **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. Typical graphical products displaying track with cone of uncertainty and wind distribution forecast are presented in Fig 18.
  - **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 and hourly updates on the day of landfall 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.

Bulletins issued by Cyclone Warning services of IMD in association with the system are given in Table 18 (a-b).

Table 18 (a): Bulletins issued by Cyclone Warning Division, India Meteorological Department

S.N	Bulletin	No. of Bulletin	Issued to
1	National Bulletin	23	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, West Bengal, Tripura, Manipur, Mizoram, Nagaland, Assam, Meghalaya and Arunachal Pradesh.
2	RSMC Bulletin	22	1. IMD's website 2. WMO/ESCAP member countries through GTS and E-mail. 3. Indian Navy, IAF by E-mail
3	Tropical Cyclone Advisory Centre Bulletin (Text & Graphics)	10	1. Met Watch offices in Asia Pacific regions 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	10	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	Warnings through SMS	5 times	SMS through (i) IMD network for disaster managers at national level and concerned states (ii) Department of Electronics and Information Technology
6	Warnings through Social Media	5	Cyclone Warnings were uploaded on Social networking sites like Face book and Tweeter since inception to weakening of system (every time when there was change in intensity).
7	Press Release	2	Disaster Managers, Media persons by email and uploaded on website
8	Press Briefings	Daily	Regular briefing daily

Table-18 (b): Bulletins issued by RMC Chennai/ACWC Kolkata/CWC Bhubaneswar

S.No.	Type of Bulletin Number	No. of Bulletins issued by			
		RMC Chennai	RMC Guwahati	ACWC Kolkata	CWC BBN
1.	Sea Area Bulletins	-	-	15	-
2.	Coastal Weather Bulletins	-	-	WB Coast- 8 A & N Coast- 8	6
3.	Fishermen Warnings issued	-	-	WB Coast- 12 A & N Coast- 12	12
4.	Port Warnings	-	-	WB Coast- 13 A & N Coast- 10	12
5.	Heavy Rainfall Warning	-	13	WB Coast- 1 A & N Coast- 1	1
6.	Gale/Gusty* Wind Warning	-	0/14*	-	-

7.	Information & Warning issued to State Government and other Agencies	Frequently briefed to Chief Secretaries, Disaster Management Agencies & Media	Frequently briefed to Chief Secretaries, Disaster Management Agencies & Media	Govt. of WB-6, A & N Administration - 4 by ACWC Kolkata & 17 by MO Port Blair	16

12. Summary and Conclusion:

The SCS Mora formed from a southeast Bay of Bengal & adjoining areas of central Bay of Bengal in the morning of 25th May and concentrated into a depression in the morning of 28th. The system gradually intensified into a CS in the late evening of 28th and into an SCS in the evening of 29th. Moving nearly north-northeastwards, it crossed Bangladesh coast close to south of Chittagong in the forenoon of 30th. The severe cyclonic storm, MORA developed in the onset phase of southwest monsoon. Its intensification and movement towards north-northeast helped in advance of monsoon over the BOB and some parts of northeastern states

IMD utilised all its resources to monitor and predict the genesis, track and intensification of SCS Mora. For 12, 24 and 36 hrs lead period, the operational landfall point error was 35, 59 & 00 km and landfall time error was almost NIL for all lead periods. For 12, 24 and 48 hours lead period, the track forecast error was 27, 22 & 73 km and intensity forecast error based on absolute error was 2.1, 3.0 & 3.4 kts.

14. Acknowledgements:

India Meteorological Department (IMD) duly acknowledges the contribution from Bangladesh Meteorological Department for their valuable support especially for the hourly observations and imageries from Khepupara, Cox's Bazar and Molvibazar DWR on the day of landfall. We also thank contribution from all the stake holders who contributed to the successful monitoring, prediction and warning service of SCS Mora by IMD. We acknowledge the contribution of National Centre for Medium Range Weather Forecasting Centre (NCMRWF), Noida, Indian National Centre for Ocean Information Services (INCOIS), Hyderabad National Institute of Ocean Technology (NIOT), Chennai and Space Application Centre, Indian Space Research Organisation (SAC-ISRO), Ahmedabad and IIT Bhubaneswar, 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, Regional Meteorological Centre Guwahati, Meteorological Centre Agartala, Agricultural Meteorology Division, Pune, Numerical Weather Prediction Division, Satellite Division and Information System and Services Division at IMD, New Delhi is also acknowledged.