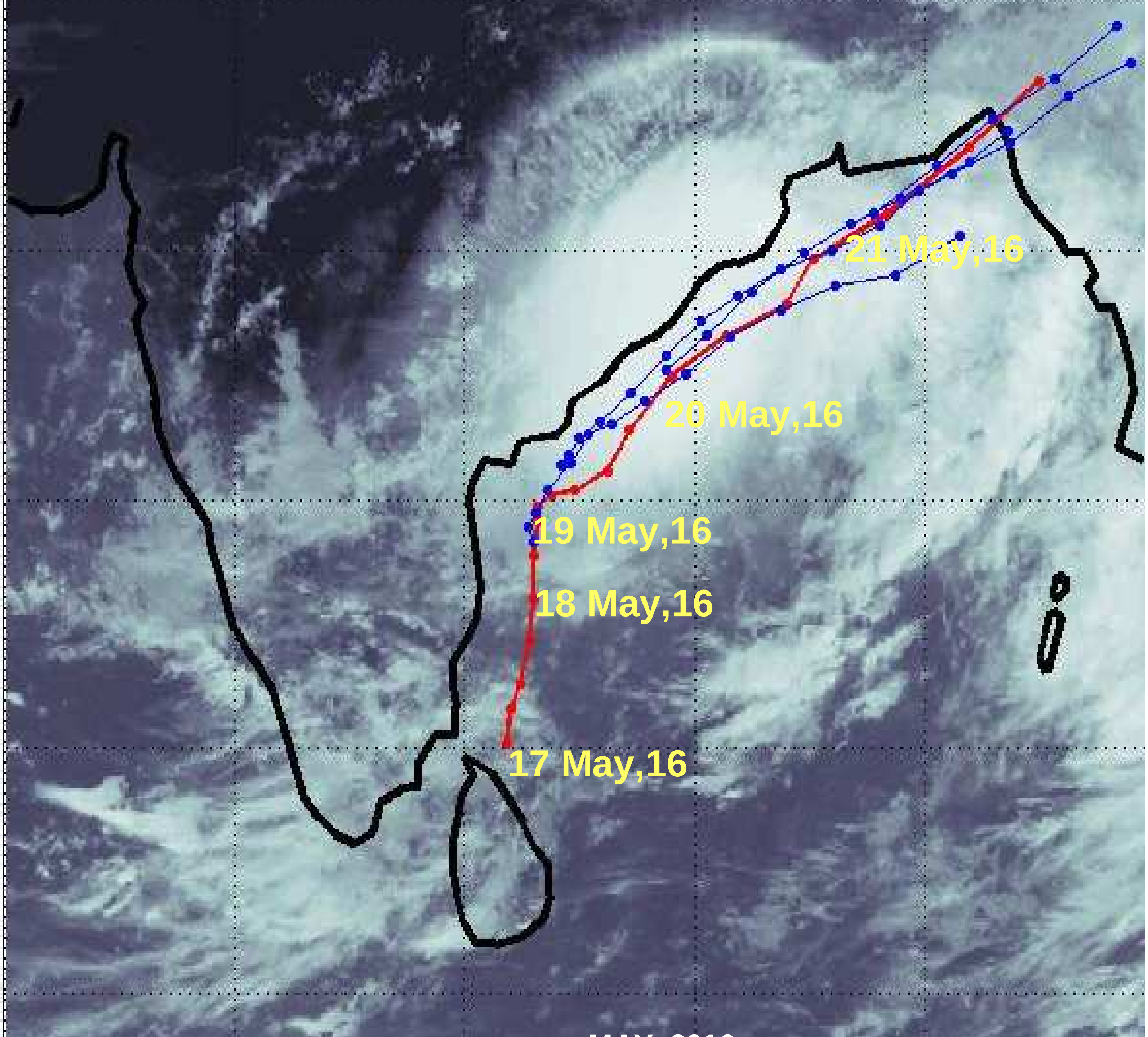
Real-time Monitoring and Prediction of Tropical Cyclone ROANU

SAC/AOSG/ASD/SR-07/2016



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Abstract	The accurate and timely advance prediction of tropical cyclones is very important to disseminate the warnings and preparedness. Prediction of development of any cyclone system in the North Indian Ocean is being done at Space Applications Centre (ISRO) Ahmedabad, using the in-house developed algorithms. Once the system is developed its track and intensity are predicted and disseminated through web-portal SCORPIO linked to MOSDAC. The real-time prediction of cyclone ROANU has been presented in this report. The real-time monitoring of cyclones and its structural analysis using satellite observations are also discussed.
Key words	Tropical cyclone, track prediction, center determination, models, satellite observations
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1. Introduction

Indian sub-continent is one of the most adversely affected cyclone active basins that experience on an average 4-5 cyclones every year. In comparison to other cyclone basins this region is the most vulnerable due to relatively dense coastal population, shallow bottom topography and coastal configuration. Though the cyclones formed in this region are considered to be weaker in intensity and smaller in size as compared to other regions, yet the number of deaths in the region is highest in the globe (3,00,000 human deaths were estimated from tropical cyclone (TC) associated storm surge in Bangladesh in 1970). Out of 9 recorded cases of heavy loss of human lives worldwide (~ 40,000) by cyclones during last 300 years, 7 cases (77%) occurred in Indian sub-continent (Frank and Hussain, 1971). To overcome such loss, advance prediction of cyclones in terms of their genesis, track and intensity is highly important. The timely prediction of impending cyclonic activity can save life of people and help in decision making for taking preventive measures like evacuation during the cyclone landfall. The predictions of TC are generated based on the models using satellite observations and ground based radar networks when cyclone reaches close to the land. Due to the advancements in numerical prediction models and satellite observations with high temporal and spatial resolutions, during the last decades, the track prediction accuracy has improved drastically. However, the prediction of cyclogenesis and cyclone intensity is still challenging.

Prediction of development of any cyclone system in the North Indian Ocean (NIO) including the Bay of Bengal (BoB) and Arabian Sea is being done as a regular exercise at Space Applications Centre (ISRO) Ahmedabad, using the in-house developed algorithms. Once the system is developed in the NIO basin its track and intensity are predicted in real-time and disseminated through web-portal Satellite based cyclone real-time prediction in Indian Ocean (SCORPIO) linked to MOSDAC (www.mosdac.gov.in). The similar exercise was performed during the formation of cyclone “ROANU” in NIO during 18-21 May, 2016, which has been discussed in the present report.

1.1 Overview of Tropical cyclone ROANU (18-21 May, 2016)

Tropical cyclone “ROANU” was the first tropical cyclone that formed in the North Indian Ocean basin in the year 2016. ROANU was a weak tropical cyclone but caused severe flooding in Sri Lanka and Bangladesh. The cyclone was formed from a low pressure area that developed south of Sri Lanka on 14th May. This low pressure system then gradually drifted northwards and intensified into a cyclonic storm on 19th May and named as cyclone ROANU by India Meteorological Department (IMD). The cyclone moved along the east coast of Sri Lanka and India and made landfall in Bangladesh on May 21st affecting Bangladesh, Myanmar, coastal region of India and Sri Lanka. It has been reported that due to the cyclone there were more than 100 deaths in Sri Lanka and Bangladesh. ROANU also brought torrential rainfall to the Indian states of Tamil Nadu, Andhra Pradesh and Odisha as it drifted close to the coast. The observed track of cyclone with the intensity classification categories has been shown in the Fig.1. The cyclone observations (latitude, longitude, intensity) have been taken from the joint typhoon warning centre (JTWC). The IMD classification of cyclone categories has been given in the Table 1. Different intensity categories have been presented in the different colors.

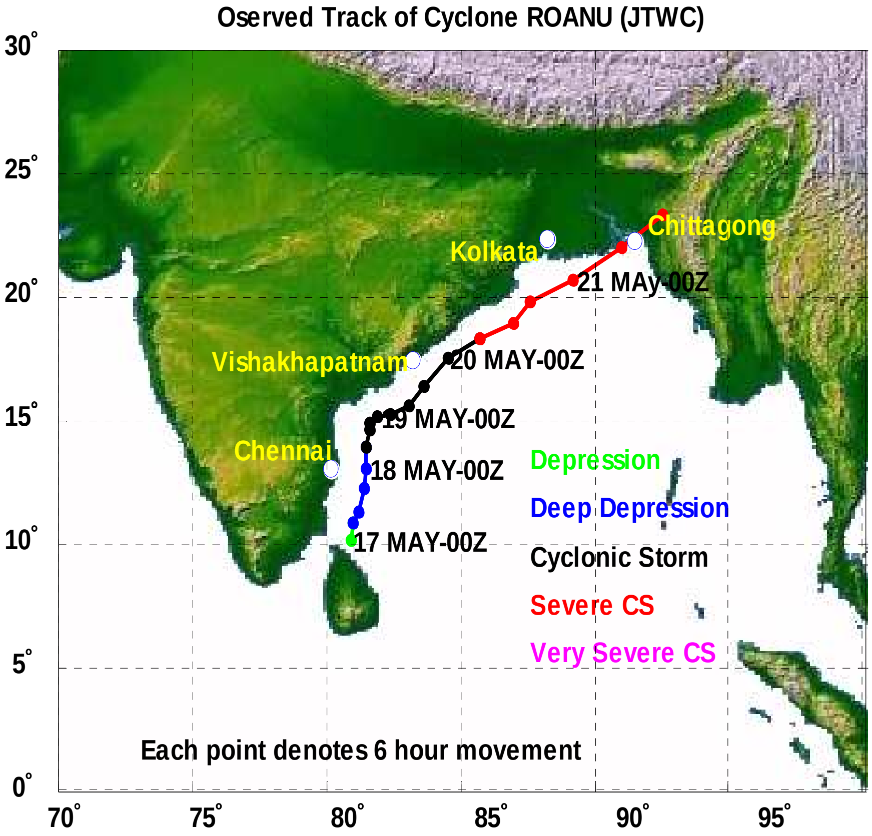

Figure 1: Observed track and intensity of cyclone RONAU (track positions and intensity values taken from JTWC)

Table 1: IMD classification of categories of cyclonic system

System	**Associated wind speed (knots)**
Low pressure area	<17
Depression	17-27
Deep Depression	28-33
Cyclonic Storm	34-47
Severe Cyclonic Storm (SCS)	48-63
Very SCS	64-85
Extremely SCS	86-119
Super Cyclonic Storm	>119

After achieving the intensity of cyclonic storm on 19th May, despite favorable outflow and warm sea surface temperatures (SSTs) reaching 31° C, it could not intensify rapidly due to its proximity to land and moderate vertical wind shear. The diurnal temperature variation over land and the persistent wind shear began to affect the deep convection obscuring the low-level circulation center (LLCC). In the late hours of that day, cyclone showed a weakening trend after most of the convection covering the LLCC was sheared off. During that time, it was located approximately 150 km from Vishakhapatnam. However, the wind shear soon decreased and the storm reestablished deep convection over and around the LLCC, forming a central dense overcast in a period of 6 hours. As a result, it re-intensified as it accelerated east-northeastwards towards the coast of Bangladesh, and reached its peak intensity with winds of 85 km/h (50 mph) and a minimum central pressure of 983 hPa. On 21st May, ROANU made landfall near Chittagong, Bangladesh. Continuing to accelerate inland, it steadily weakened and degenerated into a remnant low the next day.

Developments of the cyclone ROANU was continuously monitored by the visible and infrared observations from geo-stationary satellites viz., INSAT-3D and KALPANA and high resolution microwave satellite viz., SAPHIR onboard Megha-Tropiques. Other foreign satellites (viz., WINDSAT, RAPIDSACT etc.) also provided very good observations over these cyclonic systems, which were found to be very helpful for its prediction and structural analysis. Using the observations and models the real-time predictions of cyclogenesis, track, intensity, rainfall and wind structure were performed. The real-time prediction of the cyclone using in-house developed algorithms and the satellite observations over the system that helped in monitoring and prediction has been discussed in this report. The in-house developed techniques used for the cyclone prediction are briefly discussed in the section 2. The separate sections are made for the detail discussion of predictions and analysis. The error analysis of the real-time predictions was also performed using the real-time observed values provided by JTWC. The further validation will be carried out after the availability of the best track data from the operational agencies viz., JTWC and IMD.

2. Data and Methodology

A system has been formed in the SAC to predict the cyclones from its birth till death. This starts with predicting the earliest signatures of development of a low pressure system i.e. tropical cyclogenesis. After the declaration of system as tropical cyclone or cyclonic storm by JTWC or IMD, its track is predicted and updated during the life period of the cyclone till its landfall occurs. The track prediction also includes its landfall time and position prediction. Predictions of cyclone intensity and rainfall are also generated. All these predictions are disseminated in the real-time through a web server "Satellite based cyclone observations and real-time prediction in Indian Ocean" i.e. SCORPIO linked with MOSDAC (www.mosdac.gov.in).

2.1 Prediction of tropical cyclogenesis

The prediction of tropical cyclogenesis (TCG) of the cyclonic systems that develop in the NIO is being done at SAC using two in-house developed techniques viz., (i) TCG prediction based on multi-model ensemble (MME) technique and (ii) TCG prediction by wind pattern matching technique. MME technique utilizes the global model output for 1-15 days and provides the extended range TCG prediction i.e. 5-15 days advance genesis prediction (Jaiswal et al., 2016). Wind pattern matching technique utilizes the scatterometer derived surface wind observations and provides 1-4 days advance TCG prediction (Jaiswal and Kishtawal, 2011; 2013).

During the cyclone active months of the NIO i.e. April-June and October-December, the cyclogenesis prediction techniques are regularly run to detect the earliest signatures of any possibility of cyclonic activity in the Bay of Bengal (BoB) and Arabian Sea. These cyclogenesis prediction techniques are summarized in the following sections.

2.1.1 <u>Extended range TCG prediction based on multi-model ensemble technique</u>

The extended range prediction of cyclogenesis aimed at predicting cyclonic activity with a lead time of ~10 days. The algorithm is based on the forecasts generated by the global models viz., UKMO, NCEP and ECMWF, which are obtained from TIGGE-portal. TIGGE, the THORPEX Interactive Grand Global Ensemble, is a key component of THORPEX: a World Weather Research Programme to accelerate the improvements in the accuracy of 1 day to 2 week high-impact weather forecasts for the benefit of humanity. The TIGGE archive consists of ensemble forecast data from ten global Numerical Weather Prediction (NWP) centre, starting from October 2006, which has been made available for scientific research. TIGGE has become a focal point for a range of research projects, including research on ensemble forecasting, predictability and the development of products to improve the prediction of severe weather. Using the above data the multi-model ensemble technique was developed by optimizing the number of models and the significant variables for cyclogenesis prediction. After several experiments it was found that the wind components (u and v at 10 m level) and mean sea level pressure (mslp) from the above three model have potential to predict the low pressure systems and cyclonic activities in the NIO region (Jaiswal et al., 2016). The TIGGE data has 2 days latency in the archival, thus, forecasts made on any day uses the two days back initial conditions.

2.1.2 Short range TCG prediction based on wind pattern matching technique

The short range TCG prediction using wind pattern matching technique is based on the premise that there is some similarity between the low level wind pattern of the developing systems which can be detected and used to identify the developing and non developing low pressure systems. In this technique the real-time observed winds are matched to the wind patterns archived within the database of all developed systems in the past and the most similar wind pattern was selected. This similarity was quantified using a matching index as given in the following expression.

$$cc = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(A_i - \overline{A}\right)*\left(B_i - \overline{B}\right)}{\sqrt{\frac{1}{N}\sum_{i}^{N}\left(\left|A_i - \overline{A}\right|\right)^2} \times \sqrt{\frac{1}{N}\sum_{i}^{N}\left(\left|B_i - \overline{B}\right|\right)^2}} \qquad (1)$$

where $\overline{A}$ and $\overline{B}$ represents the mean value of the complex vectors *A* and *B* respectively. *N* is the dimension of vector *A* (or *B*) and *A* and *B* are the complex numbers formed using the wind vectors [*for example A = (u+iv)*].

If the matching index value is found to be greater or equal to some pre-defined threshold values (0.6 for NIO), the cyclogenesis is predicted. The scatterometer data of QuikSCAT and OSCAT were used in the development and testing of the algorithm (Jaiswal and Kishtawal, 2011; 2013). During the years 2010-13, OSCAT data was used for the real-time cyclogenesis prediction using the above discussed approach. In the year 2014 the OSCAT stopped working and thereafter the surface wind observations from other foreign satellites (viz., WINDSAT and RAPIDSCAT) have been used in the real-time prediction of TCG in NIO at SAC.

2.2. Cyclone Track Prediction

After the formation of tropical cyclone in the Indian Ocean, track predictions are carried out using in-house developed Lagrangian advection cyclone track prediction model (SAC-LAGAM). A brief summary of the model has been given in the following subsections.

2.2.1 SAC-Lagrangian Advection Model

SAC-Lagrangian Advection model is dynamical framework based computationally efficient model (Singh et al, 2011; 2012). It requires the high resolution $0.5^0 \times 0.5^0$ atmospheric winds and temperature forecasts from Global forecast System (GFS), which is global numerical weather prediction model run by NOAA, and the initial position of cyclone which is obtained from JTWC. The cyclone track prediction is provided using SAC- Lagrangian Advection model upto 96 hour with 6 hour interval. As a first step, the steering flow has been computed for every 6-hour forecast interval up to 96 hours, using the analysis as well as forecast wind fields data at 21 pressure levels (100-1000 mb) by the weighted average scheme. The weight for each level was assigned by estimating the potential vorticity (PV) which is adapted from the study by Hoover et al., 2006. Then a cyclonic vortex is removed using a synthetic cyclone which is constructed by using the vorticity equation (Chan and Williams, 1987):

$$\frac{\partial \zeta}{\partial t} + V.\nabla(\zeta + f) = 0$$

Where ζ is the vorticity and $f = \beta y + f_0$. Here y denotes latitudinal displacement, f_0 is the value of coriolis parameter at y = 0 and β is the rate of change of coriolis parameter with latitude. In case of axisymmetric vortex, the velocity is calculated using the equation (Chan and Williams, 1987):

$$V(r) = V_m\left(\frac{r}{r_m}\right)\exp\left[\frac{1}{b}\left(1-\left(\frac{r}{r_m}\right)^b\right)\right]$$

Where V_m and r_m denote the maximum value of tangential velocity and the radius at which V_m occurs, respectively. This synthetic cyclone was used to remove the existing cyclonic wind fields present in the steering flow to achieve the residual steering current. To avoid the discontinuity of wind fields due to removal of cyclonic circulation, tapered weights *W (k)* are used for generation of residual flow fields. Now, resulting steering flow that is obtained after removing the cyclonic vortex from steering flow is used in model to forecast the cyclone track. The computation for the trajectory of the cyclone (or the cyclone track) is initiated by interpolating the steering wind from model grid points to the initial location of the cyclone (Brand, 1981).

The above discussed techniques and models are used in the real-time for the prediction of cyclone ROANU.

3. Results: Prediction of TC ROANU

Real-time cyclogenesis and track prediction of TC ROANU was carried out at SAC using the above discussed algorithms. The results of real-time prediction and the validation of the forecasts have been discussed in this section.

3.1 Real-time prediction of tropical cyclogenesis of TC ROANU

The development of any cyclonic activity is regularly monitored by the above discussed two cyclogenesis techniques viz., extended range cyclogenesis prediction using multi-model ensemble based technique and short range cyclogenesis prediction using scatterometer observation based wind pattern matching technique.

The result of the extended range cyclogenesis prediction using multi-model ensemble technique generated on 16 May and 17 May, 2016 are shown in Fig. 2a, and 2b, respectively. The three panels in the figure shows the possibility of formation of low pressure systems or cyclones in terms of probability which is computed based on the available number of forecasts and the models (top left panel), the time of its formation in terms of days from the forecast initial day (top right panel) and the intensity in terms of maximum attained wind speed (bottom panel). The forecast generated on 16 May, indicates a low possibility (30%) of formation of tropical cyclone in the next 3 days, in the BoB that is developing near Sri Lanka and moving along the east coast of India. The forecast generated on 17 May indicated the medium possibility (50%) of formation of tropical cyclone in the same area.

The earliest prediction of cyclogenesis of cyclone ROANU was given on 16th May by MME based cyclogenesis prediction technique. However, the system was designated as tropical cyclone on 19th May, 2016 by IMD. Thus the multi-model based cyclogenesis technique predicted the development of tropical cyclone 3 days before its formation.

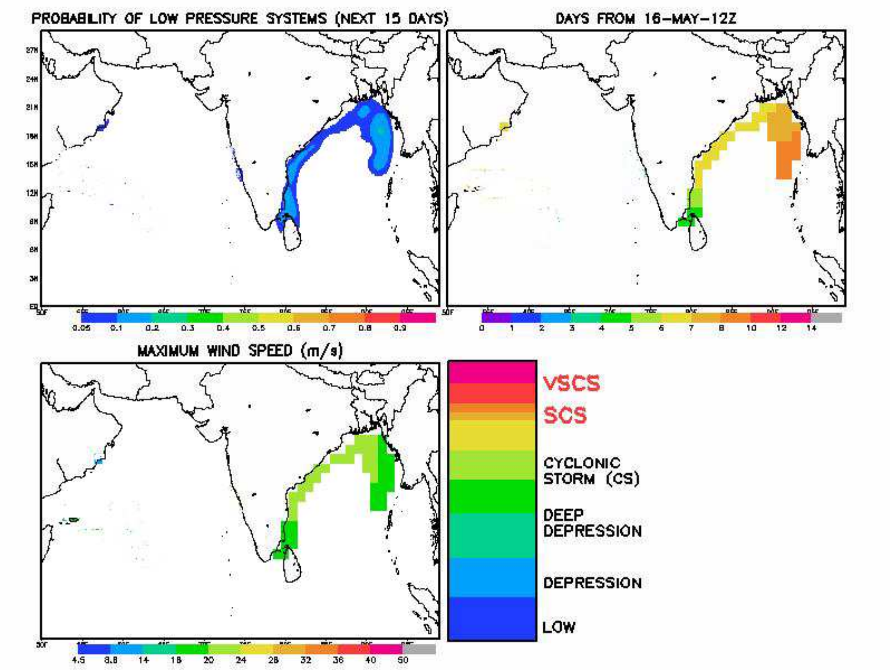

Figure 2a: Real-time forecast generated on 12Z 16 May showing the development of cyclone in Bay of Bengal (on 19th May), which is making landfall at Bangladesh (in the next 7 days).

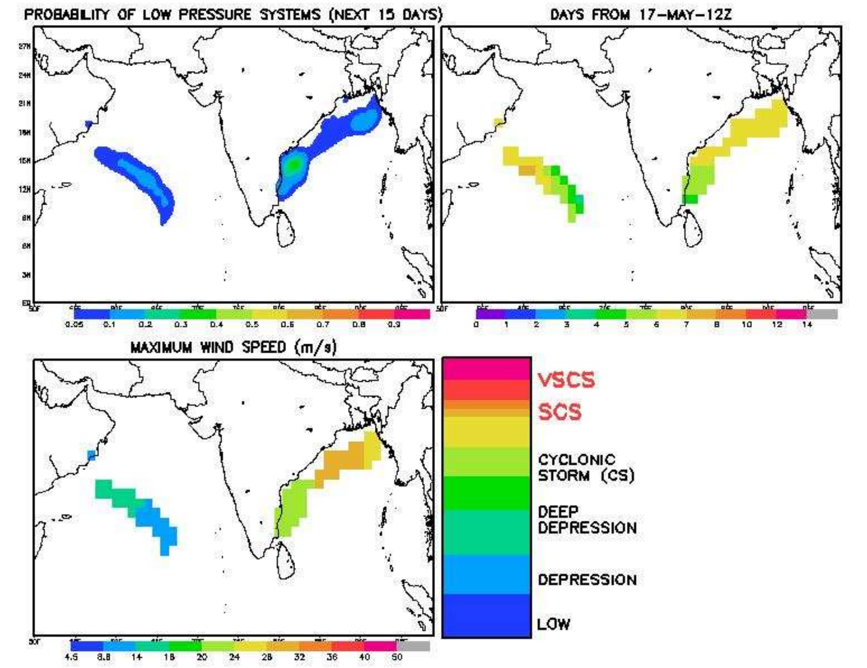

Figure 2b: Real-time forecast generated on 12Z 17 May showing the development of cyclone in Bay of Bengal, which is making landfall at Bangladesh (in the next 6 days).

The wind pattern matching based technique indicated a strong signal of cyclogenesis using the RAPIDSCAT data, on 04 Z 14 May, 2016. The wind matching index value was found as 0.7 which was higher than the threshold value 0.6. The surface winds obtained by RAPIDSCAT are shown in the Fig. 3, where the cyclogenesis region has been marked with the box. Cyclone ROANU was declared as tropical cyclone on 19 May, 2016. Thus, the wind pattern matching based technique predicted the cyclogenesis of TC approximately 5 days before the official declaration of the system as a cyclonic storm by IMD. The passes over the system during its genesis stage i.e.14-18 May have been shown in the Fig. 3.

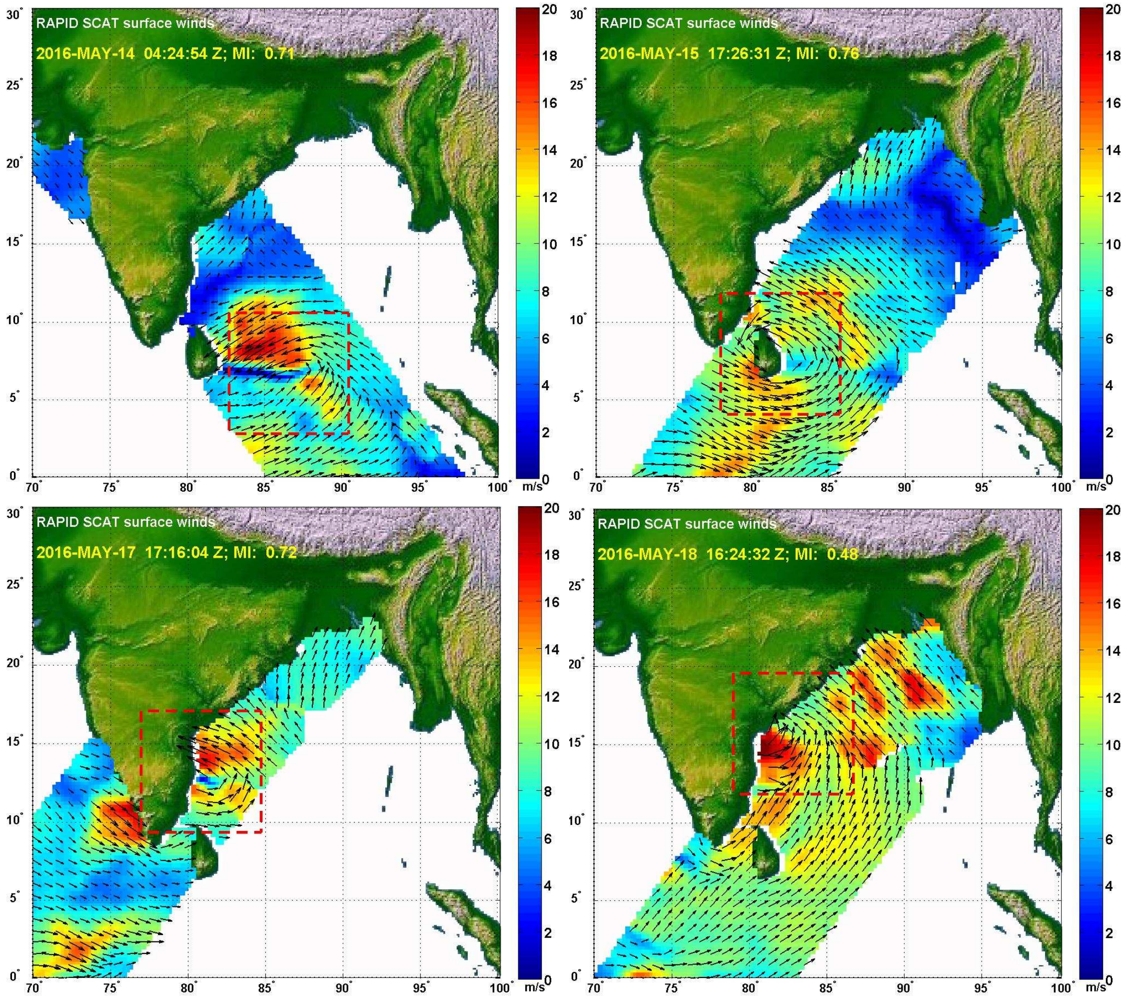

Figure 3: RSCAT winds during the cyclogenesis of TC ROANU. The earliest cyclogenesis signature was detected on 14th May 2016.

3.1 Real-time track prediction of TC ROANU

After the formation of TC ROANU (designated as tropical storm by JTWC or IMD) its track was predicted using the SAC-Lagrangian Advection model. The forecasts were generated on 06Z 18 May, 00Z of 19-21 May, 2016. All the real-time predicted tracks along with the observed track of JTWC have been shown in the Fig. 4. Each point in the figure is representing the six hour movement of the cyclone. The forecasts generated on different initial conditions have been shown in different colors.

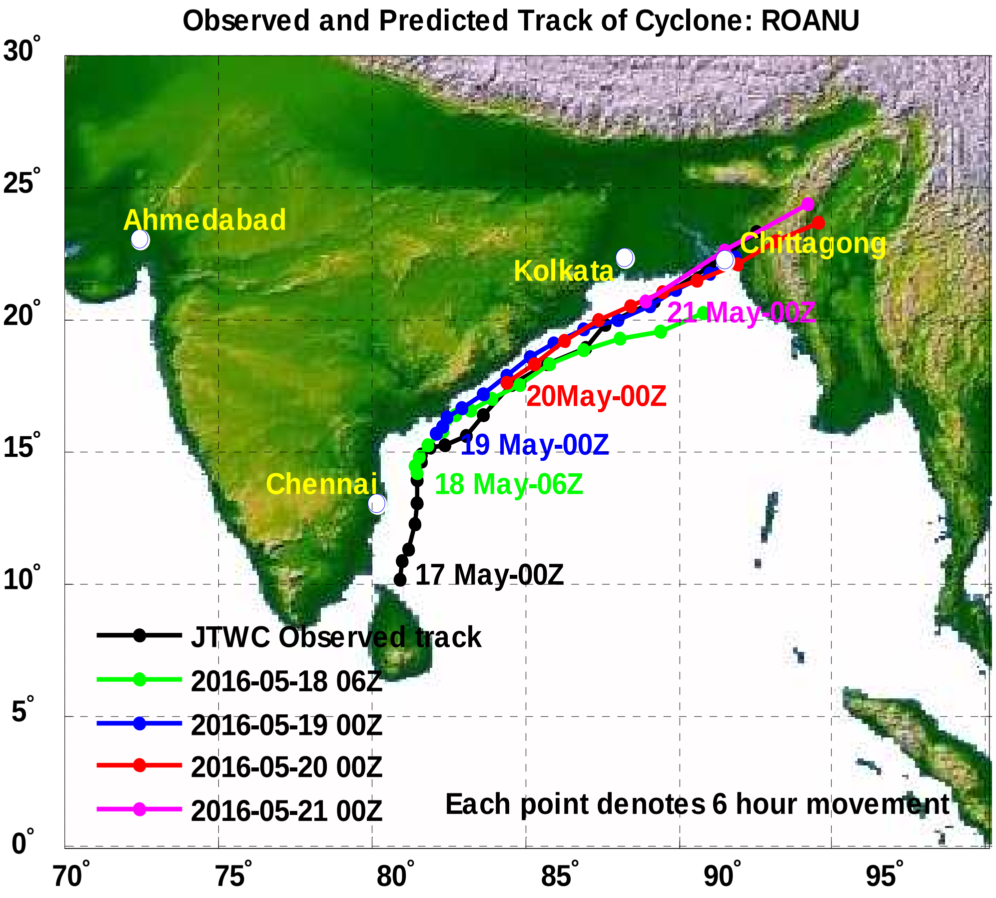

Figure 4: Real-time predicted track of TC ROANU at different initial conditions.

It can be seen from the figure that all the predicted tracks were close to the observed track of JTWC and showing the consistent landfall location.

The direct position error (DPE), cross track (CT) and along track (AT) component of track forecast error were calculated with respect to JTWC observed track position values for all the forecasts generated on different initial conditions and have been given in the

Table 2, 3, and 4, respectively. The schematic showing the computation of the track errors is shown in the Fig. 5.

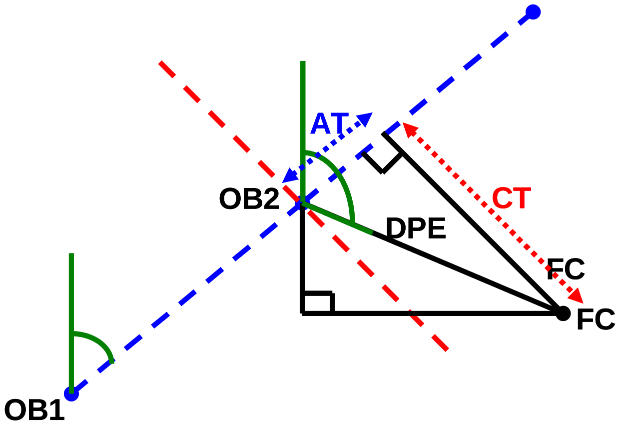

Figure 5: Schematic showing the positional forecast errors (Heming, 1994).

Average track forecast error (DPE) for TC ROANU was found as 107 at 24 hrs, 131 at 48 hrs and 189 at 72 hrs. Average along track forecast error (AT) for was found as 85 at 24 hrs, 113 at 48 hrs and 58 at 72 hrs. Average cross track forecast error (CT) was found as 49 at 24 hrs, 85 at 48 hrs and 180 at 72 hrs. It can be seen that in 24 and 48 hour average cross track error was less than the average along track error but in 72 hours forecast along track error was much less than the cross track error value. The landfall point error have also been computed and given in the Table 5. Within 24 hr landfall forecast error generated on 00Z 21 May was found as 14 km with 3 hrs delay.

Table 2: Direct position track error (km) of SAC-Lagrangian advection track prediction model for TC ROANU

FCST Initial time → Lead time↓	18May 06 Z	19 May 00Z	20 May 00Z	21 May 00Z	Average track error (km)
12	93.66	117.06	113.42	83.23	101.84
24	122.18	84.61	116.57		107.79
36	170.95	67.37	68.13		102.15
48	181.59	79.37			130.48
60	138.78	266.05			202.42
72	189.37				189.37

Table 3: Along track error (km) of SAC-Lagrangian advection track prediction model for TC ROANU

FCST Initial time → Lead time↓	18May 06 Z	19 May 00Z	20 May 00Z	21 May 00Z	Average along track error (km)
12	86.18	78.59	24.98	83.23	68.25 (4)
24	121.16	31.23	103.68		85.36 (3)
36	154.51	53.92	68.13		92.19 (3)
48	147.03	78.05			112.54 (2)
60	131.25	266.05			198.65 (2)
72	58.06				58.06 (1)

Table 4: Cross track error (km) of SAC-Lagrangian advection track prediction model for TC ROANU

FCST Initial time → Lead time↓	18May 06 Z	19 May 00Z	20 May 00Z	21 May 00Z	Average cross track error (km)
12	36.69	86.75	110.63	0.0	58.52 (4)
24	15.73	78.63	53.28		49.21 (3)
36	73.16	40.40	0.00		37.85 (3_
48	106.57	62.87			84.72 (2)
60	45.09	9.01			27.05 (2)
72	180.25				180.25 (1)

Table 5: Land-fall point error (km) of SAC-Lagrangian advection track prediction model for TC ROANU

Forecast based on	Forecast Lead Time (hr)	Landfall point Error (km)	Landfall Time Error
19 May 00Z	57	34.36	12 hrs delay
20 May 00Z	33	58.28	6 hrs delay
21 May 00Z	9	13.58	3 hrs delay

4. Weakening of TC ROANU

Tropical cyclone ROANU was the first cyclone formed in the North Indian Ocean in the year 2016 near Sri Lanka coast and moved north eastward just off the east coast of India during 18-21 May. The storm moved over warm water (SST 30-31^0 C) but moderate amount of deep layer wind shear that prevented it from intensification.

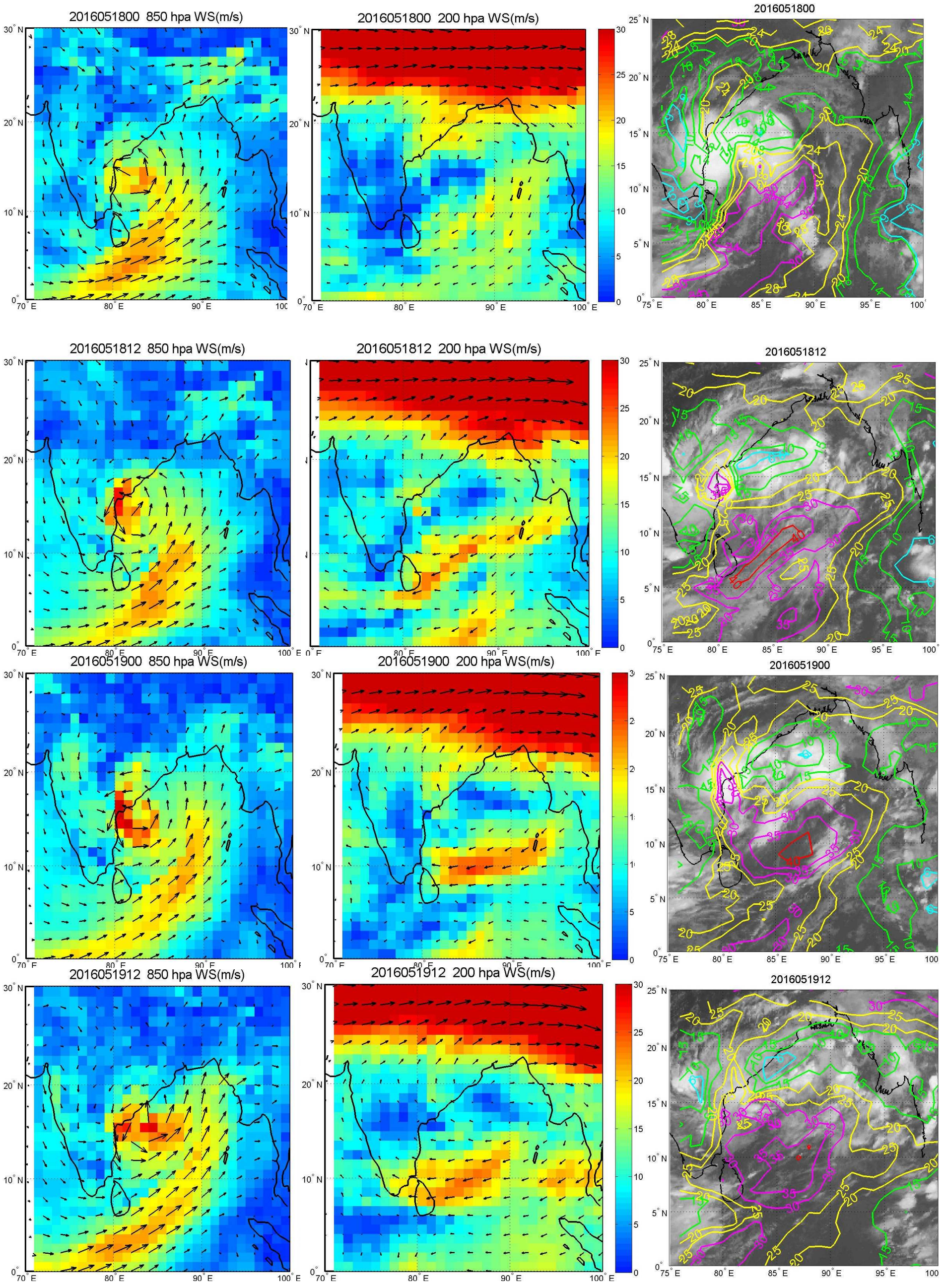
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Figure 6: Wind vectors overlaid over wind speed at 850 hpa (left), 200 hpa (middle) and wind shear contour overlaid on INDAT-3D TIR1 images (right) during life period of cyclone.

The wind flow patterns at 850 hpa and 200 hpa during the active cyclone time have been shown in the Fig. 6. The wind shear values were computed using the wind vectors at these two levels. The contours of wind shear overlaid on the TIR-1 image of INSAT-3D satellite have also been shown in the figure. It can be seen that the high shear was existing ahead of cyclone which did now allow the system for rapid intensification inspite of having favorable sea surface temperature values.

5. Satellite Observations over TC ROANU

Different sensors onboard on the geostationary and polar orbiting satellites provide observations at different times and different phases of intensification of TCs which are very useful to estimate the correct geolocation of the system and retrieve its structural parameters. Different satellite observations over TC ROANU have been discussed in this section.

5.5.1 KALPANA

TC ROANU was continuously observed by KALPANA satellite during its life time. In half hourly TIR imageries of KALPANA satellite the center location of cyclone was estimated by center determination algorithm developed at SAC (Jaiswal et al, 2010). The results were disseminated through SCORPIO web-server. One of the sample products generated in the real-time has been shown in the Fig. 7.

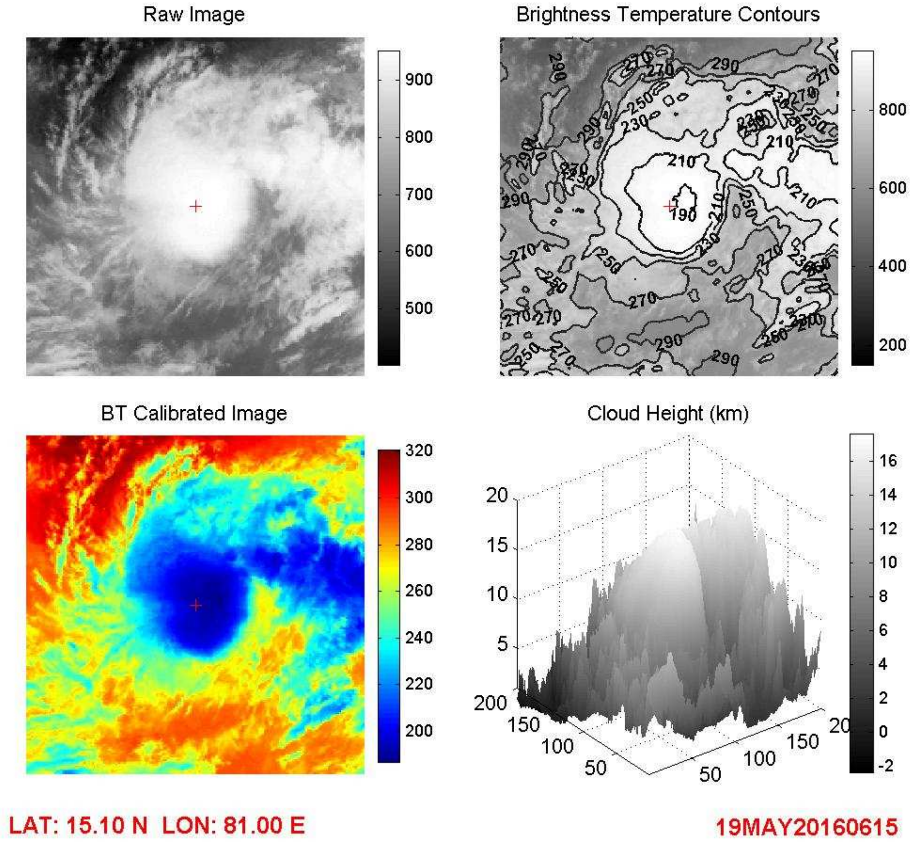
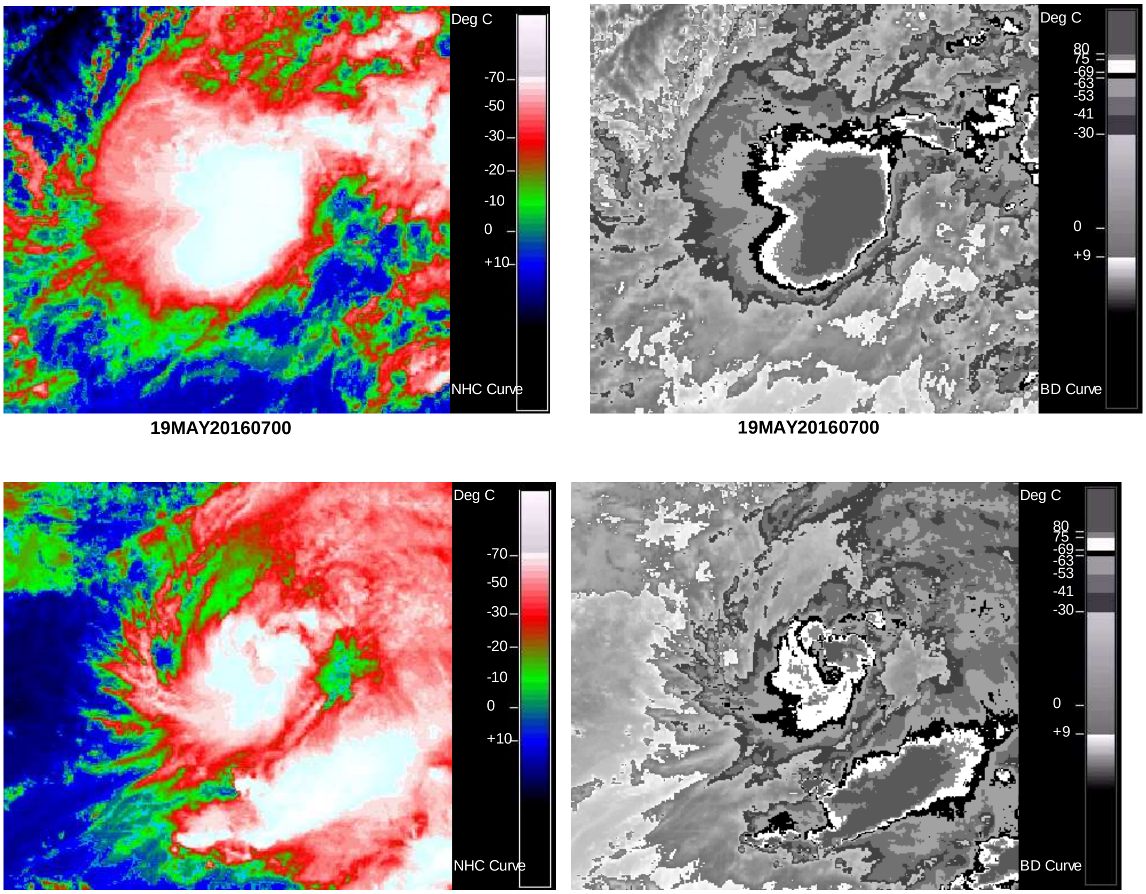


Figure 7: Center of TC estimated using KALPANA TIR image (0615Z 19 May, 2016).

5.5.2 INSAT 3D

TC ROANU was continuously observed by the half hourly acquisition of INSAT-3D satellite. The TIR-1 imageries of TC ROANU have been given in the Fig. 8 during different time span of its life. These images are very useful for the continuous monitoring of TCs and determining its structural parameters viz., center, Rmax etc. During the daytime the high resolution visible images are provided which are very useful for determining cyclone geo-location and its structural parameters. The NHC color enhanced and BD curve enhanced images are derived from TIR-1 imageries for better structural analysis of cyclone. Such sample images derived from INSAT 3D satellite for TC ROANU have been presented in the Fig. 8. The inner core cloud bands within the core of TC ROANU can be very clearly observed in these images. To limit the size of report only two images during different intensity stages of TC have been presented.



19MAY20160700 19MAY20160700

21MAY20160730 21MAY20160730

Figure 8: NHC color enhanced and BD curve enhanced TIR-1 images of cyclone ROANU by INSAT-3D satellite [0700Z 19 May, 2016(top), 0730Z, 21 May, 2016 (bottom)].

The Advanced Dvorak technique (ADT) requires half hourly acquisition of TIR data of INSAT-3D over the cyclones for its intensity estimation. The combination of the TIR-1 and visible images are used for fixing the geo-location of the cyclone.

5.5.3 SAPHIR

SAPHIR onboard Megha-Tropiques satellite is a sounding instrument with six channels near the absorption band of water vapor at 183.31 GHz. The channels provide continuous observations of 10 km resolution (at nadir) at 6 different atmospheric layers at least 2-3 times in a day. These high resolution data was found very useful to observe the internal changes in the cyclone structure during the intensification process of TCs.

During the active life period of cyclone ROANU (17-23 May, 2016), the observations were taken by the SAPHIR. The BT values observed by the 6 channels of SAPHIR on 14Z, 18 May have been shown in the Fig. 9. Such images are very useful to determine the lower level structure of cyclone and its geo-location.

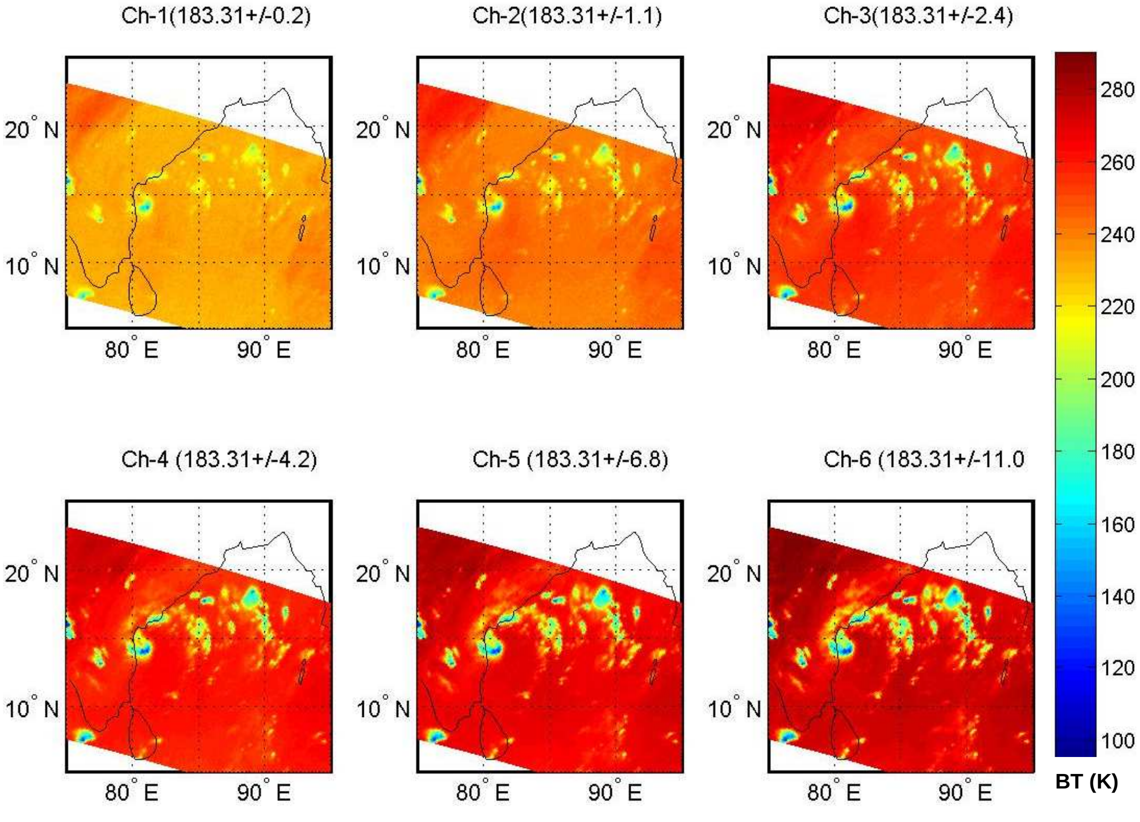
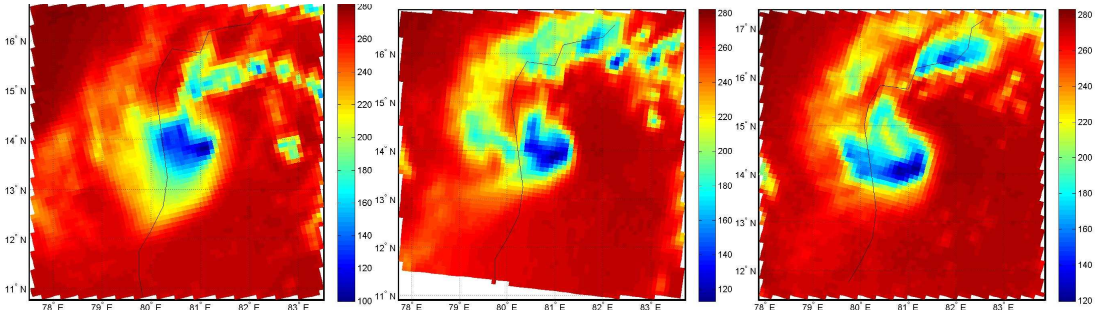
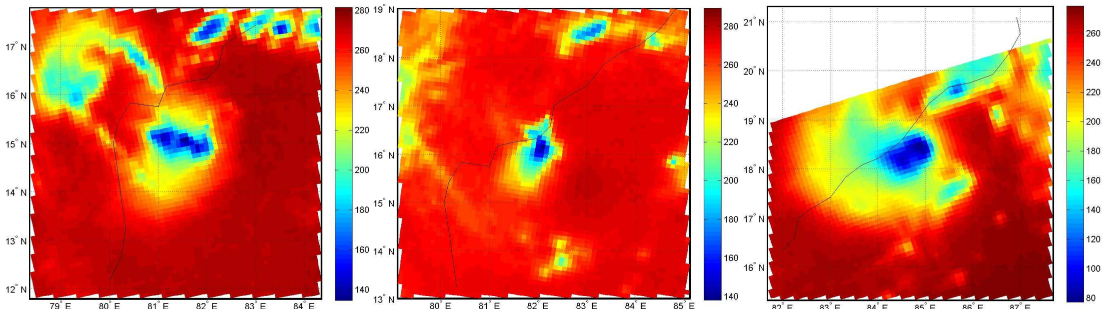


Figure 9: BT values observed by 6 channels of SAPHIR SAPHIR on 14Z, 18 MAY, 2016

The channel six provide the near surface information and hence more sensitive to cyclone lower structure. The channel-6 observations during different phases of cyclone have been shown in the Fig. 10.



0840Z 18 May, 2016 1220Z 18 May, 2016 1410Z 18 May, 2016



0830Z 19 May, 2016 1208Z 19 May, 2016 0630Z 20 May, 2016

Figure 10: BT values observed by SAPHIR channel-6 (near surface) over the cyclone ROANU

The variation of BT values over the horizontal cross section of the cyclone ROANU during different intensity phases have been plotted in the Fig. 11. Figure shows the variation of BT values observed by channel 6 of SAPHIR w.r.t. horizontal distance from the center of the cyclone. These plots reveal the sensitivity of channel 6 observations with respect to the intensity of the cyclone. It can be seen that on 17 May cyclone was weak (intensity 30 knots) and had the BT values approx. 230 K at the center. As cyclone strengthens the colder BT values were observed at the center. On 20th May, cyclone was on its peak intensity and had the coldest BT at the center approx. 90 K.

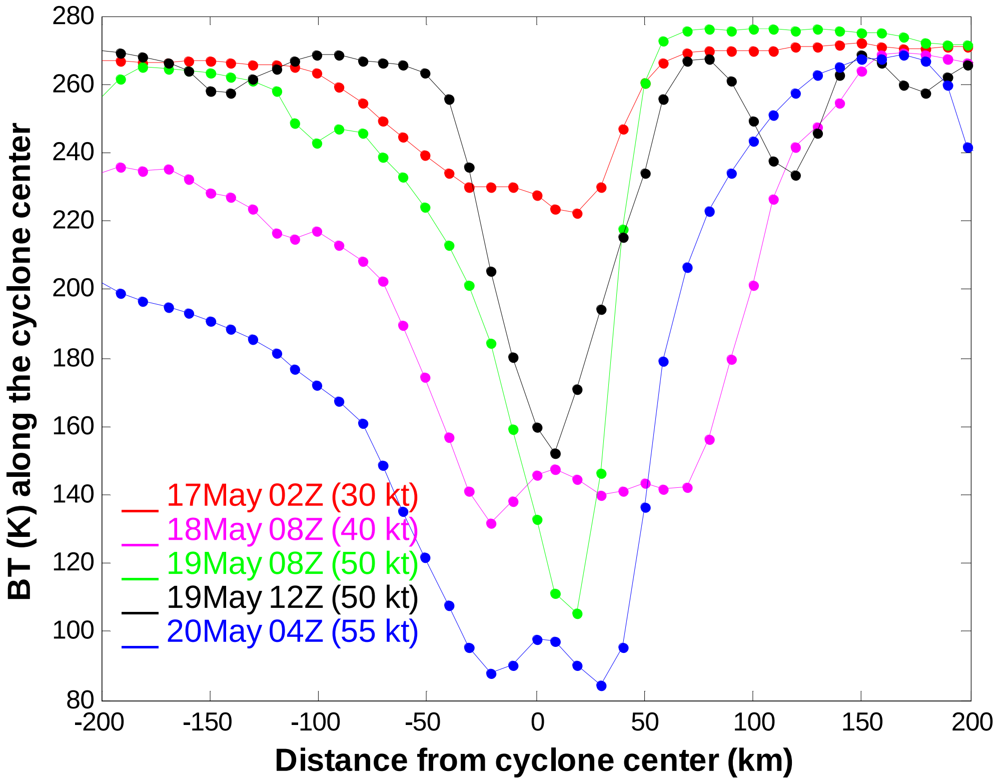


Figure 11: Channel-6 BT variation along the cyclone center.

6. Rainfall observed by INSAT-3D over TC ROANU

As a part of IMDPS, the daily, weekly, monthly and seasonal rainfall from IMSRA algorithm is produced using the half hourly INSAT-3D thermal IR data (48 images per day) (Gairola et al. 2010, 2015). These images provide qualitatively a very good idea about the intensification of the cyclone. However, it is of more importance to know the quantitative distribution of rainfall associated with the rain bands as the possible source for latent heat released due to precipitation. An example of the two successive days of IMSRA rainfall distribution over land and oceanic regions is shown in Fig. 12.

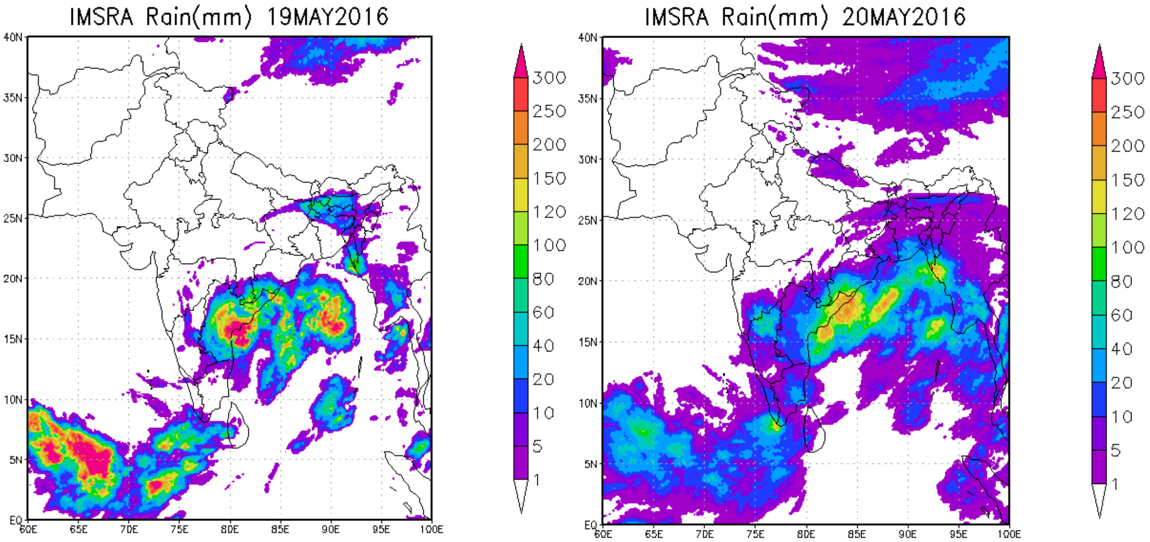


Figure 12: IMSRA rainfall distribution over land and oceanic regions (19 May, 2016)

Cyclonic Storm ROANU was relatively a weak tropical cyclone that caused severe flooding in its origin area of Sri Lanka and landfall area of Bangladesh during May 2016. The cyclone was formed from a low pressure area that developed south of Sri Lanka on 14th May, intensified into a cyclonic storm on 19th May and finally made landfall in Bangladesh on May 21st affecting Bangladesh, Myanmar, East coast of India and Sri Lanka. It has been clear from the successive figures how the cyclone Roanu also brought torrential rainfall to the Indian states of Tamil Nadu, Andhra Pradesh and Odisha as it drifted close to the coast. The observed rainfall along the track of cyclone with the intensity classification categories of cyclone has been in quite conformity.

The intensity of the cyclone is finally assessed based on rainfall distribution starting from meteorological sub-divisional scale to the district level using satellites-derived IMSRA product. Rainfall at meteorological sub-divisions from satellite-derive products is computed using the Geographic Information System (GIS) spatial analysis tools. Recently, IMSRA based rainfall maps were generated operationally using INSAT-3D and Kalpana-1 IMSRA data at different meteorological sub-divisions and suggested this technique can act as a complementary tool for the monsoon monitoring Mahesh et al. (2014).

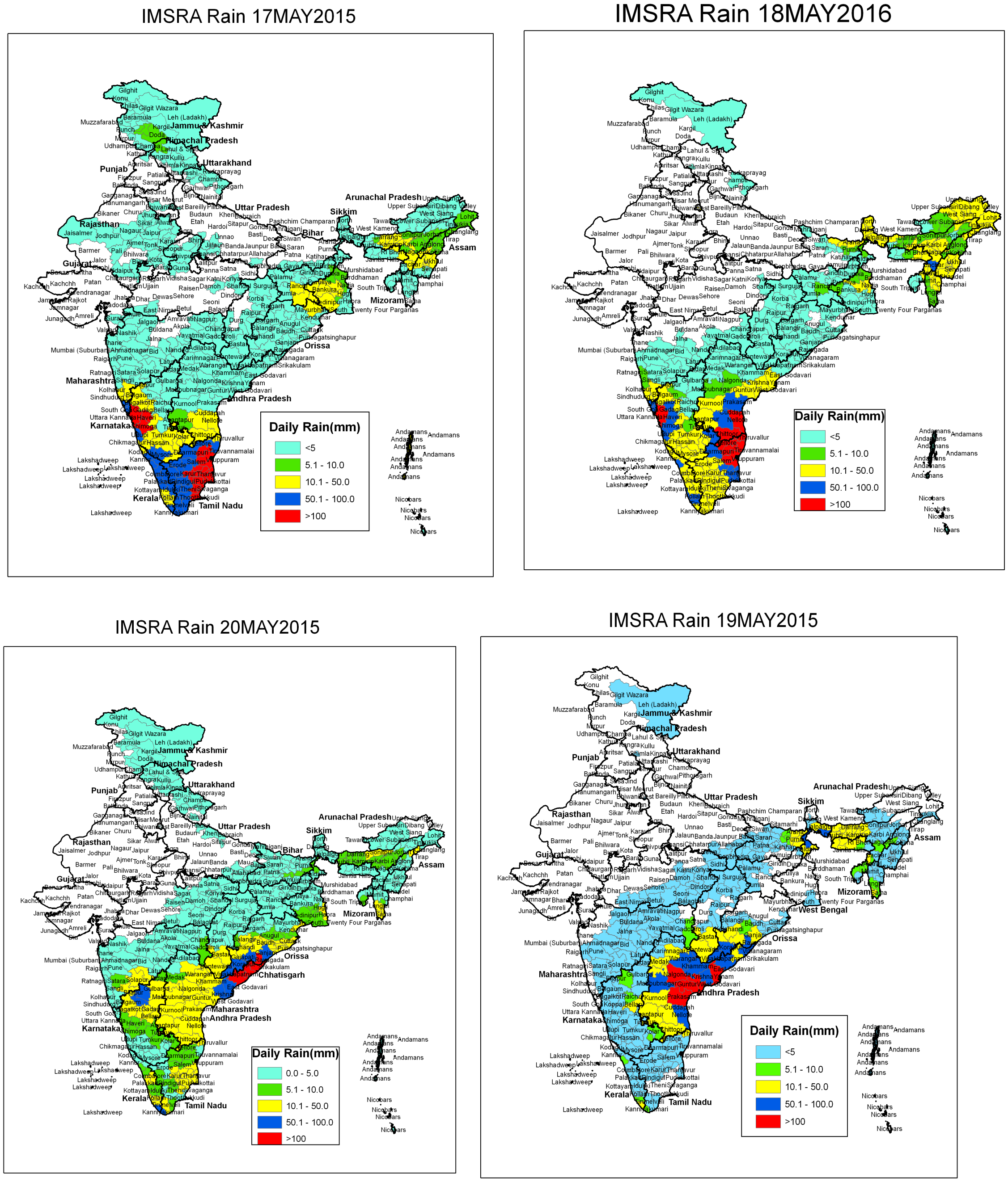


Figure 13: District wise IMSRA rainfall distribution over Indian regions

The day after an alert was sounded off regarding cyclonic storm Roanu, coastal Andhra Pradesh and Odisha and several parts of West Bengal received very to heavy rainfall and witnessed strong winds. Srikakulam district in Andhra Pradesh received 155.2mm rainfall, the highest in the country, while Kalingapatnam district received 144.6mm rain. Burdwan in West Bengal saw 94.2mm rainfall while Gopalpur Odisha received 79mm rain

Simultaneously on operational basis the daily accumulated rainfall is calculated from 48 images of INSAT-3D per day. Daily estimated rainfall using IMSRA from 14 to 20th May 2016 is represented in Fig.10 as examples showing the district wise rainfall distribution is with the evolution of cyclone from 14 to 20th May, 2016.

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