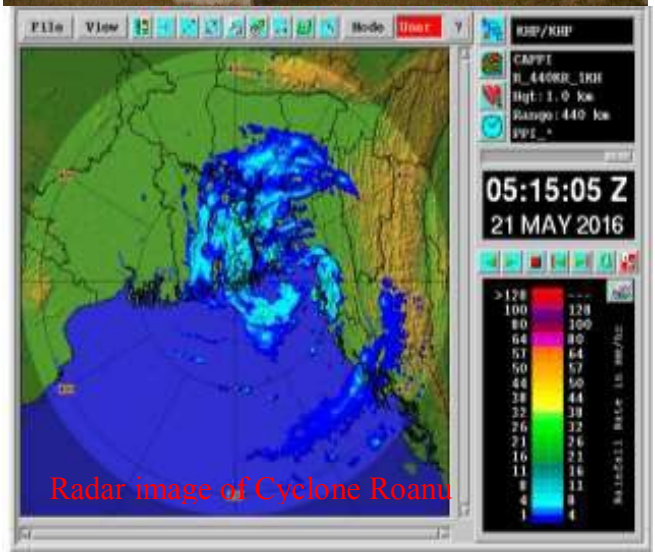
# Report on Cyclone 'Roanu'


BMD Headquarters



Damage for Cyclone Roanu

***Prepared by***

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## Preface

Cyclones are among the most devastating weather systems on the Earth. They are large scale air masses that rotate around a strong low pressure system. They are usually characterized by inward spiraling winds that rotate counterclockwise in the Northern Hemisphere. Cyclones are usually associated with strong winds and rain, high ocean waves and storm surge. Pre-monsoon (March-May) and post-monsoon (October-November) are the two primary seasons for formation of Cyclone in the Bay of Bengal. Coastal regions of Bangladesh are very much vulnerable to damage from a Cyclone.

Cyclone 'Roanu' was the first tropical storm of the season of 2016 in the Bay of Bengal. It developed as a low pressure area over Southwest Bay and adjoining areas off Sri Lanka at 0300 UTC of 15 May 2016. It concentrated in to a Depression and then Deep Depression on 17 May 2016. It intensified into a Cyclonic Storm (CS) 'Roanu' over West-Central Bay and adjoining SW Bay on 19 May 2016. It moved north-northeastwards first and then northeastwards over North Bay and finally crossed Barisal-Chittagong coast near Chittagong during 0600 to 1100 UTC of 21 May 2016.

The position and intensification of Cyclone 'Roanu' was monitored by Bangladesh Meteorological Department (BMD) from its formation to landfall and issued through 20 Special Weather Bulletins containing advisories for the stakeholders and end users including fishermen and others. Port Authorities and the Coastal District Administrations of Bangladesh were also advised in time to take proper preparation through hoisting signals following the Standing Orders on Disaster (SOD). Accordingly, causalities and the loss of lives and properties were in minimum level.

I like to give my sincere thanks to the Ministry of Disaster Management and Relief (MoDMR) and Department of Disaster Management (DDM) for taking timely initiative as per the guidance of BMD for reducing the causalities and loss of lives of the vulnerable areas.

My heartfelt thanks are due to the Meteorologists and Meteorological Technicians of Storm Warning Centre (SWC), BMD for their constant effort to release the Special Weather Bulletins for Cyclone 'Roanu' in time and preparation of this report.

Shamsuddin Ahmed
Director

# Contents

## 1. Introduction

Tropical Cyclones (TCs) are among the most devastating weather systems on the Earth. They cause considerable damage and destruction to lives and property due to strong gale winds, torrential rain and associated storm surge. Though general movement of the TCs is well known, it is desirable to have timely and reasonably accurate prediction of the tracks and intensities of such cyclones for effective implementation of the disaster mitigation. To improve the prediction, there is need of basic understanding of physics and dynamics involved in the genesis, intensity change, structure and track of tropical cyclone. The concept of Conditional Instability of Second Kind (Charney and Eliassen, 1964) indicated that cyclonic inflow in lower tropospheric boundary layer is essential for develop-ment of TCs. Gray (1968) indicated that developing and non -developing cyclones are associated with different upper tropospheric circulation patterns e.g. non-developing TCs have uni-directional upper tropospheric flow which causes vertical shear above the cloud clusters relatively strong and the developing TCs normally have multidirectional out flow that results in weak vertical shear above the cyclones. The study of Holland and Merrill (1984) concluded that not only upper tropospheric interactions but also the inner core convective heating may directly affect intensity change while lower tropospheric interactions will produce a size change which may indirectly affect the intensity or strength of Tropical cyclone. Craig and Gray (1996) showed that the intensification of numerically simulated tropical cyclones is due to Wind Induced Surface Heat Exchange (WISHE). Holland (1983) demonstrated that nonlinear combination of two processes: (i) an interaction between the cyclone and its basic current (steering current) and (ii) an interaction with the Earth's vorticity field, is responsible for movement of TCs.

The Cyclone Roanu was mainly detected and tracked by synoptic observation in addition to numerical model products and satellite imageries. Radar imageries from IMD network are also taken into consideration through internet. BMD also utilized the Dvorak technique of subjective assessment based on satellite (Dvorak, 1975, 1984) and environmental conditions for estimating the intensity. Higher sea surface temperatures (SSTs) (more than 26.5°C), a deep lower level moist layer, absence of strong vertical wind shear, increase in vorticity over the area, are favourable criteria for intensification of a tropical low to a cyclonic storm and further intensification (Gray, 1992 and Frank, 1977). The satellite based monitoring and prediction of intensification were reviewed by Kelkar (1997) and further updated by Kalsi (2006) and Bhatia et al., (2006). According to them, new developments like derivation of cyclone parameters in terms of ocean surface wind fields by scatterometer more frequently and rapid scan observations by the satellites, use of water vapour imagery with better resolutions and other derived products like Outgoing Long wave Radiation (OLR) can immensely help in not only monitoring and prediction of intensity but also in improving the Numerical Weather Prediction (NWP) model performance. According to Shea (2009), the depth of thermocline layer and hence the ocean thermal energy play a dominant role for intensification. According to him, ocean thermal energy of more than 100 KJ in the thermocline layer is favourable for intensification into a very severe cyclonic storm. The detailed review of the synoptic and thermodynamic characteristics associated with the intensification/ decay of the cyclonic storm over the north Indian Ocean are presented by Krishna Rao (1997). The review of the dynamical characteristics of intensification is given by Mohanty and Gupta (1997). A review of the prediction of tropical cyclone characteristics by NWP models is presented by Prasad (1997) and has been updated by Rama Rao *et. al* (2007). However, the intensity change at present is not properly captured in the NWP models (Rama Rao, *et al*., 2007). The genesis and movement of the cyclone 'Roanu' though could be predicted by various NWP models, with reasonable accuracy, the intensity of the system remained unpredicted by most of the models. It posed a challenge to the NWP modelling as well as other conventional, synoptic and statistical methods to predict the intensity accordingly.

Considering all the above, an in-depth study has been undertaken to analyze various features of the cyclonic storm 'Roanu' like genesis, intensification, movement, landfall and associated disastrous weather. The monitoring and prediction aspects of this cyclone by the synoptic and thermodynamic observations, satellite observations, dynamical parameters and numerical weather prediction models and their limitations have been critically examined and discussed. The critical grey areas requiring more research and investigation have been highlighted. A brief life history of cyclone Roanu is presented in section 2. Monitoring and prediction of cyclone Roanu is descrived in chapter 3. Climatological aspects, features observed through Satellite and Radar, dynamic features, storm surge prediction and damages due to the CS 'Roanu' are presented in the following sections. Summary and conclusion is given in section 14.

## 2. Brief history of Cyclone Roanu

A low pressure area developed over Southwest Bay and adjoining areas off Sri Lanka at 0300 UTC of 15 May 2016. It intensified in to a Well Marked Low over the same area at 0900 UTC of the same day. The system then moved north-northwestward and concentrated in to a Depression (Lat 11.0°N, Lon 81.0°E) over Southwest Bay and adjoining areas at 0600 UTC of 17 May 2016. The system then moved northward and intensified into Deep Depression over West-Central Bay and adjoining Southwest Bay (Lat 13.5°N, lon 81.0°E) 1200 UTC of 17 May 2016. It then moved north-northeastward further and intensified into a Cyclonic Storm (CS) 'Roanu' over West-Central Bay and adjoining SW Bay (Lat 15.0°N, lon 81.2°E). In continuation to this, cyclone 'Roanu' moved north-northeastwards first and then northeastwards over North Bay and finally crossed Barisal-Chittagong coast near Chittagong during 0600 to 1100 UTC of 21 May 2016. Continuing its east-northeastward journey, the CS gradually weakened into a DD over Mizoram at 1800 UTC of 21 May as a depression over Myanmar and adjoining Manipur at 0000 UTC of 22 May and into a well marked low pressure area over Myanmar and adjoining Nagaland & Manipur at 0300 UTC of 22 May. The observed track of the CS Roanu is shown in Fig.1.

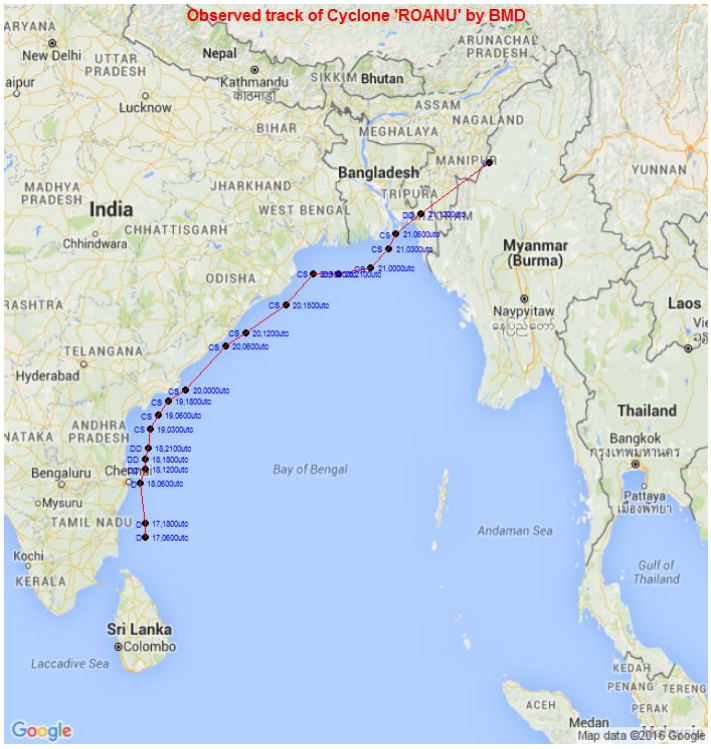


**Fig. 1:** Observed track of the Cyclone Roanu

The salient features of the system are as follows (Reference: Preliminary report of Cyclone Roanu by Cyclone Warning Division, India Meteorological Department, India).

i. Cyclone 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. It travelled a distance of about 2300 km during its life period.

iii. The Accumulated Cyclone Energy (ACE) which is a measure of damage potential was about 1.8 X $10^4$ $knot^2$.

iv. The Power Dissipation Index which is a measure of loss due to CS was 0.74 X$10^6$ $knot^3$.

v. The life period of Cyclone Roanu was 5 days.

vi. Cyclone 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.

vii. Cyclone Roanu did not intensify to a severe cyclone in spite of its long travel over the sea mainly due to land interactions and above mentioned large scale diurnal variations

viii. 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 Cyclone Roanu moved very close to the east coast of India and Sri Lanka.

ix. Cyclone Roanu lay centered about 50 km east-southeast of Chennai at 0300 UTC of 18, 68 km east-southeast of Machillipatnam at 0600 UTC of 19, 35 km southeast of Kalingapatnam at 0600 UTC of 20, 40 km southeast of Paradip at 1200 UTC of 20 and 70 km south-southeast of Sagar Island at 0000 UTC of 21May.

x. IMD predicted genesis of depression over southwest BoB on 17 May based on 0300 UTC observations of 14 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 18 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 13 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.

## 3. Monitoring and Prediction of Cyclone Roanu

### 3.1 Monitoring Cyclone Roanu

Cyclone 'Roanu' was monitored and predicted continuously since its inception by BMD. The observed track of the cyclone over the Bay of Bengal (BoB) during 17-22 May 2016 is depicted in Fig.1. The best track parameters of the systems are given in Table 1**.** At the genesis stage, the system was monitored mainly with satellite observation facilities of BMD (Himawari and FY-2D, FY-2E FY-2G). Various national and international NWP models including the products of IMD and NCMRWF were utilized to predict the genesis, track and intensity of the cyclone.

**Table 1:** Position and Status of Cyclone Roanu as per BMD Record

| Sl | Date | Time Local (UTC) | Location | Centre Lat. °N/ Lon. °E | ECP (hPa) | Estimated Sustained Surface Wind (kt) | Status/ Grade |
|---|---|---|---|---|---|---|---|
| 01. | 15.05.2016 | 09 AM (0300) | SW Bay and adjoining area | - | - | - | L |
| 02. | 15.05.2016 | 03 PM (0900) | SW Bay and adjoining Si Lanka | - | - | - | WML |
| 03. | 17.05.2016 | 12 Noon (0600) | SW Bay and adjoining area | 11.0°N/ 81.0°E | - | 40-50 kph | D |
| 04. | 17.05.2016 | Midnight (1800 ) | SW Bay and adjoining area | 11.5°N/ 81.0°E | - | 40-50 kph | D |
| 05. | 18.05.2016 | 12 Noon (0600) | SW Bay and adjoining WC Bay | 13.0°N/ 80.8°E | - | 40-50 kph | D |
| 06. | 18.05.2016 | 06 PM (1200) | WC Bay and adjoining SW Bay | 13.5°N/ 81.0°E | - | 50-60 kph | DD |
| 07. | 18.05.2016 | Midnight (1800) | WC Bay and adjoining SW Bay | 13.9°N/ 81.0°E | - | 50-60 kph | DD |
| 08. | 19.05.2016 | 03 AM (2100) | WC Bay and adjoining SW Bay | 14.3°N/ 81.1°E | - | 50-60 kph | DD |
| 09. | 19.05.2016 | 09 AM (0300) | WC Bay and adjoining SW Bay | 15.0°N/ 81.2°E | 992 hPa | 62-88 kph | CS |
| 10. | 19.05.2016 | 12 Noon (0600) | WC Bay and adjoining SW Bay | 15.5°N/ 81.5°E | 992 hPa | 62-88 kph | CS |
| 11. | 19.05.2016 | 06 PM (1200) | WC Bay and adjoining SW Bay | 15.5°N/ 81.5°E | 992 hPa | 62-88 kph | CS |
| 12. | 19.05.2016 | Midnight (1800) | WC Bay and adjoining area | 16.0°N/ 81.9°E | 992 hPa | 62-88 kph | CS |
| 13. | 20.05.2016 | 06 AM (0000) | WC Bay and adjoining area | 16.4°N/ 82.6°E | 992 hPa | 62-88 kph | CS |
| 14. | 20.05.2016 | 12 Noon (0600) | WC Bay and adjoining area | 18.0°N/ 84.2°E | 992 hPa | 62-88 kph | CS |
| 15. | 20.05.2016 | 06 PM (1200) | North Bay and adjoining WC Bay | 18.5°N/ 85.0°E | 992 hPa | 62-88 kph | CS |
| 16. | 20.05.2016 | 09 PM (1500) | North Bay and adjoining WC Bay | 19.5°N/ 86.6°E | 992 hPa | 62-88 kph | CS |
| 17. | 20.05.2016 | Midnight (1800) | Northwest Bay and adjoining Bangladesh coast | 20.6°N/ 87.7°E | 992 hPa | 62-88 kph | CS |
| 18. | 20.05.2016 | 03AM (2100) | Northwest Bay and adjoining | 20.6°N/ 88.7°E | 992 hPa | 62-88 kph | CS |

| Sl | Date | Time Local (UTC) | Location | Centre Lat. °N/ Lon. °E | ECP (hPa) | Estimated Sustained Surface Wind (kt) | Status/ Grade |
|---|---|---|---|---|---|---|---|
| | | | Bangladesh coast | | | | |
| 19. | 20.05.2016 | 06:00 AM (0000) | Northwest Bay and adjoining Bangladesh coast | 20.8°N/ 90.0°E | 992 hPa | 62-88 kph | CS |
| 20. | 20.05.2016 | 09 AM (0300) | Northwest Bay and adjoining Bangladesh coast | 21.5°N/ 90.7°E | 992 hPa | 62-88 kph | CS |
| 21. | 20.05.2016 | 12 Noon (0600) | Started to cross Barisal-Chittagong coast near Chittagong | 22.0°N/ 91.0°E | 992 hPa | 62-88 kph | CS |
| 22. | 20.05.2016 | 06 PM (1200) | Crossed Barisal-Chittagong coast near Chittagong | - | | 62-88 kph | CS |

*Note: 'L' indicates Low; 'WML' indicates Well Marked Low; 'D' indicates Depression; 'DD' indicates Deep Depression; 'CS' indicates Cyclonic Storm*

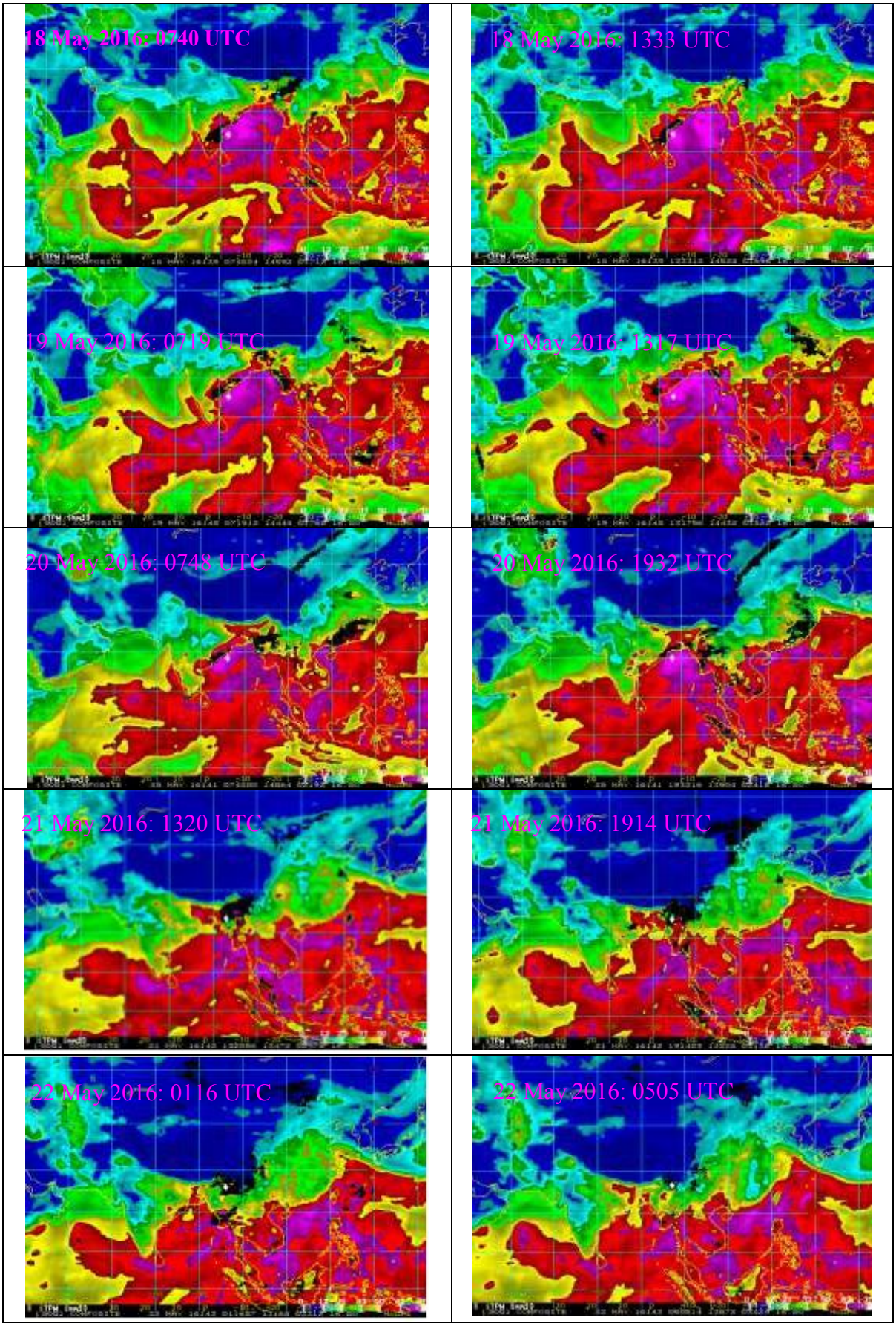


**Fig. 2:** Total precipitable water imageries during 17 to 22 May 2016 (Source: IMD)

### 3. 2 Genesis of Cyclone Roanu

A trough of low laid over southwest Bay of Bengal (BoB) with its upper air cyclonic circulation extending upto 4.5 km above mean sea level at 0300 UTC of 14 May 2016. Under this condition, a low pressure area developed over Southwest Bay of Bengal off Sri Lanka coast in the morning of 15 May 2016. It then moved north-northeastwards, intensified into a Well Marked Low Pressure Area at 0900 UTC of same day 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 16 May. At 0300 UTC of 17 May, the sea surface temperature was 30-31˚C, Ocean thermal energy was 100-120 KJ/cm$^2$, low level convergence was (20-30) x $10^{-5}$ $S^{-1}$, upper level divergence was about (20-30)x$10^{-5}$ $S^{-1}$, the low level relative vorticity was about (100-150) x$10^{-6}$ $S^{-1}$, 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 0600 UTC of 17 May over southwest BoB near latitude 11.0°N and longitude 81.0°E.

### 3.3 Intensification and Movement of Cyclone Roanu

At 1200 UTC of 18 May 2016, the sea surface temperature was 31°C, Ocean thermal energy was 150 KJ/cm$^2$, low level convergence (30 x $10^{-5}S^{-1}$), upper level divergence (40x$10^{-5}S^{-1}$) and low level relative vorticity (150-200x$10^{-6}S^{-1}$) increased, favouring intensification of the system. Upper tropospheric ridge laid along latitude 16.0°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 West-central and adjoining Southwest BoB at 1200 UTC of 18 May near latitude 13.0°N and longitude 81.0°E. The favourable environmental conditions continued and at 0300 UTC of 19 May, the upper tropospheric ridge shifted northwards and lay about 17.0°N. The system moved north-northeastwards, intensified into a Cyclonic Storm (CS) with maximum sustained winds of 62-88 KPH around the system centre at 0300 UTC of 19 May. Under favorable environmental conditions the system skirted along the east coast of India and intensified slightly with maximum sustained wind speed of 62-88 KPH. The system maintained its intensity and crossed Chittagong-Barisal coast of Bangladesh near Chittagong 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 21 May into a depression over Myanmar and adjoining Manipur at 0000 UTC of 22 May and into a Well Marked Low Pressure Area over Myanmar and adjoining Nagaland & Manipur at 0300 UTC of 22 May 2016. The total precipitable water imageries (TPW) during 17-22 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 19 May. On 20 May, it gradually decreased and it further decreased on 21 May as the system moved to the northern latitude and crossed Bangladesh coast.

### 3.4 Movement of Cyclone Roanu

Cyclone Roanu moved nearly northwards till midnight of 18 May. It then moved north-northeastwards till midnight of 19 May and then northeast/ east-northeastwards during its remaining life period. 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 18 May. Thereafter, as the system transitioned to the north of the ridge, it moved initially north-northeastwards. Thereafter, on 20 May, 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 18 to 42 km/hr by evening of 20 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.

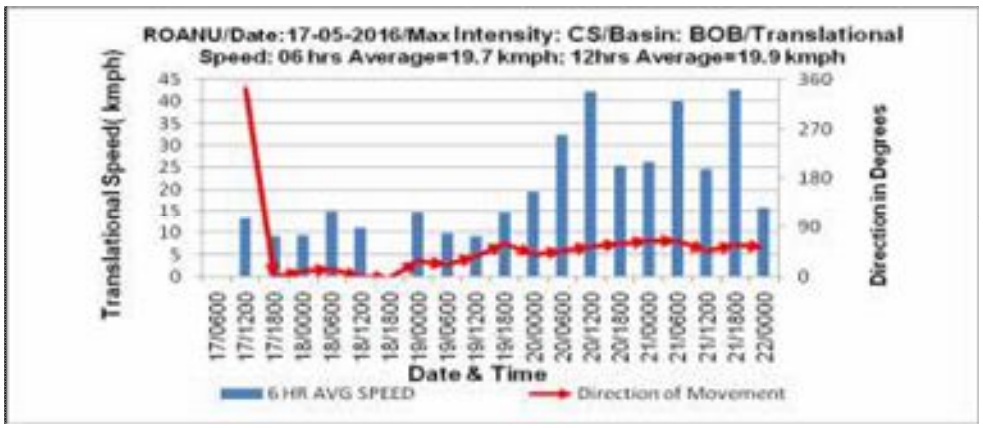


**Fig. 3**: Six hourly average translational speed (km/hr) and direction of movement in association with CS Roanu (Source: IMD)

The wind speed in middle and deep layer around the system centre indicates that from 18 May 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 850 and 200 hPa levels also increased rapidly on 20 and 21 May. As the wind shear was east-southeasterly, the convective cloud mass was sheared towards west-northwestwards of the system centre till 20 May. Thereafter, with the change in direction of wind shear as south/ southwesterly, the convective cloud mass was sheared north/ northeastwards south/ southwesterly, the convective cloud mass was sheared north/ northeastwards on the day of rainfall.

### 3.5 Maximum Sustained Surface Wind speed and estimated central pressure

The lowest estimated central pressure (ECP) and the maximum sustained wind speed are presented in Fig. 4. The lowest estimated central pressure had been 983 hPa. The estimated maximum sustained surface wind speed (MSW) (defined as $V_{max}$) was 45 knots during 1800 UTC of 20 May to 0900 UTC of 21 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 18 May, 68 km east-southeast of Machillipatnam at 0600 UTC of 19 May, 35 km southeast of Kalingapatnam at 0600 UTC of 20 May, 40 km southeast of Paradip at 1200 UTC of 20 May and 70 km south-southeast of Sagar Island at 0000 UTC of 21 May. The ECP and $V_{max}$ graph also indicates that the system intensified gradually till 1800 UTC of 20 May, maintained its intensity till landfall at 1000 UTC of 21 May and weakened gradually into a well marked low pressure area at 0300 UTC of 22 May. There was no rapid intensification and rapid weakening of the system throughout its life cycle.

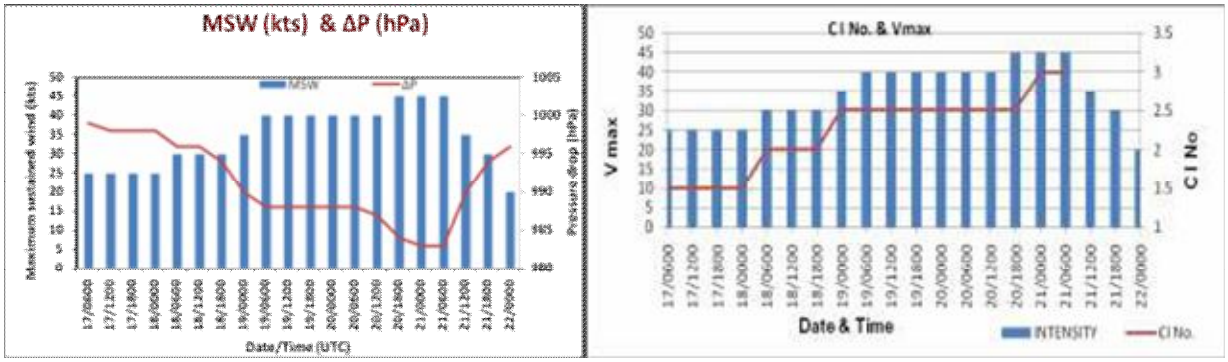


**Fig. 4:** Lowest estimated central pressure and the maximum sustained wind speed (Source: IMD)

### 3.6 Structure of cyclone Roanu

Sector wise wind distribution around the system centre is depicted in Fig. 5. It depicts that the 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 18 to 20 May 2016.

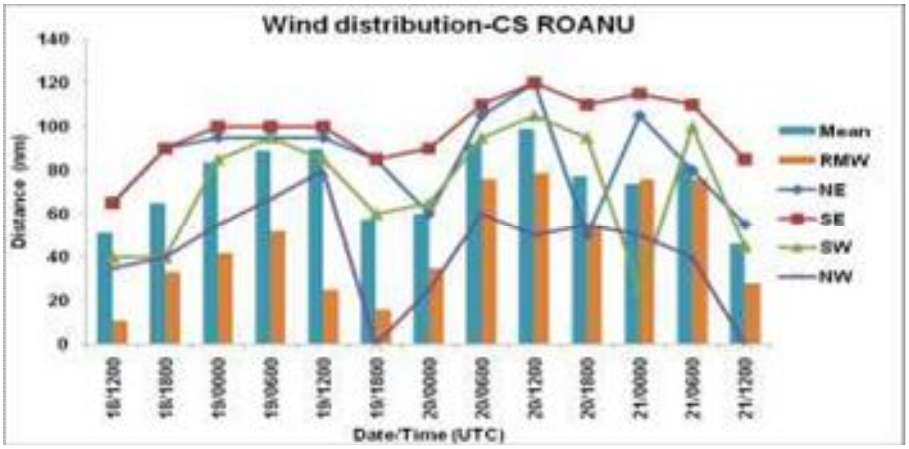


**Fig. 5:** Sector wise wind distribution of CS 'Roanu' (Source: IMD)

## 4. Climatological aspects of cyclone formed over the Bay of Bengal

Considering the area of genesis (+/- 20° around the genesis point), the cliamtological tracks of the TCs during 1891-2015 are presented in Fig. 6. 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.

**Fig. 6:** Climatological tracks of Tropical Cyclones forming within +/- 2° around the genesis point during 1891-2015 (Source: IMD)

## 5. Features of cyclone Roanu 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 (Fig. 7), 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 May. 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°N to 16.0°N and west of longitude 85.0°E. Lowest cloud top temperature (CTT) was -93°C. At 0300 UTC of 18 May, 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°N to 18.0°N and west of longitude 85.5°E. Lowest cloud top temperature (CTT) was -93°C. At 0300 UTC of 19 May, 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°N to 20.0°N and west of longitude 90.0°E. Lowest cloud top temperature (CTT) was -93°C. At 1200 UTC of 19 May, the intensity was T2.5. Associated broken low and medium clouds with embedded intense to very intense convection lay over Andhra Pradesh and West-Central BoB between latitude 13.5°N to 19.0°N and west of longitude 86.0°E. Lowest cloud top temperature (CTT) was -88°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 20 May, intensity was T2.5. 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°N to 20.0°N and west of longitude 90.0°E. Lowest cloud top temperature (CTT) was -93°C. Convection ramped up suggesting diurnal variations. At 1200 UTC of 20 May, intensity was T2.5.

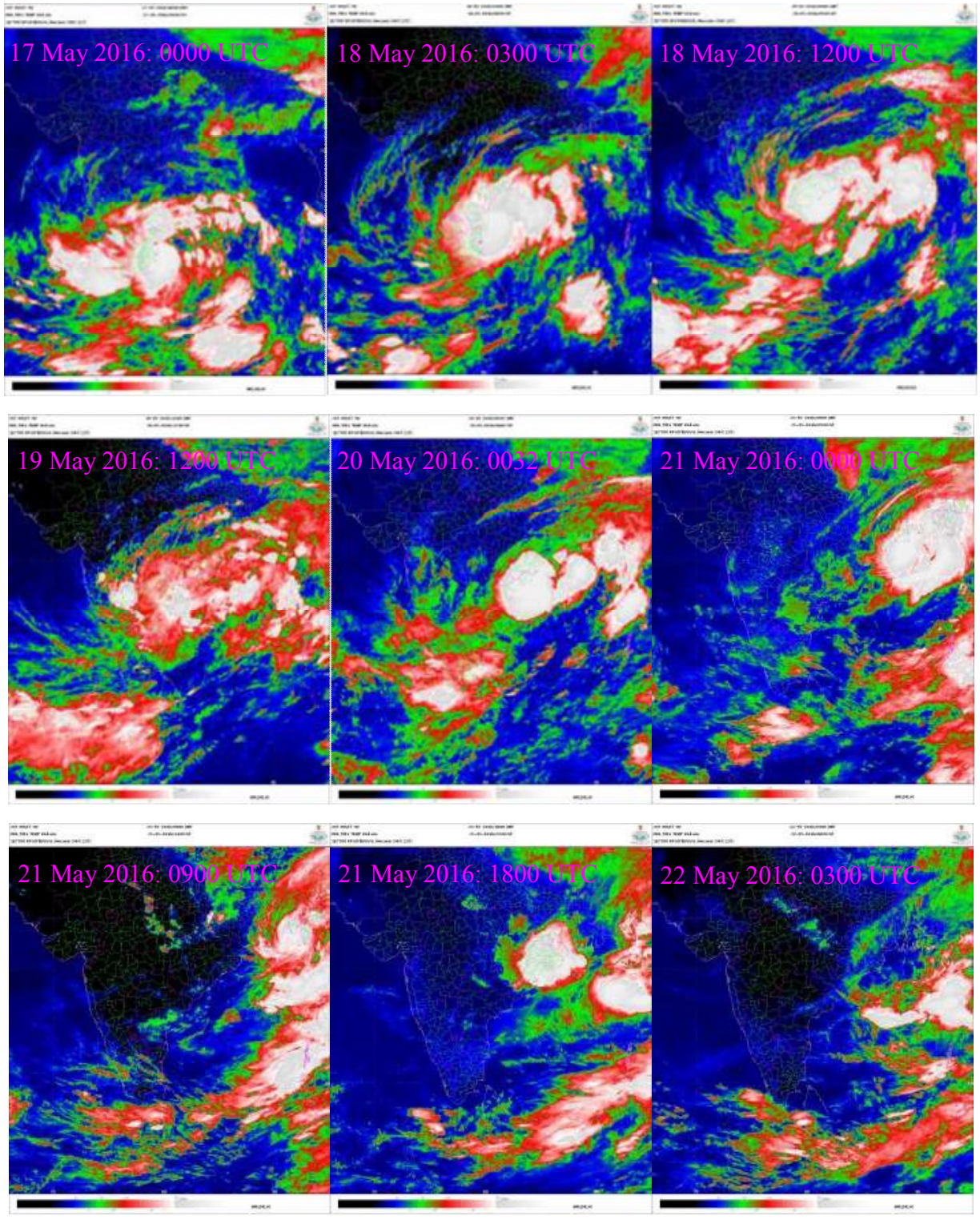


**Fig. 7:** INSAT-3D enhanced colored imageries based on during 17-22 May 2016 (Source: IMD)

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°N and west of longitude 90.0°E. Lowest cloud top temperature (CTT) was -90°C. The convection showed increase in organization 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 21 May, the intensity was T3.0. 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°N. Lowest cloud top temperature (CTT) was -93°C. At 1000 UTC of 21 May, the system crossed Bangladesh coast near north of Chittagong. At 1200 UTC of 21 May, 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°C.

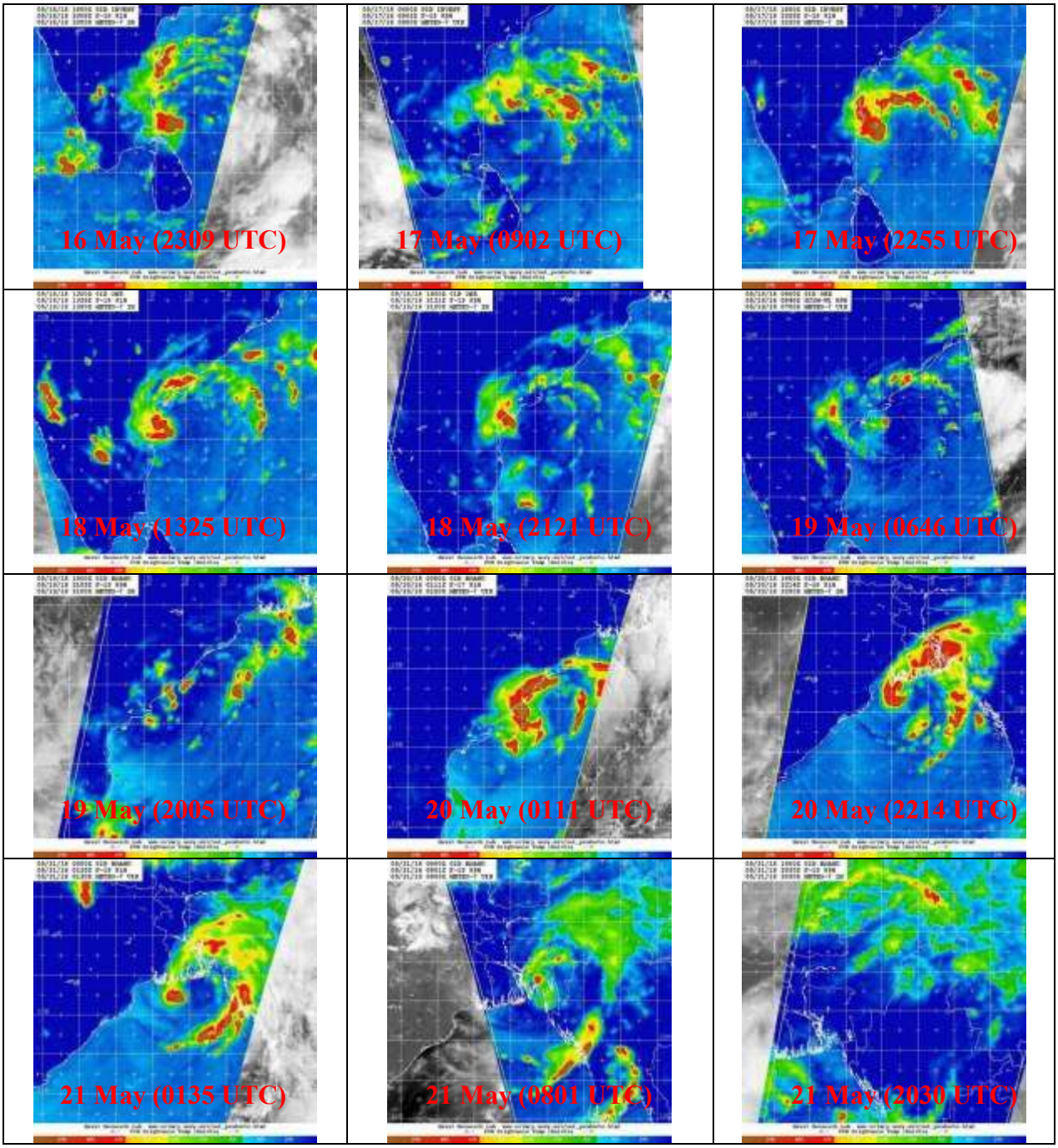


**Fig. 8:** Typical microwave imageries during 17 to 22 May 2016 (Source: IMD)

### 5.2 Microwave features

F-15, F-16, F-17 and GCOM-W1 microwave imageries of the Cyclone Roanu covering its life period from 17 to 22 May 2016 are presented in Fig. 8. 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.

### *5.3 Features observed through BMD 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 20-21 May 2016 are presented in Fig. 10. Typical imageries from Indian radars are presented in Figs. 9-11.

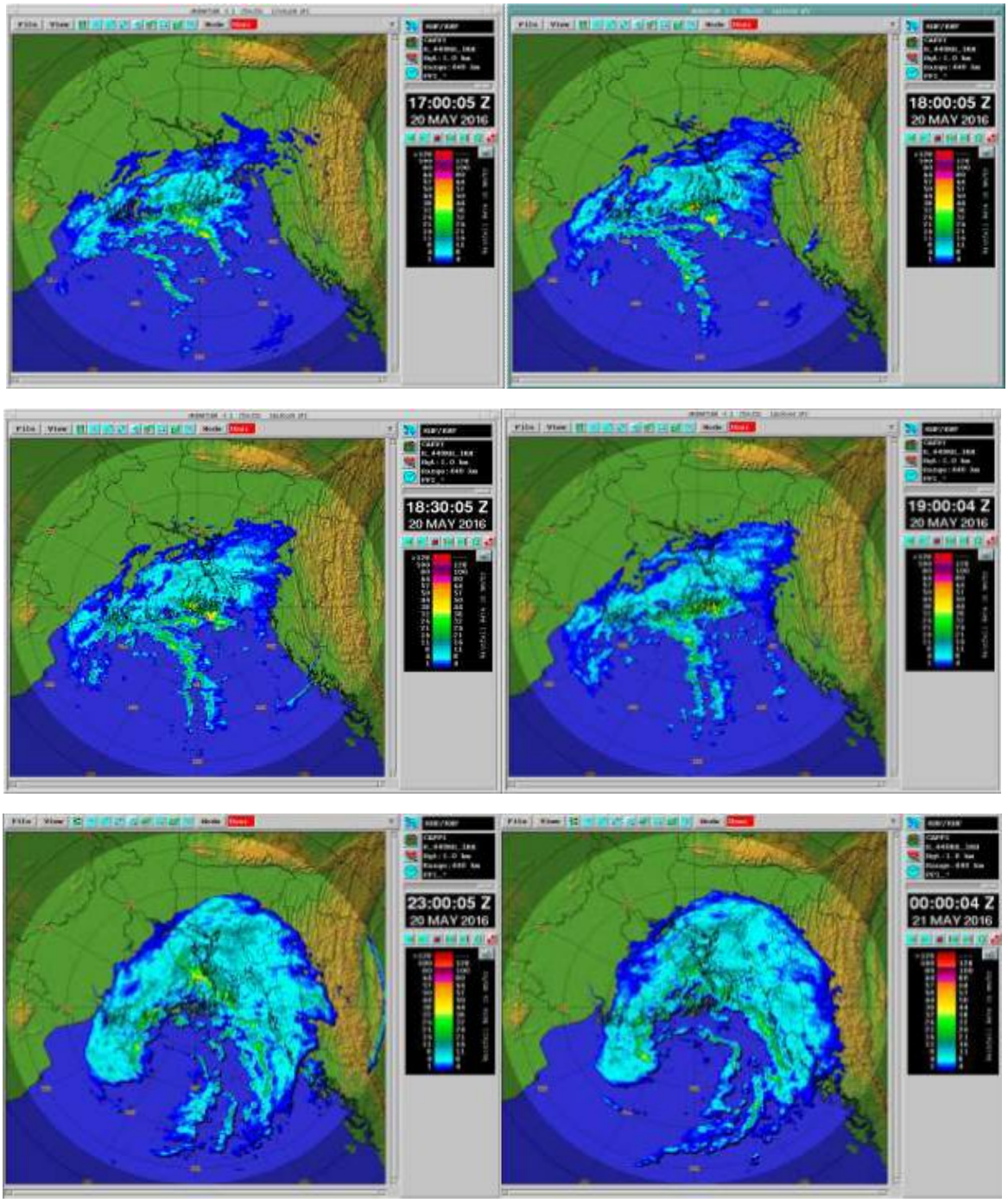


**Fig. 9:** Khepupara Radar imageries during 20 and 21 May 2016 in association with Cyclone Roanu

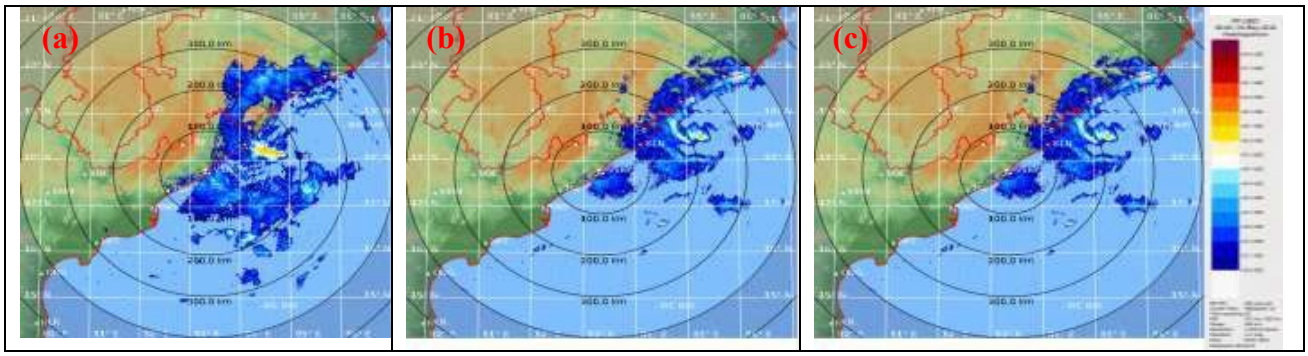


**Fig. 10:** Plan Position Indicator (PPI) (dBZ) imageries from DWR Vishakhapatnam at (a) 0359, (b) 0649 and (c) 0729 UTC of 20 May 2016 (Source: IMD)

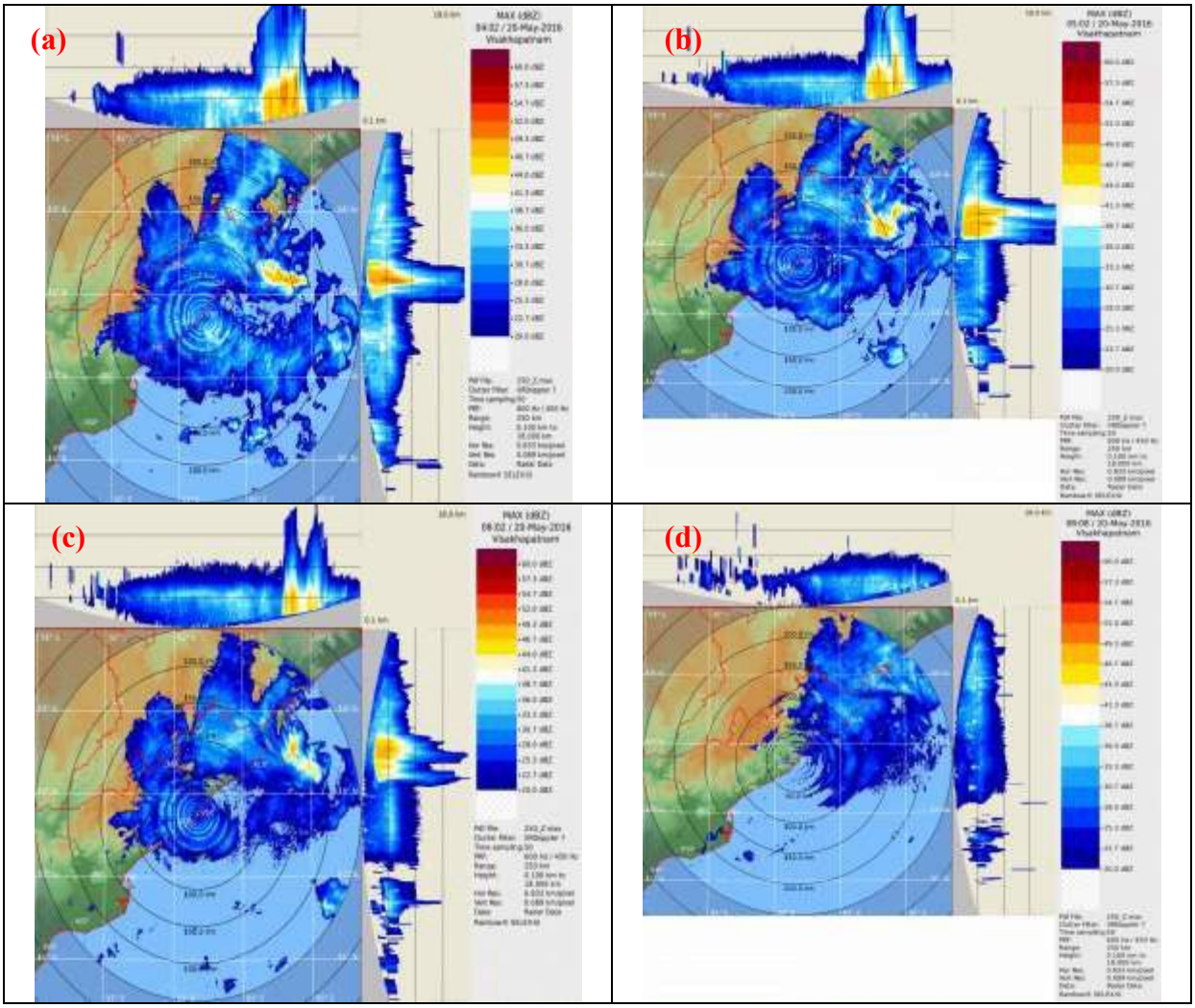


**Fig. 11:** Max (dBZ) imageries from DWR Vishakhapatnam at (a) 0402, (b) 0502, (c) 0602 and (d) 0608 UTC of 20 May 2016 (Source: IMD)

## 6. Dynamical features

Dynamic features associated with cyclone Roanu are given in Figs. 12-19.

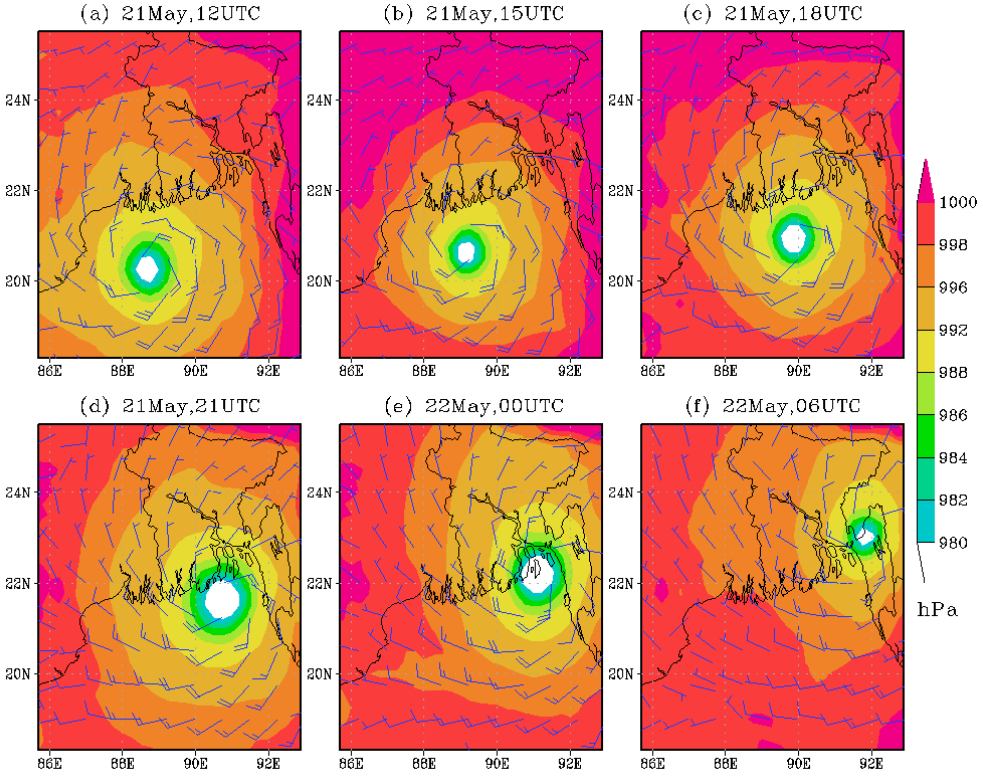


**Fig. 12:** Pressure Field (03 hourly) associated with cyclone 'Roanu' extracted from ECMWF Model (collaboration with met.no) based on the initial conditions of 0000 UTC of 19 May 2016

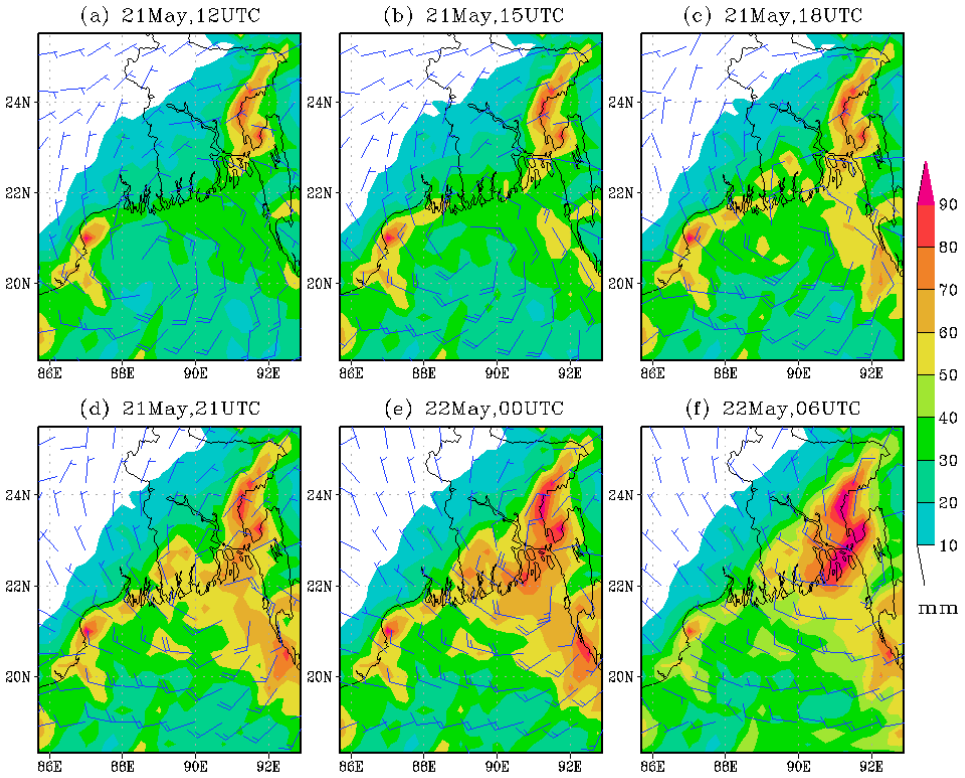


**Fig. 13:** Surface wind and rainfall associated with cyclone 'Roanu' from ECMWF Model (collaboration with met.no) based on the initial conditions of 0000 UTC of 19 May 2016

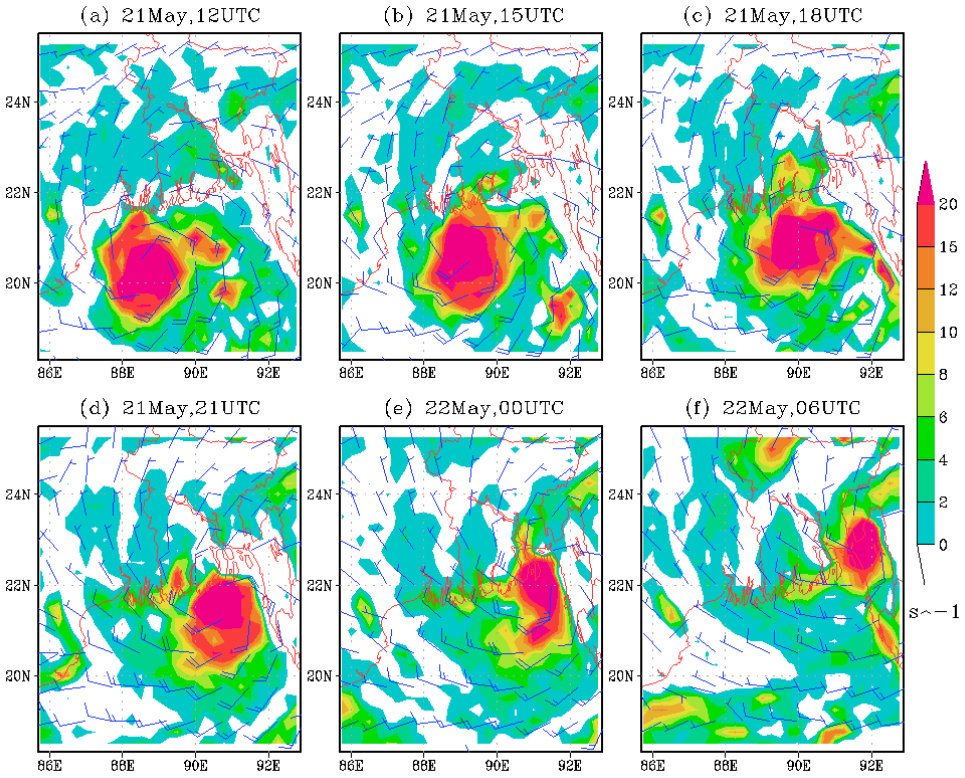


**Fig. 14:** Surface wind ($ms^{-1}$) and vorticity ($s^{-1}$) associated with cyclone 'Roanu' from ECMWF Model (collaboration with met.no) based on the initial conditions of 0000 UTC of 19 May 2016

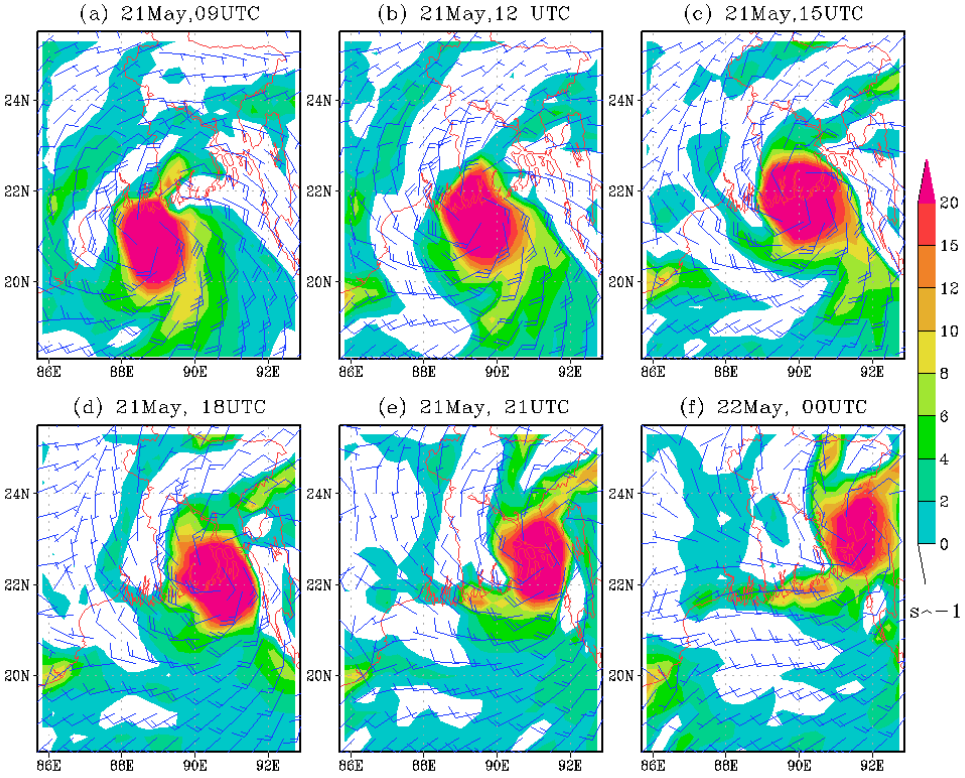


**Fig. 15:** Surface wind ($ms^{-1}$) and vorticity ($s^{-1}$) associated with cyclone 'Roanu' simulated by WRF model simulated based on the initial conditions of 0000 UTC of 17 May 2016

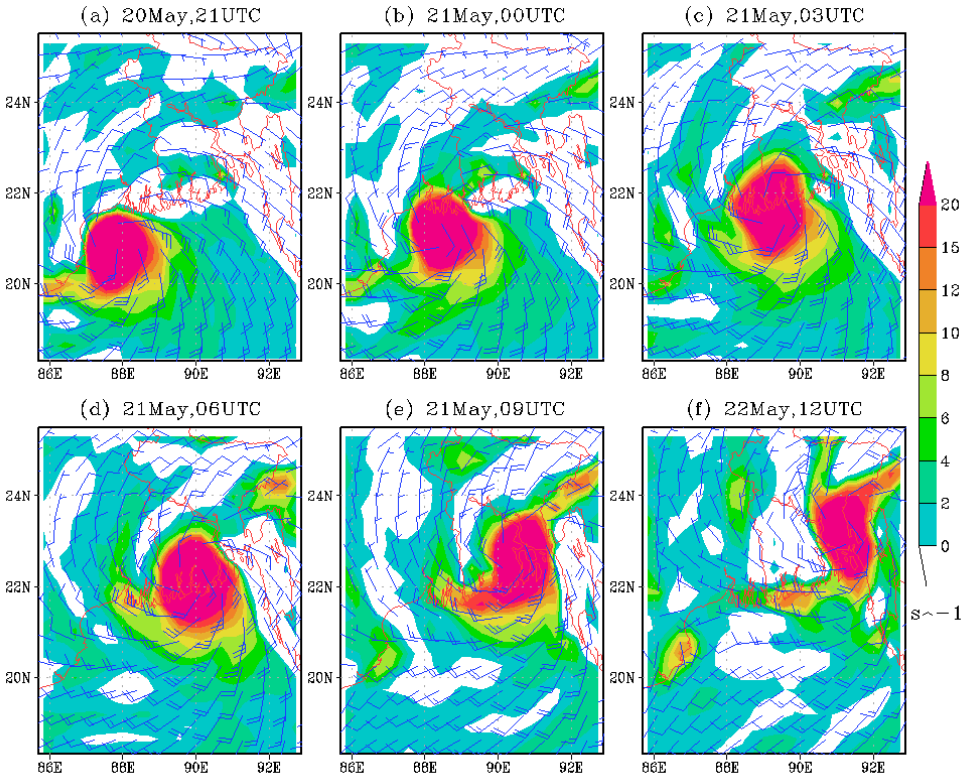


**Fig. 16:** Surface wind ($ms^{-1}$) and vorticity ($s^{-1}$) associated with cyclone 'Roanu' simulated by WRF model simulated based on the initial conditions of 0000 UTC of 18 May 2016

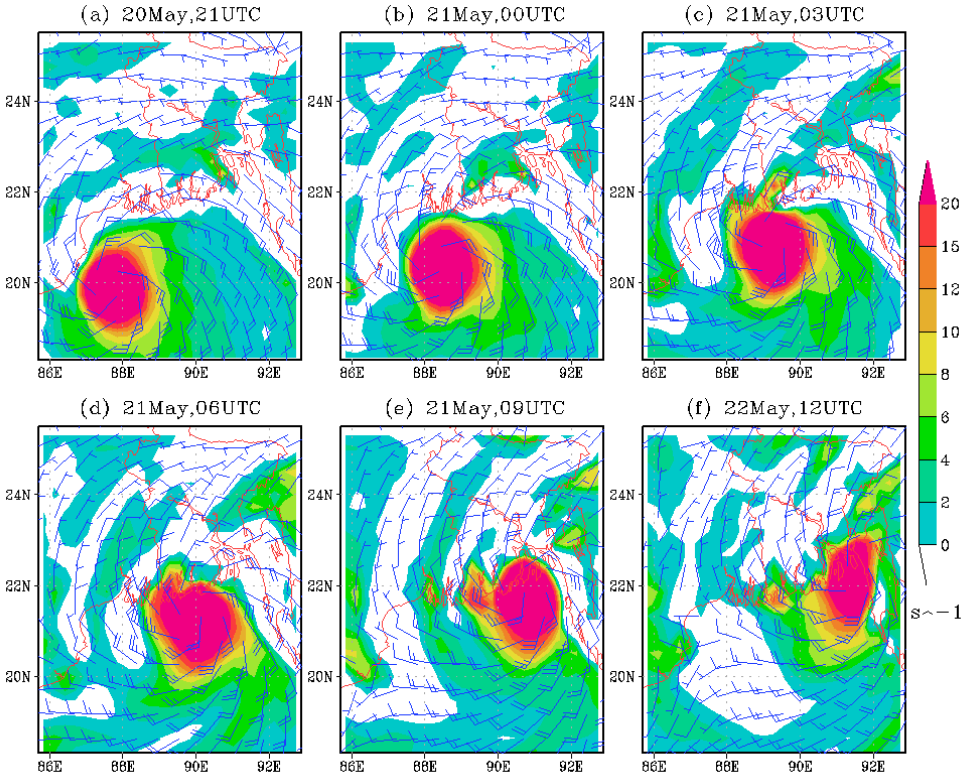


**Fig. 17**: Surface wind ($ms^{-1}$) and vorticity ($s^{-1}$) associated with cyclone 'Roanu' simulated by WRF model simulated based on the initial conditions of 0000 UTC of 19 May 2016

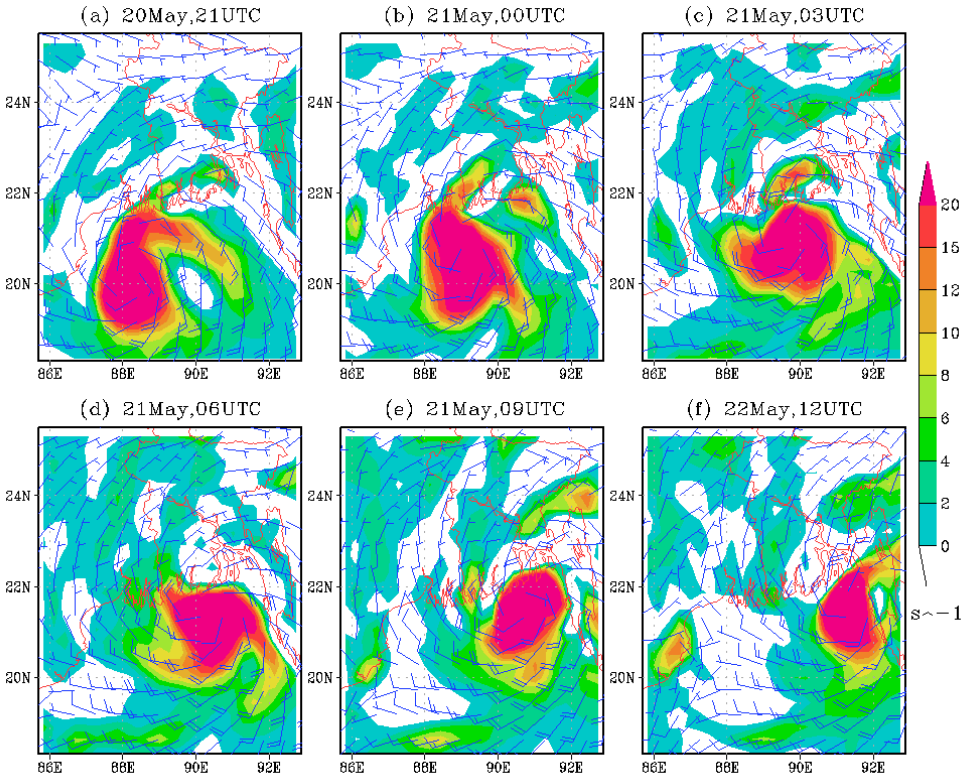


**Fig. 18:** Surface wind ($ms^{-1}$) and vorticity ($s^{-1}$) associated with cyclone 'Roanu' simulated by WRF model simulated based on the initial conditions of 0000 UTC of 20 May 2016

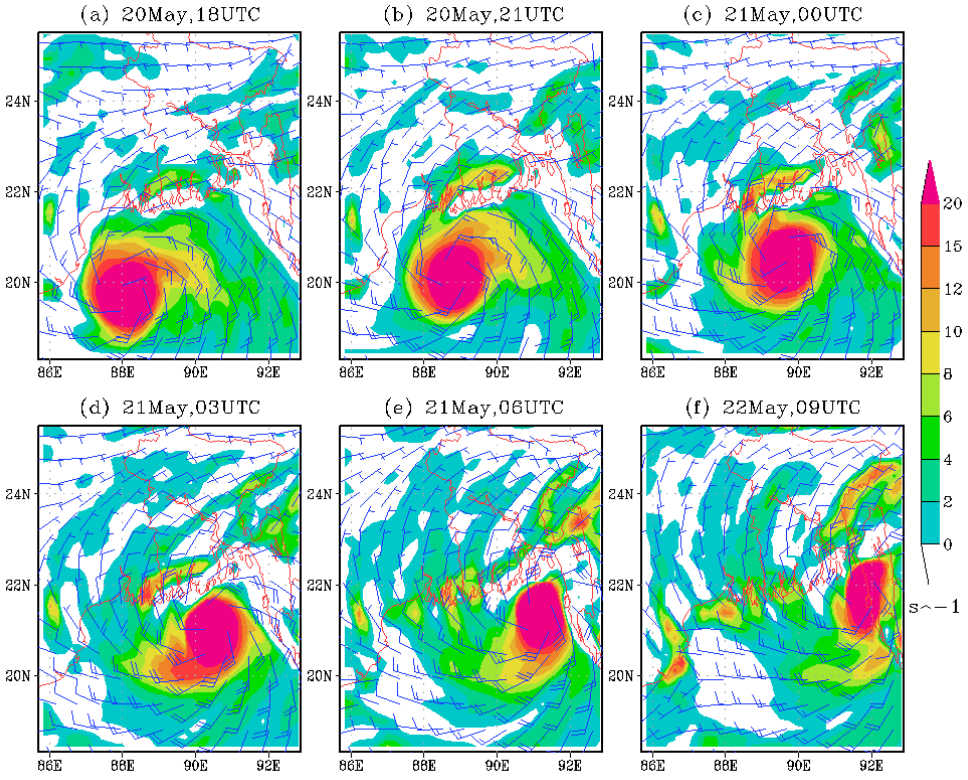


**Fig. 19:** Surface wind ($ms^{-1}$) and vorticity ($s^{-1}$) associated with cyclone 'Roanu' simulated by operational WRF model at BMD based on the initial conditions of 0000 UTC of 20 May 2016

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 20 May lying to the west of the system centre could not be captured well. In comparison NCUM analysis could simulate and track the system better (Figs. 20-23).

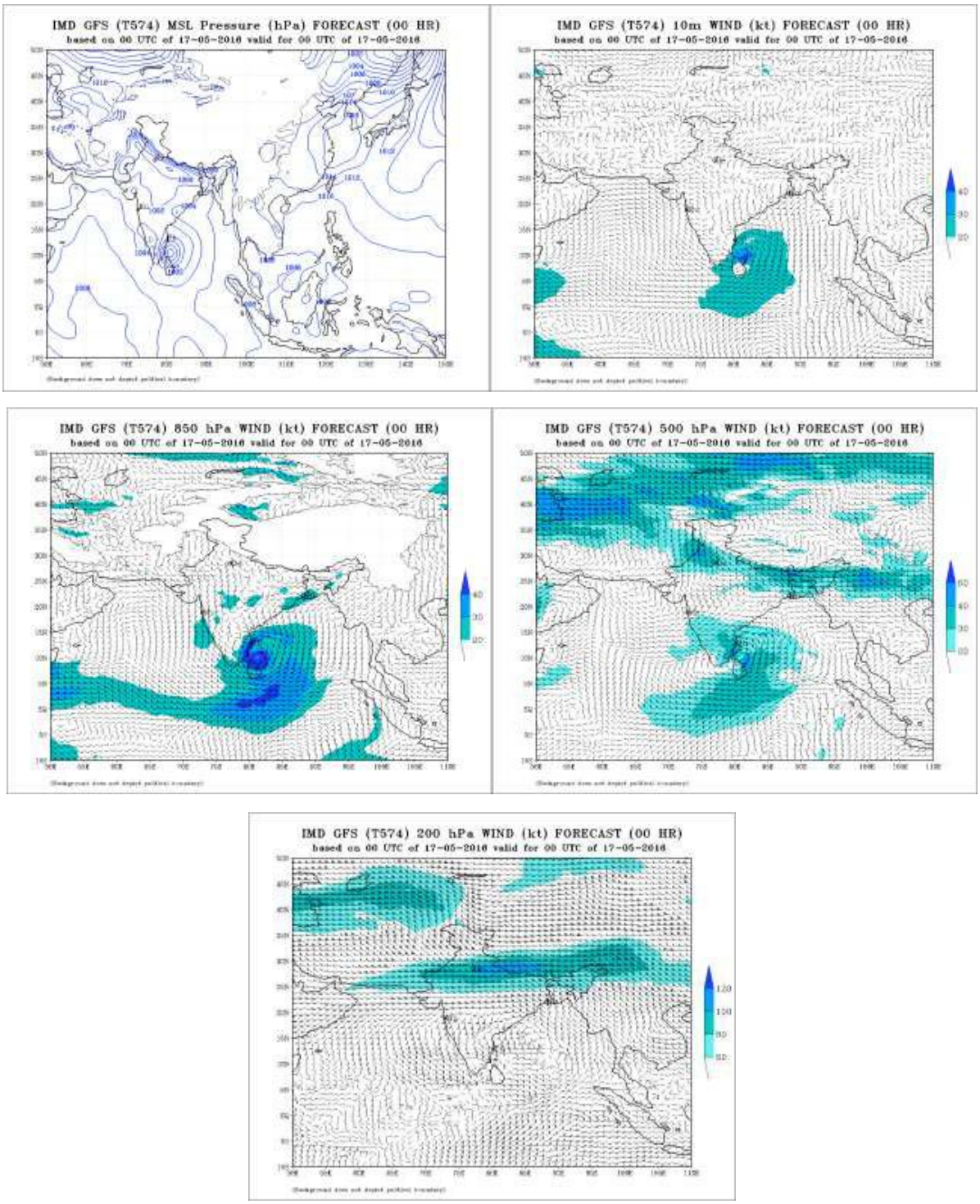


**Fig. 20:** IMD GFS MSLP, 10 m wind and winds at 850, 500 and 200 hPa levels based on 0000 UTC of 17 May 2016

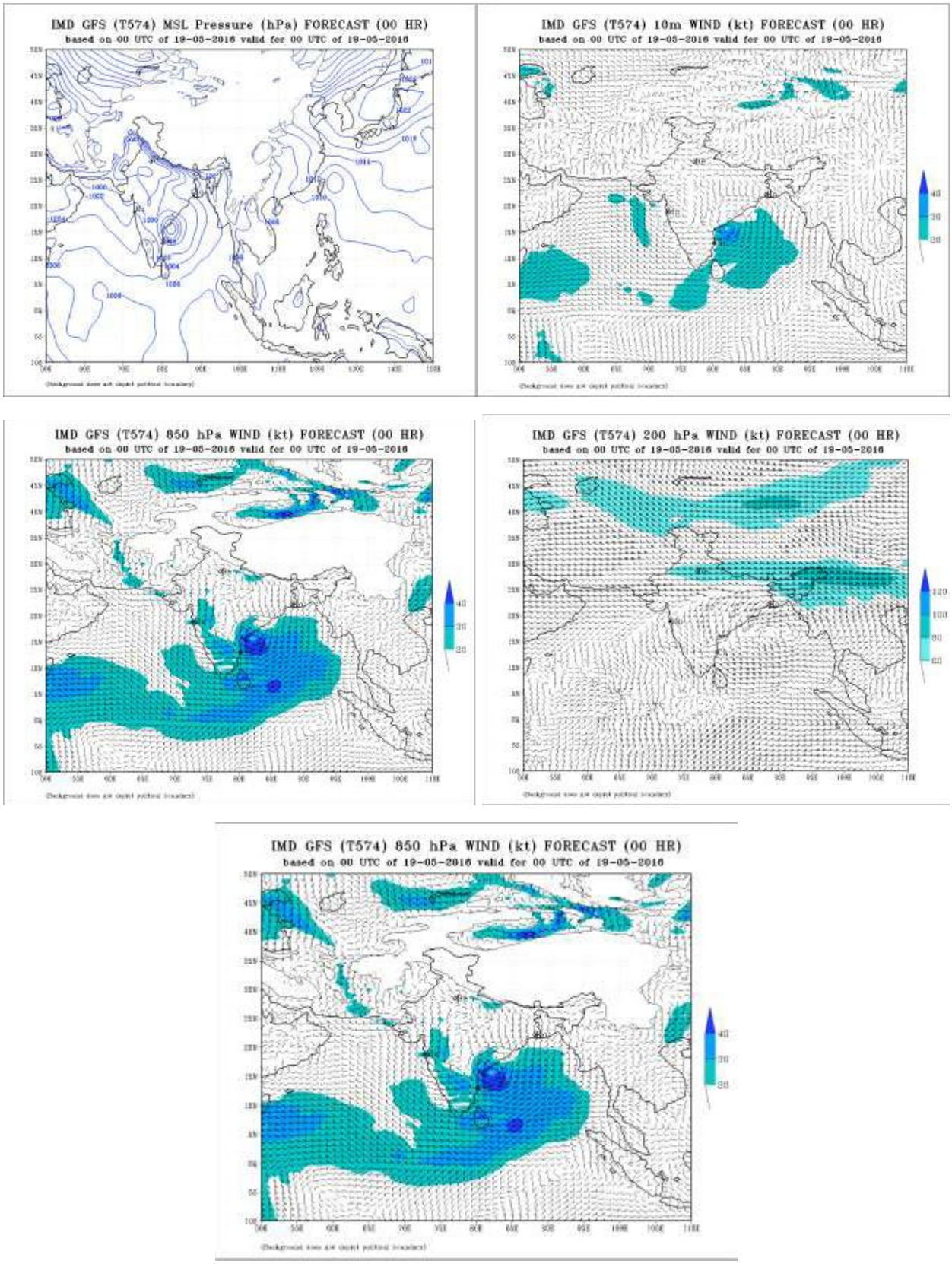


**Fig. 21:** IMD GFS analysis of MSLP, 10 m wind, winds at 850, 500 and 250 hPa based on 0000 UTC of 19 May 2016

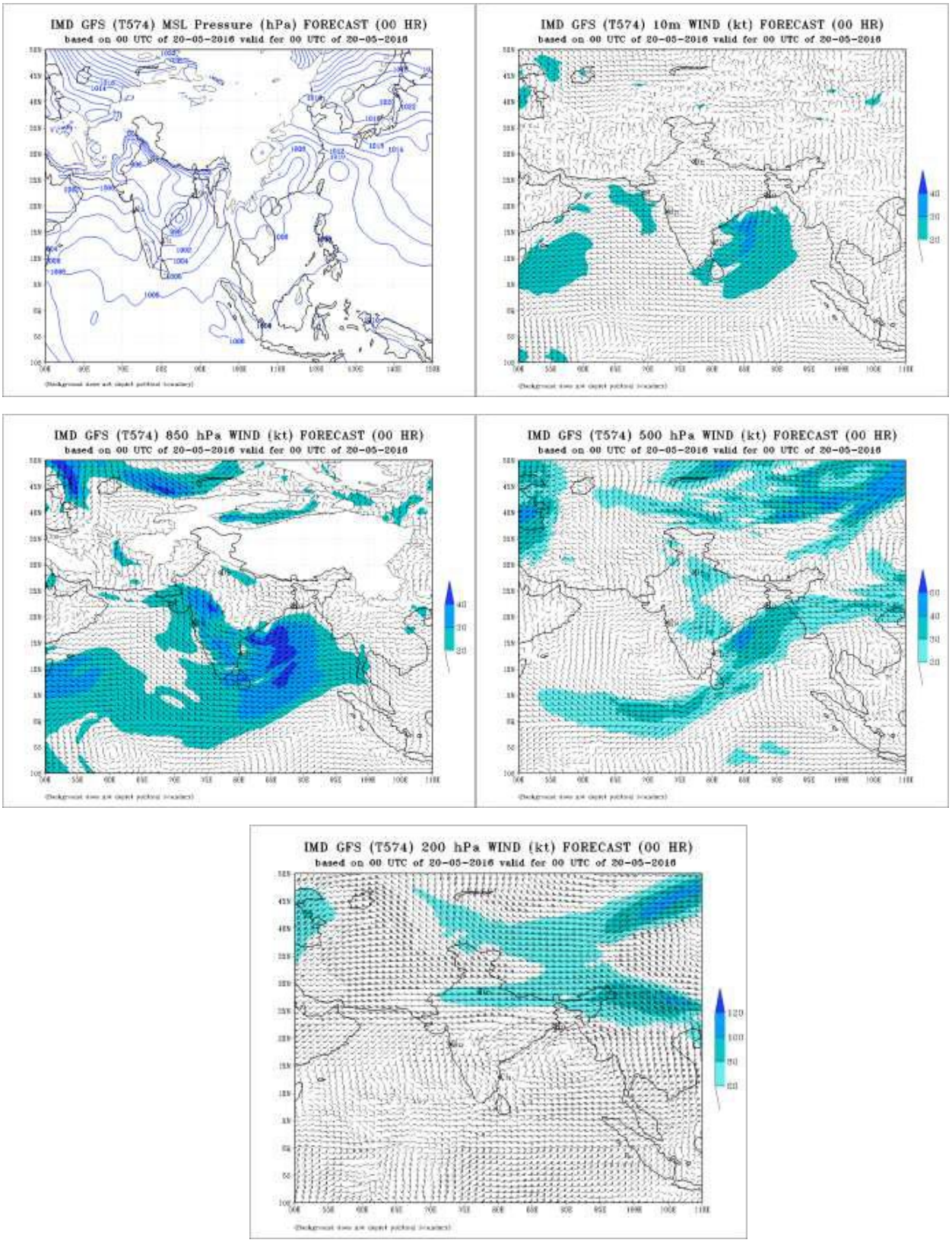


**Fig. 22:** IMD GFS analysis of MSLP, 10 m wind, winds at 850, 500 and 250 hPa based on 0000 UTC of 20 May 2016

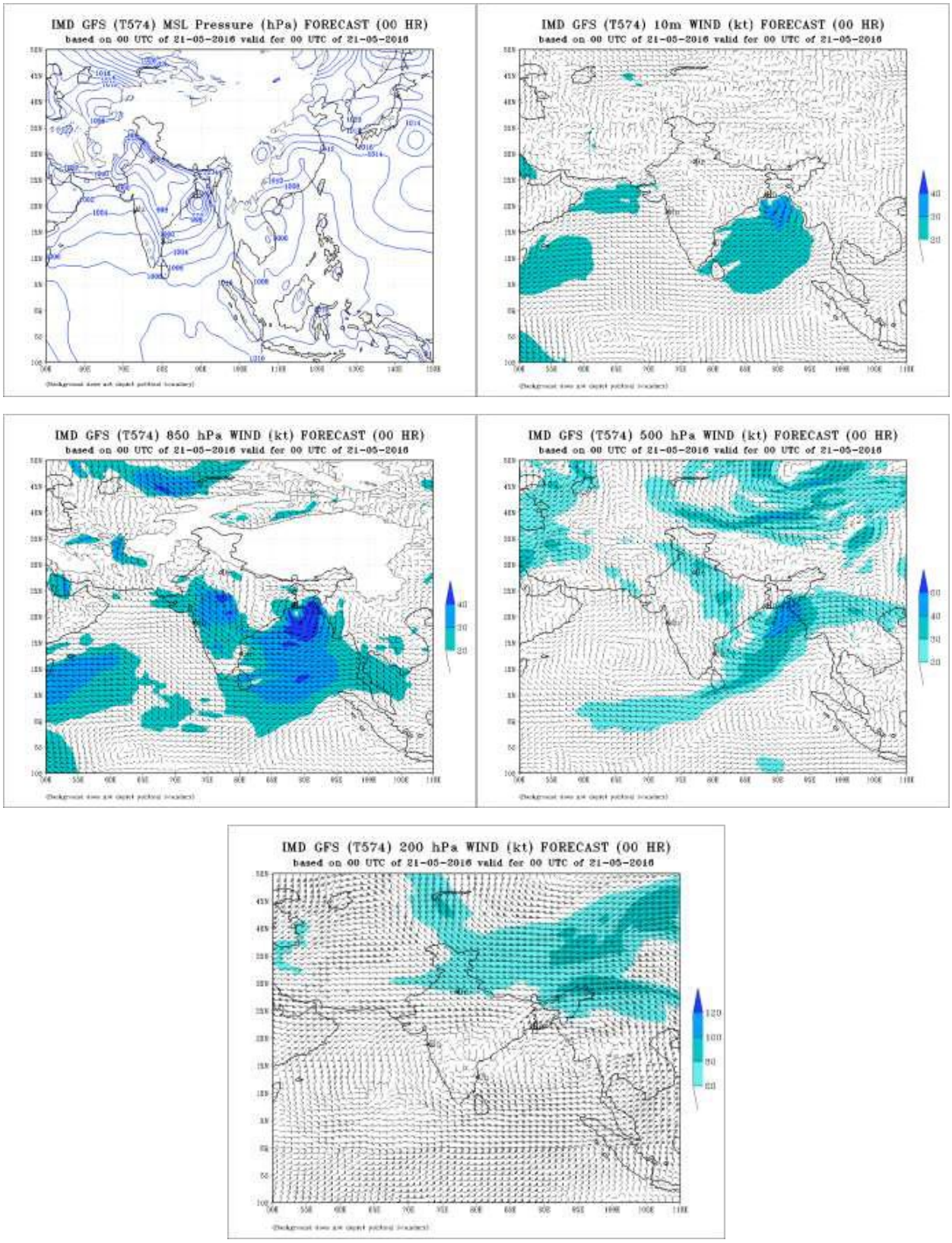


**Fig. 23:** IMD GFS analysis of MSLP, 10 m wind, winds at 850, 500 and 250 hPa based on 0000 UTC of 21 May 2016

## 7. Bulletins issued by BMD

BMD continuously monitored, predicted and issued bulletins containing track & intensity forecast 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 graphical display of the observed and forecast track with cone of uncertainty and the wind forecast for different quadrants were uploaded in the BMD website (http://www.bmd.gov.bd) regularly. The prognostics and diagnostics of the systems were described in the BMD bulletins are briefly described in Table 2.

**Table 2:** Bulletins issued by BMD, Dhaka

| Date | Time | Status | Location | Position | Bulletin | Signal | Comments |
|---|---|---|---|---|---|---|---|
| 15.05.2016 | 09 AM | Low | SW Bay and adjoining area | - | - | - | - |
| 15.05.2016 | 03 PM | Well Marked low | SW Bay and adjoining Si Lanka | - | - | - | - |
| 17.05.2016 | 12 Noon 0600 UTC) | Depression | SW Bay and adjoining area | Lat 11.0°N, Lon 81.0°E | Special Weather Bulletin-1 | Ctg-01 Cox-01 Mon-01 Payra-01 | - |
| 17.05.2016 | Midnight (1800 UTC) | Depression | SW Bay and adjoining area | Lat 11.5°N, lon 81.0°E | Special Weather Bulletin-2 | Ctg-01 Cox-01 Mon-01 Payra-01 | - |
| 18.05.2016 | 12 Noon (0600 UTC) | Depression | SW Bay and adjoining WC Bay | Lat 13.0°N, lon 80.8°E | Special Weather Bulletin-3 | Ctg-01 Cox-01 Mon-01 Payra-01 | Fishing boats & Trawlers over north Bay and Deep sea: Come close to the coast and proceed with caution |
| 18.05.2016 | 06 PM (1200 UTC) | Deep Depression | WC Bay and adjoining SW Bay | Lat 13.5°N, lon 81.0°E | Special Weather Bulletin-4 | Ctg-01 Cox-01 Mon-01 Payra-01 | Fishing boats & Trawlers over north Bay and Deep sea: proceed with caution |
| 18.05.2016 | Midnight (1800 UTC) | Deep Depression | WC Bay and adjoining SW Bay | Lat 13.9°N, lon 81.0°E | Special Weather Bulletin-5 | Ctg-01 Cox-01 Mon-01 Payra-01 | Fishing boats & Trawlers over north Bay and Deep sea: proceed with caution |
| 19.05.2016 | 03 AM | Deep Depression | WC Bay and adjoining SW Bay | Lat 14.3°N, lon 81.1°E | Special Weather Bulletin-6 | Ctg-01 Cox-01 Mong-01 Payra-01 | Fishing boats & Trawlers over north Bay and Deep sea: proceed with caution |
| 19.05.2016 | 09 AM | Cyclonic Storm 'Roanu' | WC Bay and adjoining SW Bay | Lat 15.0°N, lon 81.2°E | Special Weather Bulletin-7 | Ctg-02 Cox-02 Mon-02 Payra-02 | Fishing boats & Trawlers over north Bay and Deep sea ahve been advised to come close to the coast so that they can take shelter within a short notice. They are also advised not to venture into the deep sea. |
| 19.05.2016 | 12 Noon | Cyclonic Storm 'Roanu' | WC Bay and adjoining SW Bay | Lat 15.5°N, lon 81.5°E | Special Weather Bulletin-8 | Ctg-04 Cox-04 Mon-04 Payra-04 | Fishing boats & Trawlers over north Bay and Deep sea have been advised to come close to the coast so that they can take shelter within a short notice. They are also advised not |

| Date | Time | Status | Location | Position | Bulletin | Signal | Comments |
|---|---|---|---|---|---|---|---|
| | | | | | | | to venture into the deep sea. |
| 19.05.2016 | 06 PM | Cyclonic Storm 'Roanu' | WC Bay and adjoining SW Bay | Lat 15.5°N, lon 81.5°E | Special Weather Bulletin-9 | Ctg-04 Cox-04 Mon-04 Payra-04 | Fishing boats & Trawlers over north Bay and Deep sea have been advised to remain close to the coast so that they can take shelter within a short notice. They are also advised not to venture into the deep sea. |
| 19.05.2016 | Midnight | Cyclonic Storm 'Roanu' | WC Bay and adjoining area | Lat 16.0°N, lon 81.9°E | Special Weather Bulletin-10 | Ctg-04 Cox-04 Mon-04 Payra-04 | Fishing boats & Trawlers over North Bay and Deep Sea have been advised to remain close to the coast so that they can take shelter within a short notice. They are also advised not to venture into the deep sea. |
| 20.05.2016 | 06:00 AM | Cyclonic Storm 'Roanu' | WC Bay and adjoining area | Lat 16.4°N, lon 82.6°E | Special Weather Bulletin-11 | Ctg-04 Cox-04 Mon-04 Payra-04 | Fishing boats & Trawlers over North Bay and Deep Sea have been advised to remain close to the coast so that they can take shelter within a short notice. They are also advised not to venture into the deep sea. |
| 20.05.2016 | 12:00 Noon | Cyclonic Storm 'Roanu' | WC Bay and adjoining area | Lat 18.0°N, lon 84.2°E | Special Weather Bulletin-12 | Ctg-04 Cox-04 Mon-04 Payra-04 | Fishing boats & Trawlers over North Bay and Deep Sea have been advised to remain close to the coast so that they can take shelter within a short notice. They are also advised not to venture into the deep sea. |
| 20.05.2016 | 06:00 PM | Cyclonic Storm 'Roanu' | North Bay and adjoining WC Bay | Lat 18.5°N, lon 85.0°E | Special Weather Bulletin-13 | Ctg-07 Cox-06 Mon-07 Payra-07 | Fishing boats & Trawlers over North Bay and Deep Sea have been advised to remain close to the coast so that they can take shelter within a short notice. They are also advised not to venture into the deep sea. |
| 20.05.2016 | 09:00 PM | Cyclonic Storm 'Roanu' | North Bay and adjoining WC Bay | Lat 19.5°N, lon 86.6°E | Special Weather Bulletin-14 | Ctg-07 Cox-06 Mon-07 Payra-07 | Fishing boats & Trawlers over North Bay and Deep Sea have been advised to take shelter immediately and will remain shelter till further notice. |
| 20.05.2016 | Midnight | Cyclonic Storm 'Roanu' | Northwest Bay and adjoining Bangladesh coast | Lat 20.6°N, lon 87.7°E | Special Weather Bulletin-15 | Ctg-07 Cox-06 Mon-07 Payra-07 | Fishing boats & Trawlers over North Bay and Deep Sea have been advised to take shelter immediately and will remain shelter |

| Date | Time | Status | Location | Position | Bulletin | Signal | Comments |
|---|---|---|---|---|---|---|---|
| | | | | | | | till further notice. |
| 20.05.2016 | 03:00 AM | Cyclonic Storm 'Roanu' | Northwest Bay and adjoining Bangladesh coast | Lat 20.6°N, lon 88.7°E | Special Weather Bulletin-16 | Ctg-07 Cox-06 Mon-07 Payra-07 | Fishing boats & Trawlers over North Bay and Deep Sea have been advised to take shelter immediately and will remain shelter till further notice. |
| 20.05.2016 | 06:00 AM | Cyclonic Storm 'Roanu' | Northwest Bay and adjoining Bangladesh coast | Lat 20.8°N, lon 90.0°E | Special Weather Bulletin-17 | Ctg-07 Cox-06 Mon-07 Payra-07 | Fishing boats & Trawlers over North Bay and Deep Sea have been advised to take shelter immediately and will remain shelter till further notice. |
| 20.05.2016 | 09:00 AM | Cyclonic Storm 'Roanu' | Northwest Bay and adjoining Bangladesh coast | Lat 21.5°N, lon 90.7°E | Special Weather Bulletin-18 | Ctg-07 Cox-06 Mon-07 Payra-07 | Fishing boats & Trawlers over North Bay and Deep Sea have been advised to take shelter immediately and will remain shelter till further notice. |
| 20.05.2016 | 12:00 Noon | Cyclonic Storm 'Roanu' | Started to cross Barisal-Chittagong coast near Chittagong | Lat 22.0°N, Lon 91.0°E | Special Weather Bulletin-19 | Ctg-07 Cox-06 Mon-07 Payra-07 | Fishing boats & Trawlers over North Bay and Deep Sea have been advised to take shelter immediately and will remain shelter till further notice. |
| 20.05.2016 | 12:00 Noon | Cyclonic Storm 'Roanu' | Crossed Barisal-Chittagong coast near Chittagong | - | Special Weather Bulletin-20 | Ctg-07 Cox-06 Mon-07 Payr-07 | Fishing boats & Trawlers over North Bay and Deep Sea have been advised to take shelter immediately and will remain shelter till further notice. |

## 8. Damage due to Cyclone Roanu

As per the report of print and electronic media and Department of Disaster Management (DDM), overall 1,10,684 families were partially and 29,168 fully affected by Cyclone Roanu. 24 people lost their lives 2 were reported missing (Table 3). Some damage photographs from Bangladesh Meteorological Department are presented in Figs. 24-27.

**Table 3:** District wise list of damage and causalities due to the Cyclone Roanu

| Sl | District | No of affected family | | No of affected People | | Dead | Injured | Missing |
|---|---|---|---|---|---|---|---|---|
| | | Partial | Full | Partial | Full | | | |
| 1 | Chittagong | 49,330 | 17,912 | 19,401 | 19,912 | 12 | - | - |
| 2 | Cox's Bazar | 6,230 | 1,715 | 7,022 | 1,228 | 3 | - | - |
| 3 | Chandpur | 12,500 | 510 | 7,000 | 450 | - | - | - |
| 4 | Noakhali | 14,000 | 6,500 | 3,270 | 1,300 | 3 | - | - |
| 5 | Feni | 55 | 30 | 55 | 20 | 1 | - | 2 |
| 6 | Laxmipur | 16,000 | - | 17,000 | 0 | 1 | 1 | - |
| 7 | Bagerhat | - | - | - | - | - | - | - |
| 8 | Khulna | 1,000 | 100 | 120 | 40 | - | - | - |
| 9 | Satkhira | - | - | - | - | - | - | - |
| 10 | Barisal | 2,000 | - | 500 | - | - | - | - |
| 11 | Patuakhali | 1,100 | 400 | 400 | - | 1 | - | - |
| 12 | Firozpur | 9 | 1 | 9 | 1 | - | - | - |
| 13 | Bhola | 2,500 | 1,500 | 2,500 | 1,500 | 3 | - | - |
| 14 | Barguna | 4,960 | - | 2,000 | - | - | - | - |
| 15 | Jhalakhati | 1,000 | 500 | 200 | 50 | - | - | - |
| Total | | 110,684 | 29,168 | 59,477 | 24,501 | 24 | 1 | 2 |


**Fig. 24:** (a) Volunteers of Red Crescent carried out publicity campaign to make the people aware of risks of cyclone and asked them to take shelter in safer place, (b) Red Cross volunteers call people to evacuate before "Roanu" hit in Cox's Bazar, (c) Red Cross Volunteers are helping to people to move cyclone shelter, (d) People are moving to the Cyclone Shelter, (e) Villagers stay at a shelter center after their homes were hit by cyclone Roanu in southernmost coastal district of Bangladesh on May 21, 2016 and (f) Houses destroyed by cyclone Roanu at Banshkhali, Chittagong.


**Fig. 25:** (a) Cyclone Roanu unleashed heavy rain and strong winds (photo from Daily Newspaper), (b) People of Barguna district marooned by flash flood triggered by cyclone 'Roanu', (c) Homes have been submerged or destroyed in landslides by cyclone wind and surges, (d) Houses destroyed by cyclone Roanu, (e) People trying to salvage belongings from their ruined houses at Premashia in Banshkhali upazila of Chittagong and (f) A village destroyed by cyclone Roanu in Chittagong district of Bangladesh.


**Fig. 26:** (a) A man wades in water in southernmost coastal district of Bangladesh, on May 21, 2016. Cyclone Roanu slammed into the Bangladesh coastlines after making landfall in a southernmost coastal district on Saturday afternoon, leaving a trail of devastation, (b) People carry useful materials during heavy rain in southernmost coastal district of Bangladesh, on May 21, 2016, (c) Storm Surge over southern district of Bangladesh, on May 21, 2016, (d) A man collects items from his house on Sunday that collapsed in the adjacent pond in Tojumuddin of Bhola during cyclone Roanu a day before, (e) Fishing boats are in anchor to avoid the risk of cyclone Roanu and (f) Corrugated tins of the houses of the roofs are damaged and lying in water due to cyclone Roanu.


**Fig. 27:** (a) Several local shops damaged in Boubazar area of Rangabali upazila in Patuakhali as cyclone Roanu makes landfall, (b) Coastal Bhola district faced damaging effects even before the cyclone hit the Bangladesh coast, (c) People look for shelter as tidal surge submerged residential areas of Cox's Bazar town (Photo: Focus Bangla), (d) Surging waters damaged the coastal embankment in Shahporir Dwip of Teknaf, Cox's Bazar (Photo: Prothom Alo), (e) Cyclone Roanu crossed Bangladesh's coast line, sea waters surged into coastal areas in Patenga, Chittagong in the morning of 21 May 2016 and (f) Bangladeshi villagers make their way to shelter in Cox's Bazar during 21 May 2016

## 9. Track prediction by NWP models

Track prediction by various NWP models is presented in Figs. 28-33. Based on initial conditions of 1200 UTC of 17 May, 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 21 May. All models suggested movement of cyclone close to east coast of India and recurvature

towards Bangladesh coast.

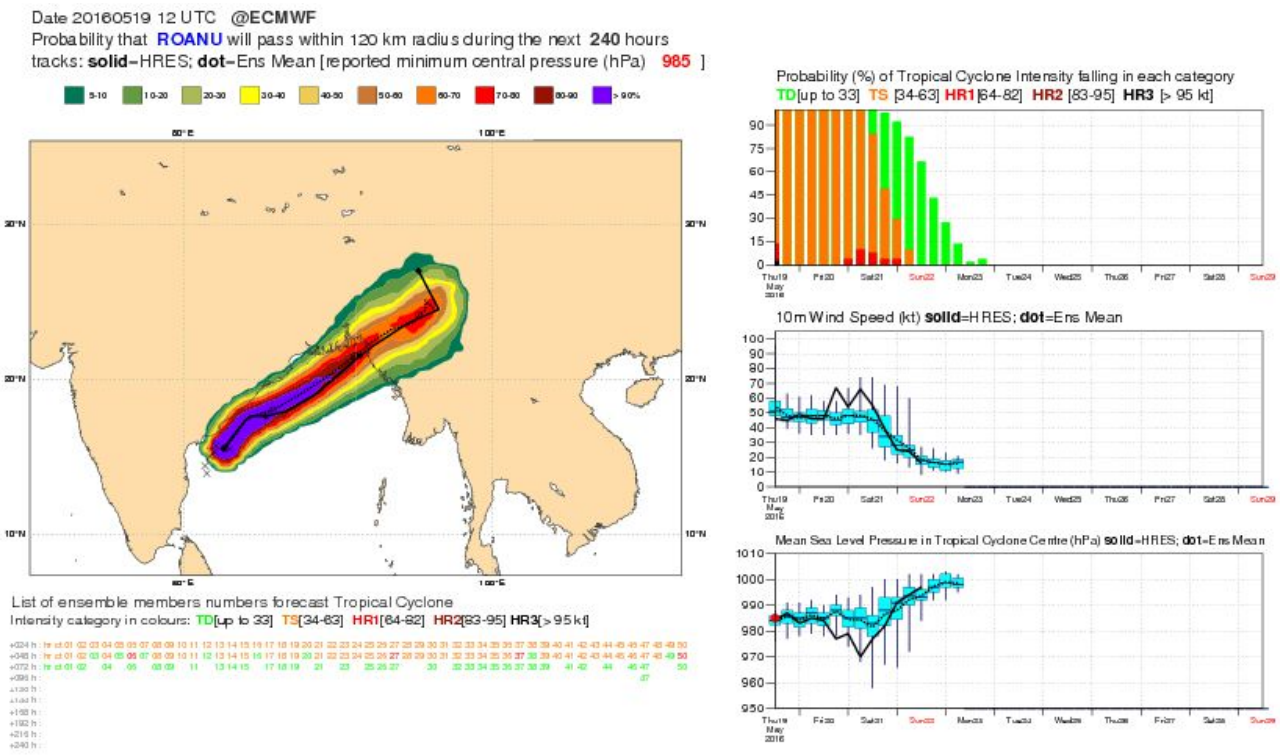


**Fig. 28:** ECMWF predicted trajectories of Cyclone Roanu at 0000 UTC of 19 May 2016

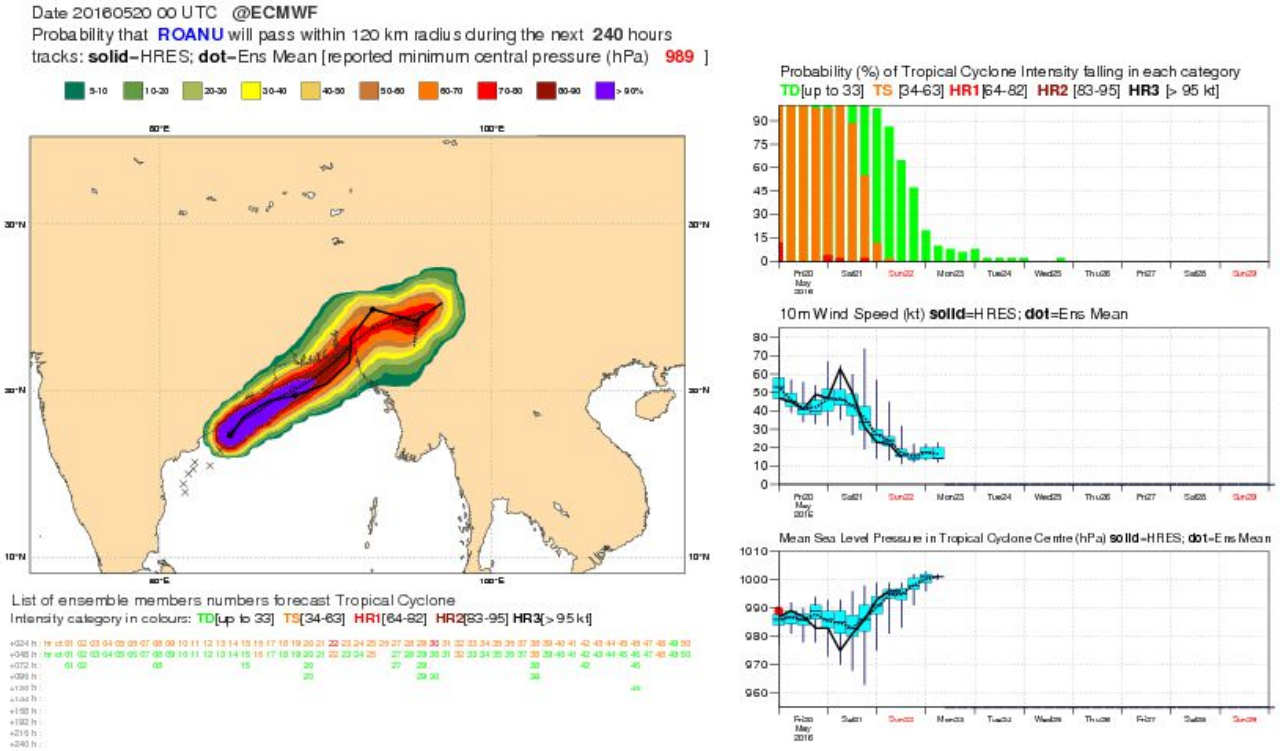


**Fig. 29:** ECMWF predicted trajectories of Cyclone Roanu at 0000 UTC of 20 May 2016

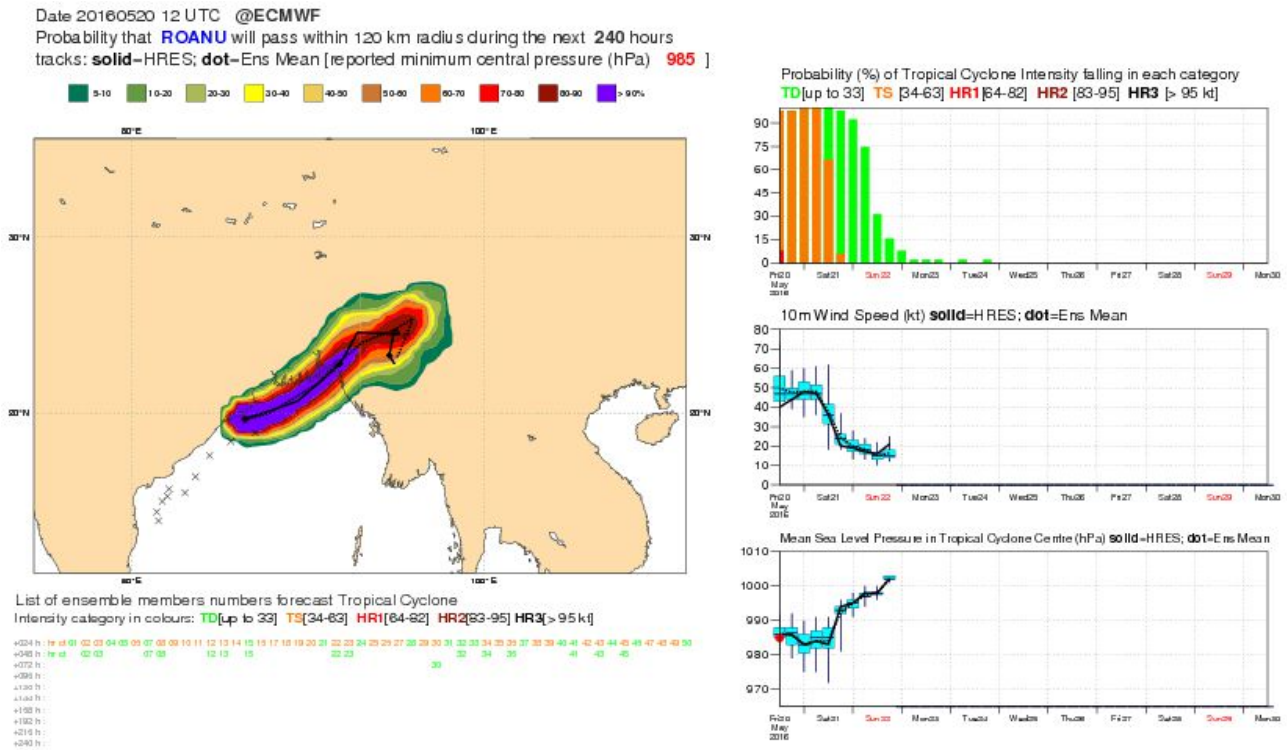


**Fig. 30:** ECMWF predicted trajectories of Cyclone Roanu at 1200 UTC of 20 May 2016

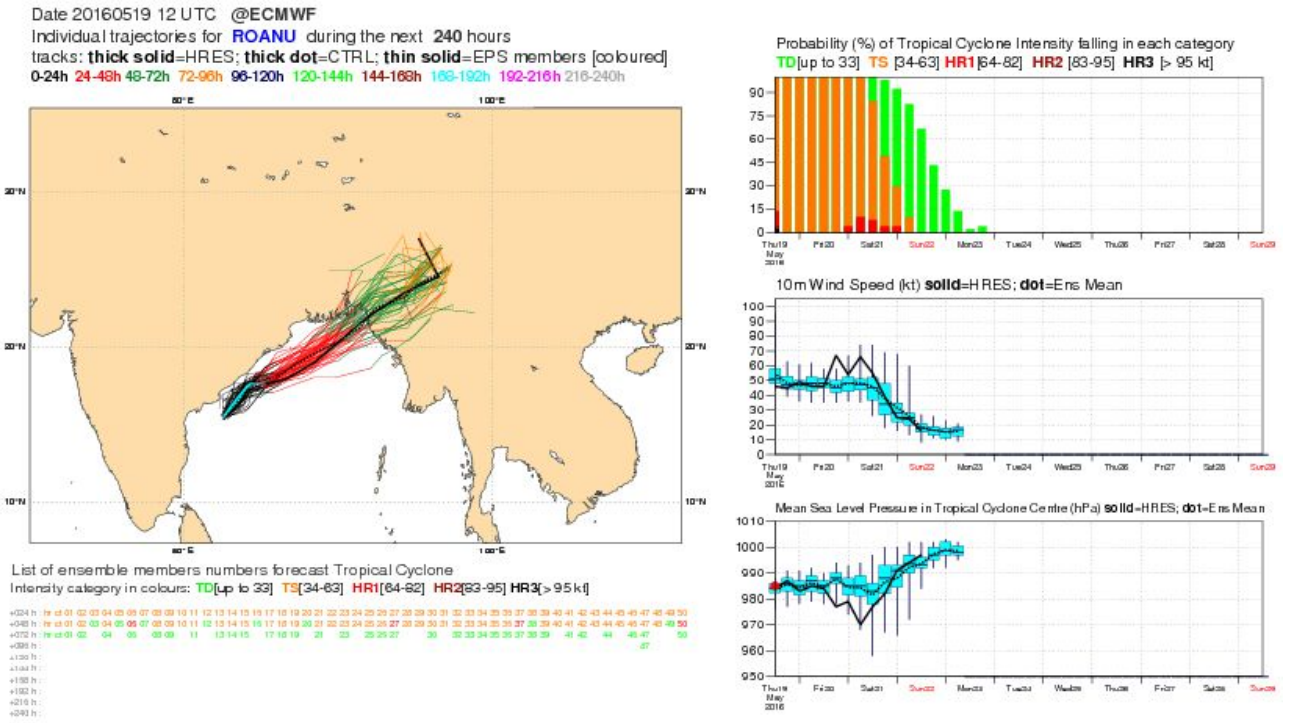


**Fig. 31:** ECMWF Ensemble prediction of trajectories of Cyclone Roanu at 0000 UTC of 19 May 2016

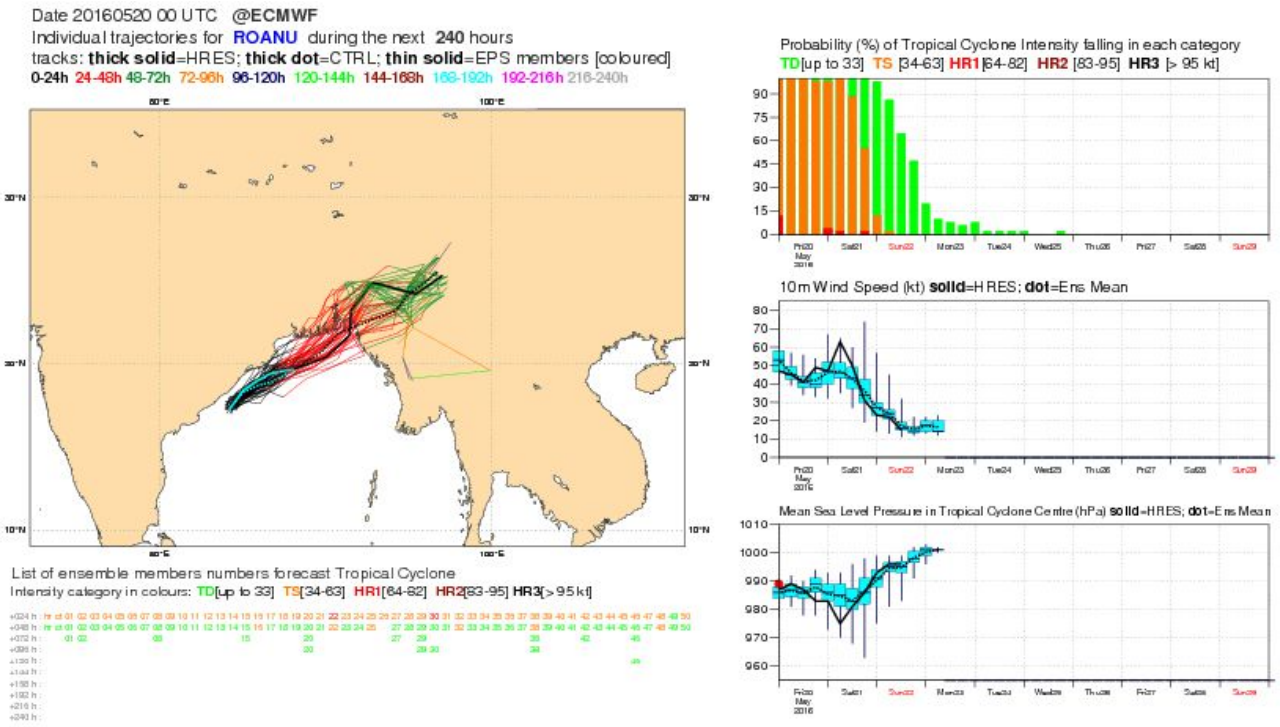


**Fig. 32:** ECMWF Ensemble prediction of trajectories of Cyclone Roanu at 0000UTC of 20 May 2016

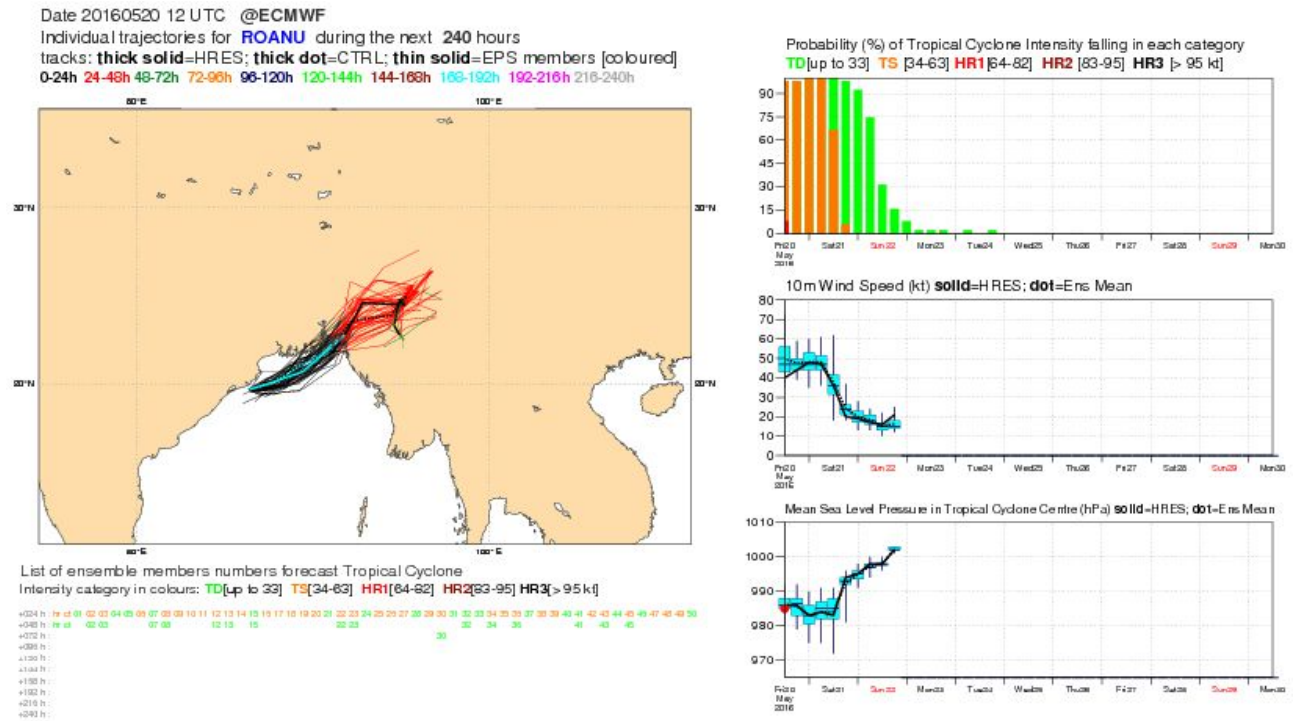


**Fig. 33:** ECMWF Ensemble prediction of trajectories of Cyclone Roanu at 1200 UTC of 20 May 2016

Track prediction by various NWP models is presented in Figs. 34-36. Based on initial conditions of 1200 UTC of 17 May, 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 21 May. All models suggested movement of cyclone

close to east coast of India and recurvature towards Bangladesh coast.

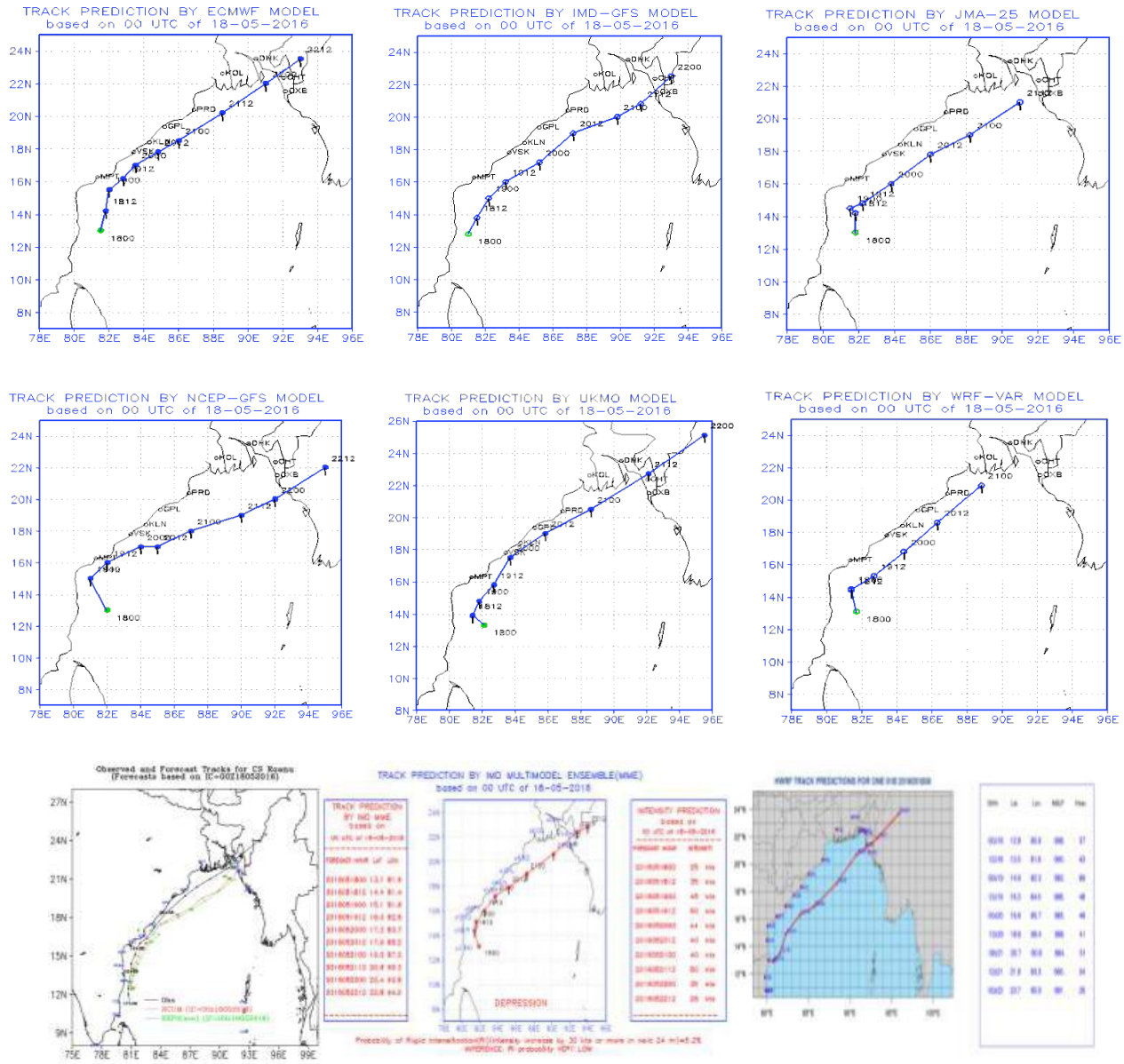


**Fig. 34**: Predicted track of Cyclone Roanu based on 0000 UTC of 18 May 2016 (Source: IMD)

Based on initial conditions of 0000 UTC of 19 May 2016, all models predicted landfall northwest of Chittagong. UKMO predicted landfall close to Chittagong around 1000 UTC of 21 May. MME and HWRF also predicted landfall close to Chittagong around 1800 UTC of 21 May.

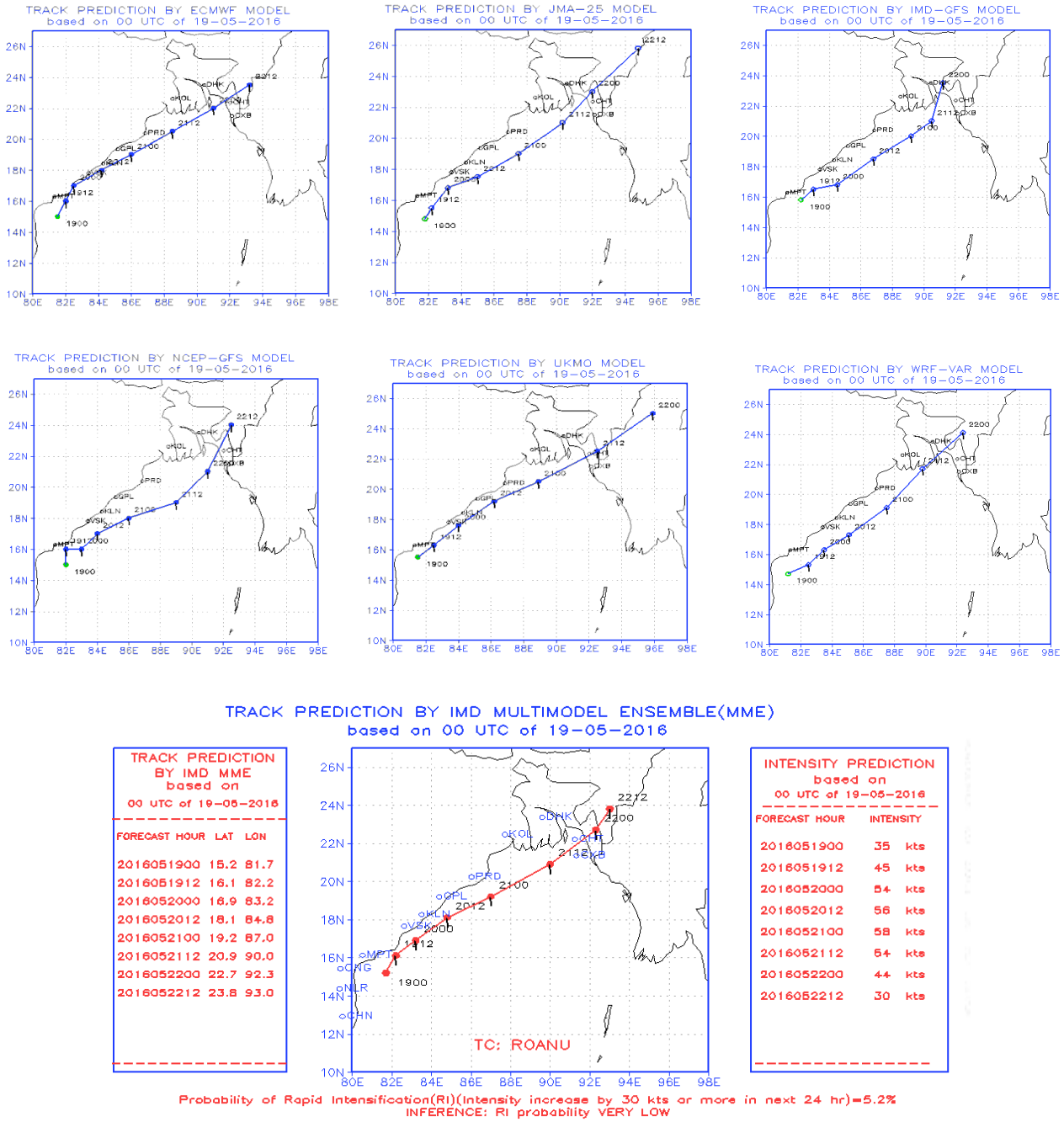


**Fig. 35:** Predicted track of CS Roanu based on 0000 UTC of 19 May 2016 (Source: IMD)

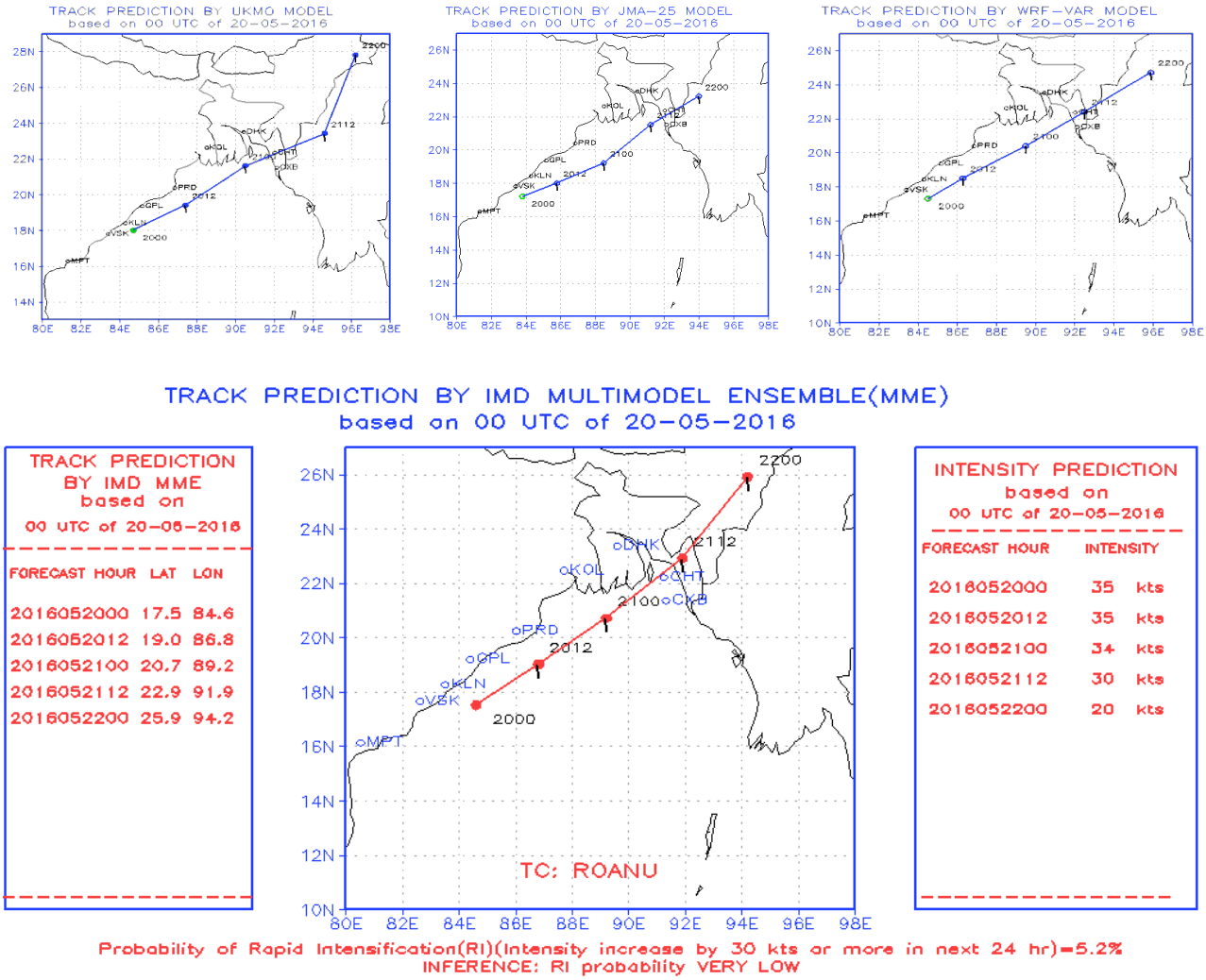


**Fig. 36**: Predicted track of CS Roanu based on 0000 UTC of 20 May 2016 (Source: IMD)

## 10. Rainfall prediction by NWP models

Simulated rainfalls through different NWP models are depicted in Figs. 37-44.

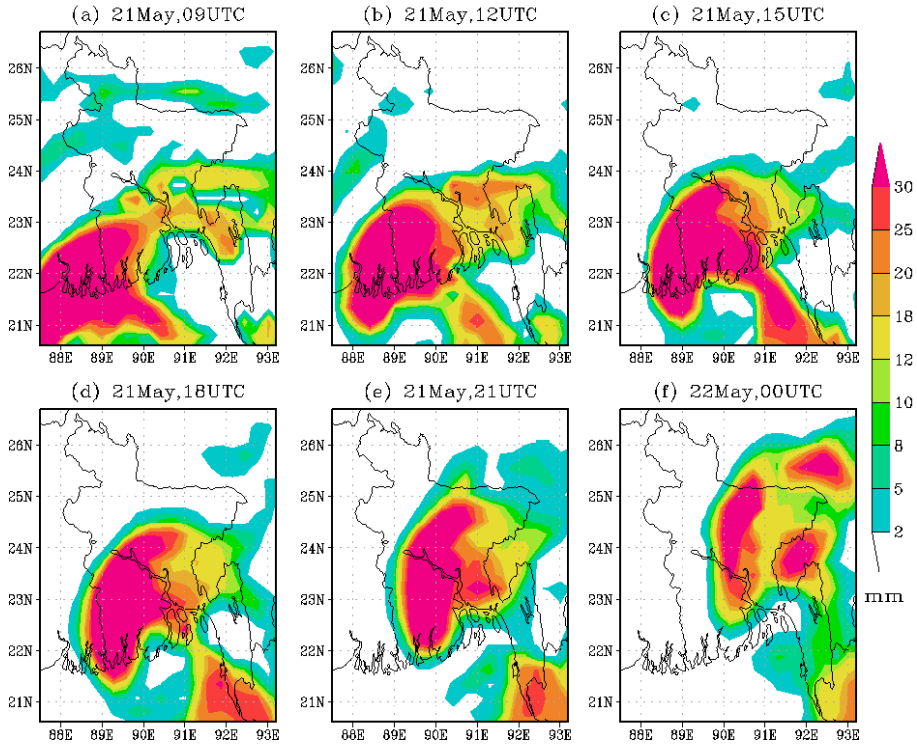


**Fig. 37:** Rainfall (03 hourly) associated with cyclone 'Roanu' simulated by WRF model simulated based on the initial conditions of 0000 UTC of 17 May 2016

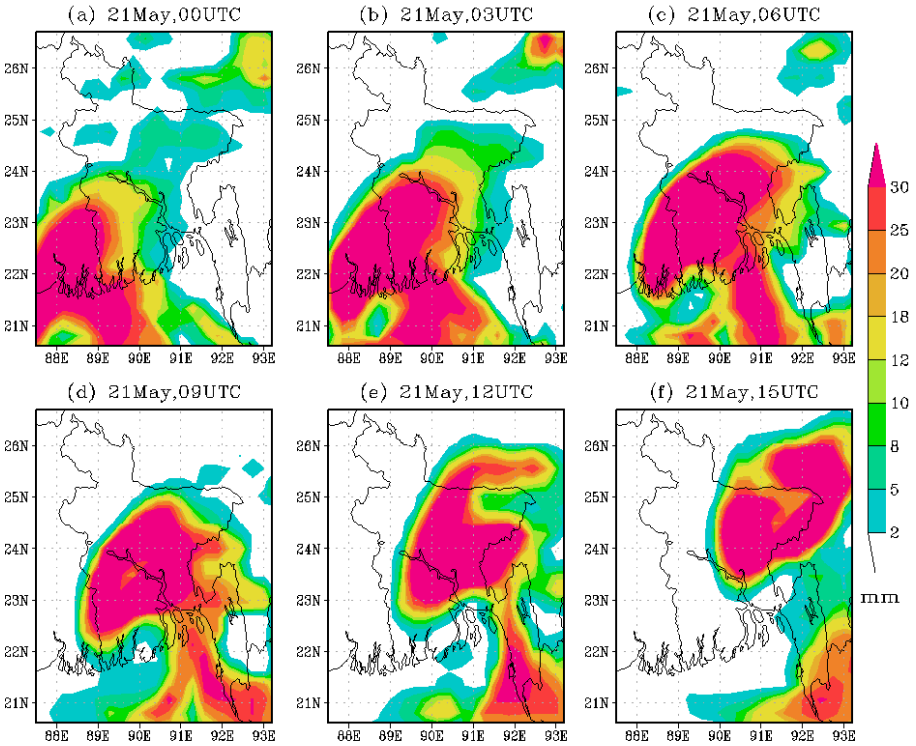


**Fig. 38:** Rainfall (03 hourly) associated with cyclone 'Roanu' simulated by WRF model simulated based on the initial conditions of 0000 UTC of 18 May 2016

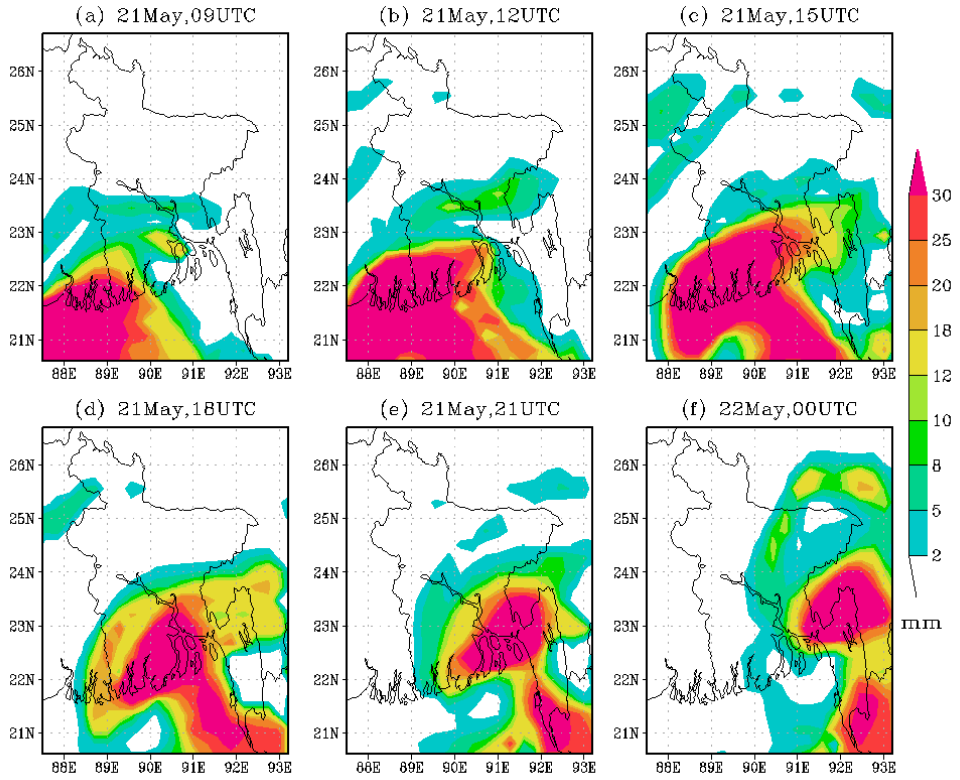


**Fig. 39:** Rainfall (03 hourly) associated with cyclone 'Roanu' simulated by WRF model simulated based on the initial conditions of 0000 UTC of 19 May 2016

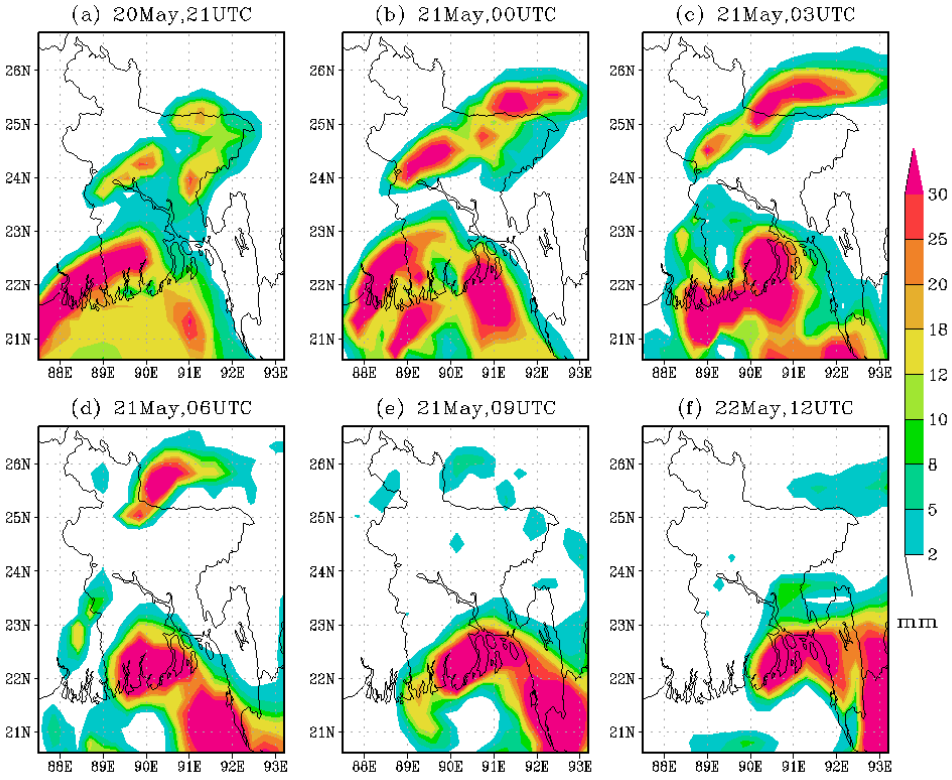


**Fig. 40:** Rainfall (03 hourly) associated with cyclone 'Roanu' simulated by WRF model simulated based on the initial conditions of 0000 UTC of 20 May 2016

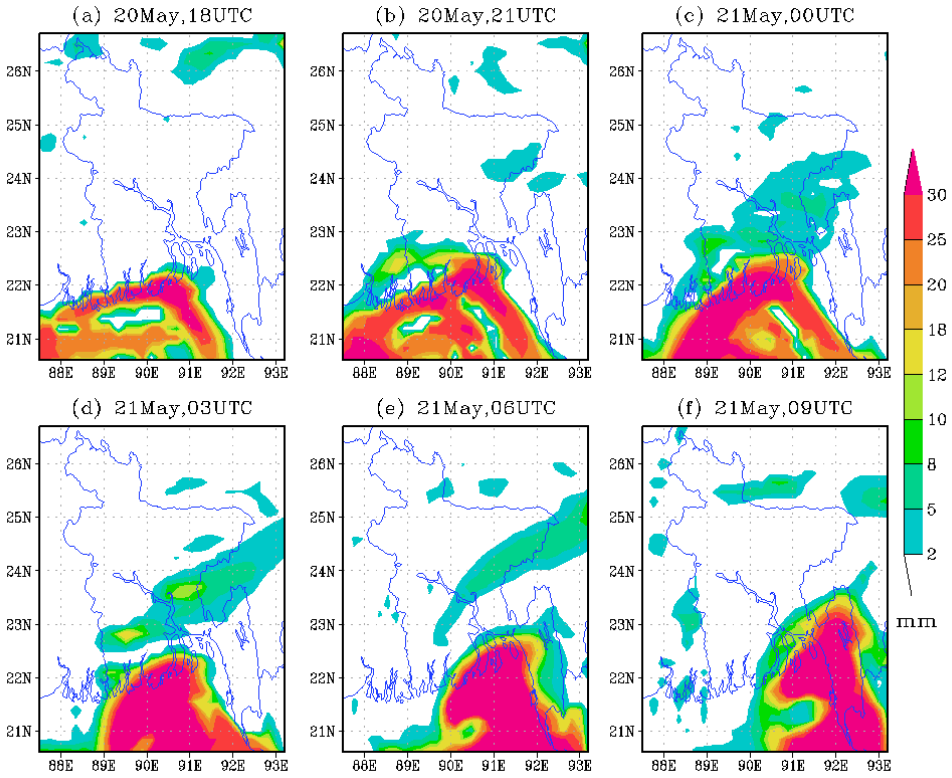


**Fig. 41:** Rainfall (03 hourly) associated with cyclone 'Roanu' simulated by operational WRF model at BMD based on the initial conditions of 0000 UTC of 20 May 2016

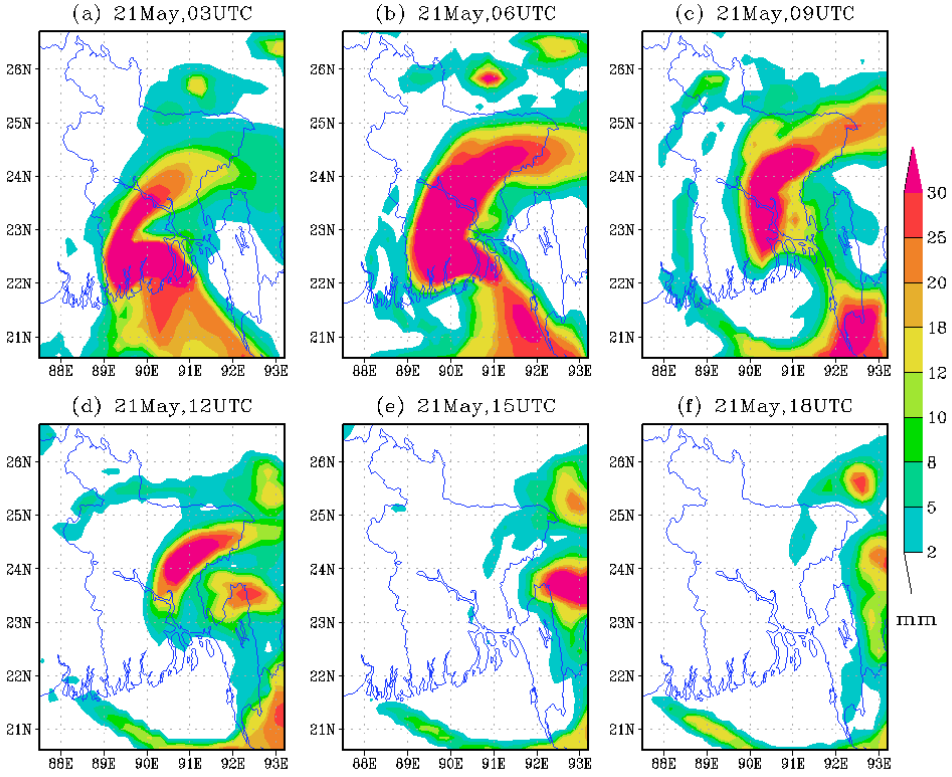


**Fig. 42:** Rainfall (03 hourly) associated with cyclone 'Roanu' simulated by operational WRF model at BMD based on the initial conditions of 0000 UTC of 21 May 2016

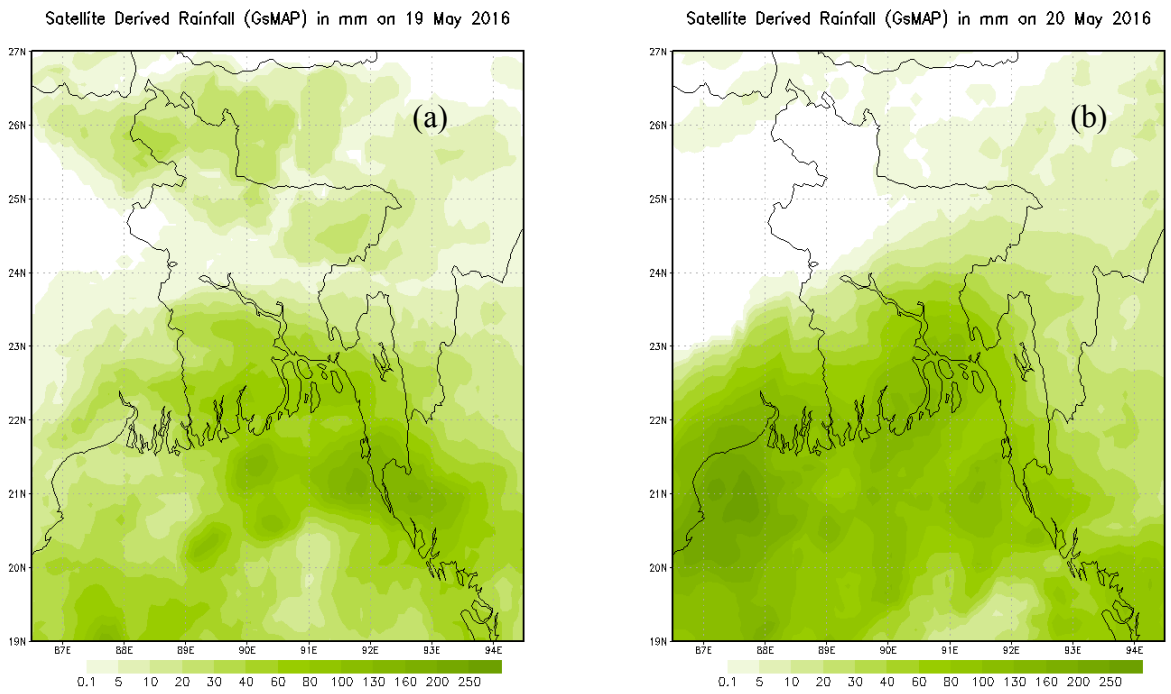


**Fig. 43:** Satellite derived (GsMap) rainfall associated with cyclone Roanu during (a) 19 May 2016, (b) 20 May 2016

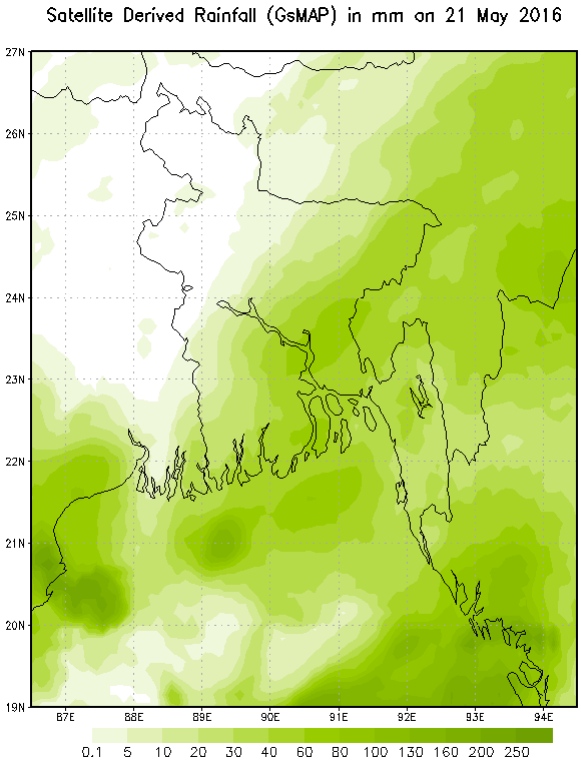


**Fig. 44:** Satellite derived (GsMap) rainfall associated with cyclone Roanu during 21 May 2016

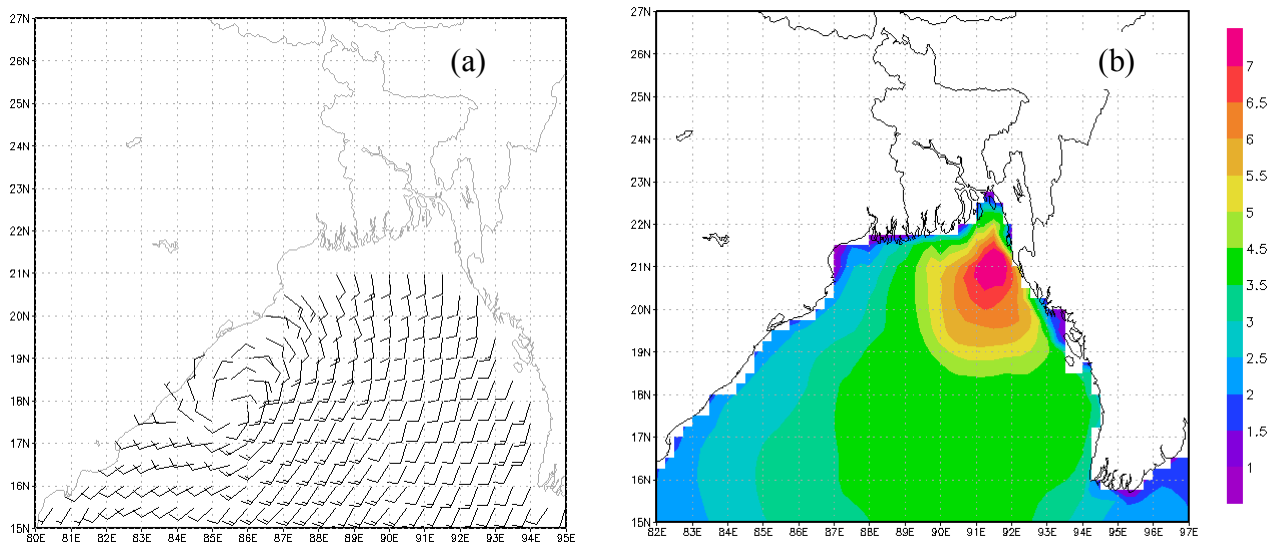


**Fig. 45: (a)** Satellite derived Wind (m/s) at 12 UTC of 20 May 2016 and (b) ECMWF predicted wave height (m) at 06 UTC of 21 May 2016 associated with cyclone Roanu

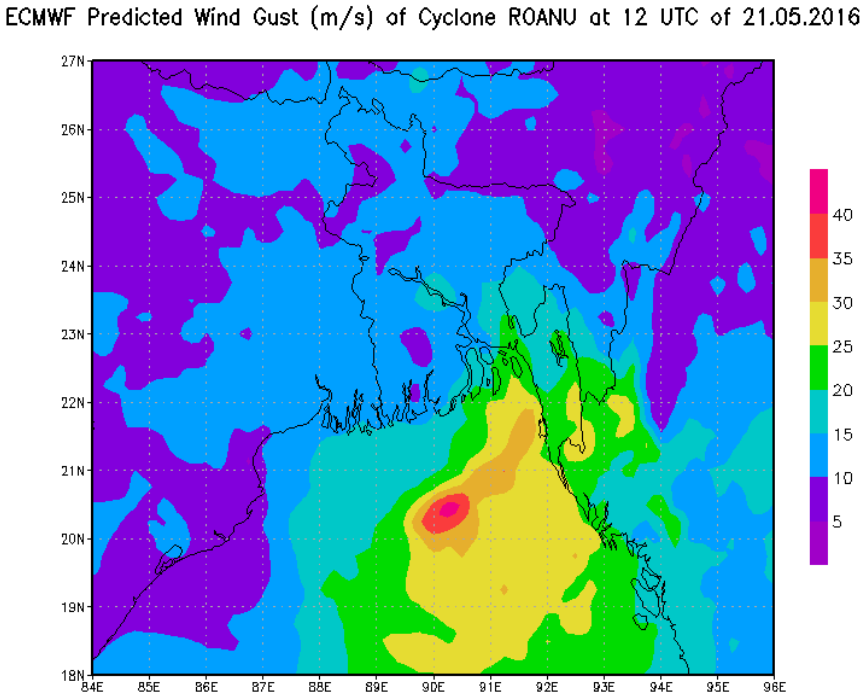


**Fig. 46:** ECMWF predicted Gusty Wind (m/s) at 12 UTC of 21 May 2016 associated with cyclone Roanu

## 11. Heavy rainfall prediction by HWRF model

The forecast rainfall swaths by Hurricane WRF (HWRF) model are presented in Figs. 47 and 48. 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 17 May, over Andhra Pradesh and south Odisha coast based on initial conditions of 18 May. It could capture rainfall over north Andhra Pradesh, Odisha and West Bengal coast based on initial conditions of 19 May, Odisha and west Bengal coast based on initial conditions of 20 and 21 May 2016. It also predicted occurrence of heavy rainfall over Bangladesh and adjoining

northeastern states of India based on the initial conditions of 17 May onwards.

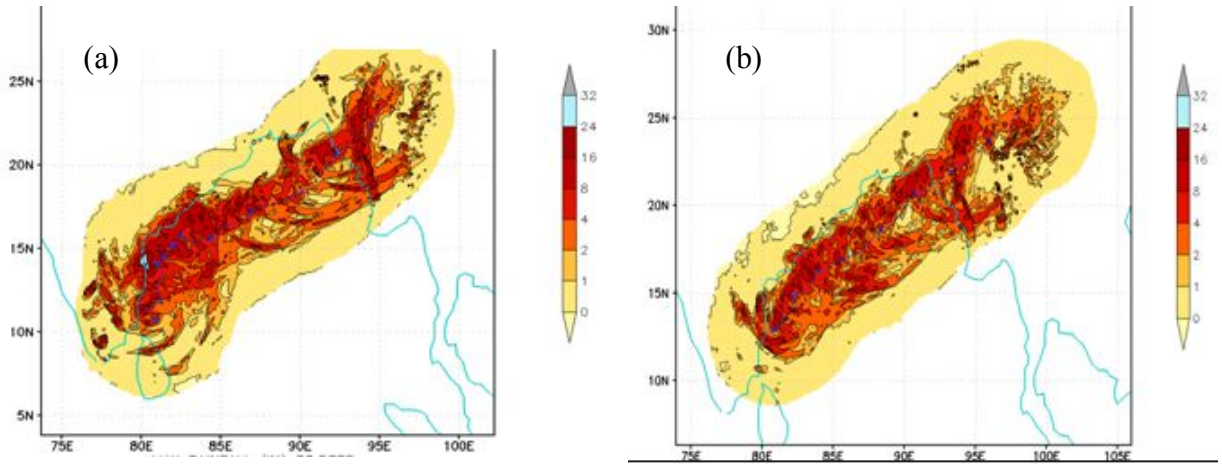


**Fig. 47:** HWRF rain swath (inch) based on 0600 UTC of 17 May and 0000UTC of 18 May 2016 initial conditions (Source: IMD)

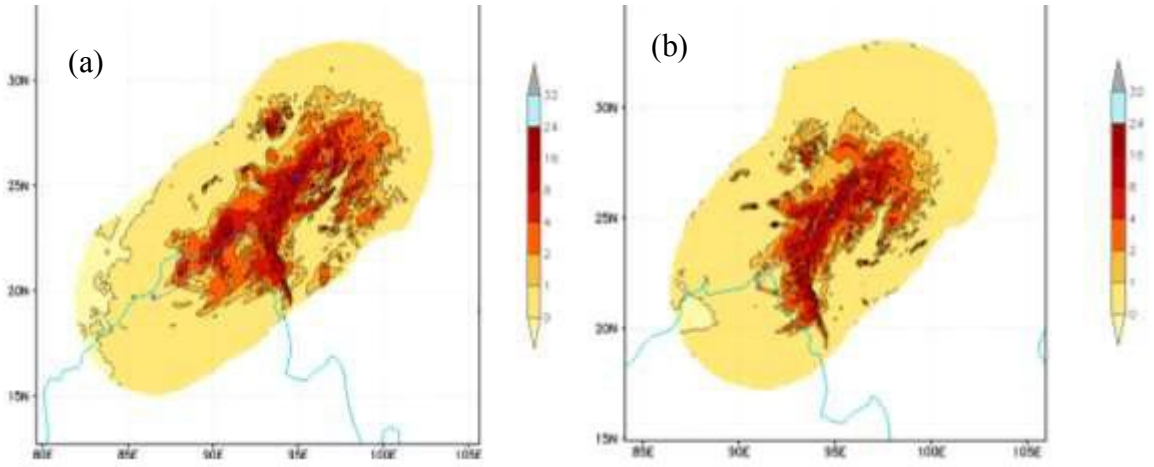


**Fig. 48:** HWRF rain swath (inch) based on 0000 UTC of (a) 19May and (b) 20 May 2016 initial conditions (Source: IMD)

## 12. Storm Surge prediction

Storm surge height predicted by BMD (using IIT-D Storm Surge Model) is depicted in Fig. 49. Predicted surge by Indian National Centre for Ocean Information Services (INCOIS) Advance Circulation (ADCIRC) model are presented in Fig. 50. 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.

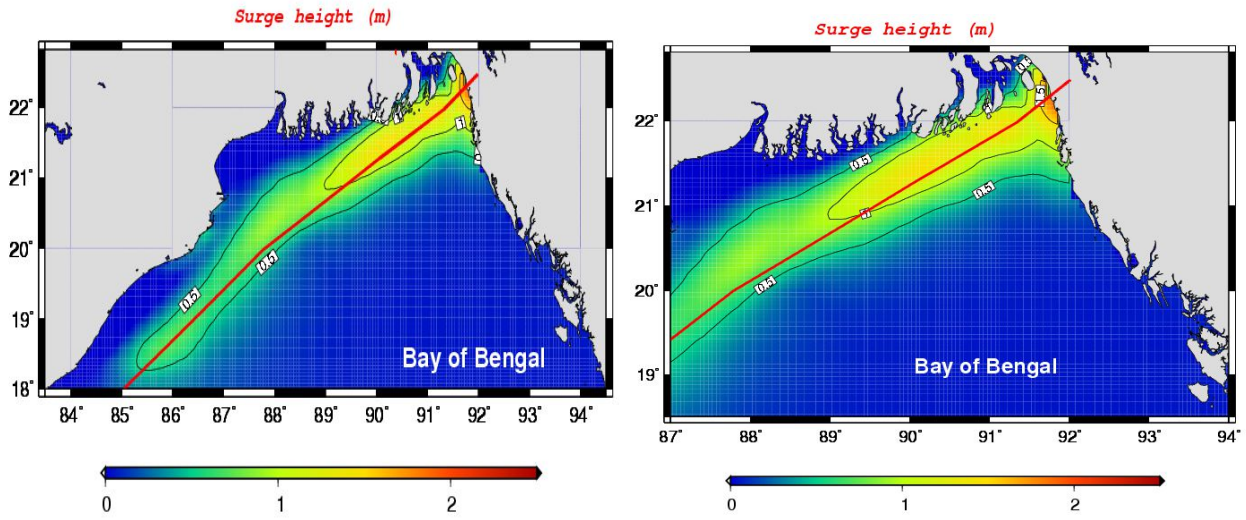


**Fig. 49:** BMD predicted (using IIT-D Storm Surge Model) surge height near (a) Bangladesh coast and North Bay (large view) and (b) Bangladesh coast and North Bay (close view)

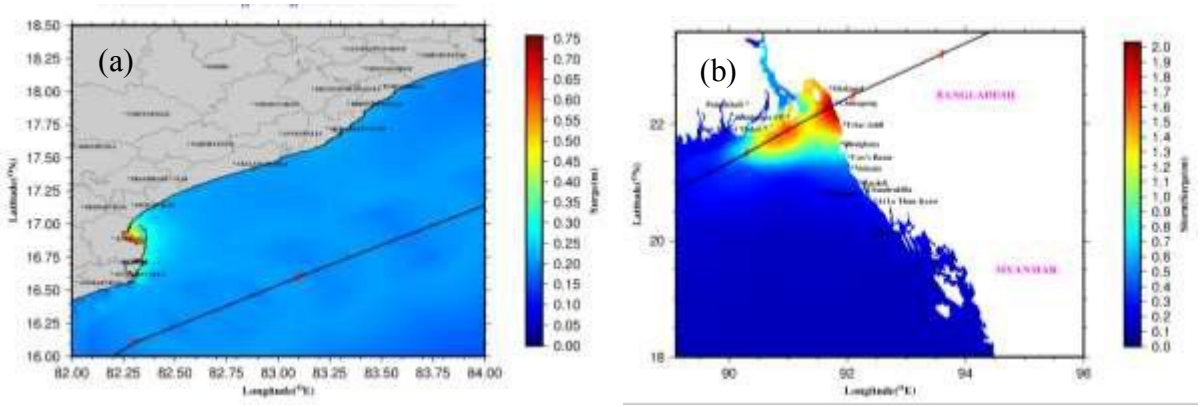


**Fig. 50:** INCOIS (India) model predicted surge height near (a) Kakinada coast, Andhra Pradesh and (b) Bangladesh coast (Source: IMD)

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. 51). However, the realized surge was around 1-1.5 m at the time of landfall. Hence, IIT Delhi model under-predicted the storm surge.

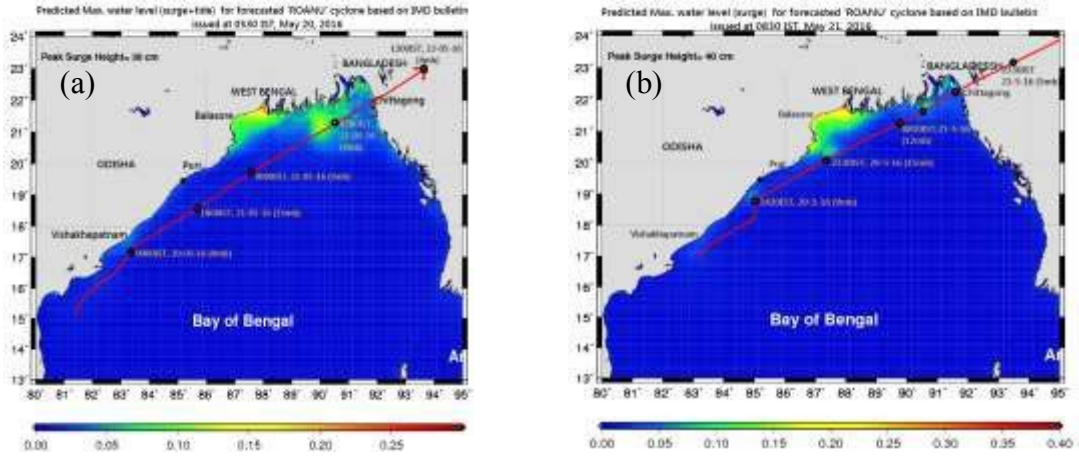


**Fig. 51:** IIT-Delhi storm surge forecast issued at (a) 0000 UTC of 20 May and (b) 0300 UTC of 21 May 2016

## 13. Adverse weather forecast verification

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by BMD are presented in Tables 4-7.

**Table 4:** Recorded wind Speed related to cyclone Roanu

| Station | Lat | Lon | Maximum Wind speed | Direction | Time (utc) |
|---|---|---|---|---|---|
| Sandwip | 22.48 | 91.43 | 38 kts/ 70 kph | NE'ly | 0740 utc |
| Sitakunda | 22.63 | 91.70 | 40 kts/74 kph | E'ly | 0715 utc |
| Rangamati | 22.63 | 92.15 | 16 kts/30 kph | SSE'ly | 0900 utc |
| Comilla | 23.43 | 91.18 | 40 kts/74kph | SE'ly | 0800 utc |
| Chandpur | 23.23 | 90.70 | 07kts/ 13kph | E'ly | 0041 utc |
| Maijdee Court | 22.87 | 91.10 | 35 kts/65 kph | E'ly | 0700- 0800 utc |
| Feni | 23.03 | 91.42 | 35 kts/65 kph | W'ly | 0930 utc |
| Hatiya | 22.45 | 91.10 | 30 kts/56 kph | S'ly | 0400 utc |
| Cox's Bazar | 21.45 | 91.97 | 45 kts/ 83 kph | SSE'ly | 0336 and 0435 utc |
| Kutubdia | 21.82 | 91.85 | 30 kts/56 kph | SE'ly | 0800 utc |
| Teknaf | 20.87 | 92.30 | 31 kts/ 57 kph | E'ly | 0041 utc |
| Khulna | 22.78 | 89.57 | 20 kts/37 kph | NE'ly | 0530 utc |
| Barisal | 22.72 | 90.37 | 25 kts/46 kph | NE'ly | 0615 utc |
| Patuakhali | 22.33 | 90.33 | 32 kts/ 59 kph | NNW'ly | 0400 utc |
| Khepupara | 21.98 | 90.23 | 35 kts/65 kph | NW'ly | 0345- 0356 utc |
| Bhola | 22.68 | 90.65 | 17 kts/32 kph | NE'ly | 0500 utc |

**Table 5:** Recorded rainfall (mm) related to cyclone Roanu during 17-22 May 2016

| Station | Lat | Lon | Dates | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 17 May | 18 May | 19 May | 20 May | 21 May | 22 May |
| Dhaka | 23.77 | 90.38 | 0 | 22 | 1 | 21 | 52 | Trace |
| Mymensingh | 24.73 | 90.42 | 0 | 23 | 19 | 2 | 8 | 0 |
| Tangail | 24.25 | 89.93 | 0 | 0 | 0 | Trace | 6 | 0 |
| Faridpur | 23.60 | 89.85 | 1 | 8 | 1 | 11 | 42 | 0 |
| Madaripur | 23.17 | 90.18 | 10 | 1 | 24 | 76 | 73 | 1 |
| Chittagong (AP) | 22.22 | 91.80 | 10 | 1 | 34 | 33 | 60 | 1 |
| Sandwip | 22.48 | 91.43 | 1 | 85 | 41 | 41 | 53 | 0 |
| Sitakunda | 22.63 | 91.70 | 10 | 66 | 26 | 49 | 68 | 0 |
| Rangamati | 22.63 | 92.15 | 18 | 18 | 14 | 32 | 86 | 0 |
| Comilla | 23.43 | 91.18 | 8 | 2 | 17 | 85 | 110 | 4 |
| Chandpur | 23.23 | 90.70 | 4 | 30 | 15 | 89 | 85 | 0 |
| Maijdee Court | 22.87 | 91.10 | 6 | 54 | 62 | 91 | 66 | 0 |
| Feni | 23.03 | 91.42 | 2 | 63 | 16 | 46 | 123 | 1 |
| Hatiya | 22.45 | 91.10 | 4 | 25 | 94 | 70 | 52 | 0 |
| Cox's Bazar | 21.45 | 91.97 | 4 | 2 | 76 | 93 | 69 | Trace |
| Kutubdia | 21.82 | 91.85 | 15 | Trace | 43 | 73 | 65 | 18 |
| Teknaf | 20.87 | 92.30 | 1 | 2 | 97 | 118 | 16 | 42 |
| Sylhet | 24.90 | 91.88 | 182 | 119 | 4 | 40 | 48 | 5 |
| Srimangal | 24.30 | 91.73 | 10 | 21 | 13 | 11 | 83 | 10 |

| Station | Lat | Lon | Dates | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 17 May | 18 May | 19 May | 20 May | 21 May | 22 May |
| Rajshahi | 24.37 | 88.70 | 0 | 0 | 57 | Trace | 0 | 0 |
| Ishwardi | 24.15 | 89.03 | 0 | 0 | 5 | 0 | 0 | 0 |
| Bogra | 24.85 | 89.37 | 6 | 10 | 11 | 0 | 4 | 0 |
| Rangpur | 25.73 | 89.27 | 25 | 55 | 3 | 1 | 0 | 0 |
| Dinajpur | 25.65 | 88.68 | 63 | 66 | 3 | 0 | 0 | 0 |
| Syedpur | 25.75 | 88.92 | 38 | 43 | 1 | 0 | 0 | 0 |
| Khulna | 22.78 | 89.57 | 1 | 0 | 14 | 49 | 51 | Trace |
| Mongla | 22.47 | 89.60 | 1 | 1 | 45 | 95 | 47 | 4 |
| Satkhira | 22.72 | 89.08 | 0 | 2 | 20 | 37 | 20 | 0 |
| Jessore | 23.20 | 89.33 | 22 | 1 | 51 | 9 | 12 | 2 |
| Chuadanga | 23.65 | 88.82 | 5 | 0 | Trace | 0 | Trace | 0 |
| Barisal | 22.72 | 90.37 | 0 | 6 | 30 | 158 | 98 | 21 |
| Patuakhali | 22.33 | 90.33 | 0 | 6 | 70 | 175 | 61 | 0 |
| Khepupara | 21.98 | 90.23 | 0 | 23 | 113 | 180 | 112 | 6 |
| Bhola | 22.68 | 90.65 | 7 | 8 | 33 | 169 | 73 | Trace |

**Table 6:** Recorded storm surge situation during Cyclone 'Roanu'

| Station | Lat | Lon | Observed Storm Surge | Comments |
|---|---|---|---|---|
| Kutubdia | 21.82 | 91.85 | 03-04 Feet | As per the opinion of BMD's observer |
| Cox's Bazar | 21.45 | 91.97 | About 5 Feet during high tide and about 3 Feet during low tide | As per the opinion of BMD's Officer |

** No storm surge was observed as per the remaining coastal observatories of BMD

**Table 7:** District wise list of damage and causalities due to the Cyclone Roanu
(As pre the report prepared by Department of Disaster Management of Bangladesh)

| Sl | District | No of affected family | | No of affected People | | Dead | Injured | Missing |
|---|---|---|---|---|---|---|---|---|
| | | Partial | Full | Partial | Full | | | |
| 1 | Chittagong | 49,330 | 17,912 | 19,401 | 19,912 | 12 | - | - |
| 2 | Cox's Bazar | 6,230 | 1,715 | 7,022 | 1,228 | 3 | - | - |
| 3 | Chandpur | 12,500 | 510 | 7,000 | 450 | - | - | - |
| 4 | Noakhali | 14,000 | 6,500 | 3,270 | 1,300 | 3 | - | - |
| 5 | Feni | 55 | 30 | 55 | 20 | 1 | - | 2 |
| 6 | Laxmipur | 16,000 | - | 17,000 | 0 | 1 | 1 | - |
| 7 | Bagerhat | - | - | - | - | - | - | - |
| 8 | Khulna | 1,000 | 100 | 120 | 40 | - | - | - |
| 9 | Satkhira | - | - | - | - | - | - | - |
| 10 | Barisal | 2,000 | - | 500 | - | - | - | - |
| 11 | Patuakhali | 1,100 | 400 | 400 | - | 1 | - | - |
| 12 | Firozpur | 9 | 1 | 9 | 1 | - | - | - |
| 13 | Bhola | 2,500 | 1,500 | 2,500 | 1,500 | 3 | - | - |
| 14 | Barguna | 4,960 | - | 2,000 | - | - | - | - |
| 15 | Jhalakhati | 1,000 | 500 | 200 | 50 | - | - | - |
| | Total | 110,684 | 29,168 | 59,477 | 24,501 | 24 | 1 | 2 |

## 14. Summary and Conclusion

The Cyclone Roanu formed from a low pressure area over southwest Bay of Bengal and adjoining areas off Sri Lanka coast on 15 May 2016 and concentrated into a well marked low (WML) in the afternoon of same day. It intensified into a Depression at noon of 17 May and further intensified into Deep Depression in the afternoon of 18 May and then into a cyclonic storm at 09 AM of 19 May. It moved nearly north to north-northeastwards initially, then east-northeastwards and finally crossed Barisal-Chittagong coast near Chittagong (north of Chittagong) during 12 Noon to 05 PM (0600-1100 UTC) of 21 May 2016. Despite its long journey over sea, it did not intensify into a severe cyclonic storm.

BMD utilized all its resources to monitor and predict the genesis, track and intensification of Cyclone Roanu. The forecast of its genesis, track, intensity, time and location of landfall were predicted well with sufficient lead time. Its movement across the Bay is also predicted well in advance.

## 15. Acknowledgements of RSMC New Delhi

Regional Specialized Meteorological Centre (RSMC), New Delhi acknowledges the contribution of Bangladesh Meteorological Department for providing real time Radar Products for tracking the system and valuable information. IMD mentioned 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. BMD also acknowledged the collaboration of Nowegian Meteorological Agency (met. no) for providing ECMWF Products to BMD.

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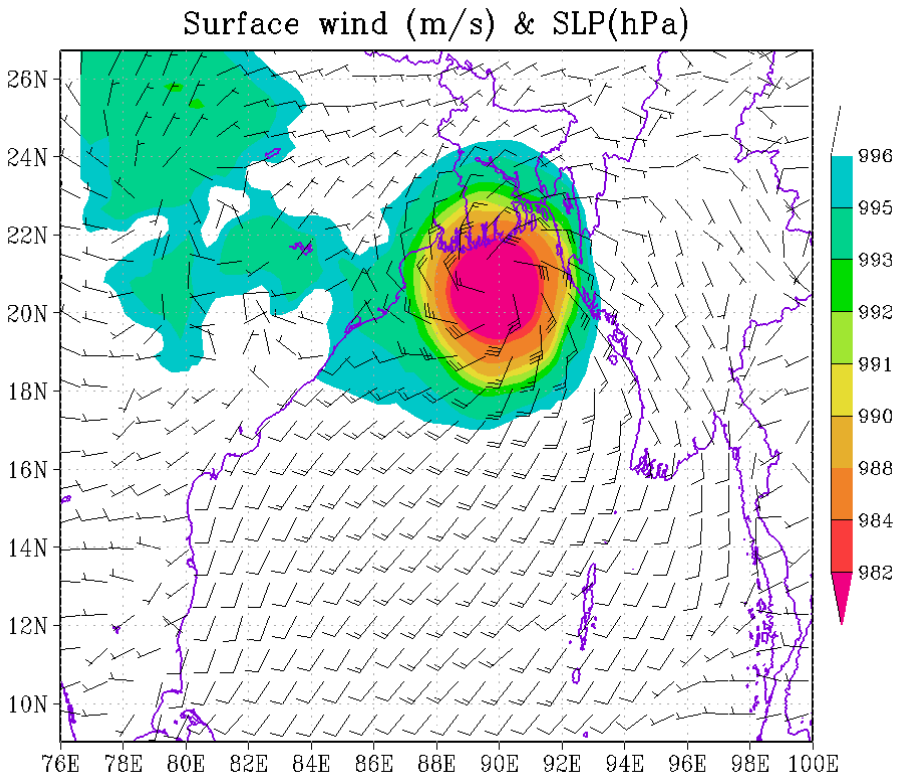
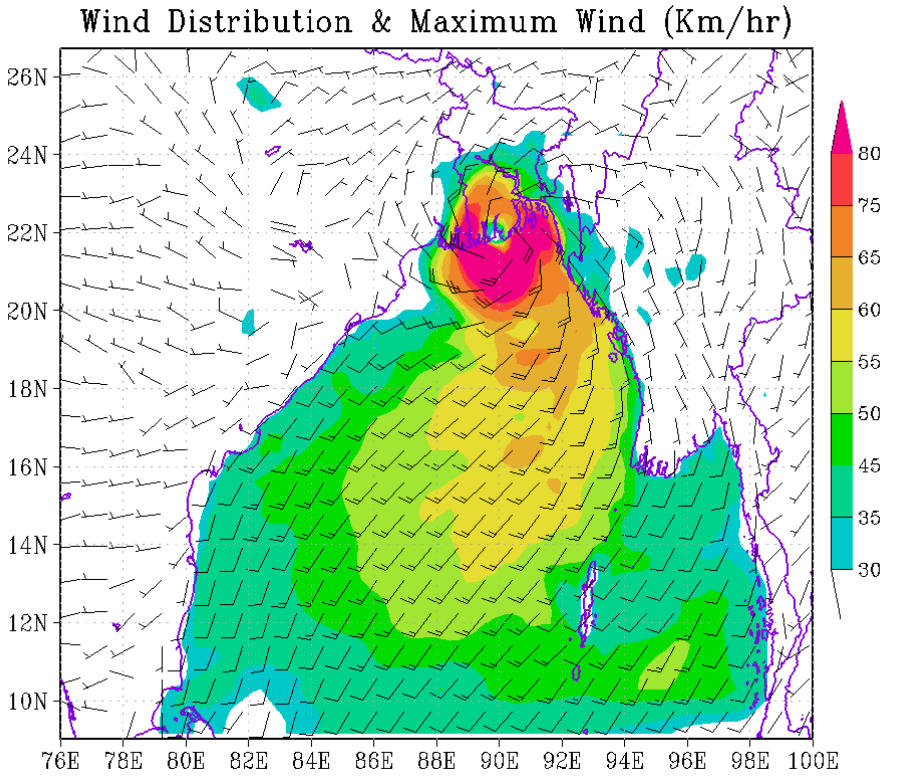

Surface wind (m/s) & SLP(hPa)
26N
24N
22N
20N
18N
16N
14N
12N
10N
76E 78E 80E 82E 84E 86E 88E 90E 92E 94E 96E 98E 100E
996
995
993
992
991
990
988
984
982


Wind Distribution & Maximum Wind (Km/hr)
26N
24N
22N
20N
18N
16N
14N
12N
10N
76E 78E 80E 82E 84E 86E 88E 90E 92E 94E 96E 98E 100E
80
75
65
60
55
50
45
35
30