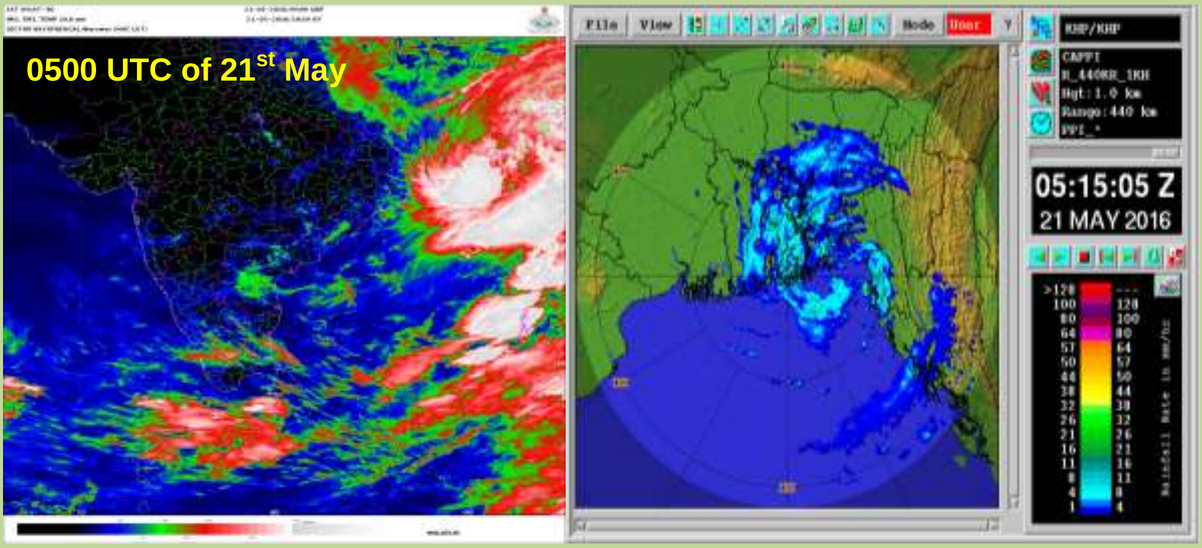
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Cyclonic Storm,'Roanu' over the Bay of Bengal (17-22 May 2016): A Report



INSAT-3D enhanced colored IR imagery & DWR Khepupara imagery based on 0500 UTC of 21st May

Cyclone Warning Division

India Meteorological Department

New Delhi

JUNE 2016

Cyclonic Storm 'Roanu' over the Bay of Bengal
(17-22 May 2016)

1. Introduction

A low pressure area developed over southwest Bay of Bengal (BoB) off Sri Lanka coast in the evening of 14th May 2016. Moving northeastwards, it lay as a well marked low pressure area over southwest BoB and adjoining Sri Lanka in the morning of 15th. It further moved northwestwards and lay over Sri Lanka and adjoining areas of Gulf of Mannar & southwest BoB in the morning of 16th. Moving thereafter, north-northwestwards, it concentrated into a **depression (D)** and lay centered over southwest BoB off Tamil Nadu coast in the morning of 17th near latitude 11.0^{0}N and longitude 81.0^{0}E. It further moved nearly northwards, intensified into a **deep depression (DD)** and lay centred over westcentral and adjoining southwest BoB near latitude 13.3ºN and longitude 81.0 ºE at 0300 UTC of 18th. The favourable environmental conditions continued and the system moved north-northeastwards skirting Tamil Nadu and Andhra Pradesh coast. It intensified into a **cyclonic storm (CS)** over westcentral BoB and lay centered near latitude 15.1^{0}N and longitude 81.4^{0}E with maximum sustained winds of 35 knots around the system centre at 0000 UTC of 19th. The system continued to skirt along the east coast of India while moving northeastwards and intensified slightly with maximum sustained wind speed reaching 40 knots at 0600 UTC of 19th and to 45 knots at 1800 UTC 20th May. The system maintained its intensity of 45 knots and crossed Bangladesh coast near latitude 22.6^{0}N and longitude 91.6^{0}E, to the north of Chittagong around 1000 UTC of 21st May as a CS. After landfall, the system started weakening due to land interactions. Continuing its east-northeastward journey, the **CS** gradually weakened into a **DD** over Mizoram at 1800 UTC of 21st, into a depression over Myanmar and adjoining Manipur at 0000 UTC of 22nd and into a well marked low pressure area over Myanmar and adjoining Nagaland & Manipur at 0300 UTC of 22nd May. The observed track of the CS Roanu is shown in Fig.1. The salient features of the system are as follows.

- **(i)** CS Roanu followed a unique track, moving very close to Sri Lanka and east coast of India. It recurved northeastwards and crossed Bangladesh coast to the north of Chittagong.
- **(ii)** Lowest estimated central pressure (ECP) was 983 hPa with a pressure drop of 11 hPa.
- **(iii)** The CS travelled a distance of about 2300 km during its life period.
- **(iv)** The Accumulated Cyclone Energy (ACE) which is a measure of damage potential was about 1.8 X 10^4 $knot^2$.
- **(v)** The Power Dissipation Index which is a measure of loss due to CS was 0.74 X 10^6 $knot^3$.
- **(vi)** The life period of CS Roanu was 5 days.
- **(vii)** CS Roanu showed large scale diurnal variations w.r.t. its central cloud cover and spiral bands in terms of depth of cloud and area of coverage. While the

cloud mass intensified towards early morning, it showed signs of weakening towards sunset.

(viii) CS Roanu did not intensify to a severe cyclone inspite of its long travel over the sea mainly due to land interactions and above mentioned large scale diurnal variations.

(ix) Though it did not cross Sri Lanka and India coasts, it caused adverse weather like heavy rain and strong wind all along east coast of Sri Lanka and India. It was mainly due to the fact that the CS Roanu moved very close to the east coast of India and Sri Lanka. CS Roanu lay centered about 50 km east-southeast of Chennai at 0300 UTC of 18th, 68 km east-southeast of Machillipatnam at 0600 UTC of 19th, 35 km southeast of Kalingapatnam at 0600 UTC of 20th, 40 km southeast of Paradip at 1200 UTC of 20th and 70 km south-southeast of Sagar Island at 0000 UTC of 21st May.

(x) IMD predicted genesis of depression over southwest BoB on 17th May based on 0300 UTC observations of 14th May (about 72 hours in advance).

(xi) The nearly north-northeastward and northeastward movement of the system and landfall over Bangladesh was predicted since the formation of deep depression on 18th May morning (more than 72 hours in advance of landfall).

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

(xiii) First informatory message was issued on 13th May with forecast of associated weather including heavy rainfall, gale wind warnings for Tamil Nadu & Puducherry and Kerala coasts for next 48 hours. No landfall forecast was issued for any state in east coast of India. However, the warning against the heavy rainfall and squally/ gale winds along the coasts of Andhra Pradesh, Odisha and West Bengal were issued regularly to the concerned disaster managers, media and general public etc.

(xiv) Every three hourly TC Advisories were issued to WMO/ESCAP member countries including Sri Lanka and Bangladesh.

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

2. Monitoring of CS,'Roanu'

The cyclone was monitored & predicted continuously since its inception by IMD. The observed track of the cyclone over BoB during 17th -22nd May is presented in Fig.1. The best track parameters of the systems are presented in Table 1**.**

At the genesis stage, the system was monitored mainly with satellite observations. Various national and international NWP models and dynamical-statistical models including IMD's and NCMRWF's global and meso-scale models, dynamical statistical models for genesis and intensity 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.

3. Brief life history

3.1. Genesis

A trough of low lay over southwest Bay of Bengal (BoB) with embedded upper air cyclonic circulation extending upto 4.5 km above mean sea level at 0300 UTC of 14th May. Under its influence, a low pressure area developed over southwest Bay of Bengal off Sri Lanka coast in the evening of 14th May 2016. Moving north-northeastwards, it lay as a well marked low pressure area at 0300 UTC of 15th over southwest BoB and adjoining Sri Lanka. It further moved slightly northwestwards and lay over Sri Lanka and adjoining areas of Gulf of Mannar & southwest BoB at 0300 UTC of 16th. At 0300 UTC of 17th, the sea surface temperature was 30-31˚C, Ocean thermal energy was 100-120 KJ/cm^2, low level convergence was (20-30) x 10^{-5} second^{-1}, upper level divergence was about (20-30)x10^{-5} second^{-1}, the low level relative vorticity was about (100-150) x10^{-6} second^{-1}, vertical wind shear of horizontal wind was moderate (10-20 knots). Upper tropospheric ridge lay along 15.0˚N. Considering large scale features, Madden Julian Oscillation was also favourable and lay in Phase-3 with amplitude >1. Under these favourable conditions, the system moved north-northwestwards, concentrated into a **depression (D)** and lay centered at 0300 UTC of 17th over southwest BoB near latitude 11.0^{0}N and longitude 81.0^{0}E.

3.2. Intensification and Movement

At 0300 UTC of 18th, the sea surface temperature was 31˚C, Ocean thermal energy was 150 KJ/cm^2, low level convergence (30 x 10^{-5} second^{-1}), upper level divergence (40x10^{-5} second^{-1}) and low level relative vorticity (150-200x10^{-6} second^{-1}) increased, favouring intensification of the system. Upper tropospheric ridge lay along latitude 16.0^{0}˚N. MJO lay in phase-4 with amplitude > 1. Under the influence of favourable environmental conditions the system moved nearly northwards and intensified into a **deep depression (DD)** and lay centred over westcentral and adjoining southwest BoB at 0300 UTC of 18th near latitude 13.3ºN and longitude 81.0ºE. The favourable environmental conditions continued and at 0000 UTC of 19th, the upper tropospheric ridge shifted northwards and lay about 17.0^{0}N. The system moved north-northeastwards, intensified into a **cyclonic storm (CS)** with maximum sustained winds of 35 knots around the system centre at 0000 UTC of 19th. Under favourable environmental conditions the system skirted along the east coast of India and intensified slightly with maximum sustained wind speed reaching 45 knots at 1800 UTC 20th May. The system maintained its intensity and crossed Bangladesh coast near latitude 22.6^{0}N and longitude 91.6^{0}E around 1000 UTC as a CS. Thereafter, the system started weakening due to land interactions. Continuing its east-northeastward journey the system gradually weakened into a DD over Mizoram at 1800 UTC of 21st, into a depression over Myanmar and adjoining Manipur at 0000 UTC of 22nd and into a well marked low pressure area over Myanmar and adjoining Nagaland & Manipur at 0300 UTC of 22nd May.

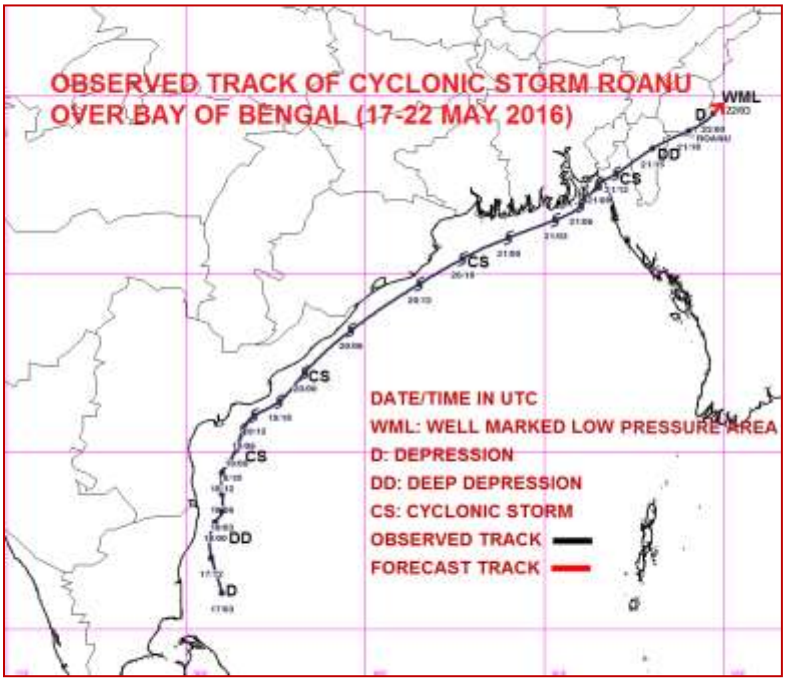


Fig.1 Observed track of CS,'Roanu' over BoB during 17th -22nd May 2016

Table 1: Best track positions and other parameters of the Cyclonic Storm, 'ROANU' over the Bay of Bengal during 17-22May, 2016

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
17/05/2016	0300	11.0/81.0	1.5	1000	25	3	D
	0600	11.3/80.9	1.5	999	25	3	D
	1200	12.0/80.7	1.5	998	25	3	D
	1800	12.5/80.7	1.5	998	25	4	D
18/05/2016	0000	13.0/80.8	1.5	998	25	4	D
	0300	13.3/81.0	2.0	997	30	5	DD
	0600	13.8/81.0	2.0	996	30	5	DD
	1200	14.4/81.0	2.0	996	30	5	DD
	1800	14.4/81.0	2.0	994	30	5	DD
19/05/2016	0000	15.1/81.4	2.5	990	35	7	CS
	0300	15.6/81.6	2.5	990	35	7	CS
	0600	15.6/81.6	2.5	988	40	8	CS
	0900	15.6/81.6	2.5	988	40	8	CS
	1200	16.0/81.9	2.5	988	40	8	CS
	1500	16.2/82.2	2.5	988	40	8	CS
	1800	16.4/82.6	2.5	988	40	8	CS
	2100	16.8/82.8	2.5	988	40	8	CS
20/05/2016	0000	17.2/83.3	2.5	988	40	8	CS
	0300	18.0/84.2	2.5	988	40	8	CS
	0600	18.4/84.6	2.5	988	40	9	CS

	0900	18.8/85.0	2.5	988	40	9	CS
	1200	19.7/86.5	2.5	987	40	9	CS
	1500	20.1/87.1	2.5	986	40	9	CS
	1800	20.4/87.7	2.5	984	45	11	CS
	2100	20.7/88.4	2.5	983	45	11	CS
21/05/2016	0000	21.0/89.0	3.0	983	45	11	CS
	0300	21.5/90.3	3.0	983	45	11	CS
	0600	21.9/91.0	3.0	983	45	11	CS
	0900	22.5/91.5	3.0	983	45	11	CS
	The system crossed southeast coast of Bangladesh near lat. 22.6^{0}N and long. 91.6^{0}E around 1000 UTC						
	1200	22.8/92.0		990	35	6	CS
	1500	23.5/93.0		992	30	4	DD
	1800	24.0/94.0		994	30	4	DD
22/05/2016	0000	24.5/94.7		996	20	3	D
	0300	The system weakened into a well marked low pressure area over Myanmar and adjoining Nagaland & Manipur					

The total precipitable water imageries (TPW) during 17th to 22nd May are presented in Fig.2. It indicates that due to cross equatorial flow warm and moist air continued to converge around the system centre till 19th. On 20th, it gradually decreased and it further decreased on 21st as the system moved to the northern latitude and crossed Bangladesh coast.

3.3 Movement

CS Roanu moved nearly northwards till midnight of 18th May. It then moved north-northeastwards till midnight of 19th and then northeast/ east-northeast for the remaining life period of the system. Under the influence of anticyclonic circulation located to the northeast of the system centre, it moved initially north-northwestwards and then it came close to the ridge and hence moved northwards till midnight of 18th. Thereafter, as the system transitioned to the north of the ridge, it moved initially north-northeastwards. Thereafter, on 20th, it came under the influence of trough in mid tropospheric westerlies lying to the west of system centre which helped in northeast/east-northeastwards movement of the system and also increase in translational speed of the system. The translational speed gradually increased from almost zero around midnight of 18th to 42 kmph by evening of 20th May. The six hourly movement of CS Roanu is presented in Fig.3. The system had a track length of about 2300 km during its life period.

The wind speed in middle and deep layer around the system centre is presented in Fig.4. It indicates that from 18th onwards, the middle to upper level steering flow was supporting the above direction and speed of movement. Under the influence of middle and upper tropospheric trough, the wind shear around the system between 200 and 850 hPa levels also increased rapidly on 20th and 21st. As the wind shear was east-southeasterly, the convective cloud mass was sheared towards west-northwestwards of the system centre till 20th. Thereafter, with the change in direction of wind shear as south/southwesterly, the convective cloud mass was sheared north/northeastwards on the day of landfall.

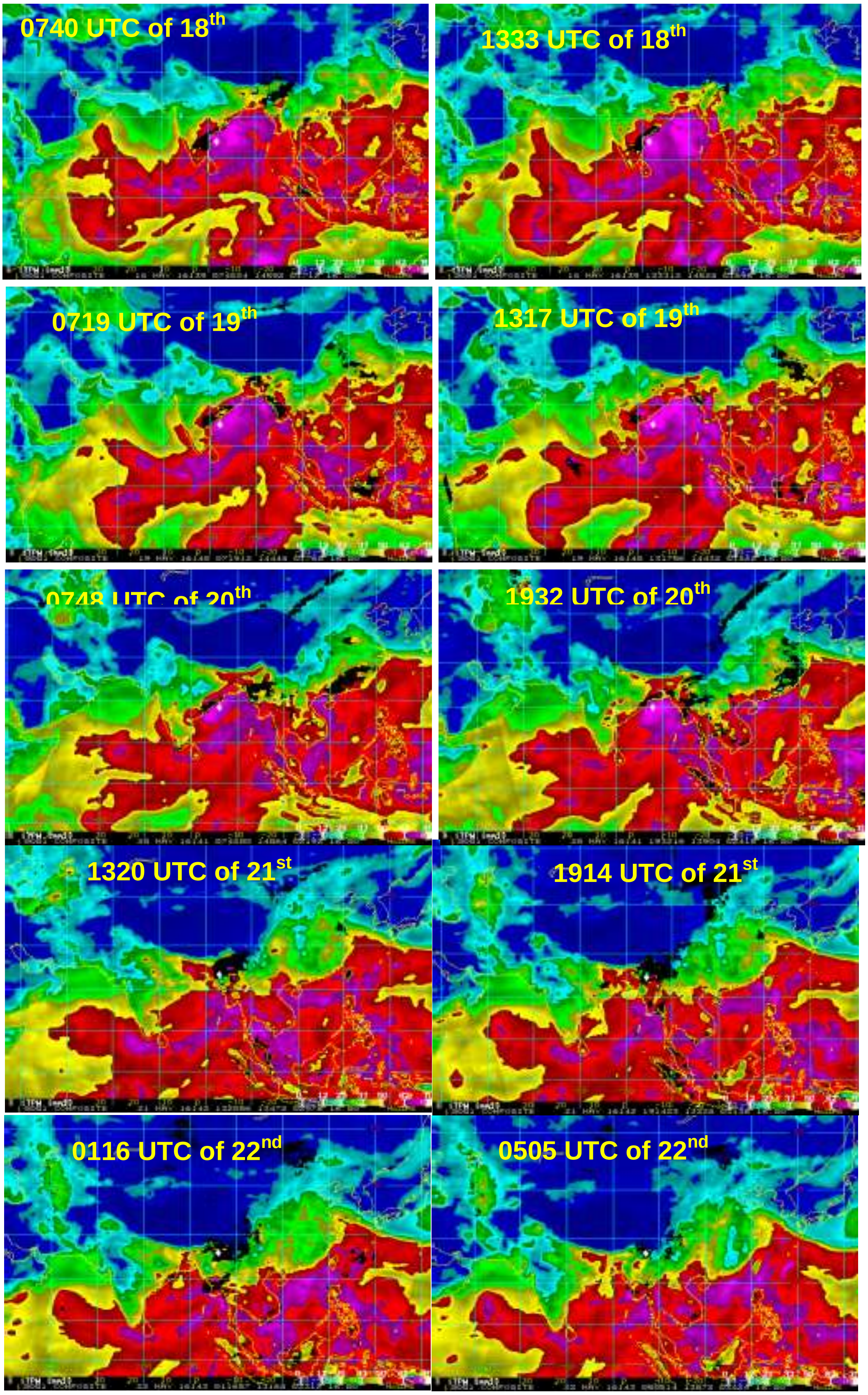


Fig.2 Total precipitable water imageries during 17th to 22nd May 2016

As a result even though the cyclone did not cross the Indian coast, the sheared convective cloud mass to the west-northwest caused heavy to very heavy rainfall all along the Indian coast. It also caused heavy to very heavy rainfall over Bangladesh and northeast states of India as well as Myanmar on 21st and 22nd due to shearing of convection to north/northeast.

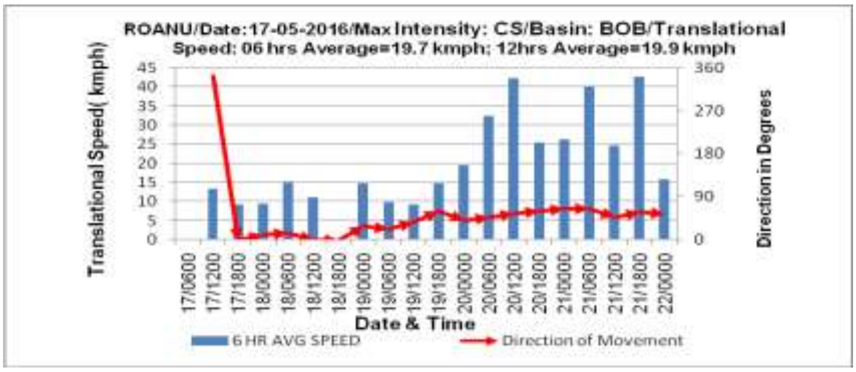


Fig.3 Six hourly average translational speed (kmph) and direction of movement in association with CS Roanu

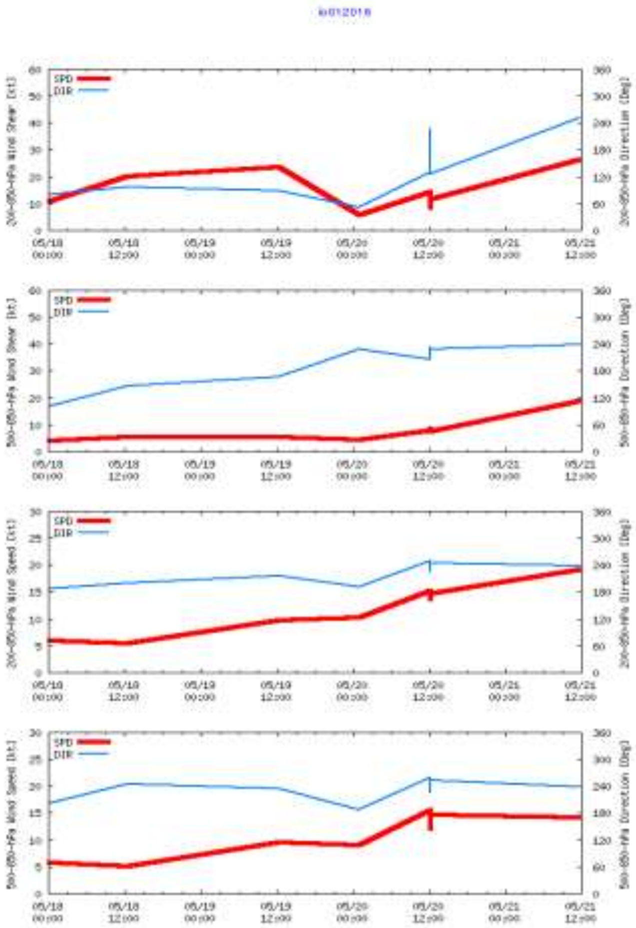


Fig.4 Wind shear and wind speed in the middle and deep layer around the system during 18th to 21st May 2016.

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

The lowest estimated central pressure and the maximum sustained wind speed are presented in Fig.5. The lowest estimated central pressure had been 983 hPa. The estimated maximum sustained surface wind speed (MSW) was 45 knots during 1800 UTC of 20th to 0900 UTC of 21st May. At the time of landfall, the ECP was 983 hPa and MSW was 45 knots (cyclonic storm). The figure also indicates that the system did not intensify much despite its long journey over sea mainly because of its proximity with land. Throughout its life cycle, the system skirted along the east coast of India and lay as close as 50 km east-southeast of Chennai at 0300 UTC of 18th, 68 km east-southeast of Machillipatnam at 0600 UTC of 19th, 35 km southeast of Kalingapatnam at 0600 UTC of 20th, 40 km southeast of Paradip at 1200 UTC of 20th and 70 km south-southeast of Sagar Island at 0000 UTC of 21st May. The ECP and Vmax graph also indicates that the system intensified gradually till 1800 UTC of 20th, maintained its intensity till landfall at 1000 UTC of 21st and weakened gradually into a well marked low pressure area at 0300 UTC of 22nd May. There was no rapid intensification and rapid weakening of the system throughout its life cycle.

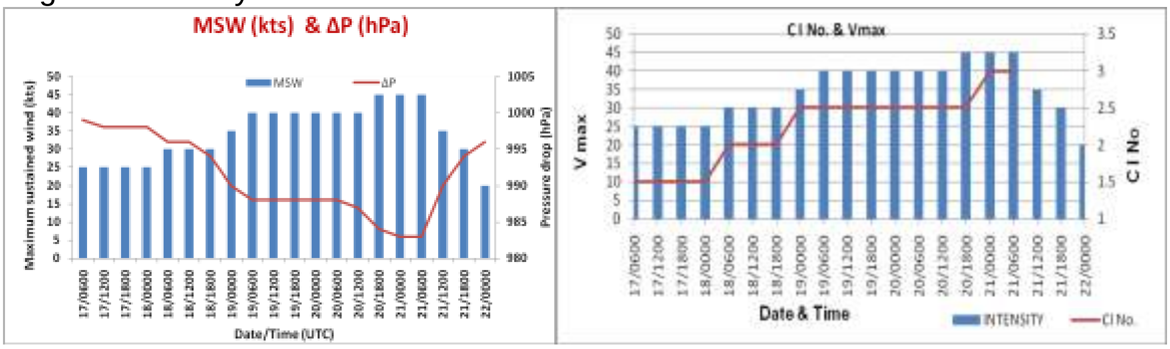


Fig.5 Lowest estimated central pressure and the maximum sustained wind speed

3.4. Structure

Sectorwise wind distribution around the system centre is presented in Fig.6. It depicts that maximum winds were observed in southeast sector followed by northeast and southwest sector. The wind distribution also showed diurnal variations like convection. Maxima in wind distribution and radius of maximum wind (RMW) were observed normally at 0600 UTC at a lag of 6 hours to convection maxima. Similarly minima was observed at 1800 UTC at a lag of about 6 hours from convection minima observed at 1200 UTC during 18th to 20th.

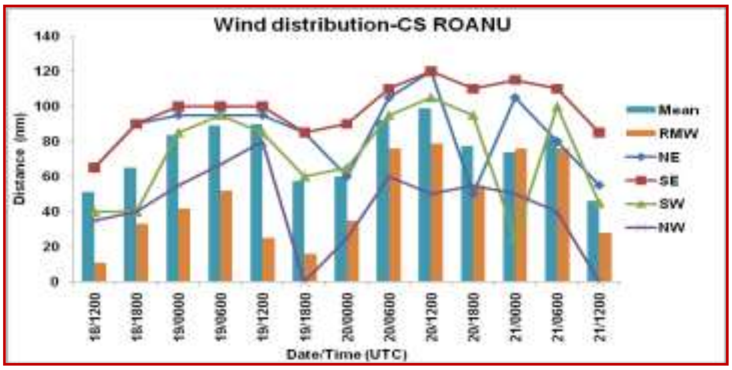


Fig.6 Sectorwise wind distribution of CS, Roanu.

4. Climatological aspects

Considering the area of genesis (+/- 2^0 around the genesis point), the cliamtological tracks of the TCs during 1891-2015 are presented in Fig.7. It indicates that climatologically, about 50% of the tracks moved northwestwards and crossed Tamil Nadu coast whereas another 50 % moved north-northeast/northeastwards. Out of the 3 systems recurving northeastwards, 2 dissipated over the sea and only 1 crossed West Bengal coast during May, 1936. Hence comparing the climatological tracks, the track of Roanu was unique in nature moving very close to the coast and recurving northeastwards towards Bangladesh coast.

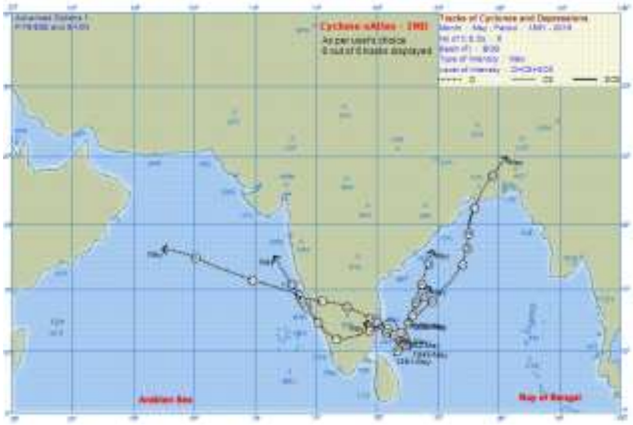


Fig7. Climatological tracks of TCs forming within +/- 2^0 around the genesis point during 1891-2015.

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 on 0300 UTC of 17^{th}. The cloud pattern was curved band type. Convection wrapped 0.2 on log 10 spiral. Associated broken low and medium clouds with embedded intense to very intense convection lay over north Sri Lanka, Tamil Nadu, Comorin, Palk Strait, Gulf of Mannar, southwest BoB and the area between between latitude 9.0^0N to 16.0^0N and west of longitude 85.0^0E. Lowest cloud top temperature (CTT) was -93^0C. At 0300 UTC of 18^{th}, the system attained the intensity of T 2.0. The cloud pattern was central dense overcast (CDO) type. Associated broken low and medium clouds with embedded intense to very intense convection lay over north Tamil Nadu, Andhra Pradesh, southwest BoB and adjoining westcentral BoB between latitude 10.0^0N to 18.0^0N and west of longitude 85.5^0E. Lowest cloud top temperature (CTT) was -93^0C. At 0300 UTC of 19^{th}, the system intensified to T2.5. Associated broken low and medium clouds with embedded intense to very intense convection lay over north Andhra Pradesh, adjoining Odisha and westcentral BoB between latitude 12.0^{0}N to 20.0^{0}N and west of longitude 90.0^{0}E. Lowest cloud top temperature (CTT) was -93^{0}C. At 1200 UTC of 19th, the intensity was T 2.5. Associated broken low and medium clouds with embedded intense to very intense convection lay over Andhra Pradesh and westcentral BoB between latitude 13.5^{0}N to 19.0^{0}N and west of longitude 86.0^{0}E. Lowest cloud top temperature (CTT) was -88^{0}C. LLCC was located on the east side of convection. The pattern was shear type with center 1/3 deg into dark grey. Convection associated with Roanu weakened considerably during previous 6 hrs. Cloud top temperatures warmed notably and organization diminished from a consolidated mass near the center to broken convection along the southern band. At 0300 UTC of 20th, intensity was T 2.5. Associated broken low and medium clouds with embedded intense to very intense convection lay over north coastal Andhra Pradesh, Odisha, westcentral and adjoining northwest BoB between latitude 14.0^{0}N to 20.0^{0}N and west of longitude 90.0^{0}E. Lowest cloud top temperature (CTT) was -93^{0}C. Convection ramped up suggesting diurnal variations. At 1200 UTC of 20th, intensity was T 2.5. Associated broken low and medium clouds with embedded intense to very intense convection lay over north coastal Andhra Pradesh, Odisha, northwest and adjoining westcentral BoB over the area north of latitude 15.5^{0}N and west of longitude 90.0^{0}E. Lowest cloud top temperature (CTT) was -90^{0}C. The convection showed increase in organisation during past six hrs. It continued to exhibit large scale diurnal variation with respect to central dense overcast clouds and the curved bands intensity and size. At 0300 UTC of 21st, the intensity was T 3.0. Associated broken low and medium clouds with embedded intense to very intense convection lay over Gangetic West Bengal, north & adjoining central BoB, south Bangladesh, Tripura, Manipur north of latitude 17.0^{0}N. Lowest cloud top temperature (CTT) was -93^{0}C. At 1000 UTC of 21st, the system crossed Bangladesh coast near north of Chittagong. At 1200 UTC of 21st, associated broken low and medium clouds with embedded intense to very intense convection lay over northeast BoB, Tripura, Manipur, Mizoram, southeast Bangladesh and south Assam. Lowest cloud top temperature (CTT) was -93^{0}C.

5.2 Microwave features

F-15, F-16, F-17 and GCOM-W1 microwave imageries of the CS Roanu covering its life period from 17th to 22nd May 2016 are presented in Fig.9. 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. It also helped in understanding the large scale diurnal variation of the system.

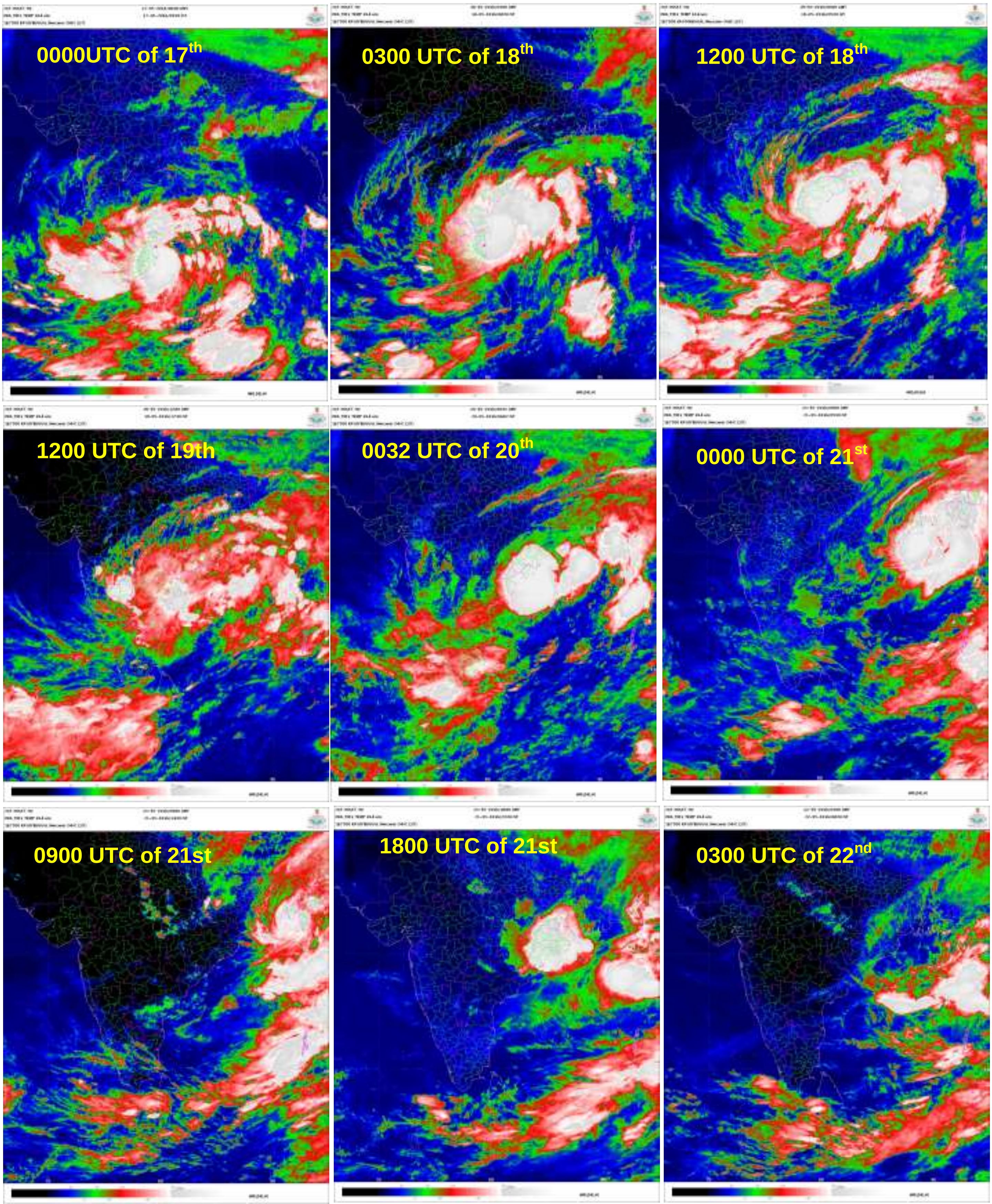


Fig.8(a) INSAT-3D enhanced colored imageries based on during 17-22 May 2016

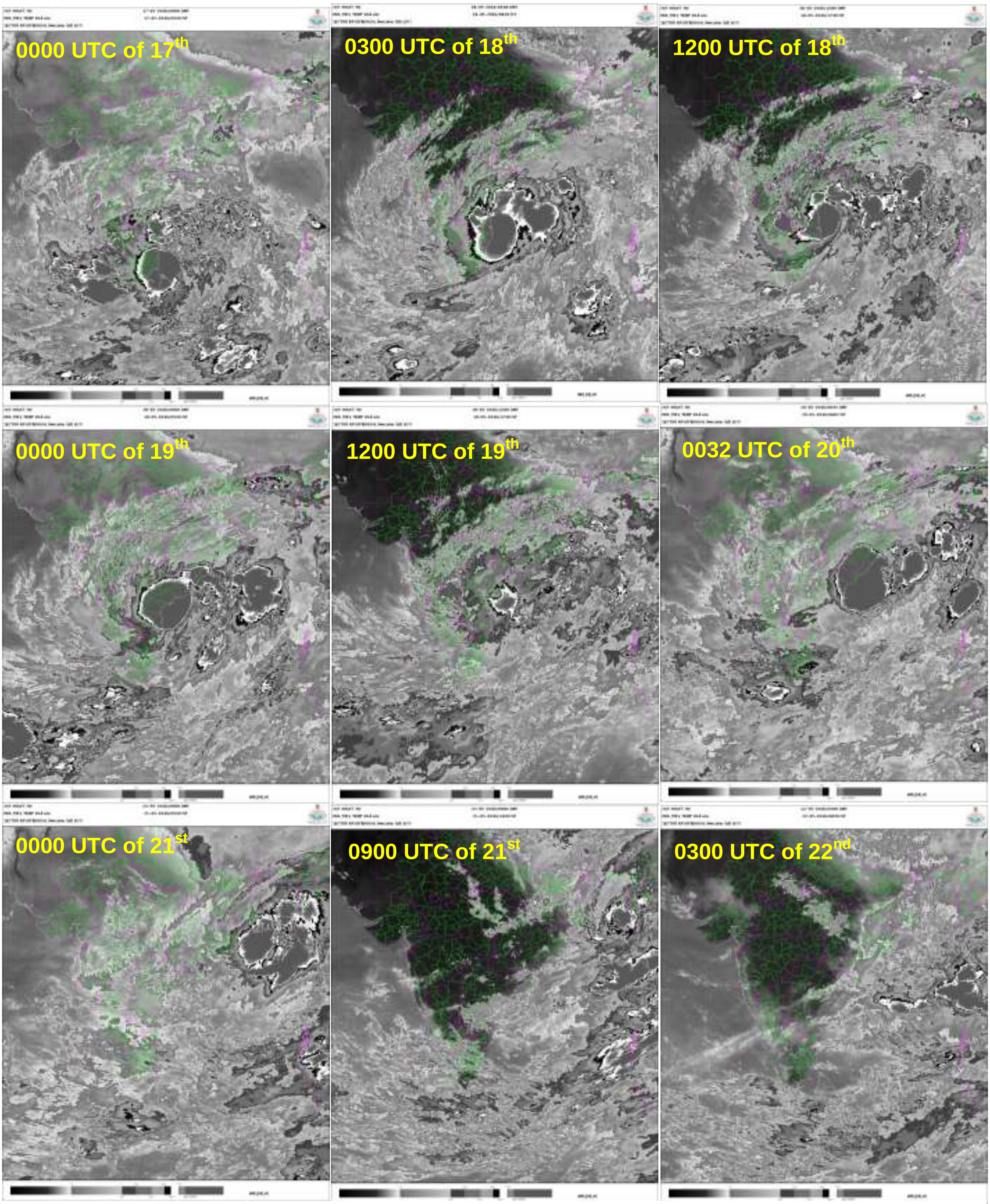


Fig. 8(b): INSAT-3D cloud top brightness temperature imageries during 17-22 May 2016.

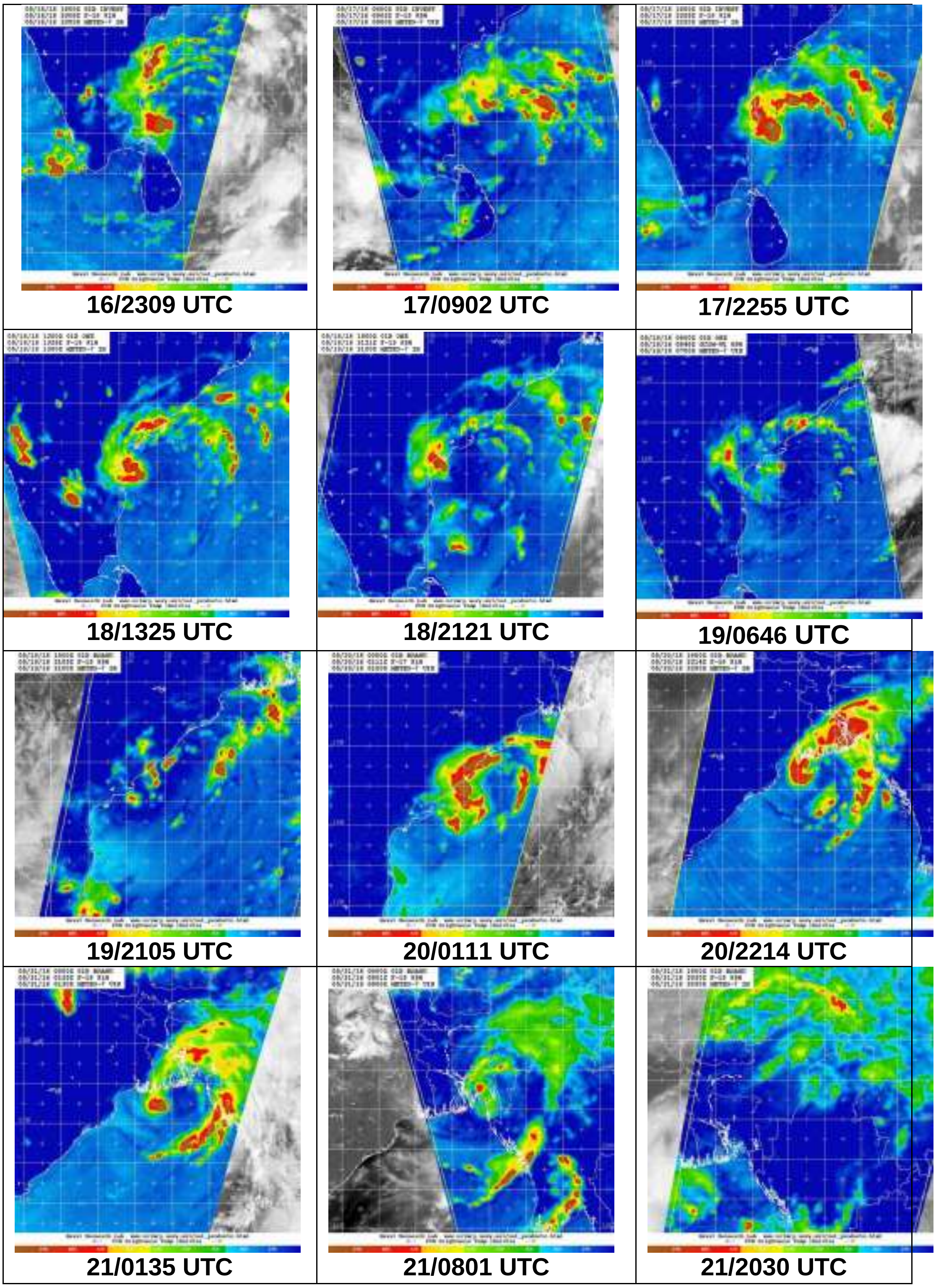


Fig.9 Typical microwave imageries during 17th to 22nd May 2016

5.3. Features observed through Radar

As the system was moving along the east coast, it was tracked by DWR Chennai, Machillipatnam, Vishakhaptanam, Paradip and Kolkata of India and DWR Khepupara & Cox's Bazar of Bangladesh. Typical Radar imageries from DWR Khepupara during 20th - 21st May are presented in Fig. 10. Typical imageries from Indian radars are presented in Fig.11.

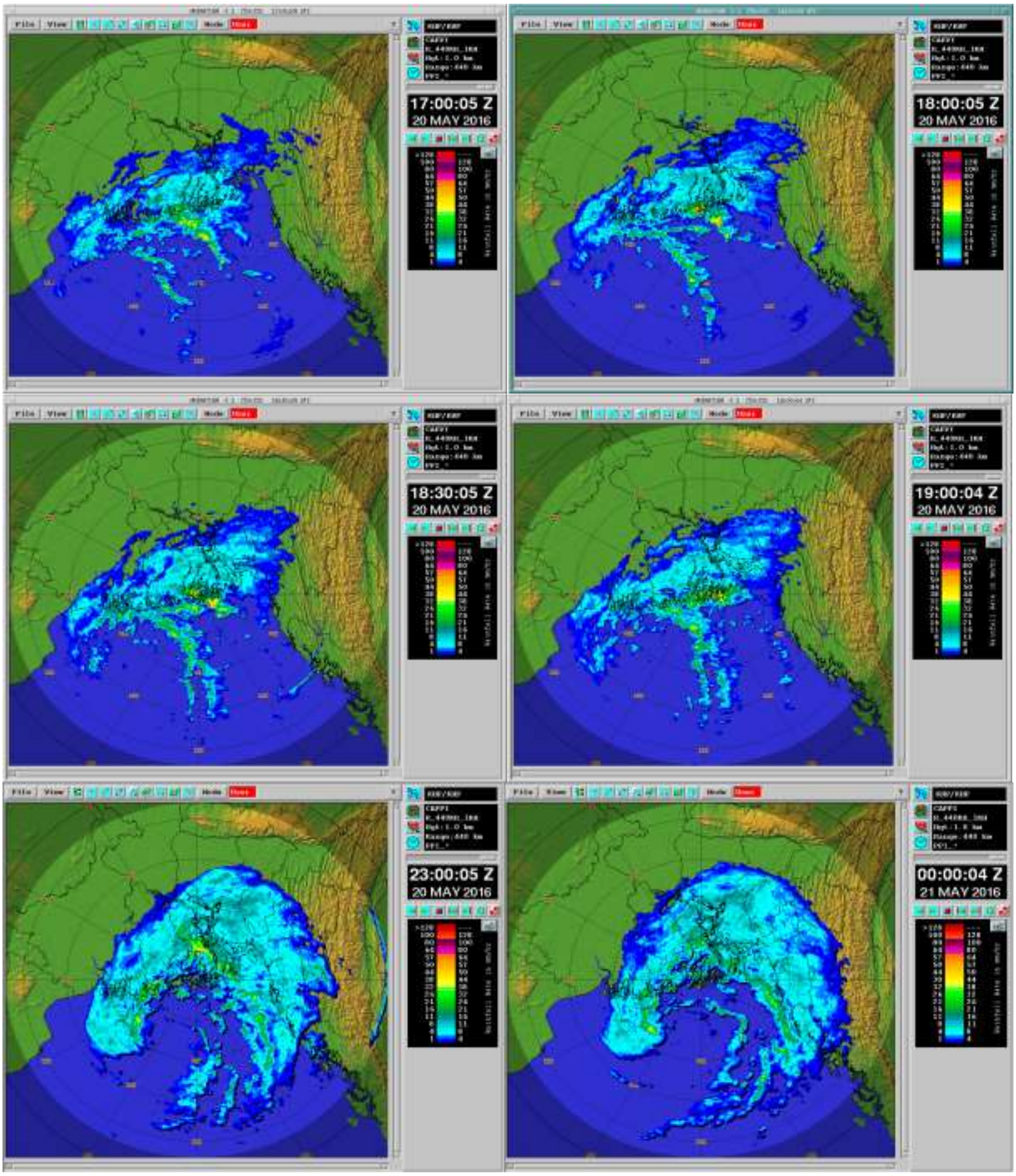


Fig.10 Typical DWR Khepupara imageries during 20th to 21st May 2016 in association with CS Roanu.

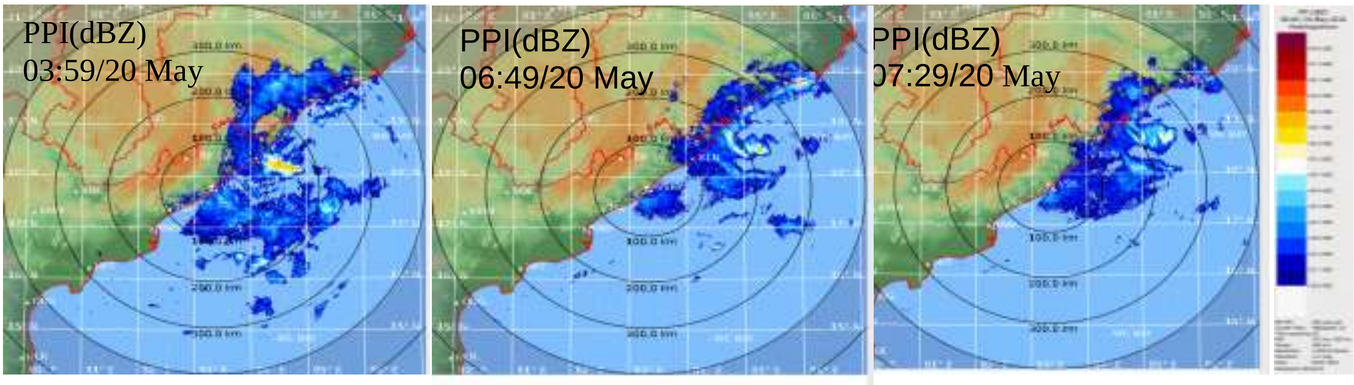


Fig. 11(a): Plan Position Indicator (PPI) (dBZ) imageries from DWR Vishakhapatnam at 0359, 0649 and 0729 UTC of 20th May

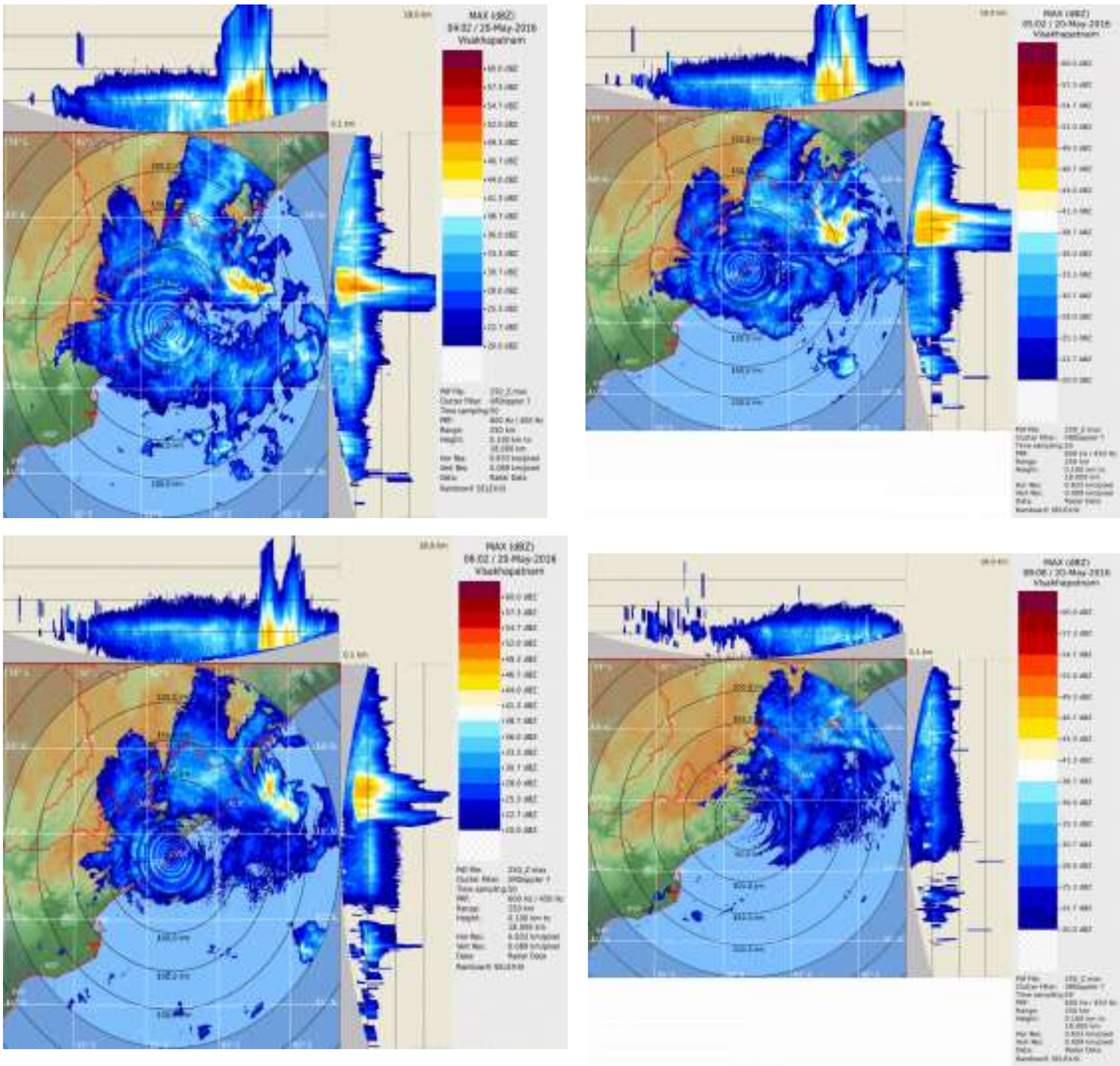


Fig. 11(b): Max (dBZ) imageries from DWR Vishakhapatnam at 0402, 0502, 0602 and 0608 UTC of 20 May

Till 19th May, as the system was moving skirting India coast along Tamil Nadu and Andhra Pradesh, there was continuous warm air advection in the western sector of the system as is evident from RS/RW observations of Chennai, Machillipatnam and Vishakhapatnam during the period. It is further exhibited in vertical profile of velocity (VVP(V)) observations taken by DWR Vishakhapatnam. One such example is presented in fig.11(c). Veering of wind with height resulted in warm air advection that helped in maintaining the intensity of the system as well as causing heavy rainfall activity along the east coast of India. On 20th and 21st, there was backing of wind resulting in cold air advection due to trough in mid latitude westerlies lying to the west of the system centre. Even though the process of advection changed during the life cycle, the large scale diurnal variations of convection in association with the system continued during 18th to 20th.

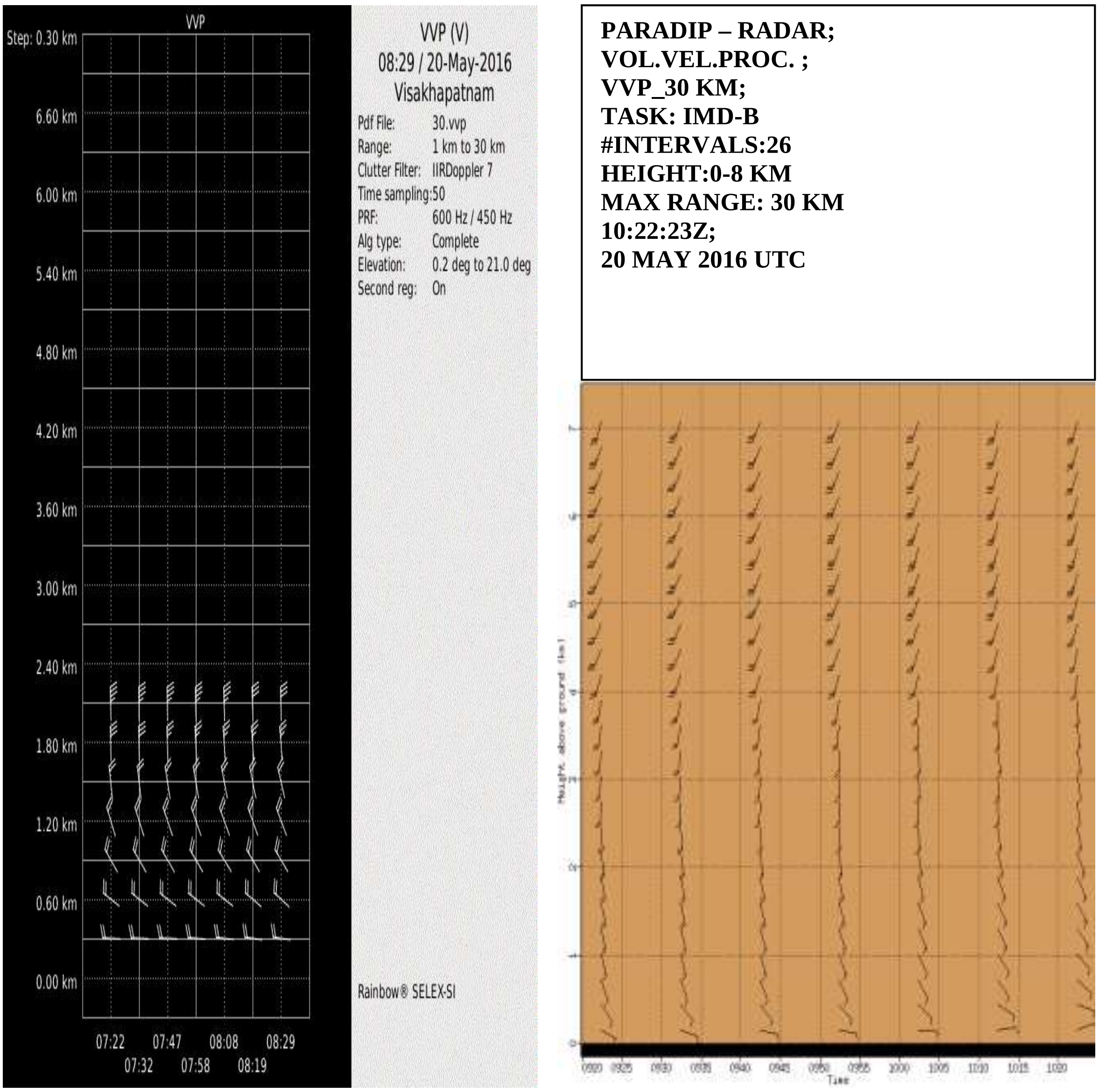


Fig. 11(c): Typical Vertical profile of velocity (VVP(2)) imageries from DWR Vishakhapatnam and CDR Paradip showing veering and backing of wind at these stations respectively

6. Dynamical features

IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels are presented in Fig.12. GFS (T574) could simulate the genesis of the system and the associated circulation features during the life period of CS Roanu. However, the deep trough in westerlies on 20th lying to the west of the system centre could not be captured well. In comparison NCUM analysis could simulate and track the system better (Fig.13).

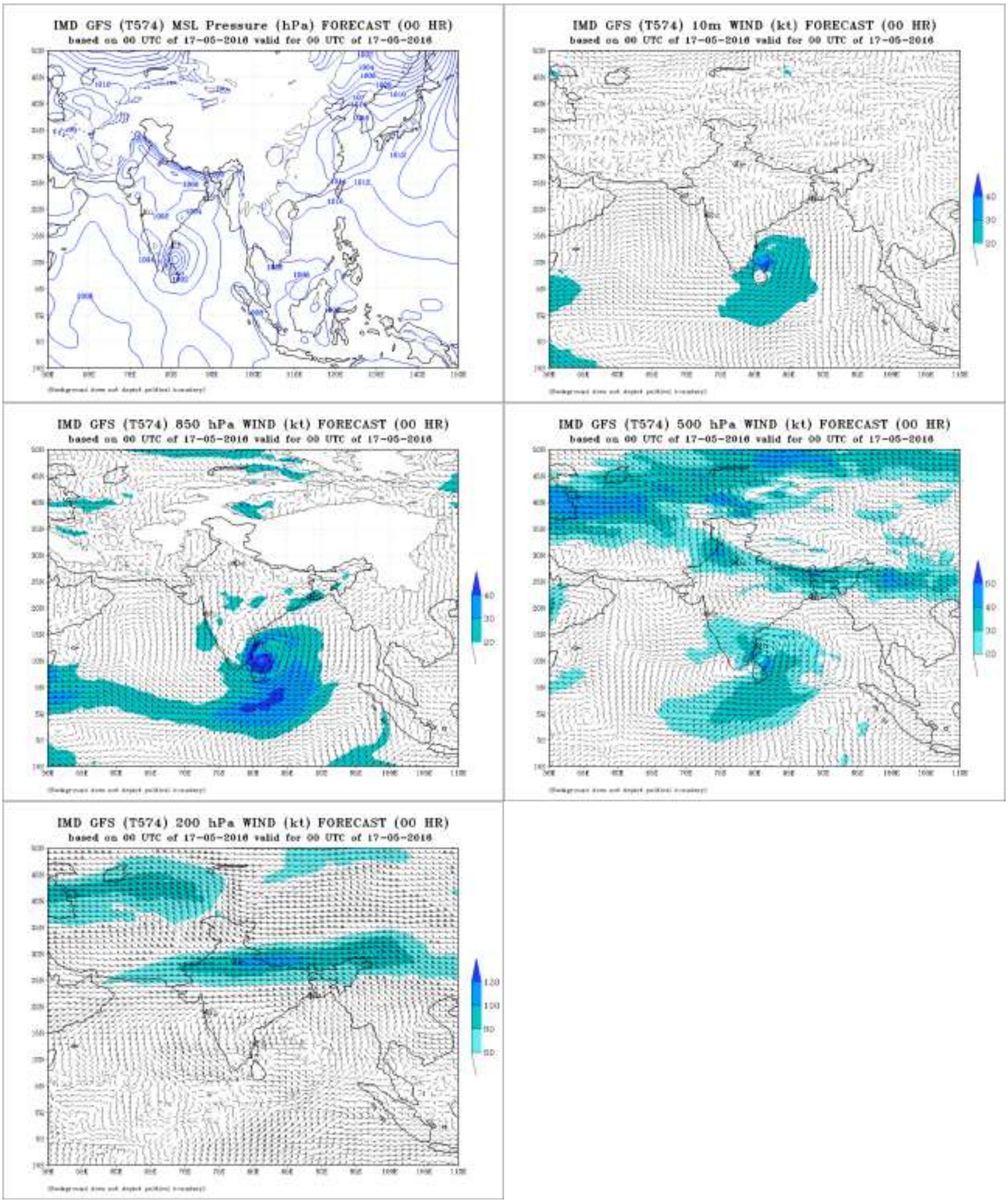


Fig. 12 (a): IMD GFS MSLP, 10 m wind and winds at 850, 500 and 200 hPa levels based on 0000 UTC of 17th May 2016

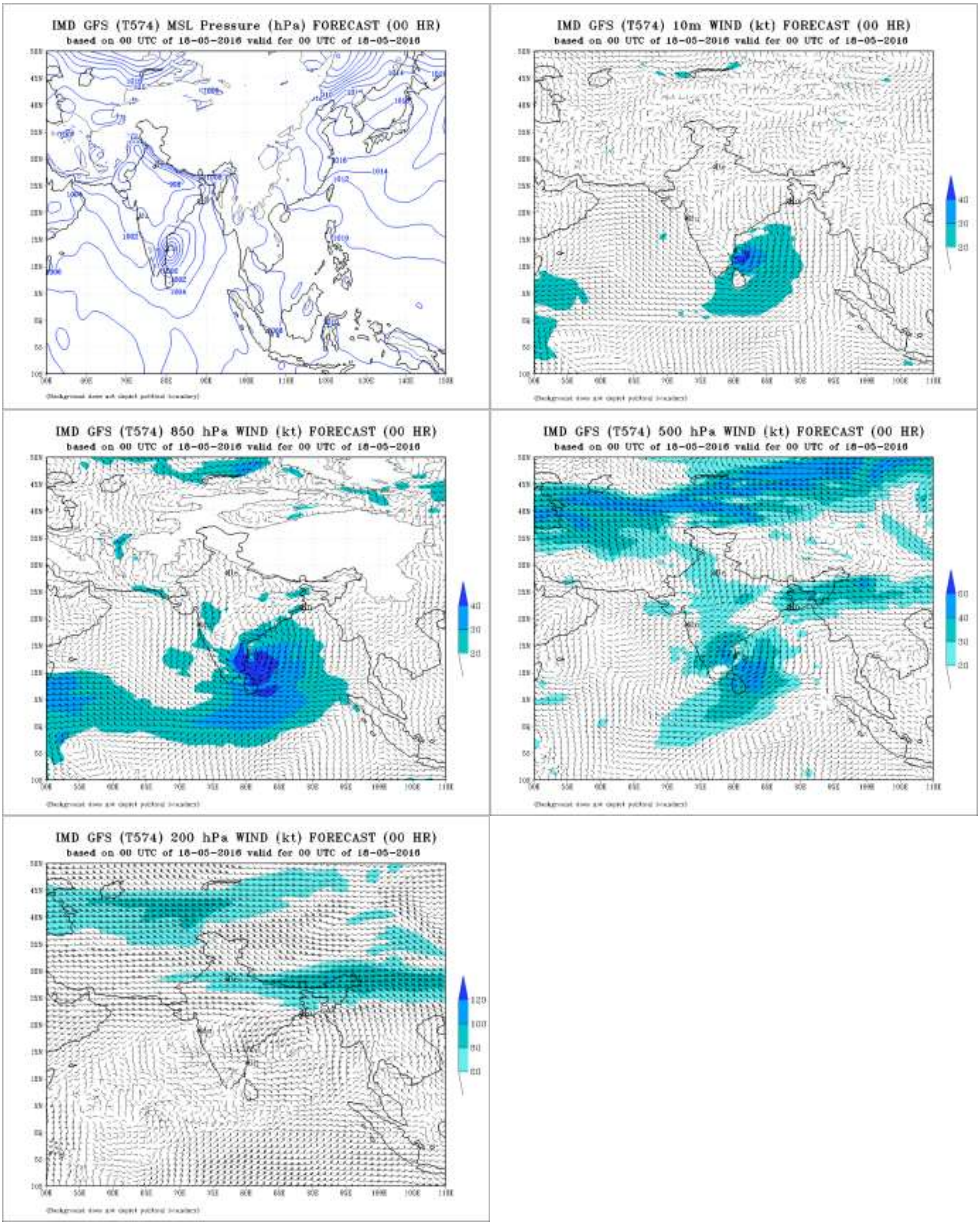


Fig. 12 (b): IMD GFS analysis of MSLP, 10 m wind, winds at 850, 500 and 250 hPa based on 0000 UTC of 18th May 2016.

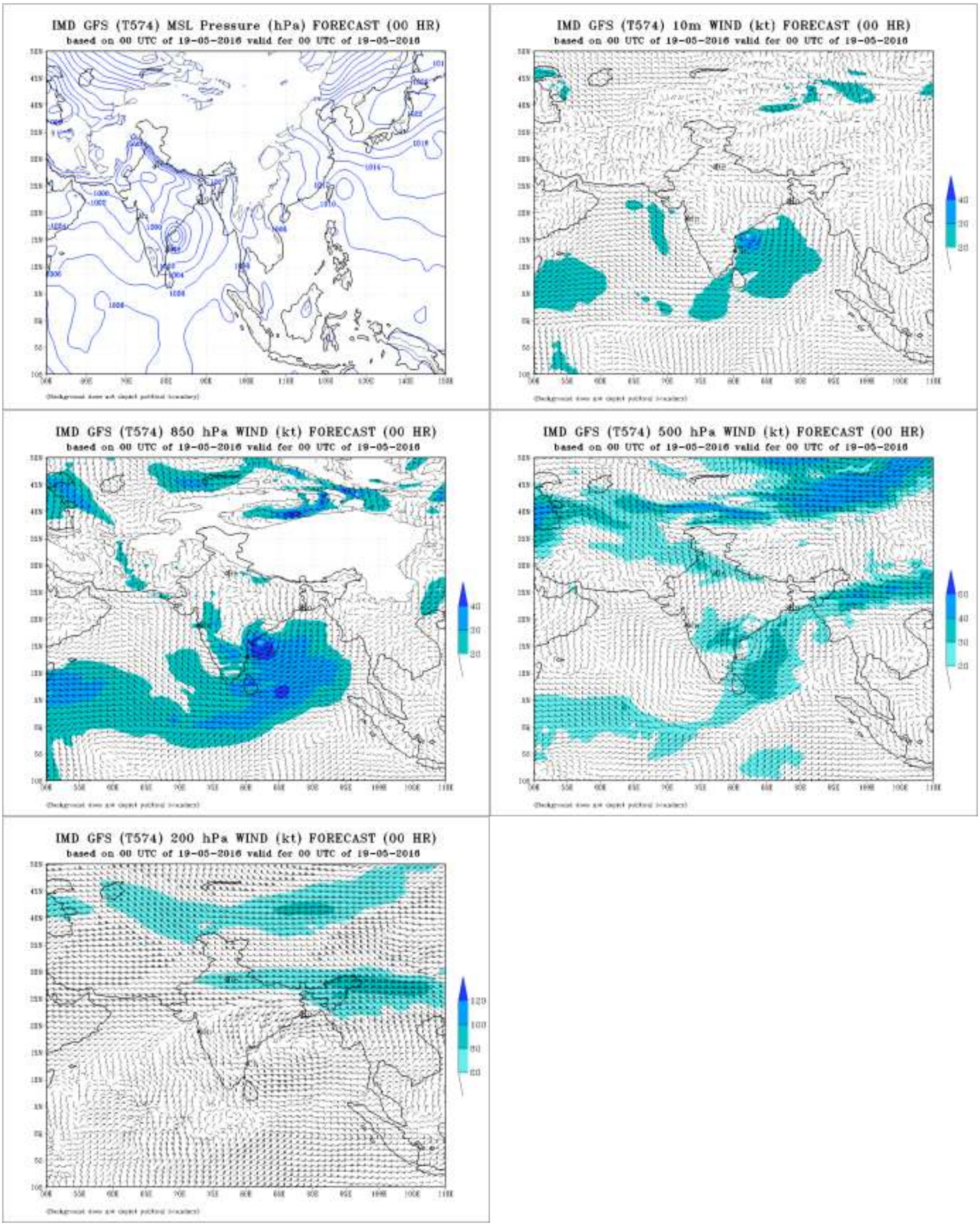


Fig. 12 (c): IMD GFS analysis of MSLP, 10 m wind, winds at 850, 500 and 250 hPa based on 0000 UTC of 19th May 2016.

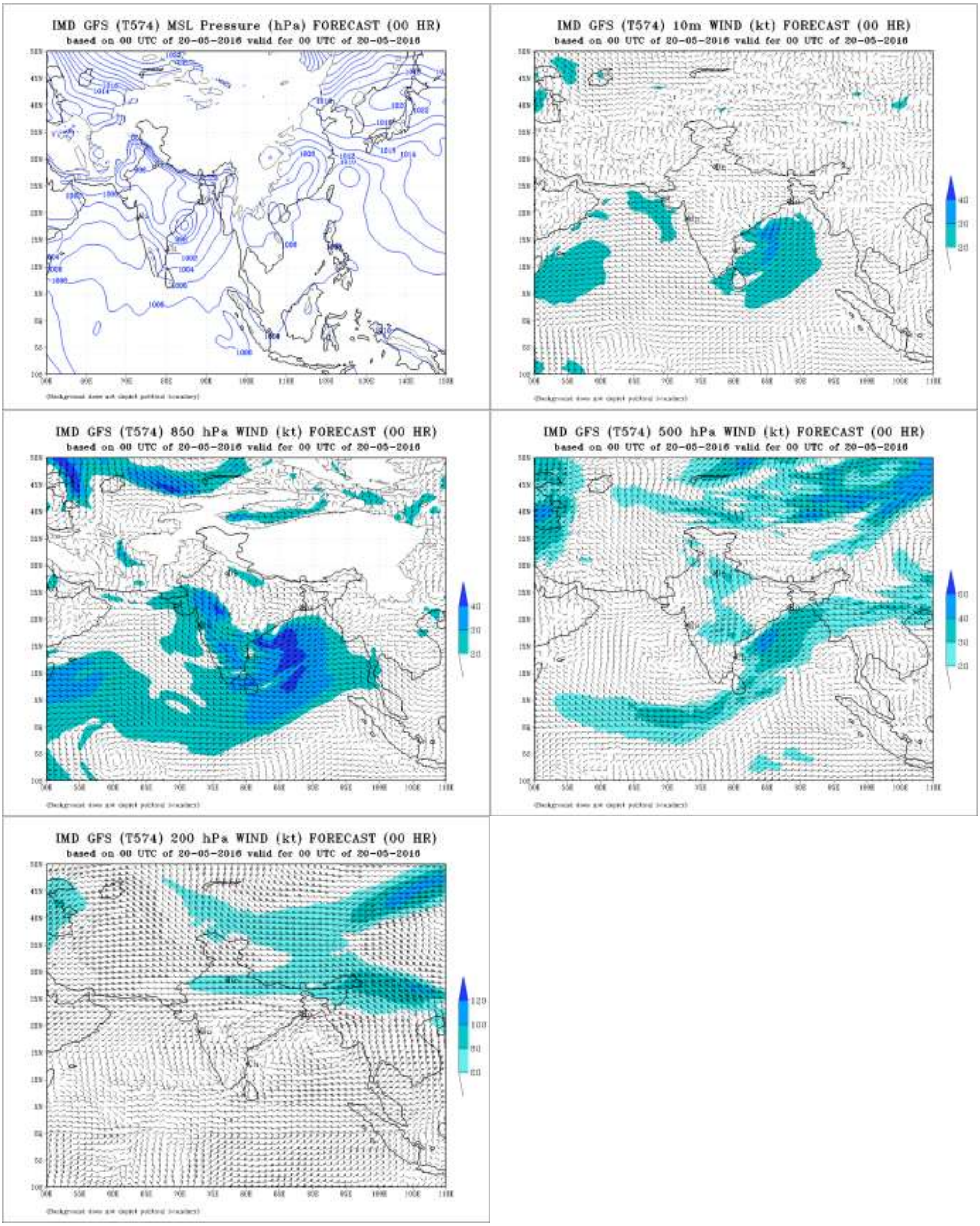


Fig. 12 (d): IMD GFS analysis of MSLP, 10 m wind, winds at 850, 500 and 250 hPa based on 0000 UTC of 20th May 2016.

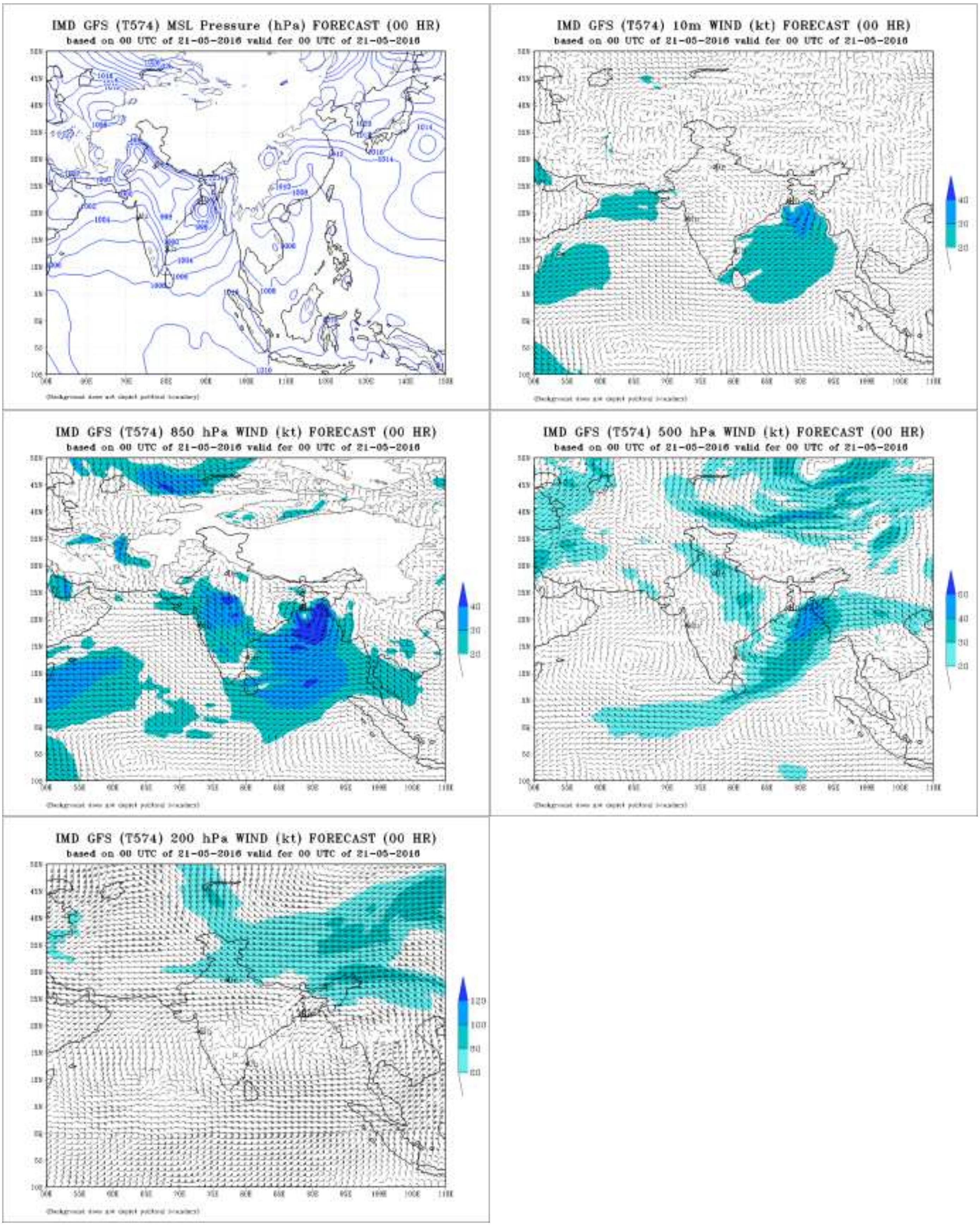


Fig. 12 (e): IMD GFS analysis of MSLP, 10 m wind, winds at 850, 500 and 250 hPa based on 0000 UTC of 21st May 2016.

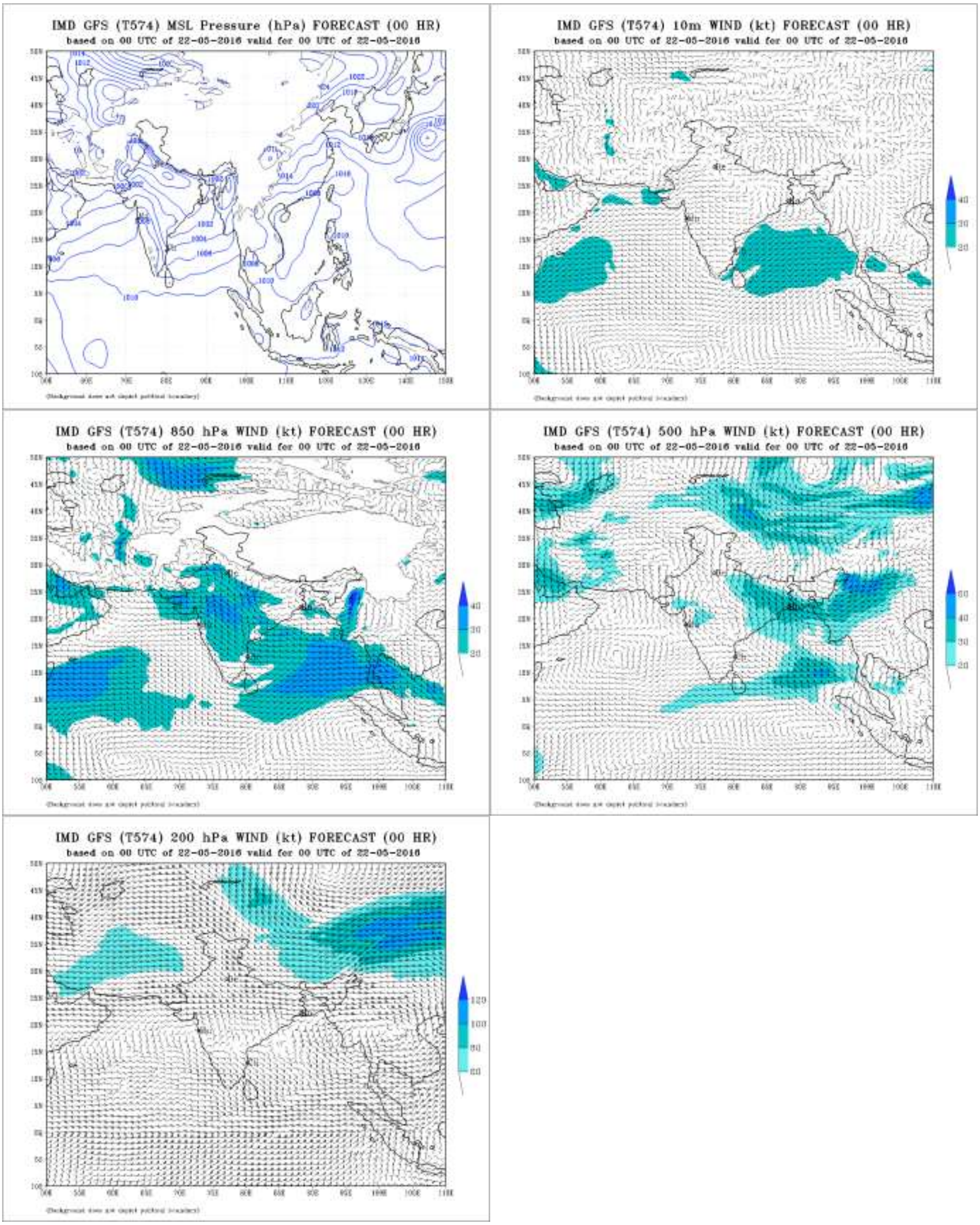


Fig. 12 (f): IMD GFS analysis of MSLP, 10 m wind, winds at 850, 500 and 250 hPa based on 0000 UTC of 22nd May 2016.

NCUM analysis of MSLP, winds at 925, 850, 500 and 200 hPa levels are presented in Fig.13.

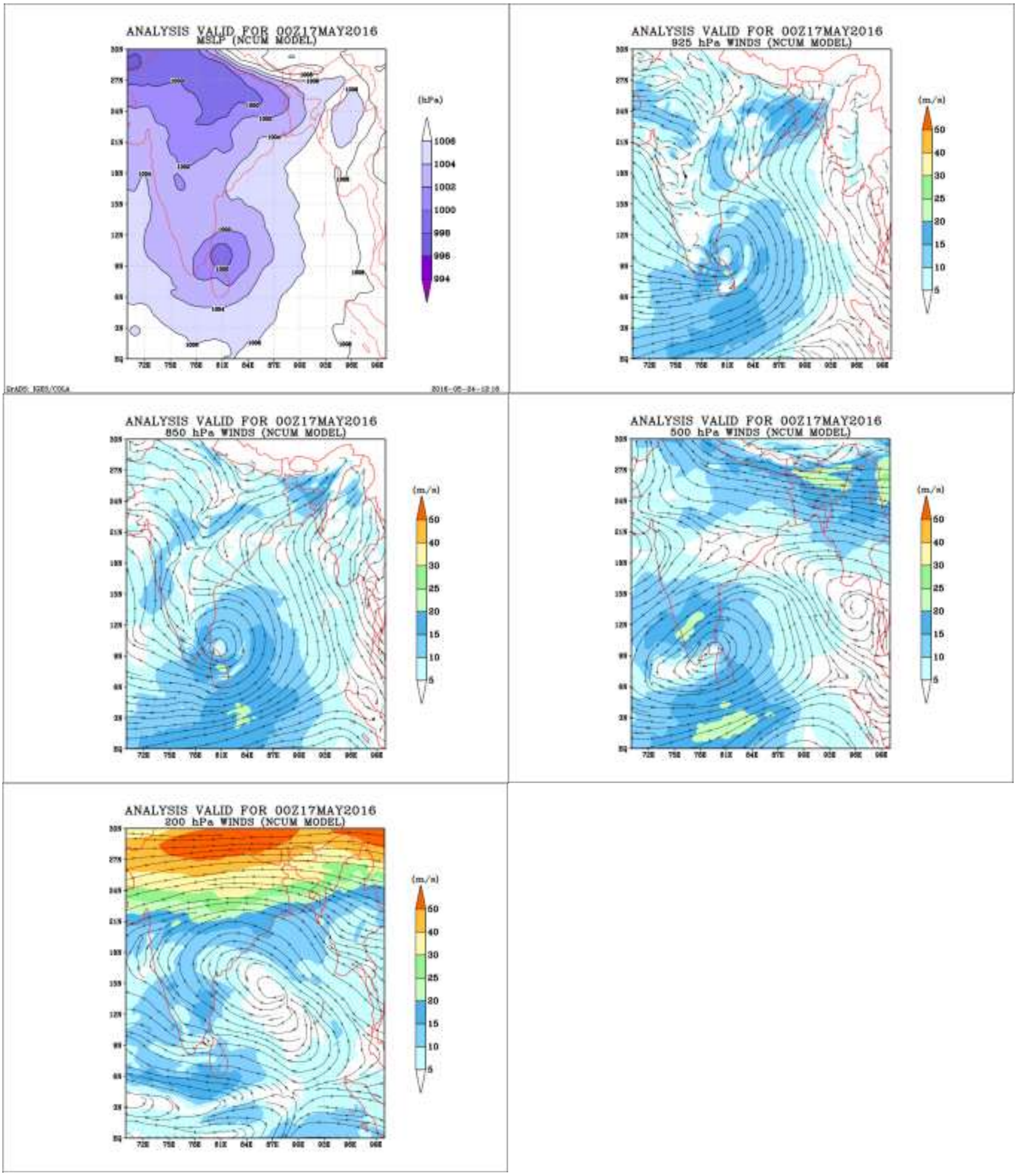


Fig. 13 (a): NCUM analysis of MSLP, winds at 925, 850, 500 and 200 hPa levels based on 0000 UTC of 17th May 2016.

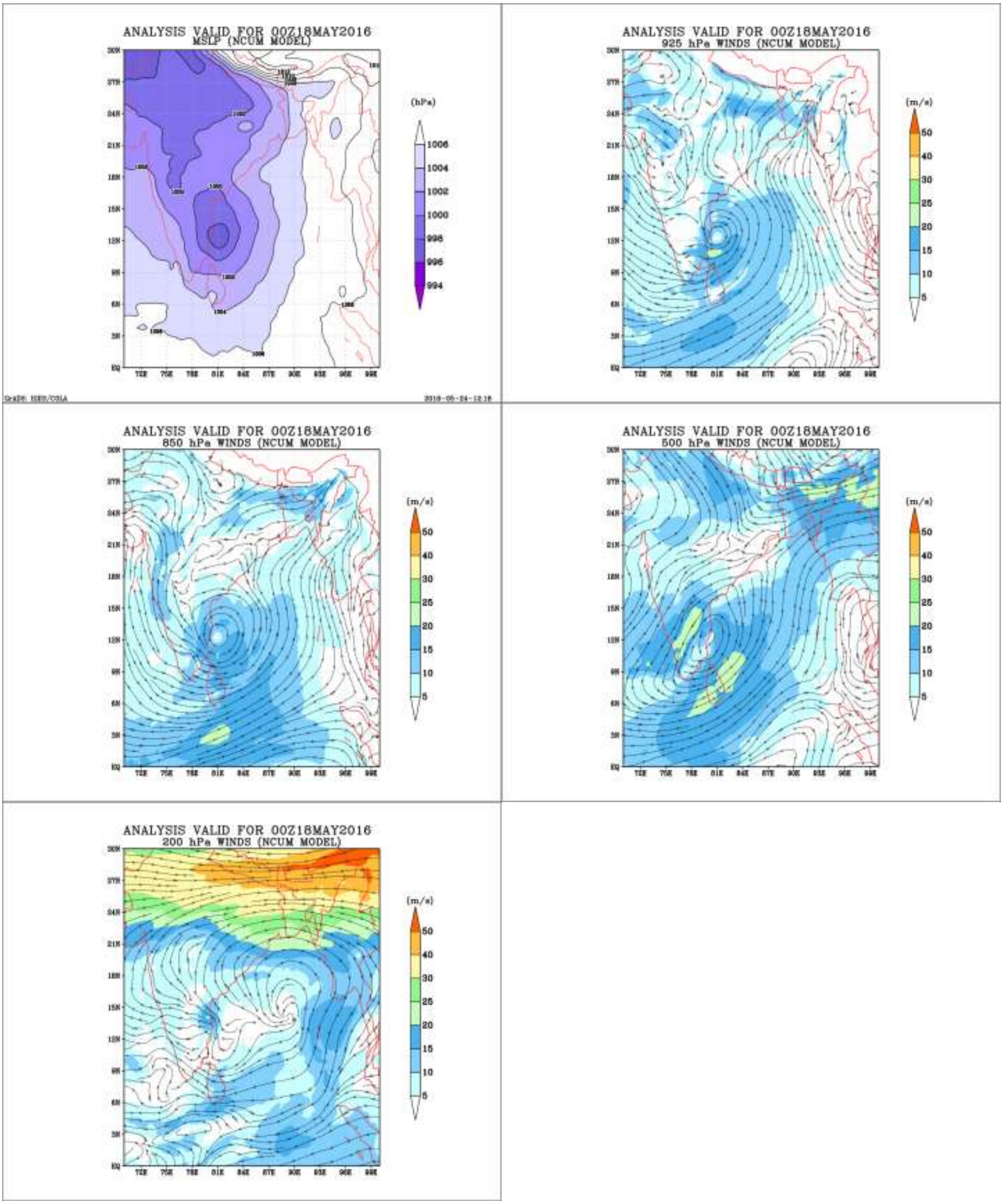


Fig. 13 (b): NCUM analysis of MSLP, winds at 925, 850, 500 and 200 hPa levels based on 0000 UTC of 18th May 2016.

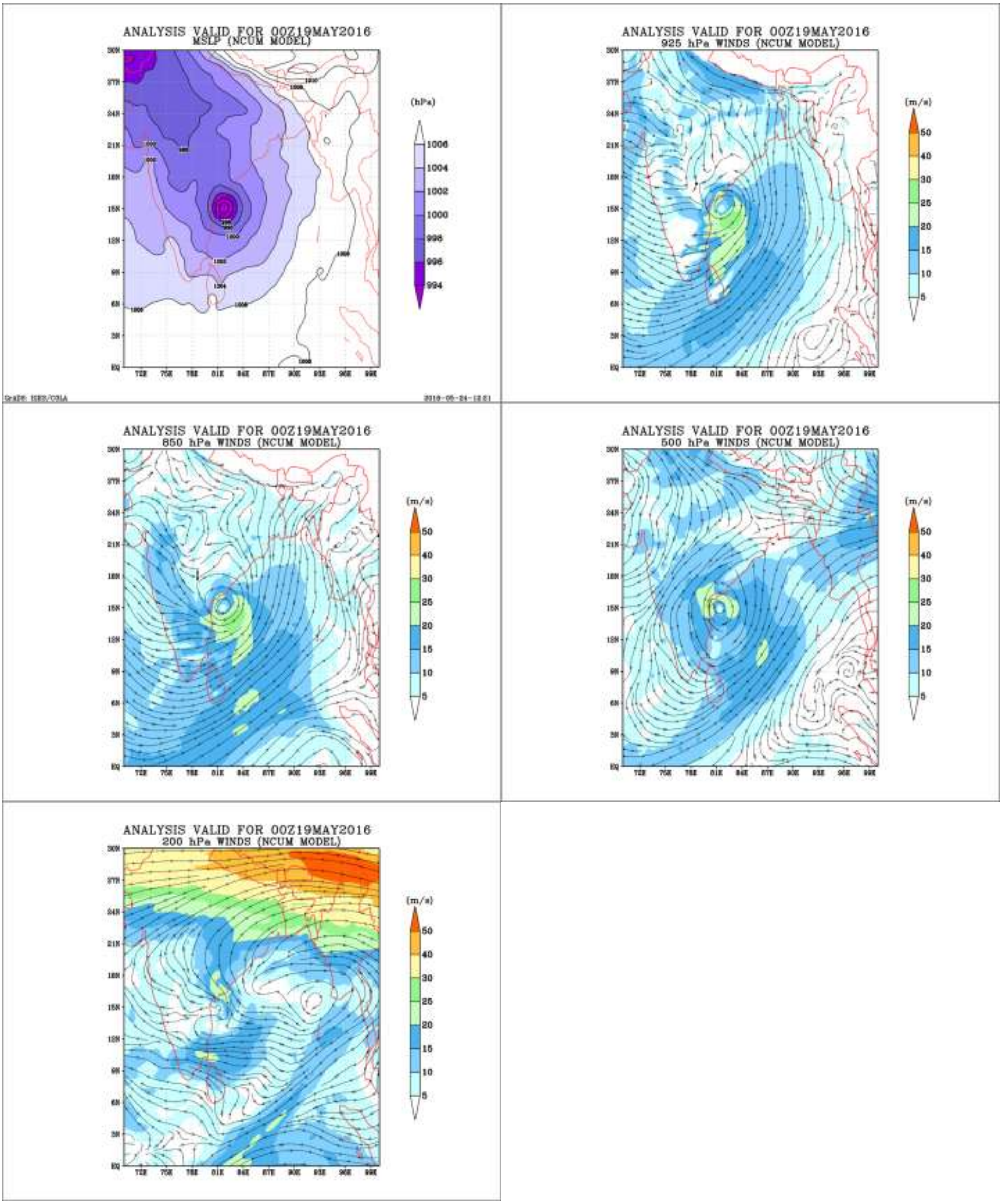


Fig. 13 (c): NCUM analysis of MSLP, winds at 925, 850, 500 and 200 hPa levels based on 0000 UTC of 19th May 2016.

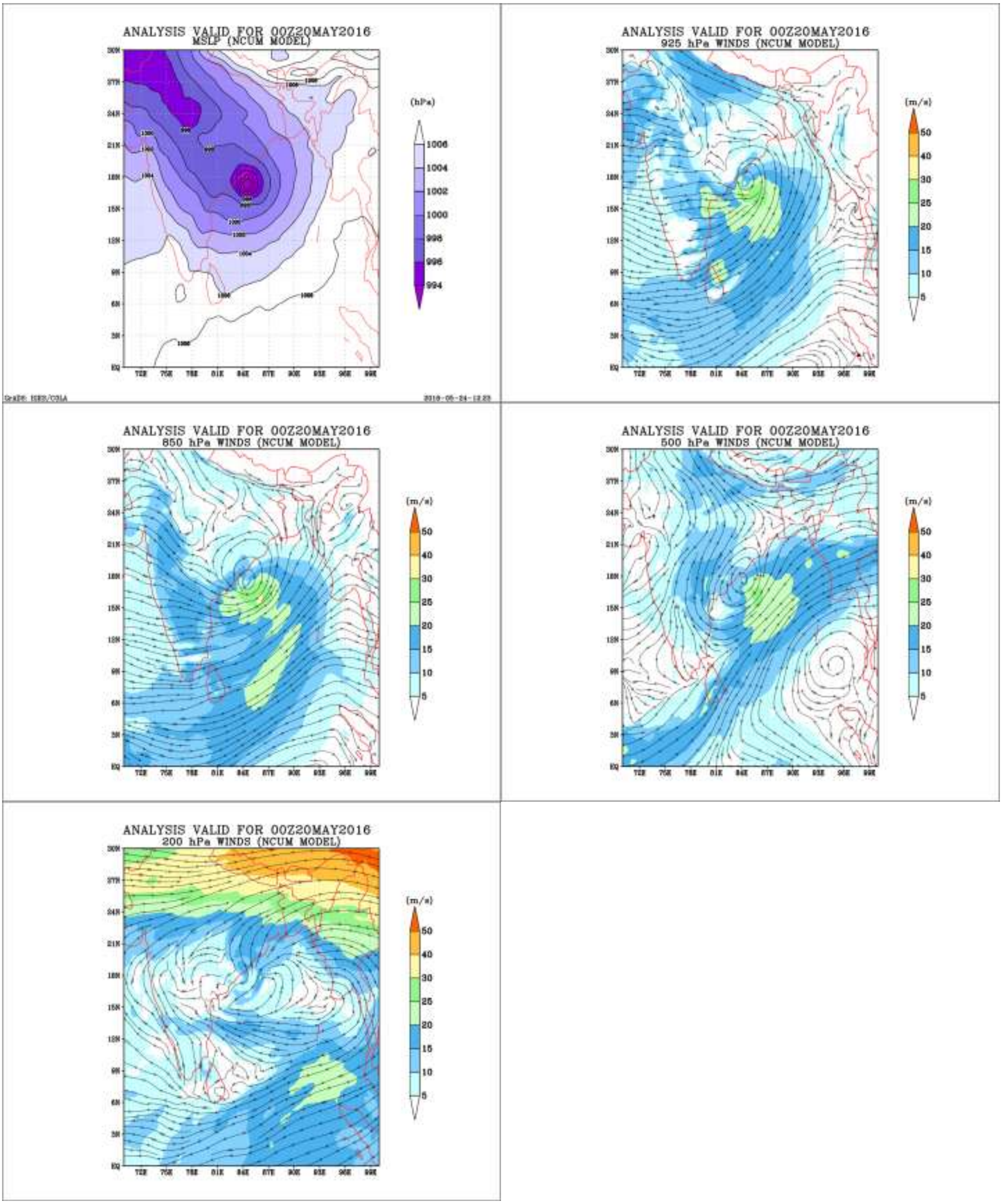


Fig. 13 (d): NCUM analysis of MSLP, winds at 925, 850, 500 and 200 hPa levels based on 0000 UTC of 20th May 2016.

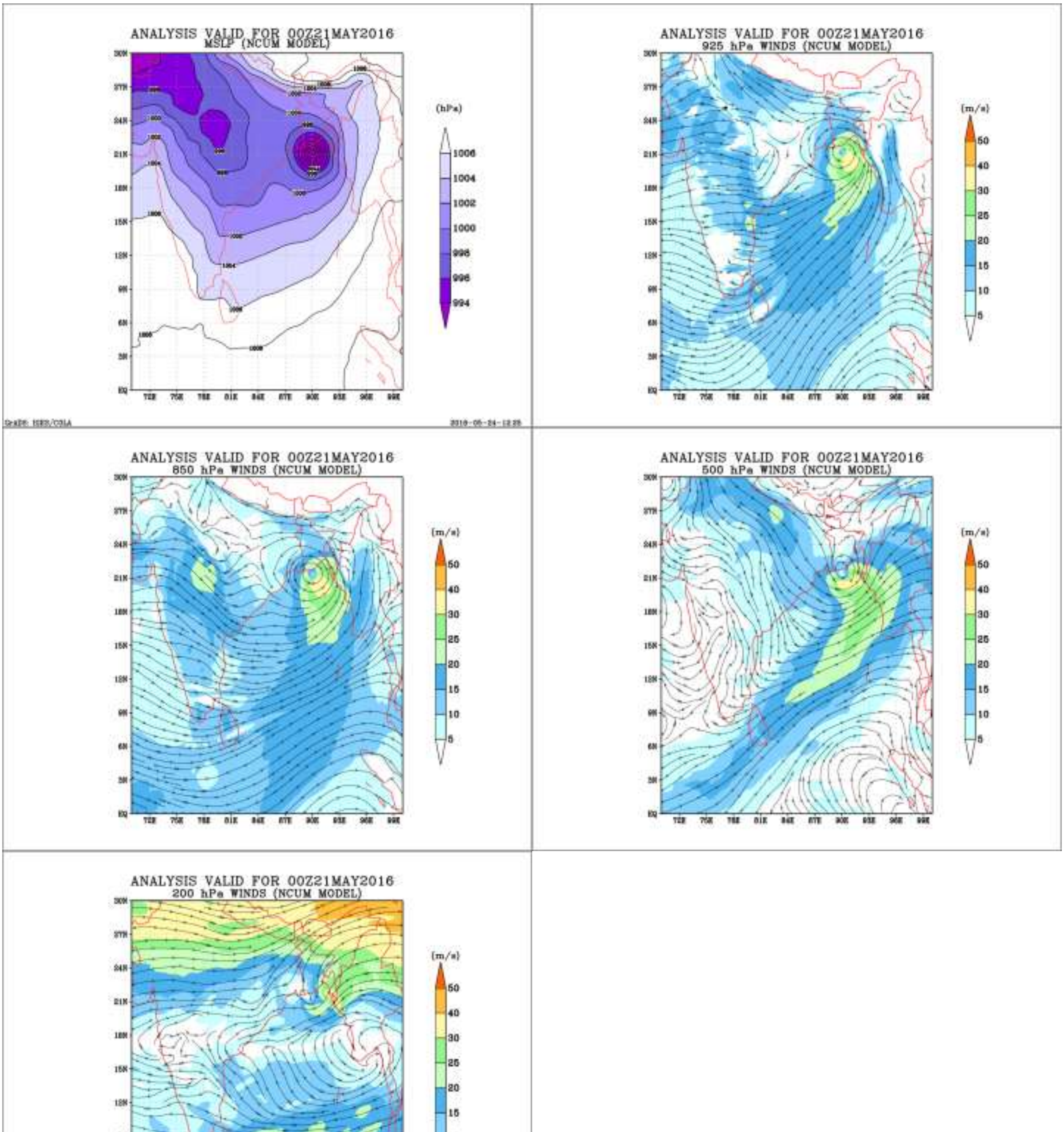


Fig. 13 (e): NCUM analysis of MSLP, winds at 925, 850, 500 and 200 hPa levels based on 0000 UTC of 21st May 2016.

7. Bulletins issued by IMD

7.1 Bulletins issued by Cyclone Warning Division, New Delhi

IMD continuously monitored, predicted and issued bulletins containing track & intensity forecast at +06, +12, +18, +24, +36, +48, +60, +72, +84 and +96 hrs or till the system weakened into a low pressure area. The above structured track and intensity forecasts were issued from the stage of deep depression onwards. The cone of uncertainty in the track forecast was also given. The radius of maximum wind and radius of≥28 knots, ≥34 knots and ≥50 knots wind in four quadrants of cyclone was issued for every six hours. The graphical display of the observed and forecast track with cone of uncertainty and the wind forecast for different quadrants were uploaded in the RSMC, New Delhi website (http://rsmcnewdelhi.imd.gov.in/) regularly. The prognostics and diagnostics of the systems were described in the RSMC bulletins and tropical cyclone advisory bulletins.

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

S.N.	Bulletin	No. of Bulletins	Issued to
1	National Bulletin	35	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, Dir. Indian Railways, Indian Navy, IAF, Chief Secretary- Kerala, Karnataka, Andhra Pradesh, Tamil Nadu, West Bengal, Odisha, Mizoram, Arunachal Pradesh, Assam, Manipur and Tripura.
2	RSMC Bulletin for WMO/ ESCAP Panel countries	33	1. IMD's website 2. All WMO/ESCAP member countries through GTS and E-mail. 3. Indian Navy, IAF by E-mail
3	Tropical Cyclone Advisory Centre Bulletin (Text & Graphics)	15	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	Cyclone Warnings through SMS		SMS through (i) IMD network for disaster managers (once daily and twice on 21st May), (ii) IMD's public registration using Department of Electronics and Information Technology network, (iii) INCOIS network (2,78,584)for fishermen and Kisan Portal for farmers (5,01,419). No. of SMS issued to public by Department of Electronics and Information Technology network is about 2,35,15
5	Cyclone Warnings through Social Media	Once daily	Cyclone Warnings were uploaded on Social networking sites like Face book and Tweeter during cyclone 'ROANU'.

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. 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. 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 Vishakhapatnam (VZK)

S.No.	Type of Bulletin Number	No. of Bulletins issued by			
		ACWC Chennai	ACWC Kolkata	CWC Bhubaneswar	CWC VZK
1.	Sea Area Bulletins	14	22	-	-
2.	Coastal Weather Bulletins	10	14	14	13
3.	Fishermen Warnings issued	20	30	24	12
4.	Port Warnings	10	32	22	10
5.	Heavy Rainfall Warning	7	06	10	02
6.	Gale Wind Warning	NIL	NIL.	08	03
7.	Information & Warning issued to State Government and other Agencies	7	05	23	23
8.	SMS	24	NIL	1600	110

8. Realized Weather:

8.1 Rainfall:

Rainfall associated with the system is depicted in Fig 13 based on IMD-NCMRWF GPM merged gauge rainfall data.

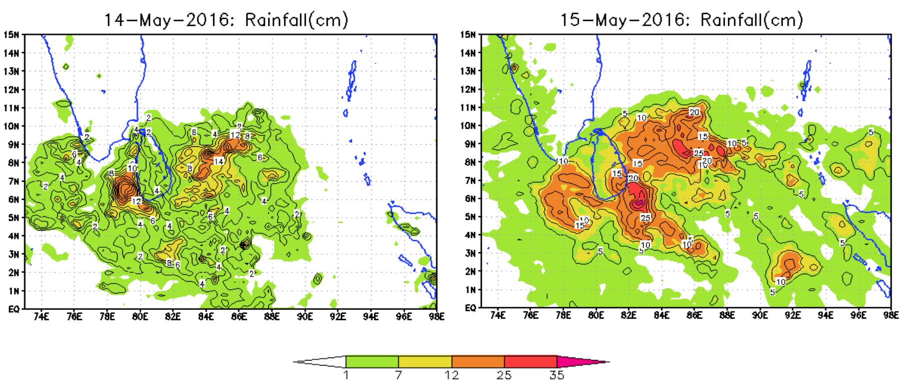


Fig.13(a): Realized rainfall (cm) during 14-15 May 2016

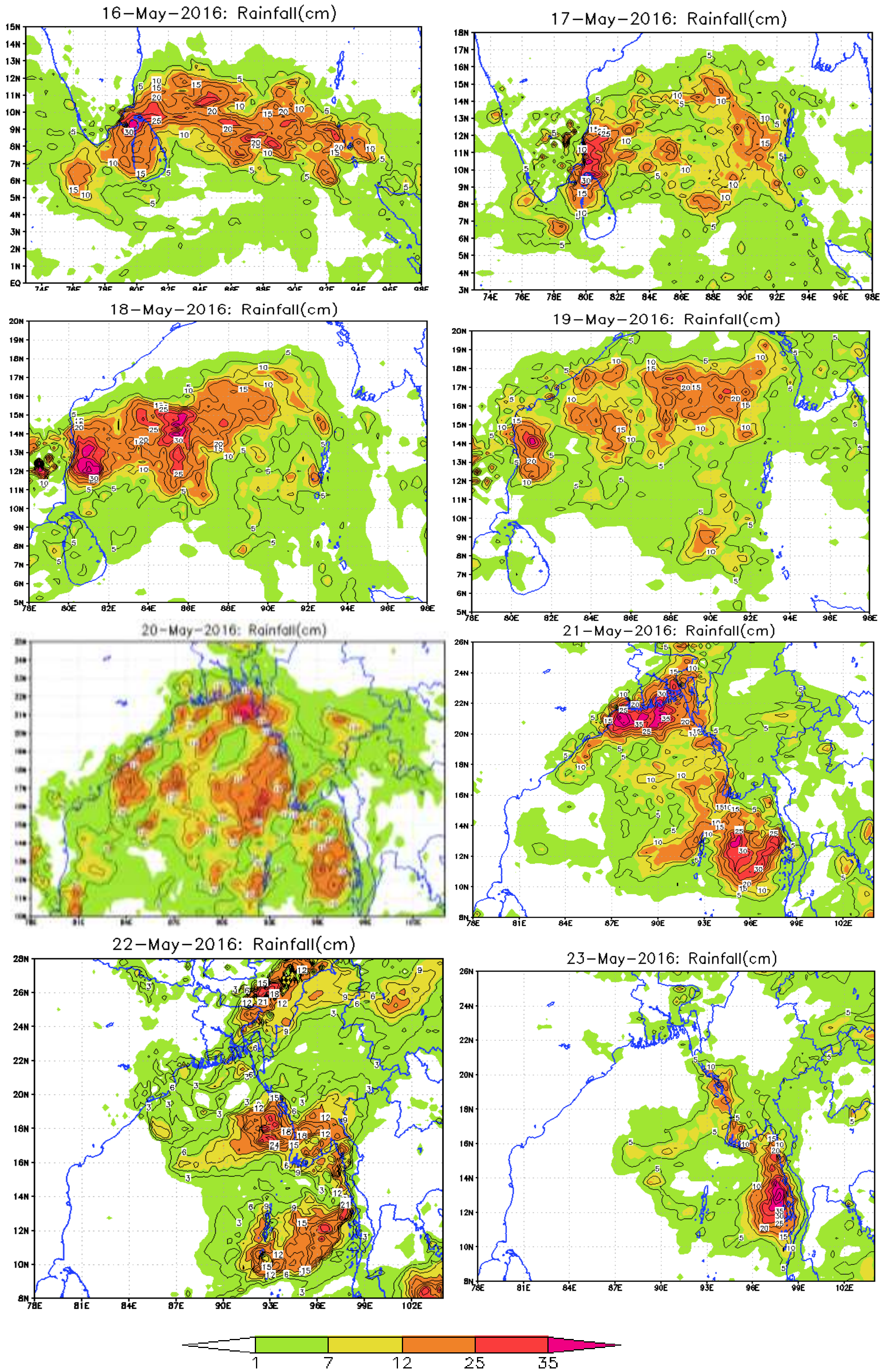


Fig. 13(b): Realized rainfall (cm) during 16-23 May 2016

Sri Lanka experienced heavy rainfall on 14th to 16th in association with the low pressure area over southwest BoB and adjoining Sri Lanka coast. The heavy rainfall belt shifted gradually northwards and was limited to north Sri Lanka and coastal Tamil Nadu on 17th and rainfall more than 35 cm was observed over the region. It then shifted towards north Tamil Nadu and adjoining south coastal Andhra Pradesh on 18th and rainfall more than 35 cm was observed over the region. On 19th coastal Andhra Pradesh and adjoining areas of north coastal Tamil Nadu experienced rainfall more than 12cm. On 20th north Andhra Pradesh, coastal Odisha and coastal West Bengal received rainfall more than 12 cm. on 21st north coastal Odisha, coastal West Bengal and Bangladesh received rainfall more than 12cm. The region of heavy rainfall moved to Bangladesh & adjoining northeastern states of India on 22nd.

9. Damage due to CS Roanu

Sri Lanka

As per media report, cyclonic storm 'Roanu' in its genesis phase as a low pressure area/ depression over southwest Bay of Bengal caused mud-slide and severe flooding in Sri Lanka. It was responsible for 101 deaths and displacing over 1,34,000 people in Sri Lanka . Landslides buried three villages in Kegalle district of Sri Lanka.

India

Roanu also brought torrential rainfall to the Indian states of Tamil Nadu, Andhra Pradesh, Kerala and Odisha as it drifted in a generally northeastward direction, close to the coast. NDRF personnels were deployed in low lying areas of these states to handle any emergency situation. No death or damage was reported by these states.

Bangladesh

As per the report received from Bangladesh Meteorological Department (BMD), overall 1,10,684 families were partially and 29,168 fully affected by CS Roanu. 24 people lost their lives and 2 were reported missing. Some damage photographs from Bangladesh Meteorological department are presented in fig. 14 (a-d).

Fig. 14 (a-b): Damaged huts and village in Chittagong

Fig.14 (c-d): Submerged homes due to heavy rains and storm surge ravaged southern district of Bangladesh on 21st May

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 GFS and 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 midlatitudes. 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.

The Met Office bi-variate approach to tracking TCs is used in the real-time to track the location of the CS ‘Roanu’. This method is in contrast to the earlier operational National Centers for Environmental Prediction (NCEP) who use any or all of MSLP, 850 hPa and 700 hPa relative vorticity (RV) and geo-potential height to track tropical cyclones (Marchok, 2002). The bi-variate method identifies TCs by examination of the 850RV field, but then fixes the TC centre to the nearest local MSLP minimum (Hamming,2015). Key advantage of the method is that it gives a strong signal of the approximate centre of the TC even for weak systems.

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 ROANU are presented and discussed.

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

Figure 15 (a-f) shows the predicted zone of cyclogenesis. Grid point analysis and forecasts of GPP could indicate the cyclogenesis zone over south west Bay of Bengal 120 hrs before its formation. 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. 16) showed potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0).

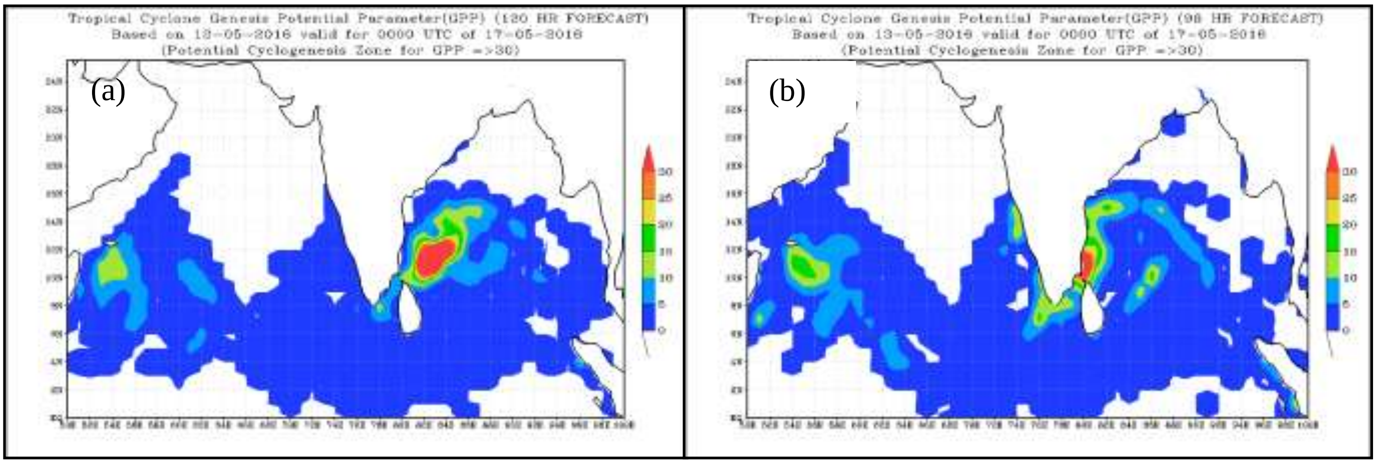


Figure 15 (a-b): Predicted zone of cyclogenesis based on 0000 UTC of 12th to 13th May 2016.

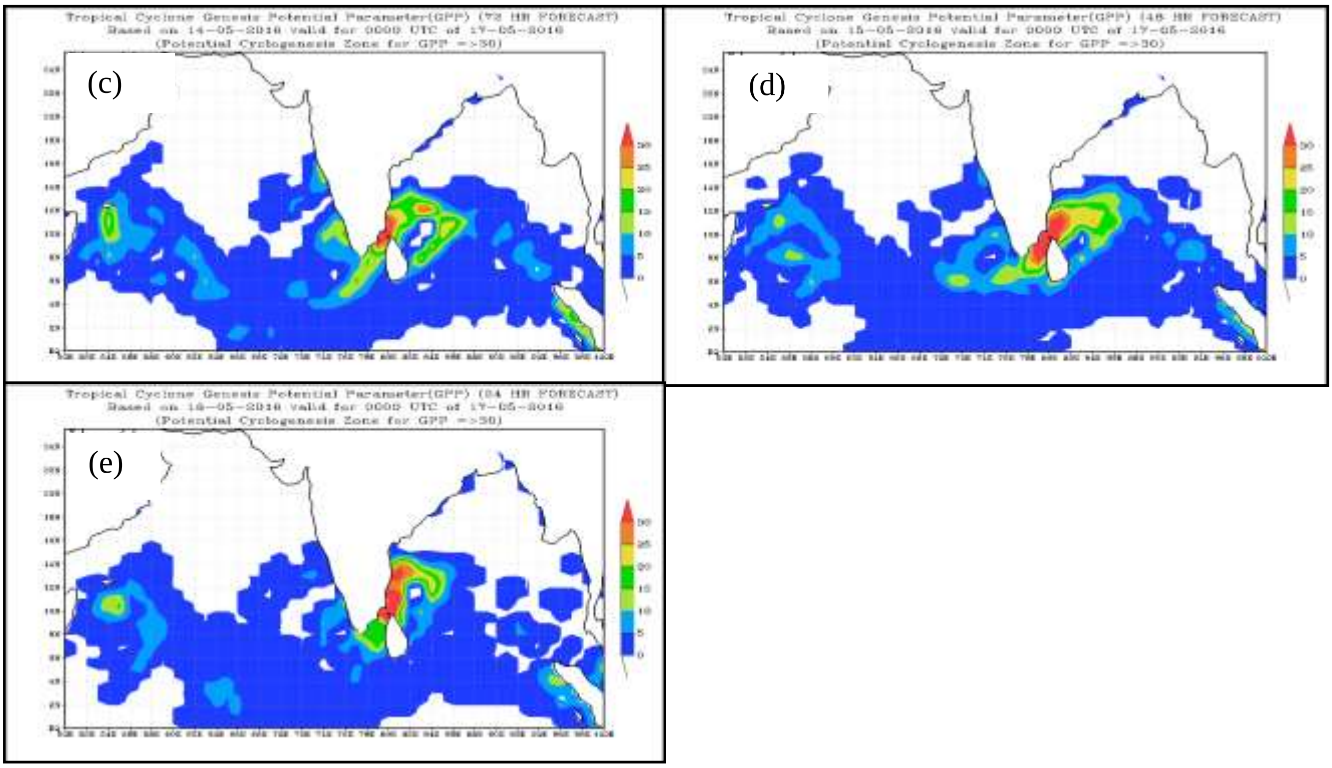


Figure 15 (c-e): Predicted zone of cyclogenesis based on 0000 UTC of 12th to 16th May 2016.

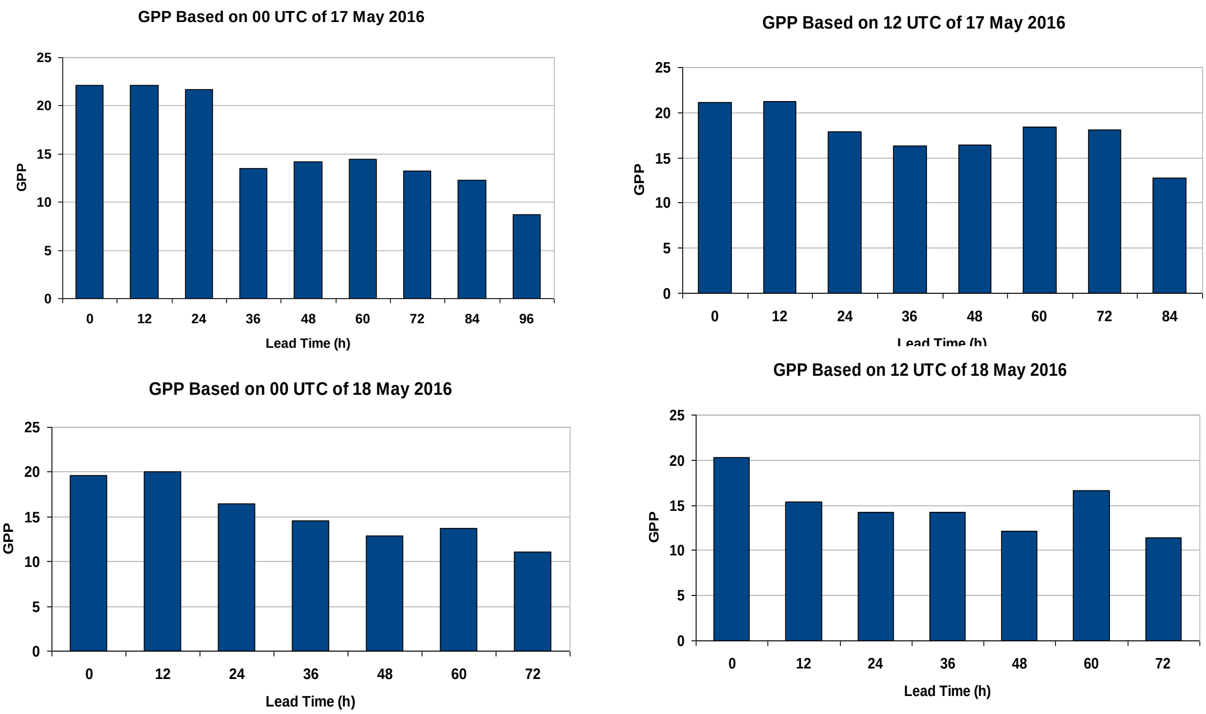


Figure 16(a-d): Area average analysis and forecasts of GPP based on 0000 & 1200 UTC of 17th and 18th May 2016

10.2 Track prediction by NWP models

Track prediction by various NWP models is presented in Fig.17.

Based on initial conditions of 1200 UTC of 17th, WRF-VAR and JMA showed dissipation over sea. All other models except UKMO predicted landfall to the south of Chittagong. UKMO predicted landfall point at 22.6°N/91.5°E at around 1500 UTC of 21st May. All models suggested movement of cyclone close to east coast of India and recurvature towards Bangladesh coast.

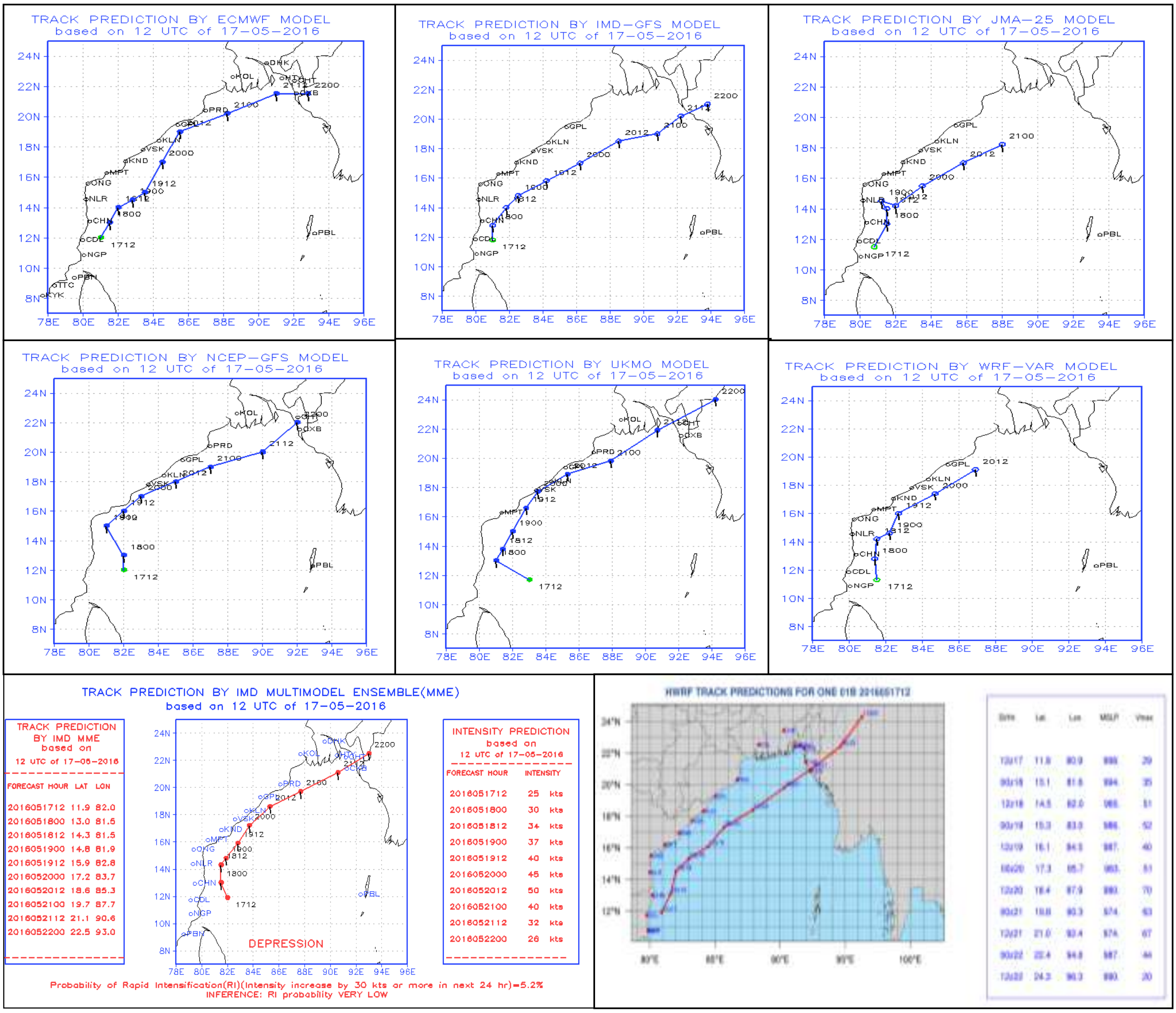


Figure 17 (a): Predicted track of CS Roanu based on 1200 UTC of 17th May 2016.

Based on the initial conditions of 0000 UTC of 18th May, JMA and WRF-VAR predicted weakening over the sea. ECMWF predicted landfall close to Chittagong near 22.5⁰N/91.5⁰E around 0400 UTC of 22nd and UKMO around 1000 UTC of 21st. All other models predicted landfall to the south of Chittagong.

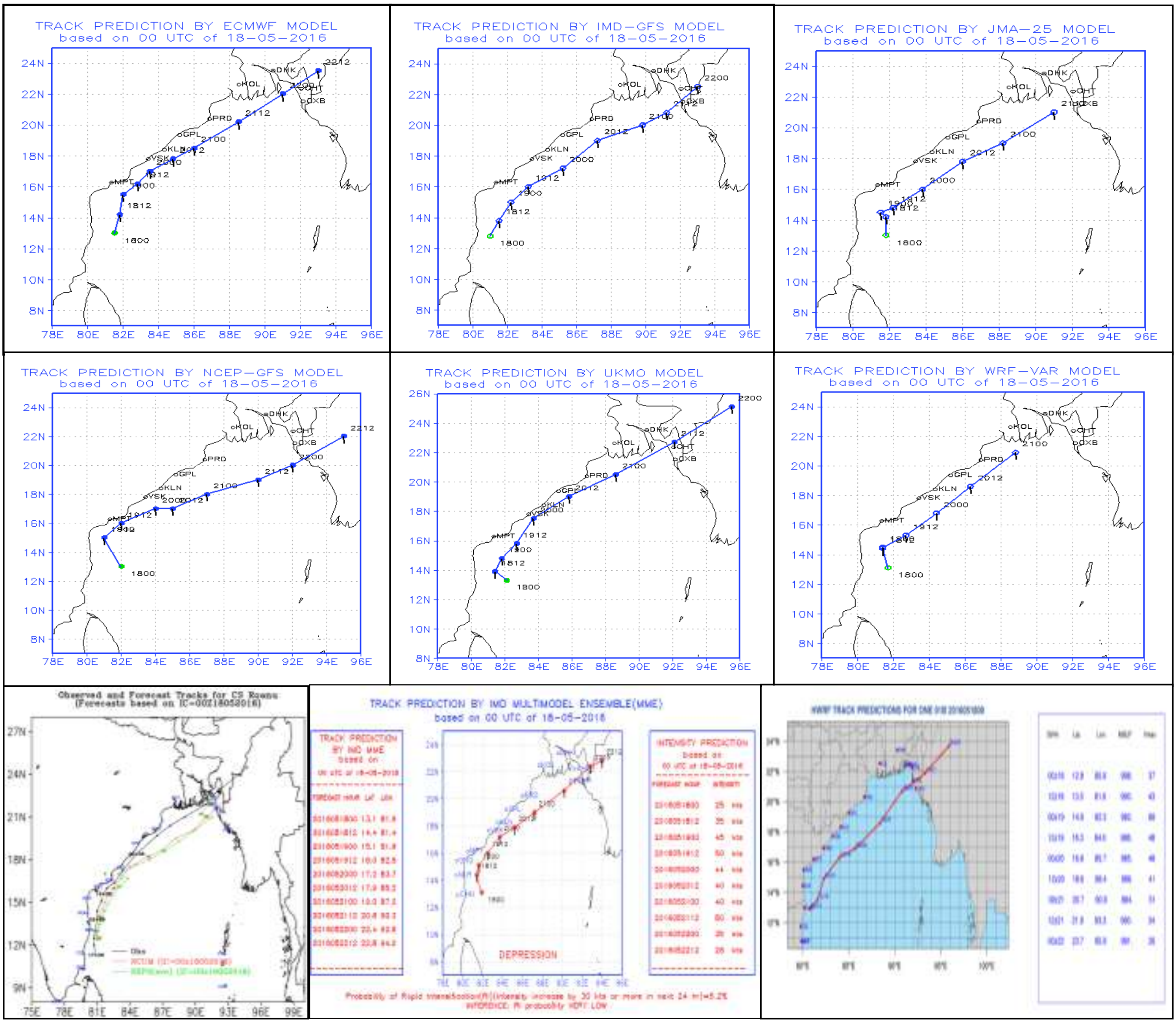


Figure 17 (b): Predicted track of CS Roanu based on 0000 UTC of 18th May 2016.

Based on initial conditions of 0000 UTC of 19th, all models predicted landfall northwest of Chittagong. UKMO predicted landfall close to Chittagong around 1000 UTC of 21st. MME and HWRF also predicted landfall close to Chittagong around 1800 UTC of 21st.

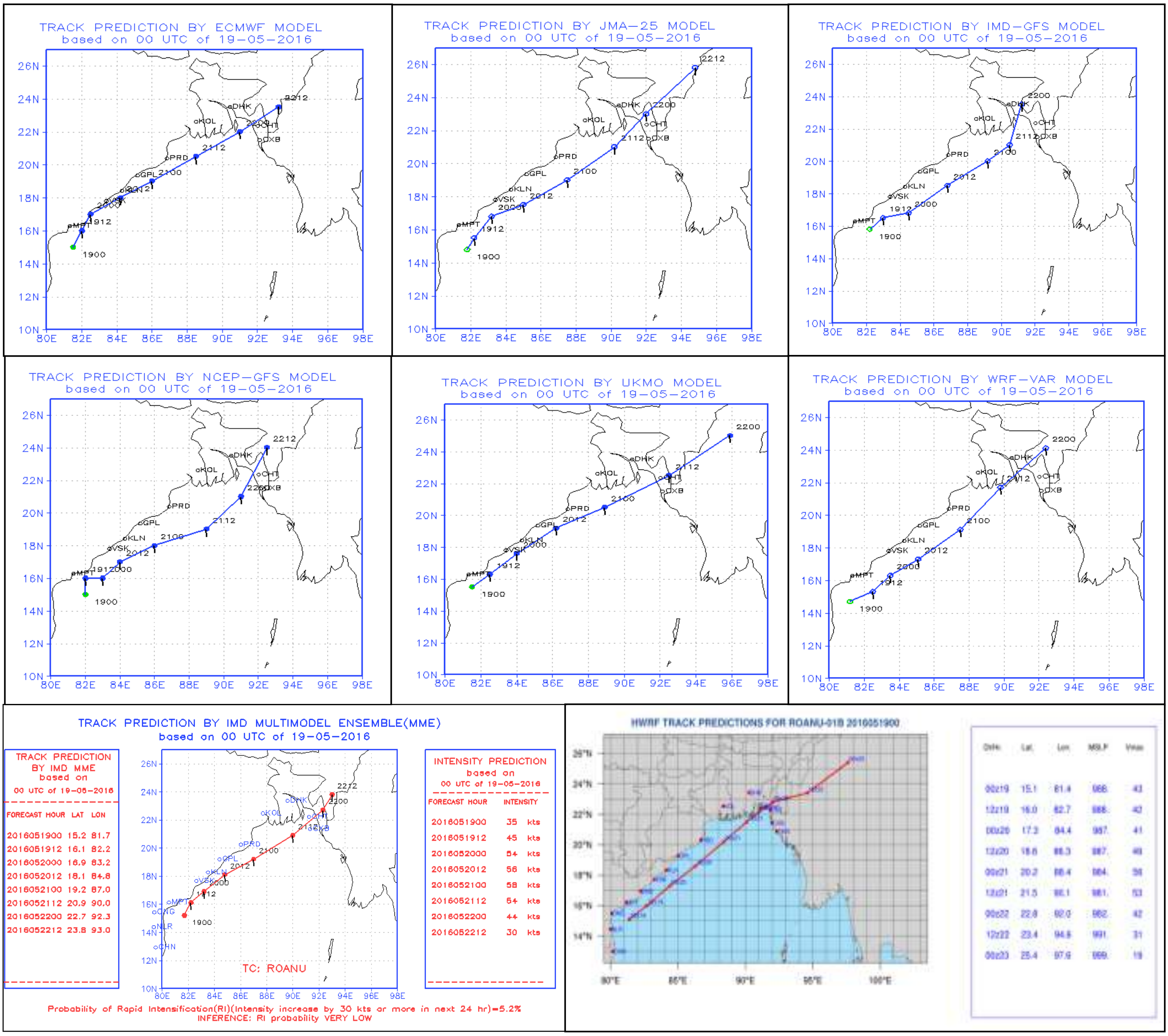


Figure 17 (c): Predicted track of CS Roanu based on 0000 UTC of 19th May 2016.

Based on initial conditions of 0000 UTC of 20th May, ECMWF and GFS predicted landfall to the northwest of Chittagong. All other models predicted landfall near Chittagong.

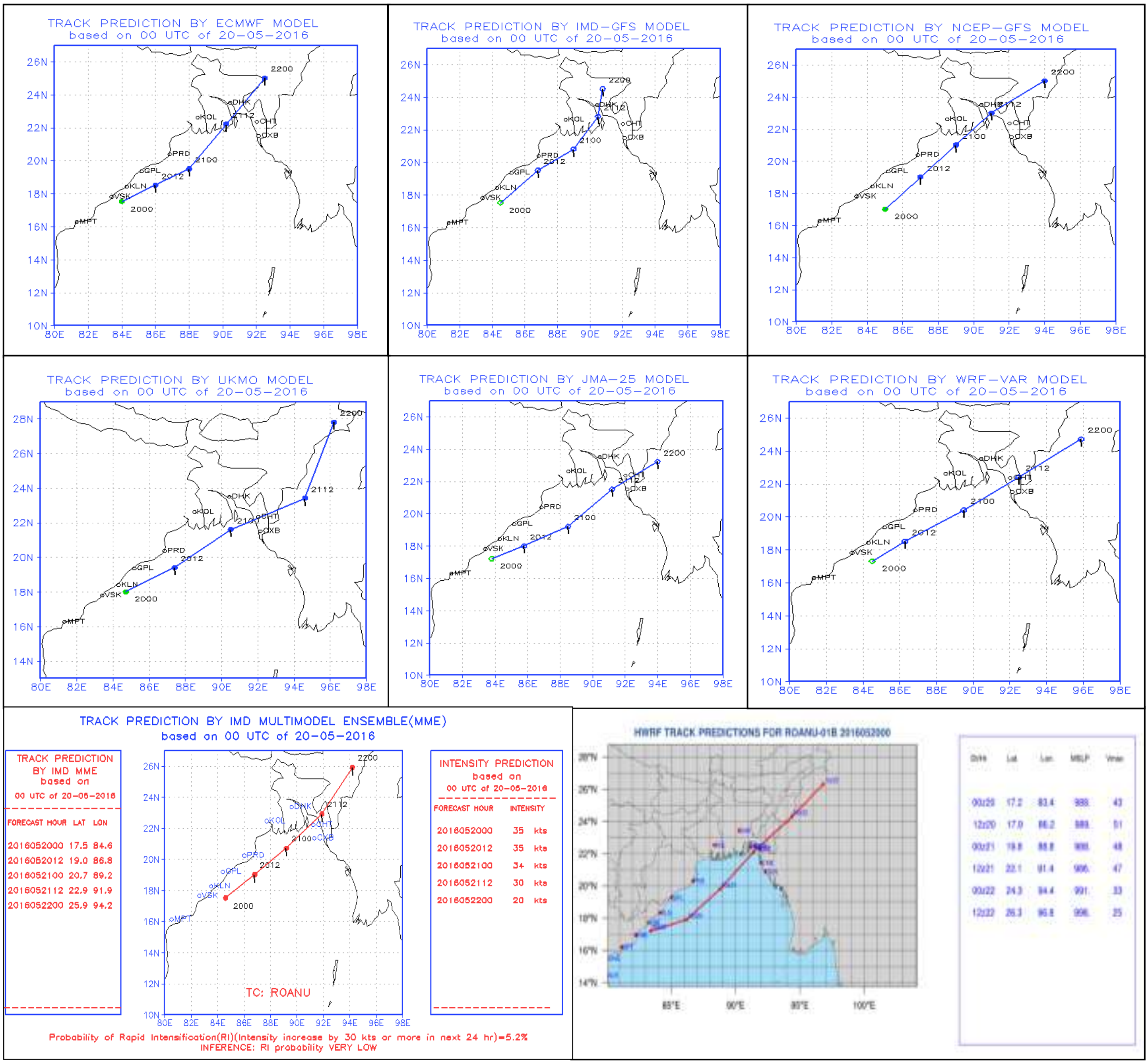


Figure 17 (d): Predicted track of CS Roanu based on 0000 UTC of 20th May 2016.

Based on initial conditions of 0000 UTC of 21st May, all models except IMD GFS and NCEP GFS predicted landfall near Chittagong. UKMO consistently showed landfall near Chittagong around 1000 UTC of 21st throughout the life cycle of Roanu.

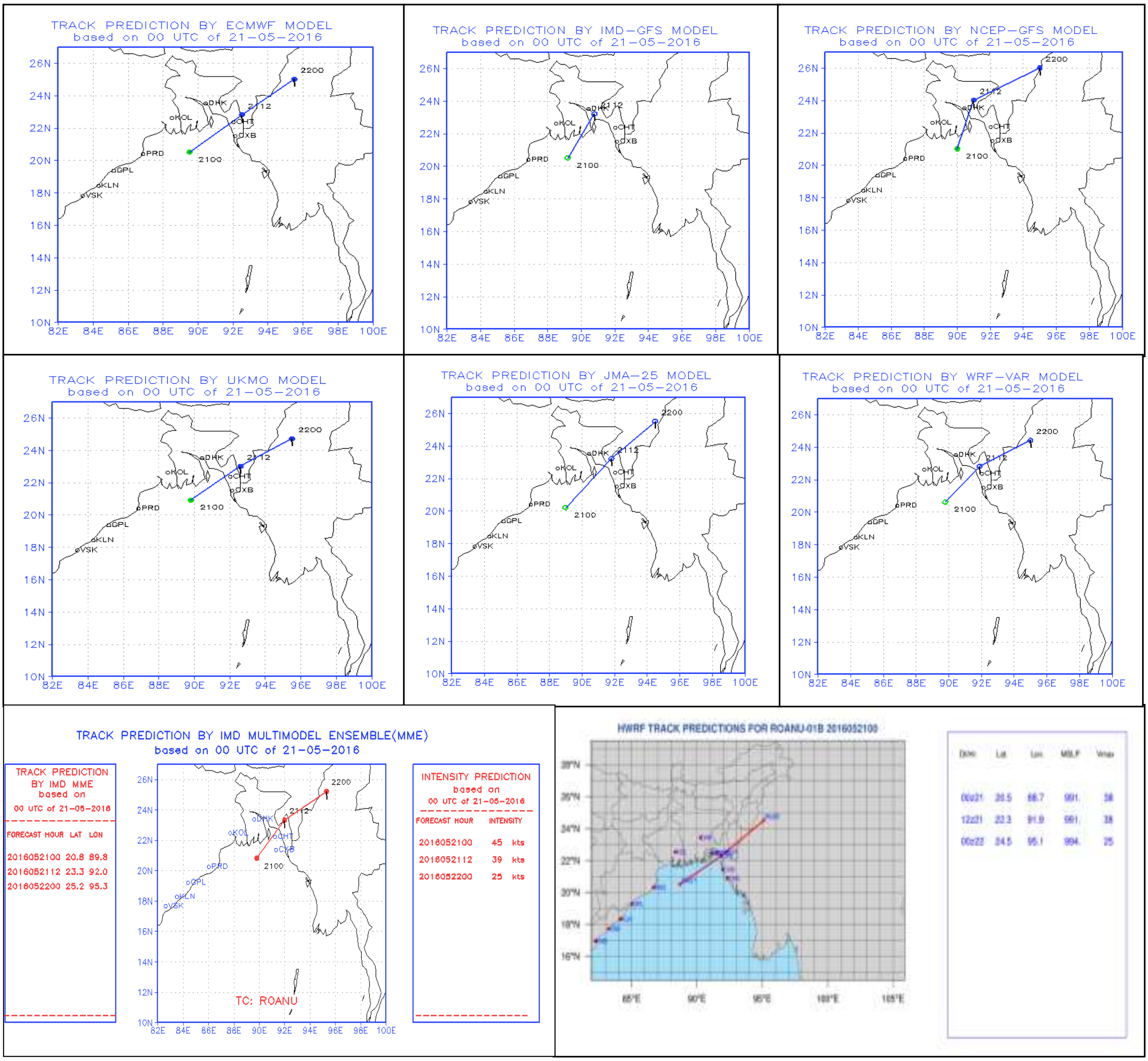


Figure 17 (e): Predicted track of CS Roanu based on 0000 UTC of 21st May 2016.

Hence to conclude, all models were unanimously predicting landfall over Bangladesh and showing movement close to the east coast of India. No model indicated landfall over Indian coast at any point.

Observed track and forecast track based on different initial conditions is presented in Fig. 17 (f).

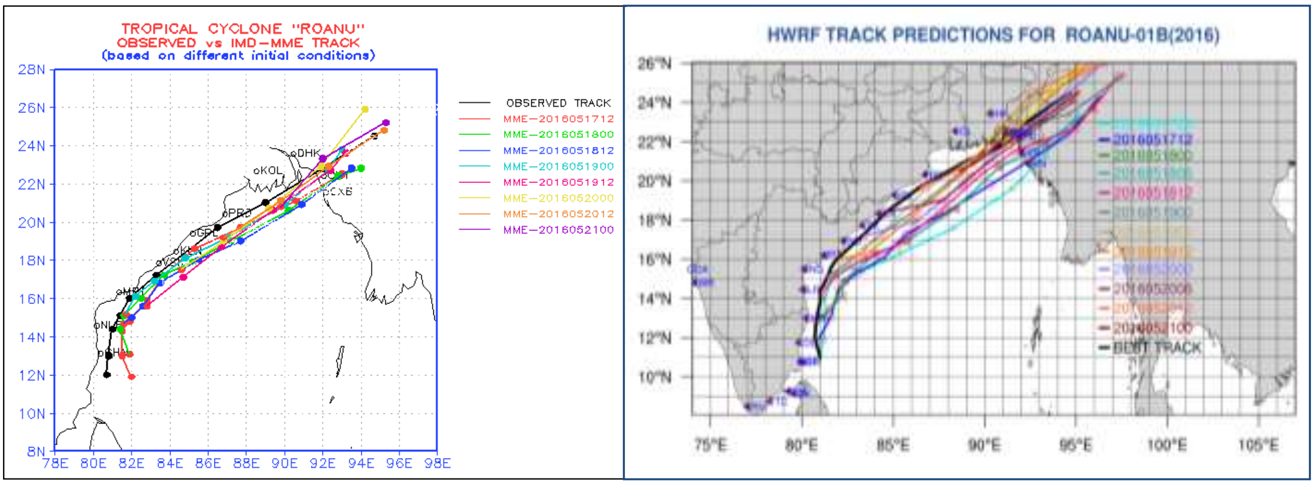


Fig. 17 (f): Observed track versus (a) IMD-MME and (b) HWRF track based on different initial conditions

Ensemble Prediction System

The probabilistic and deterministic track forecast by Meteorological service Canada (MSC), National Centre for Environment Prediction (NCEP) and consolidated forecast by both centres based on initial conditions of 1200 UTC of 18th May are presented in Fig. 18 (a). MSC predicted 5-20% and 40-60 % strike probability over Bangladesh and Myanmar respectively. NCEP members showed 40-60% strike probability over Bangladesh, near Chittagong.

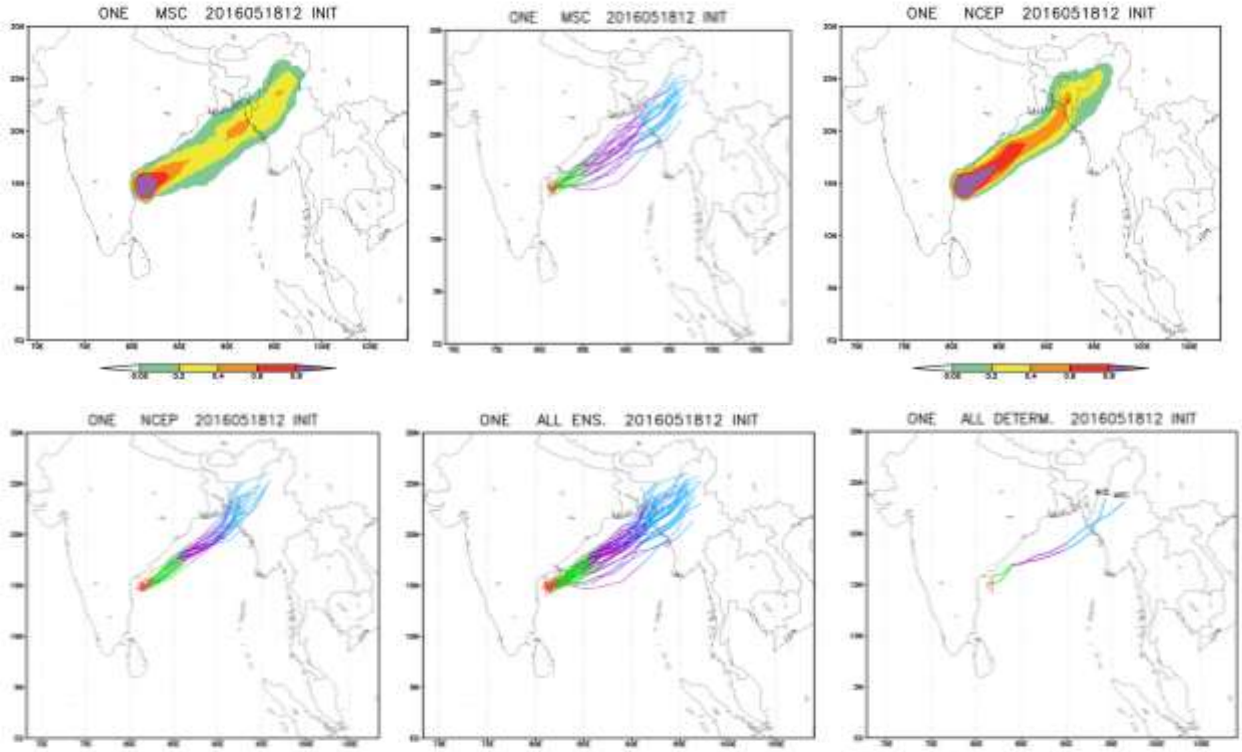


Fig. 18 (a): EPS track and strike probability forecast based on 1200 UTC of 18th May.

MSC and NCEP probabilistic and deterministic tracks based on 1200 UTC of 19th are presented in Fig. 18 (b). MSC ensemble members predicted 5-20 % strike probability over Bangladesh and 20-40 % over adjoining Myanmar. However, NCEP ensemble members predicted 60-80 % strike probability over Bangladesh and adjoining Myanmar.

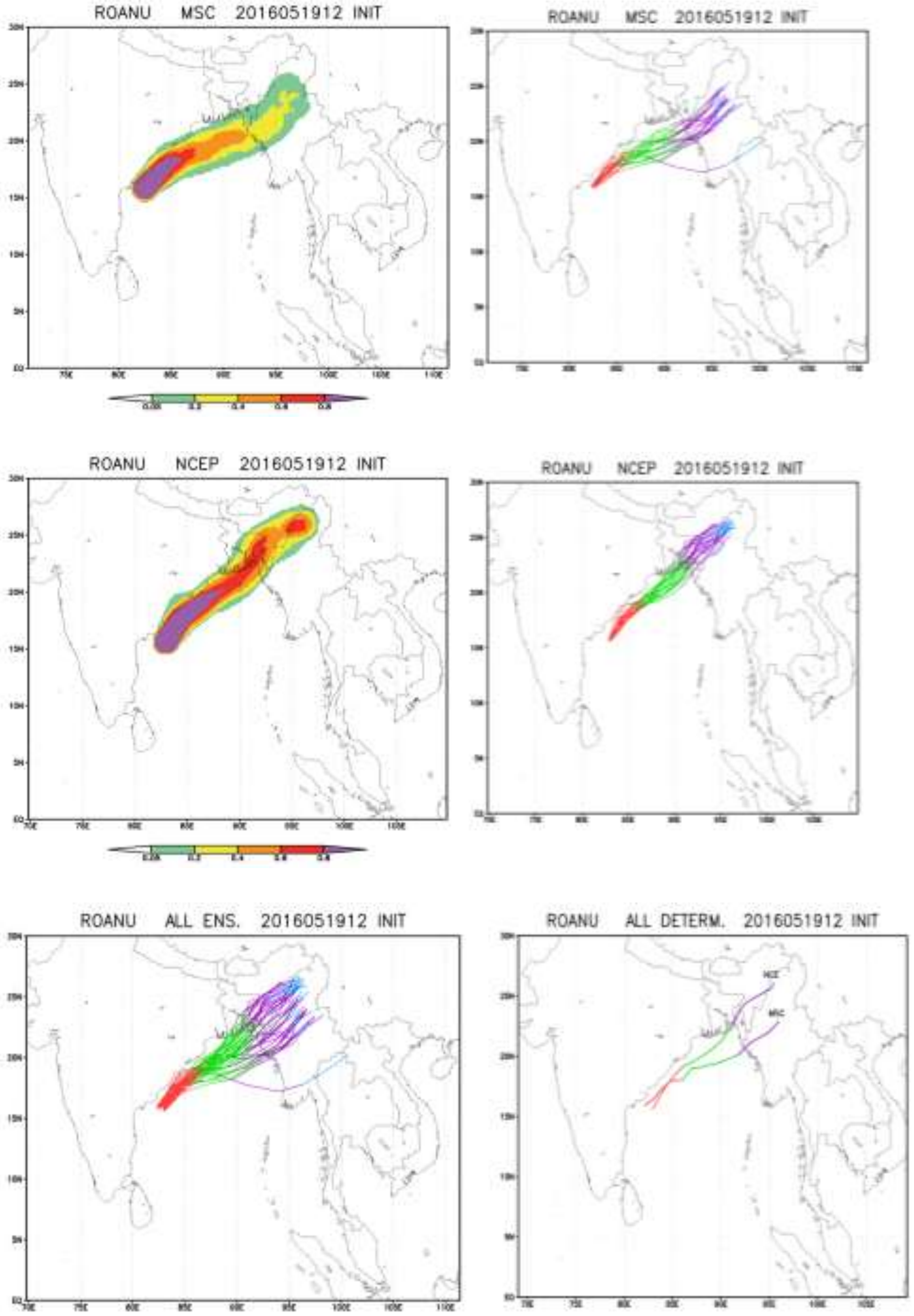


Fig. 18 (b): EPS track and strike probability forecast based on 1200 UTC of 19th May

UKMO and NCEP probabilistic and deterministic tracks based on 0000 UTC of 20th are presented in Fig. 18 (c). Ensembles from both the centres predicted 60-80 % strike probability over Bangladesh near Chittagong.

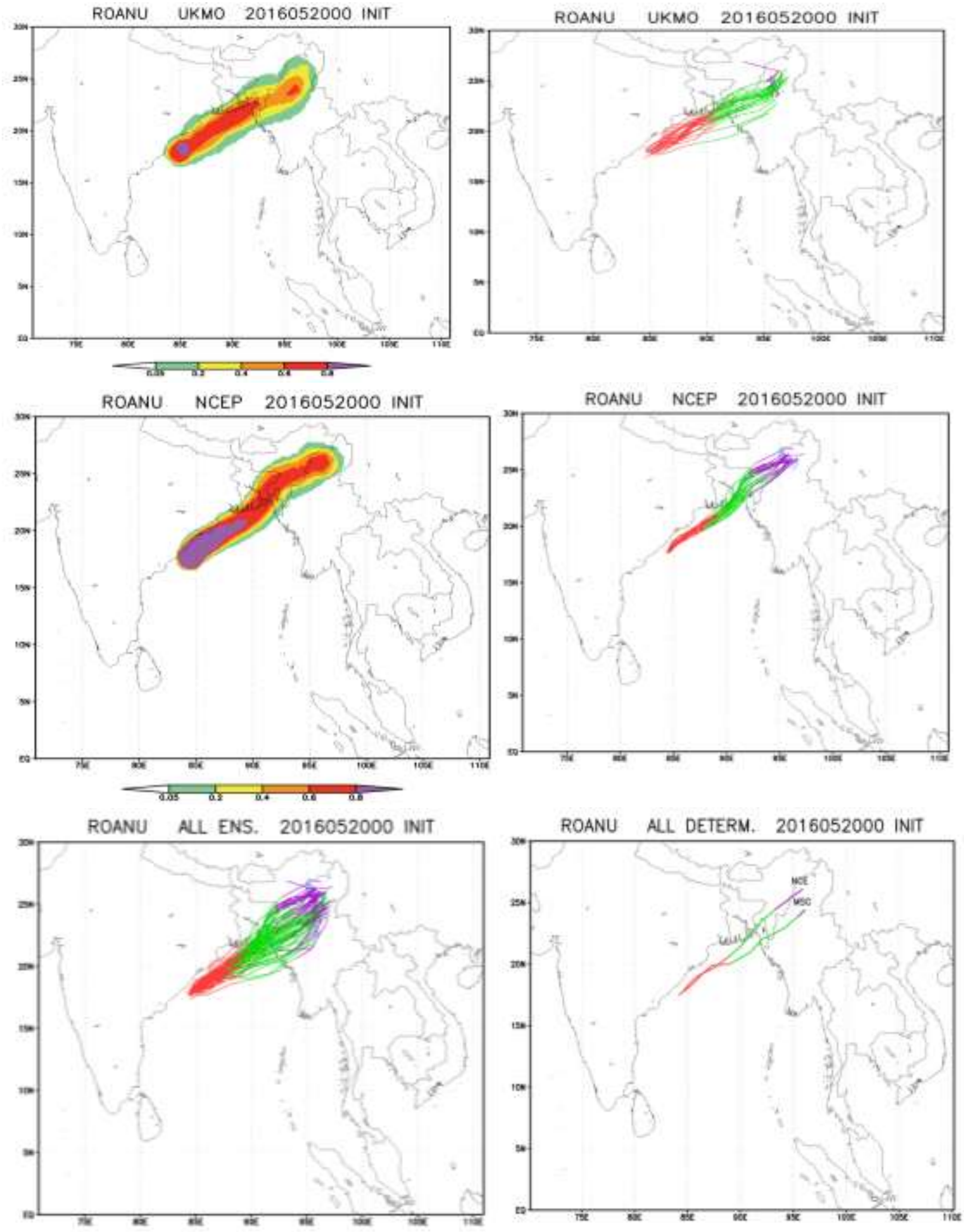


Fig. 18 (c): EPS track and strike probability forecast based on 0000 UTC of 20th May

Based on initial conditions of 1200 UTC of 20th (Fig. 18 (d)), both UKMO and NCEP members showed >80% strike probability over Bangladesh near Chittagong.

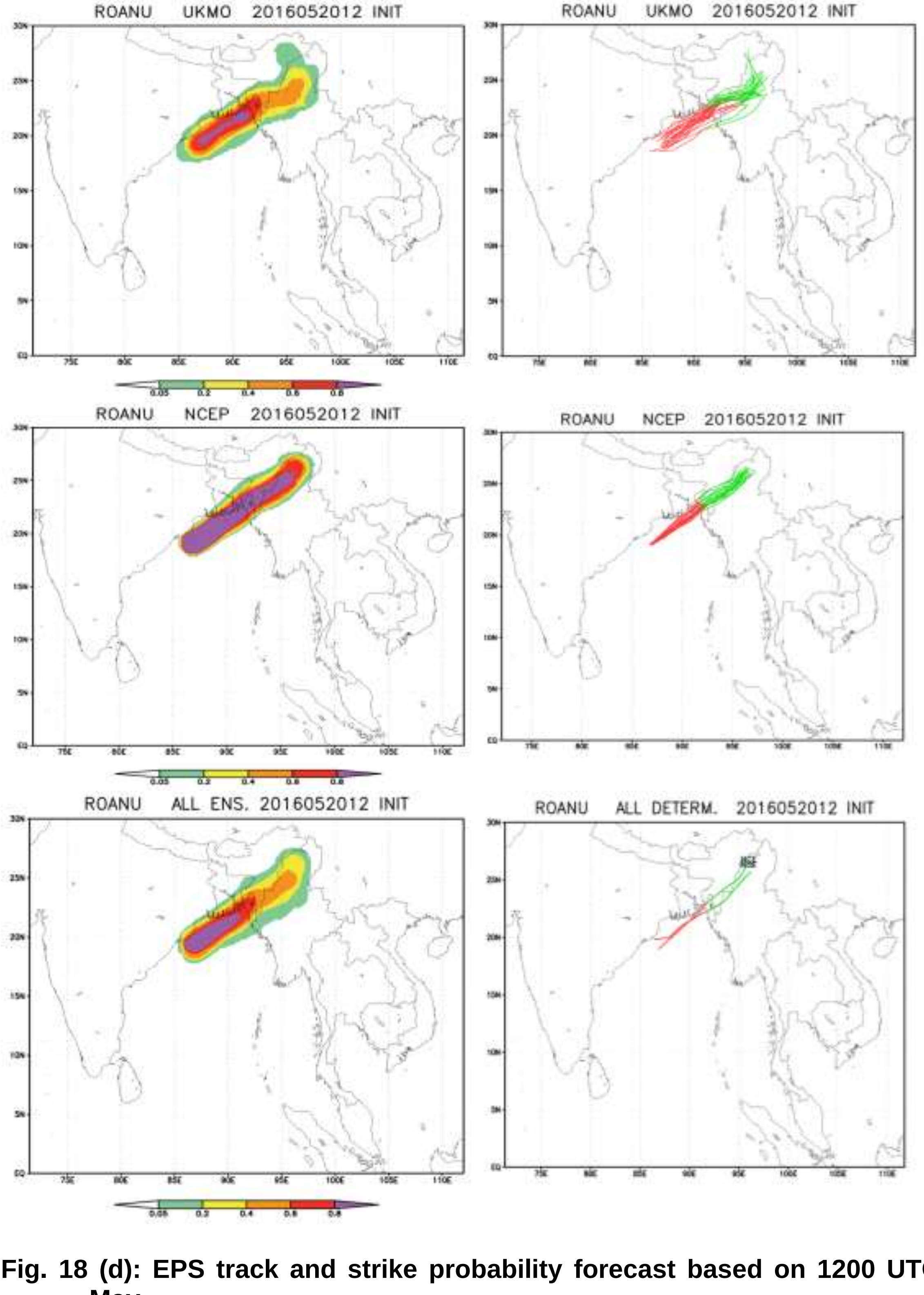


Fig. 18 (d): EPS track and strike probability forecast based on 1200 UTC of 20th May

Based on initial conditions of 0000 UTC of 21st (Fig.18 (e)) both UKMO showed 60-80% strike probability over Bangladesh and NCEP members showed >80% strike probability over Bangladesh near Chittagong. Comparing all the ensemble products, the UKMO followed by NCEP EPS performed better.

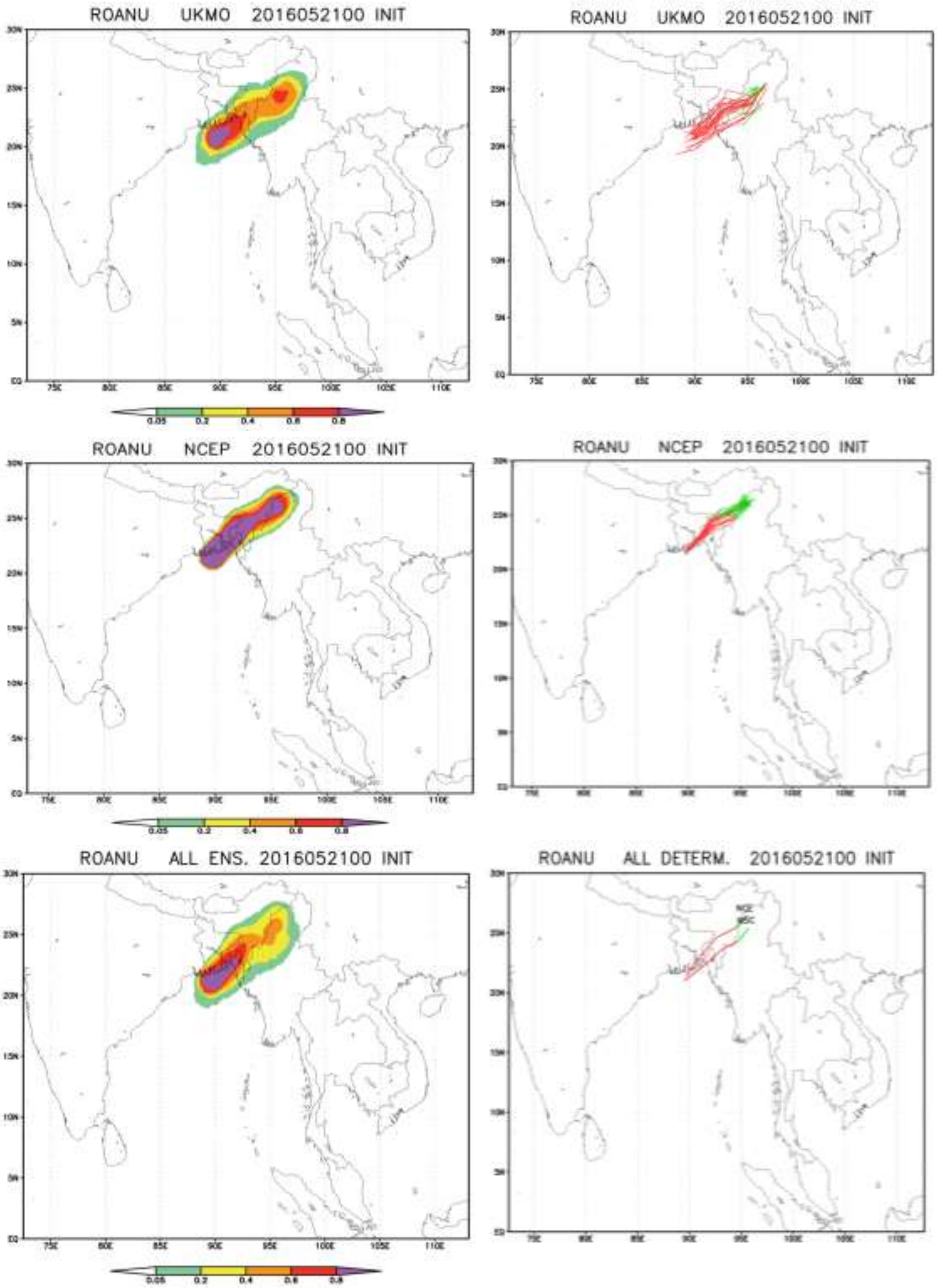


Fig. 18 (e): EPS track and strike probability forecast based on 0000 UTC of 21st May.

10.3 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 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 UKMO were significantly less for all lead periods. Average track errors of IMD-MME were the least for 24 and 48 hours lead period.

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

Lead time	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr
IMD-GFS	91(8)	110(8)	147(7)	221(6)	233(5)	216(4)	264(3)	286(2)	400(1)
IMD-WRF	87(8)	80(8)	153(7)	159(6)	153(5)	108(4)	-	-	-
JMA	90(8)	120(8)	156(7)	198(6)	216(5)	258(4)	254(3)	-	-
NCEP	104(8)	81(8)	116(7)	180(6)	365(5)	413(4)	449(3)	473(2)	391(1)
UKMO	86(8)	102(8)	155(7)	170(6)	82(5)	108(4)	93(3)	136(2)	75(1)
ECMWF	72(8)	119(8)	167(7)	203(6)	265(5)	307(4)	263(3)	323(2)	386(1)
IMD-HWRF	90(17)	114(16)	135(14)	159(12)	209(10)	245(8)	270(6)	237(4)	315(2)
IMD-MME	74(8)	60(8)	81(7)	142(6)	204(5)	255(4)	243(3)	270(2)	282(1)
NCUM	157(6)	161(6)	220(5)	202(5)	300(4)	415(4)	725(3)	786(3)	157(6)
NEPS	115(6)	143(6)	176(5)	168(5)	256(4)	278(4)	48793)	517(3)	115(6)

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

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

Lead time	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr
IMD-GFS	64	100	111	143	129	140	201	144	232
IMD-WRF	74	65	98	92	80	48	-	-	-
JMA	63	64	62	76	72	64	89	-	-
NCEP	82	51	32	69	127	103	142	147	26
UKMO	46	53	66	81	38	38	13	11	9
ECMWF	56	65	75	94	58	23	11	30	122
IMD-HWRF	55	76	77	90	80	124	162	154	188
IMD-MME	58	44	36	68	39	44	48	48	53
NCUM	70	48	80	82	48	95	39	22	-
NEPS	45	70	79	78	35	74	58	120	-

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

Lead time	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr
IMD-GFS	62	41	83	142	165	118	121	229	325
IMD-WRF	38	32	91	114	115	89	-	-	-
JMA	50	91	133	178	198	247	237	-	-
NCEP	44	55	106	150	335	396	419	448	390
UKMO	67	80	126	146	61	90	87	135	75
ECMWF	31	88	125	156	241	306	263	321	366
IMD-HWRF	55	108	125	119	130	212	250	214	218
IMD-MME	37	28	55	100	196	249	236	266	277
NCUM	130	160	210	210	315	450	750	790	-
NEPS	100	120	185	190	300	305	535	550	-

Above tables 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.

- : No forecast issued

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

Forecast Lead Time (hour) →	10 h	22 h	34 h	46 h	58 h	70 h	82 h	94 h
IMD-GFS	177	173	177	154	65	126	129	264
IMD-WRF	0	84	73	78	177	-	-	-
JMA	61	0	73	0	23	15	-	-
NCEP-GFS	159	30	187	187	23	-	251	78
UKMO	30	49	59	78	59	73	15	15
ECMWF	49	30	177	98	0	23	15	43
IMD-HWRF	39	11	49	78	110	114	170	198
IMD-MME	0	15	0	39	39	98	84	73

Landfall Point Error: Landfall Forecast Point- Actual Landfall Point

- : No forecast issued

Table-6. Landfall time forecast errors (hour) at different lead time (hr)
('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	10 h	22 h	34 h	46 h	58 h	70 h	82 h	94 h
IMD-GFS	-4	-7	-4	+4	+9	-4	+19	+4
IMD-WRF	+1	0	-1	+2	+3	-	-	-
JMA	0	+5	-7	+5	+10	+7	-	-
NCEP-GFS	-6	0	-5	-4	+18	-	+16	+14
UKMO	-2	-3	-7	-1	0	0	0	+5
ECMWF	-1	-7	+1	+4	+17	+8	+7	+5
IMD-HWRF	02	00	04	02	06	02	-03	02
IMD-MME	-1	-1	0	-1	+9	+6	+9	+8

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

Intensity prediction

The intensity forecast s of IMD-SCIP model and HWRF model are shown in Table 7. The errors were relatively higher in case of HWRF. The probability of rapid intensification (RI) index of IMD is shown in Table 8. It correctly predicted no RI for cyclone, Roanu.

Table 7: Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of SCIP model (Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr
IMD-SCIP (AAE)	5.0 (8)	8.3 (7)	9.2 (6)	6.8 (5)	8.5 (4)	13.3 (3)	10.0 (2)	3.0 (1)
IMD-SCIP (RMSE)	5.4	9.2	10.2	8.1	11.0	15.8	11.2	3.0
HWRF (AAE)	9.1 (17)	9.8 (16)	8.5 (14)	9.5 (12)	11 (10)	18.5 (8)	13.5 (6)	12.2 (4)
HWRF (RMSE)	11.7	13.6	10.5	11.7	14.4	20.0	15.1	16.7

( ) : No of forecasts verified

Table 8: Probability of Rapid intensification

Forecast based on UTC/Date	**Probability of RI predicted**	**Chances of occurrence predicted**	**Intensity changes(kt) occurred in 24h**
12/17.05.2016	5.2 %	VERY LOW	5
00/18.05.2016	5.2 %	VERY LOW	10
12/18.05.2016	2.6 %	VERY LOW	10
00/19.05.2016	5.2 %	VERY LOW	5
12/19.05.2016	5.2 %	VERY LOW	0
00/20.05.2016	5.2 %	VERY LOW	5
12/20.05.2016	5.2 %	VERY LOW	-5

10.4. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model are presented in fig.19. It indicates that the HWRF model could predict the occurrence of rainfall along Indian coast (north tamil Nadu and Andhra Pradesh) based on initial conditions of 17th, over Andhra Pradesh and south Odisha coast based on initial conditions of 18th. It could capture rainfall over north Andhra Pradesh, Odisha and West Bengal coast based on initial conditions of 19th, Odisha and west Bengal coast based on initial conditions of 20th and 21st. It also predicted occurrence of heavy rainfall over Bangladesh and adjoining northeastern states of India based on the initial conditions of 17th onwards.

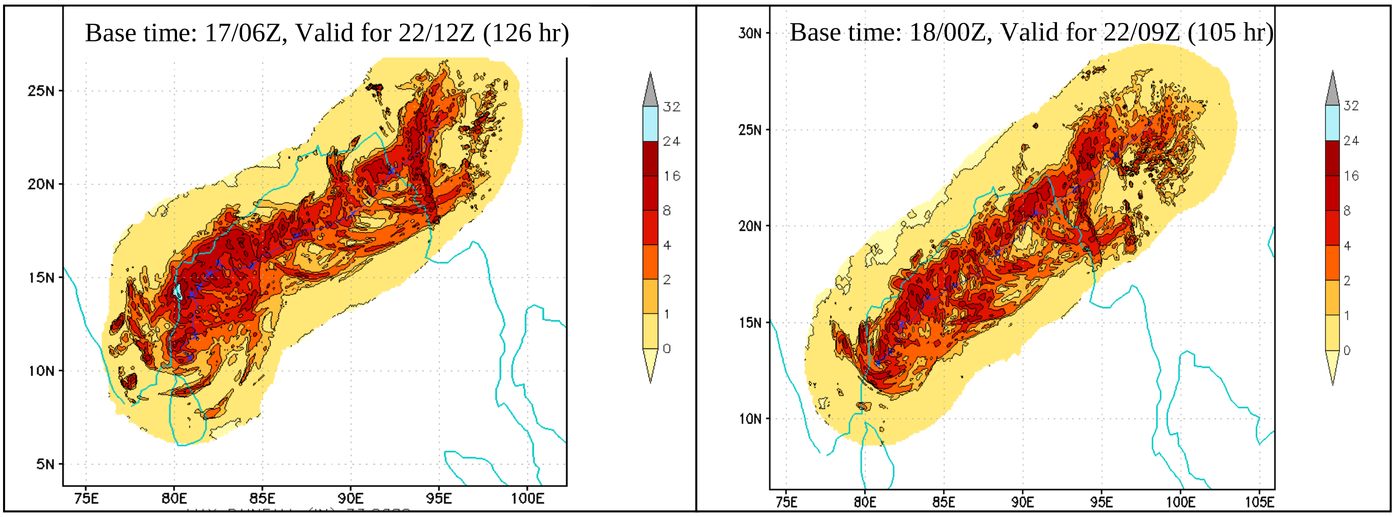


Fig. 19 HWRF rain swath (inch) based on 17/0600, 18/0000 UTC initial conditions.

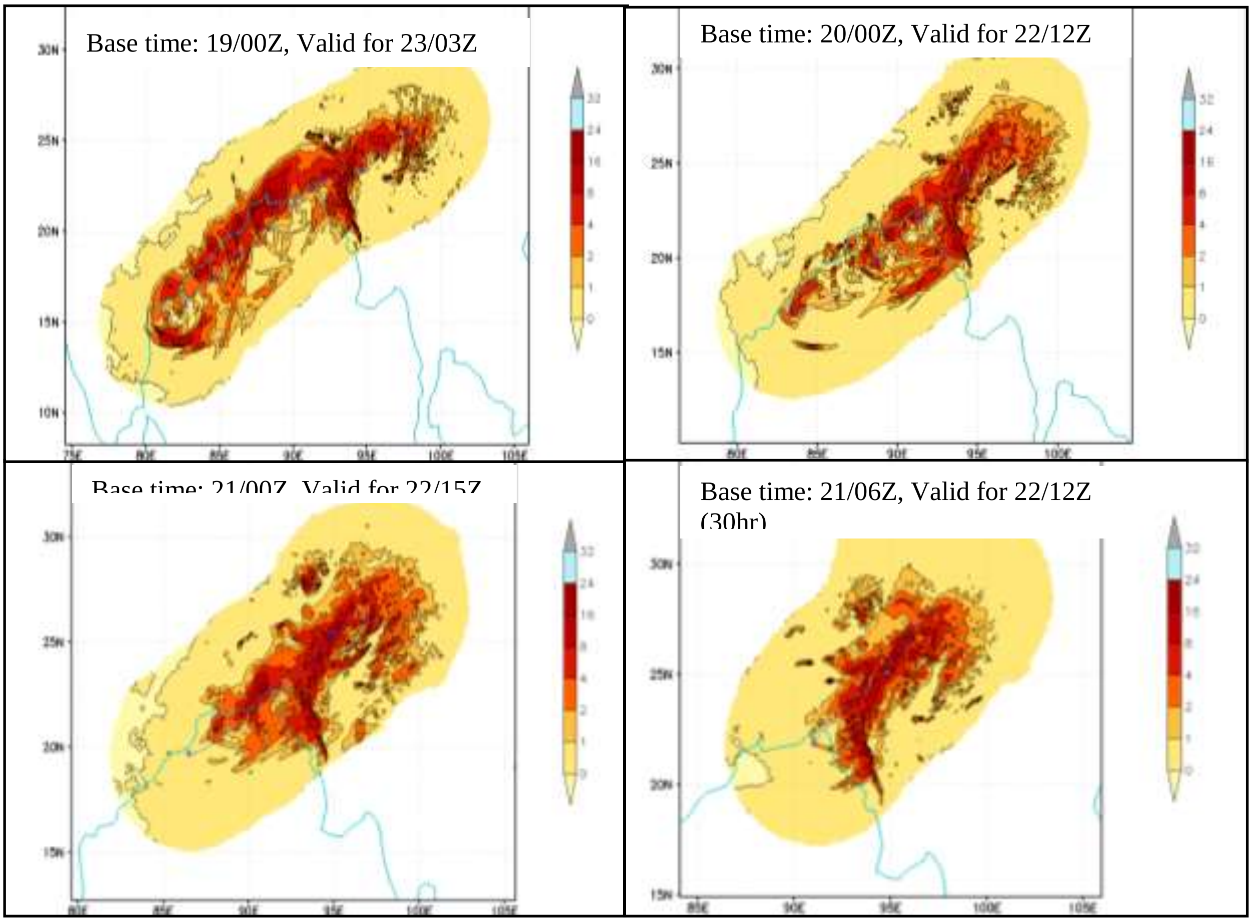


Fig.19 (contd) HWRF rain swath (inch) based on 19/0000, 20/0000, 21/0000 and 21/0600 UTC initial conditions.

10.5 Storm surge forecast

Predicted surge by Indian National Centre for Ocean Information Services (INCOIS) Advance Circulation (ADCIRC) model are presented in Fig.20. ADCIRC model run by INCOIS predicted the maximum surge of height 0.7 m along east coast of India near Kakinada, Andhra Pradesh at 1200 UTC of 19 May, 2016. No inundation extent was predicted by the model along Indian coast. This model predicted surge height of about 2 m near Chittagong at the time of landfall.

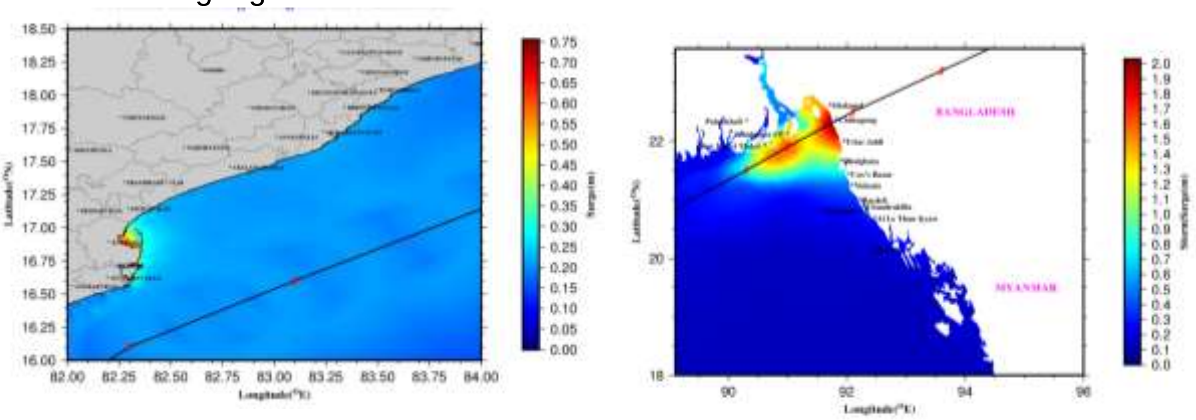


Figure.20: INCOIS model predicted surge height near (a) Kakinada coast, Andhra Pradesh and (b) Bangladesh coast

IIT-Delhi storm surge model for various coastal states of India and Bangladesh predicted storm surge of height 30-40 cm at the time of landfall near Chittagong (Fig.21). However, the realized surge was around 1-1.5 metre at the time of landfall. Hence, IIT Delhi model under-predicted the storm surge.

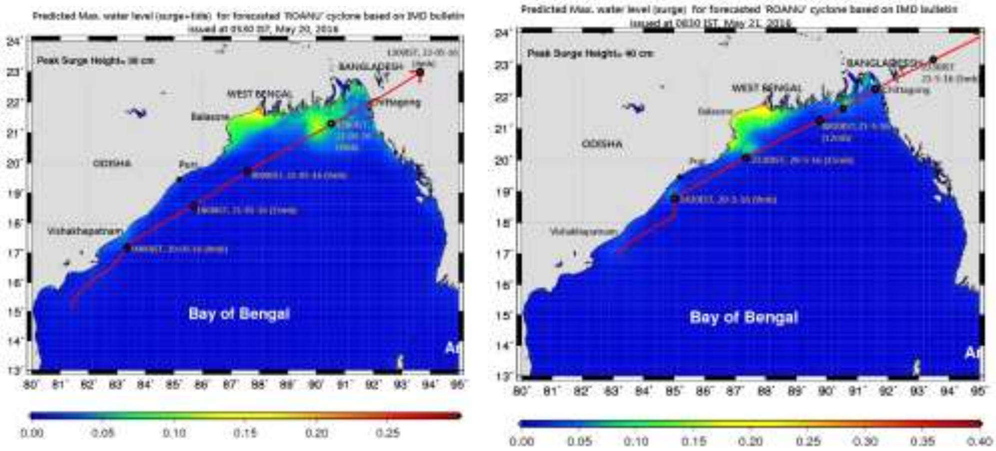


Fig.21 IIT-Delhi storm surge forecast issued at 0000 UTC of 20th May and 0300 UTC of 21st May

10.6 Ocean State Forecast by INCOIS

INCOIS issues ocean state forecast based on the bulletins issued by IMD. The forecast and observed wave heights at Digha, Gopalpur, Vishakhapatnam and Pondicherry are presented in the Fig. 22.

The real time evaluation of the wave forecasts is of great interest to users. The waves at Pondicherry showed a diurnal cycle but no high waves (less than 1.5m) attributable to the cyclone. However, Vishakhapatnam did show rough sea condition on May 19th (around 3.5m) and Gopalpur on May 20th (3.5m) and Digha on May 20th (3.0m).

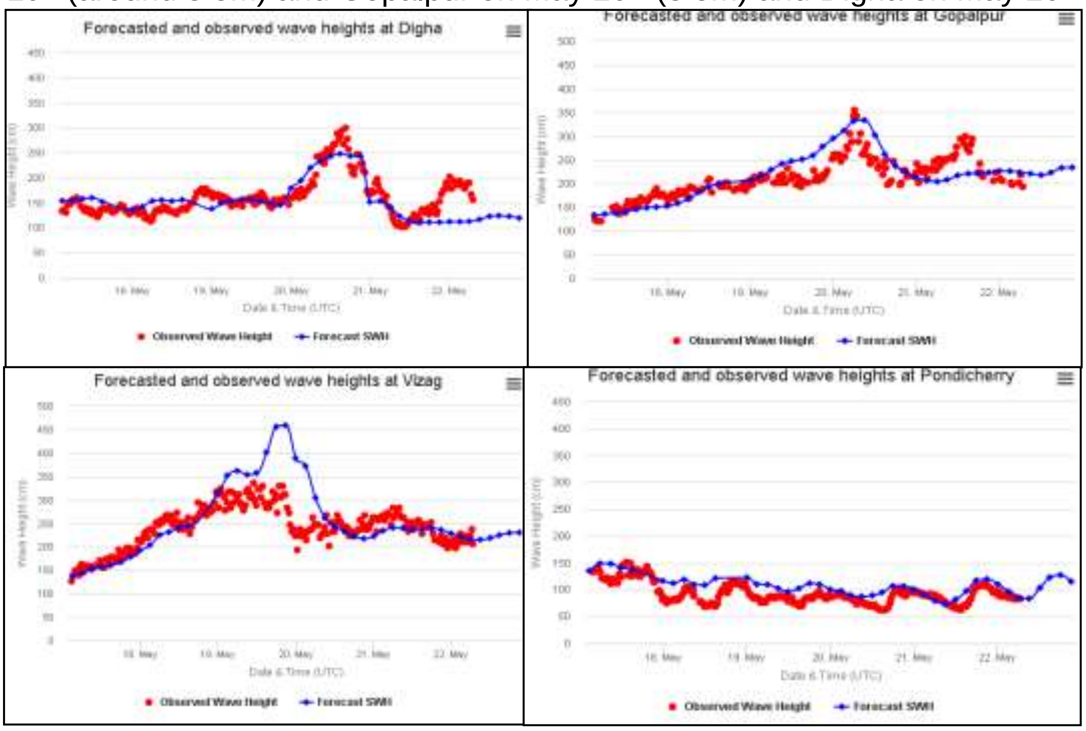


Fig.22 The forecast and observed wave heights during 18th to 22nd May 2016

11. Operational Forecast Performance

11.1 Operational Genesis forecast

(i) IMD first predicted genesis of depression over southwest BoB on 16th May based on the observations of 0830 hours IST of 13th May.

(ii) Depression formed at 0830 hours IST of 17th May. At 0830 hours IST of 14th May (72 hours in advance), IMD predicted genesis with moderate (51-75%) probability on 17th May.

(iii) At 0830 hours IST of 15th May (48 hours in advance), the genesis over BoB was predicted for 17th May with high (76-100%) probability.

11.2. Operational landfall forecast error and skill

The operational landfall forecast errors and skill are presented in Table 9. The landfall point error (LPE) has been about 17, 100 and 96 km against long period average (LPA) based on 2011-15 of 56, 94 and 106 km for 24, 48 and 72 hours lead period respectively. The LPE has been significantly lower than the LPA for 24 hours lead period and comparable to LPA for 48 and 72 hours lead period. The landfall time error (LTE) has been 1.0, 9.0 and 9.0 hours against the LPA of 4.2, 4.7 and 2.4 hours for 24, 48 and 72 hours lead period respectively. LTE had been significantly lower for 24 hours lead period and higher than LPA for 48 and 72 hours lead period. An example of forecast track along with cone of uncertainty issued on 1200 UTC of 20th May and observed track is presented in Fig.23.

The first bulletin indicating landfall over Bangladesh coast near Chittagong was given in the forecast track graphics based on 0300 UTC of 18th.

Table 9: Landfall Point and Time Error in association with CS ROANU

Lead Period (hrs)	Base Time	Landfall Point (degrees)		Landfall Time (UTC)		Operational Error		LPA error (2011-15)	
		Forecast Lat./long.	Actual Lat./long.	Forecast (Date/time)	Actual (Date/time)	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
10	21/0000	22.5/91.7	22.6/91.6	21/1100	21/1000	16	1.0	36.5	2.5
22	20/1200	22.5/91.7	22.6/91.6	21/0900	21/1000	17	1.0	56.3	4.2
34	20/0000	22.0/91.9	22.6/91.6	21/1900	21/1000	77	9.0	60.6	4.7
46	19/1200	21.9/91.1	22.6/91.6	21/1900	21/1000	100	9.0	93.5	4.7
58	19/0000	21.8/91.9	22.6/91.6	21/1800	21/1000	93	8.0	95.2	3.9
70	18/1200	21.8/91.9	22.6/91.6	21/1900	21/1000	96	9.0	105.7	2.4

The landfall point and time could not be predicted beyond 72 hours as the life of the system from DD to landfall was about 82 hours.
The LPA error is based on 12, 24,…72 hours lead period.
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

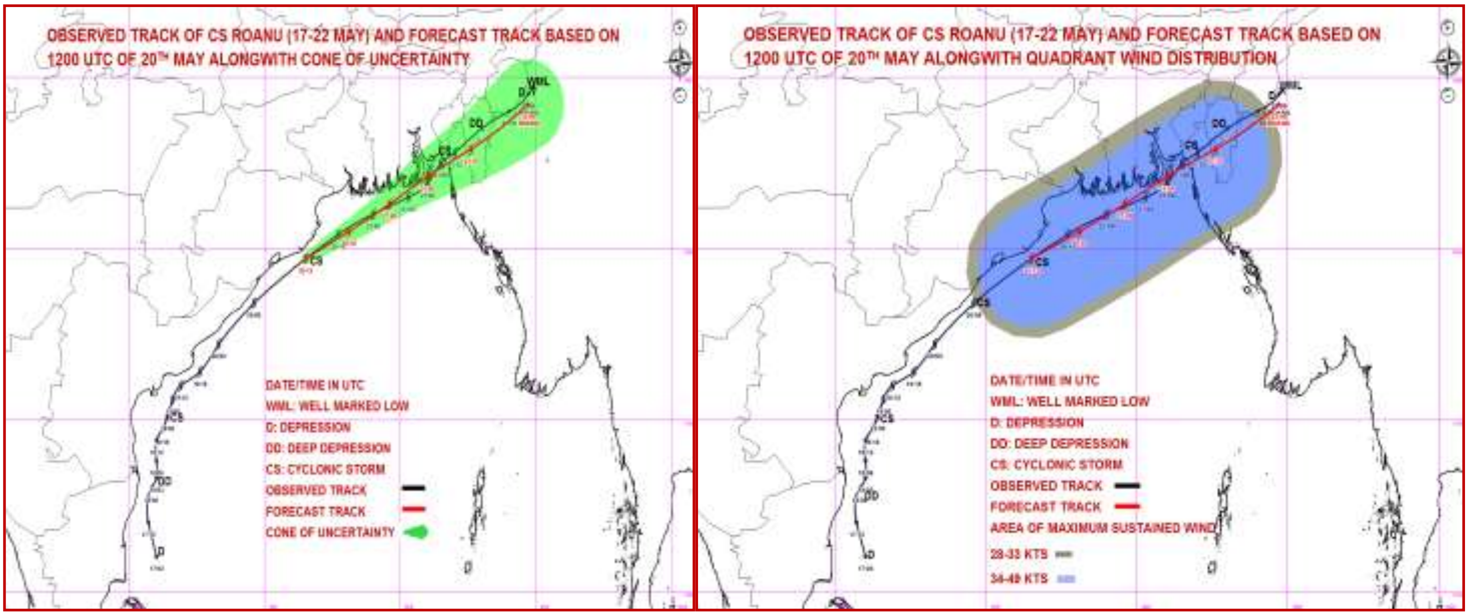


Fig.23: Observed track of CS Roanu (17-22 May 2016) and forecast track based on 1200 UTC of 20th May alongwith (a) Cone of uncertainty and (b) Quadrant wind distribution.

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 10. The track forecast errors for 24, 48 and 72 hours lead period have been 130, 252 and 299 km against the long period average (LPA) of 98, 146 and 183 km respectively. The track forecast errors have been higher than the LPA for all lead periods mainly due to recurving track. However, the skill in operational track forecast compared to CLIPER forecast has been higher than long period average for all lead periods.

Table 10 (a): Average Track forecast error in association with CS ROANU

Lead Period (hrs)	N	ATE (km)	CTE (km)	Average track forecast error (km)	Skill (%)	LPA (2011-15)	
						Track forecast error (km)	Skill (%)
12	14	96	43	83.7	48.5	59.1	41.4
24	12	158	88	130.1	66.9	97.5	48.5
36	10	192	123	180.0	73.4	120.0	58.1
48	8	209	205	252.0	75.0	145.5	62.7
60	6	95	248	290.9	78.3	160.4	67.8
72	4	128	224	299.3	82.0	183.2	69.3
84	2	124	287	326.9	82.8	204.0	71.3

N: No. of observations verified, LPA: Long Period Average (2011-15)
There was no track forecast verification for 96-120 hours due to short track of the CS.

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 11. The operational AE in intensity forecast has been significantly less than LPA as it was about 7, 3 and 6 knots against LPA of 12, 17 and 18 knots for 24, 48 and 72 hours lead period. Similarly, operational RMSE in intensity forecast has been about 8, 4 and 8 knots against LPA of 15, 22 and 22 knots for 24, 48 and 72 hours lead period respectively. The skill in intensity forecast with reference to AE is about 36%, 82% and 73% against the LPA of 36%, 56% and 67% respectively for 24, 48 and 72 hours lead period.

Table 11: Average Intensity forecast error in association with CS ROANU

Lead Period (hrs)	N	Average Intensity Error (kts)		LPA Intensity forecast Error (kts)		Gain in Skill (%) against Persistence		LPA Gain in Skill (%) against Persistence	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	14	6.9	8.1	7.1	9.4	-20.6	-6.6	20.9	27.9
24	12	6.7	8.4	11.5	14.9	35.9	42.5	36.4	40.1
36	10	5.2	6.3	14.8	19.2	50.2	48.8	49.4	52.0
48	8	3.1	3.6	16.9	21.6	81.5	80.9	55.8	59.6
60	6	7.5	7.9	17.6	22.0	72.8	76.2	62.3	67.0
72	4	5.7	7.9	17.6	22.1	73.2	70.3	67.3	72.0
84	2	3.7	5.0	20.0	27.3	90.9	87.7	73.4	76.4

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2011-15). There was no track forecast verification for 96-120 hours due to short track of the CS.

11.4. 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 12-14. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table – 12(a) .Verification of Heavy Rainfall Forecast

Date & Time	Heavy rainfall warning issued	24-hour Heavy rainfall realised ending at 0300 UTC of date
17.05.2016 0300 UTC	Heavy to very heavy falls at a few places over north coastal Tamil Nadu & Puducherry and isolated places over north interior Tamil Nadu and isolated heavy falls over south Tamil Nadu during next 24 hours. Isolated heavy to very heavy falls over north Tamil Nadu & Puducherry during subsequent 24 hours. Isolated heavy falls over south coastal Andhra Pradesh coast on 17th May 2016. Isolated heavy to very heavy falls on 18th May and	**18.05.2016:** Isolated extremely heavy rainfall and heavy to very heavy rainfall at a few places over **Tamil Nadu.** Heavy to very heavy falls at a few places over **coastal Andhra Pradesh.**

<table>
<tr>
<td></td>
<td>isolated heavy falls on 19th over coastal Andhra Pradesh.

Isolated heavy falls over Rayalaseema during the next 48 hours.

Isolated heavy rainfall on 17th, isolated heavy to very heavy falls on 18th and isolated heavy falls on 19th May over south interior Karnataka.</td>
<td rowspan="4">Isolated heavy to very heavy falls over Rayalaseema.

<u>19.05.2016:</u>

Isolated heavy to very heavy falls over Tamil Nadu.

Isolated extremely heavy rainfall and heavy to very heavy rainfall at a few places over coastal Andhra Pradesh.

Isolated heavy falls over Rayalaseema.

Isolated heavy falls over south interior Karnataka.

<u>20.05.2016:</u>

Heavy to very heavy falls at a few places with isolated extremely heavy falls over Tamil Nadu.

Heavy to very heavy falls at a few places over coastal Andhra Pradesh.

Isolated heavy falls over Rayalaseema.

Isolated heavy to very heavy falls over Odisha.

Isolated heavy falls over south interior Karnataka.

<u>21.05.2016:</u>

Heavy to very heavy falls at a few places with</td>
</tr>
<tr>
<td>18.05.2016 0300 UTC</td>
<td>Isolated heavy to very heavy falls over north Tamil Nadu & Puducherry during next 24 hours.

Heavy to very heavy falls at a few places and isolated extremely heavy falls likely over coastal Andhra Pradesh during next 48 hours.

Heavy to very heavy falls at a few places over coastal Odisha on 19th & 20th May.

Isolated heavy to very heavy falls over Rayalaseema during next 24 hours.</td>
</tr>
<tr>
<td>19.05.2016 0300 UTC</td>
<td>Heavy to very heavy falls at a few places and isolated extremely heavy falls over coastal Andhra Pradesh during next 24 hours and heavy to very heavy at a few places during subsequent 24 hours.

Heavy to very heavy falls at isolated places over coastal Odisha during next 24 hours and heavy to very heavy falls at few places on 20 May and isolated heavy on 21st May.

Isolated heavy falls over Telangana and Rayalaseema during next 24 hours.</td>
</tr>
<tr>
<td>20.05.2016 0300 UTC</td>
<td>Heavy to very heavy falls at a few places and isolated extremely heavy falls over north coastal Andhra Pradesh during next 24 hours.

Heavy to very heavy falls at a few places with extremely heavy falls at isolated places over coastal Odisha during next 24 hours and isolated heavy rainfall during subsequent 24 hrs.
Heavy to very heavy at a few places over Gangetic West Bengal during next 24 hours and isolated heavy rainfall during subsequent 24 hrs.</td>
</tr>
</table>

21.05.2016 0300 UTC	Heavy to very heavy falls at isolated places over coastal districts of West Bengal during next 12 hours. Heavy to very heavy falls at a few places & isolated extremely heavy falls over Mizoram and isolated heavy to very heavy falls over south Assam, Manipur & Tripura during next 24 hours	isolated extremely heavy falls over **Odisha.** Isolated heavy falls over **Gangetic West Bengal and coastal Andhra Pradesh.** **22.05.2016:** Heavy to very heavy falls at isolated places over **Assam & Meghalaya**. Heavy to very heavy falls at a few places over Nagaland-Manipur-Mizoram-Tripura.
22.05.2016 0300 UTC	Isolated heavy falls over east Arunachal Pradesh and Nagaland during next 24 hours.	

Based on the Table 12(a), skill scores are calculated and the same are presented in Table 12 (b) for 24 and 48 hr forecasts.

Table - 12(b) : Skill scores for 24 and 48 hr heavy rainfall forecast

Skill Parameter	24 hr forecast	48 hr forecast
Probability of detection(POD)	0.9	0.7
False alarm rate (FAR)	0.3	0.2
Missing rate (MR)	0.1	0.3
Correct non-occurrence (C-NON)	0.3	0.8
Critical success index (CSI)	0.6	0.6
Bias for occurrence	1.3	0.9
Percentage correct (PC)	66.7	73.7
Heidke skill score (HSS)	0.1	0.5

From table 12 (b), it is seen that probability of detection (POD) of heavy rainfall during life cycle of CS Roanu was 0.9 and 0.7 respectively for 24 and 48 hours lead period respectively with false alarm (FA) of 0.3 and 0.2. The critical success index (CSI) was about 66.7% and 73.7 % respectively for 24 and 48 hours lead period.

Table 13. Verification of Gale Wind Forecast

Date/ Time(IST)	**Sqall/ Gale wind Forecast**	**Recorded wind speed (knots)**
17.05.2016 0300 UTC	Squally wind speed reaching 50-60 kmph gusting to 70 kmph along and off north Tamil Nadu & Puducherry and south Andhra Pradesh coasts during next 48 hours.	Cox'Bazar : 45 Sitakunda : 40 Comilla : 40 Sandwip : 38 Khepupara and Maijdee Court : 35 knots each at the time of landfall
18.05.2016 0300 UTC	Squally wind speed reaching 55-65 kmph gusting to 75 kmph along and off north Tamil Nadu & Puducherry during next 24 hours. Wind speed reaching 55-65 kmph gusting to 75 kmph along and off Andhra Pradesh coasts during next 12	

	hours and speed reaching 65-75 kmph gusting to 85 kmph is very likely to prevail over the same region during subsequent 24 hours. Squally wind speed reaching 60-70 kmph gusting to 80 kmph around the landfall point over Bangladesh.	Bhubaneswar : 24 knots around midnight of 19th May.
19.05.2016 0300 UTC	Wind speed reaching 90-100 kmph gusting to 110 kmph along and off North Andhra Pradesh coasts during next 12 hours and speed reaching 100-110 gusting to 120 kmph during next 36 hours. Squally wind speed reaching 60-70 kmph gusting to 80 kmph to commence over south Odisha coast tonight and wind speed reaching 90-100 kmph gusting to 110 kmph from tomorrow morning Squally wind speed reaching 45-55 kmph gusting to 65 kmph to prevail along and off north Tamil Nadu & Puducherry during next 24 hours. Squally wind speed reaching 60-70 kmph gusting to 80 kmph between khepupara and Cox's Bazar in the night of 21st and early morning of 22nd.	
20.05.2016 0300 UTC	Wind speed reaching 90-100 kmph gusting to 110 kmph to prevail along & off North coastal Andhra Pradesh during next 12 hours. Wind speed reaching 90-100 kmph gusting to 110 kmph to prevail along & off Odisha coast and 60-70 gusting to 80 kmph along & off West Bengal coast during next 48 hours. Squally wind speed reaching 50-60 gusting to 70kmph between khepupara and Cox's Bazar close to Chittagong in the night of 21st.	
21.05.2016 0300 UTC	Wind speed reaching 50-60 kmph gusting to 70 kmph to prevail along & off West Bengal coast during next 12 hours and decrease thereafter. Squally wind speed reaching 40-50 kmph gusting to 60 kmph to prevail over south Assam, Manipur, Mizoram & Tripura during next 24 hours. Squally wind speed reaching 70-80 gusting to 90 between close to Chittagong in the evening of 21st.	

Table 14. 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 19 May Storm surge of about 0.5 to 1.0 metre is likely along Andhra Pradesh coast during next 24 hours.	Kutubdia reported storm surge of height 1.0-1.2 metre near 21.82^0N/91.85^0E. Cox's Bazar reported storm surge of height 1.5 metre during high tide and 1.0 metre during

0300 UTC of 20 May Storm surge of about 0.5 to 1.0 metre is likely along Andhra Pradesh coast during next 24 hours. For Bangladesh coast: Storm surge of about 1.0 to 1.5 metre is very likely near the system centre at the time of landfall.	low tide near 21.45^{0}N/91.97^{0}E.
1200 UTC of 20 May Storm surge of about 0.5 to 1.0 metre would inundate low lying areas of districts of south coastal Odisha during next 12 hours and of about 1-1.5 metre would inundate low lying areas of districts of north coastal Odisha and West Bengal during next 24 hours. Storm surge of about 1.0 to 2 metre is very likely near the system centre at the time of landfall for Bangladesh coast.	
0300 UTC of 21 May Storm surge of about 1.0 to 2 metre would occur along Bangladesh coast during next 12 hours.	

12. Summary and Conclusion:

The CS Roanu formed from a low pressure area over southwest BoB off Sri Lanka coast on 14th May and concentrated into a depression in the morning of 17th. The system gradually intensified into a cyclonic storm at 0000 UTC of 19th. It moved nearly north to north-northeastwards, recurved east-northeastwards and crossed Bangladesh coast north of Chittagong at 1000 UTC of 21st May. Despite its long journey over sea, it did not intensify into a severe cyclonic storm.

IMD utilised all its resources to monitor and predict the genesis, track and intensification of CS Roanu. The forecast of its genesis (formation of Depression) on 17th May, its track, intensity, point & time of landfall, were predicted well with sufficient lead time. Its movement away from Indian coast was also predicted well in advance with high confidence. For 24, 48 and 72 hrs lead period, the operational landfall point error was 17, 100 & 96 km; track forecast error was 130, 252 & 299 km and intensity forecast error based on absolute error was 7, 3 & 6 kts.

14. Acknowledgements:

RSMC New Delhi duly acknowledges the contribution of Bangladesh Meteorological Department for providing real time Radar products for tracking the system and valuable information for preparation of report. It is worth mentioning here that, DWR products from Khepupara and Cox's Bazar helped especially in monitoring the system prior to and during landfall in better estimation of location, intensity and landfall processes like heavy rainfall, gale wind etc. We also acknowledge the observational support from Department of Meteorology, Sri Lanka during genesis stage and the information received from Department of Meteorology and Hydrology, Myanmar for the cyclone Roanu. The contribution of the valuable inputs and guidance from NCMRWF, IIT Bhubaneswar, IIT-Delhi, INCOIS and NIOT Chennai is also recognized. The inputs from Agrimeteorology Division, Pune, NWP Division, & Satellite Division at IMD HQ New Delhi and Area Cyclone Warning Centre (ACWC) Chennai & Kolkata and Cyclone Warning Centre (CWC) Vishakhapatnam & Bhubaneswar, Meteorological Centre, MC, Hyderabad & Thiruvananthapuram and CDR Paradip are also appreciated for their timely inputs required for compilation of this report.