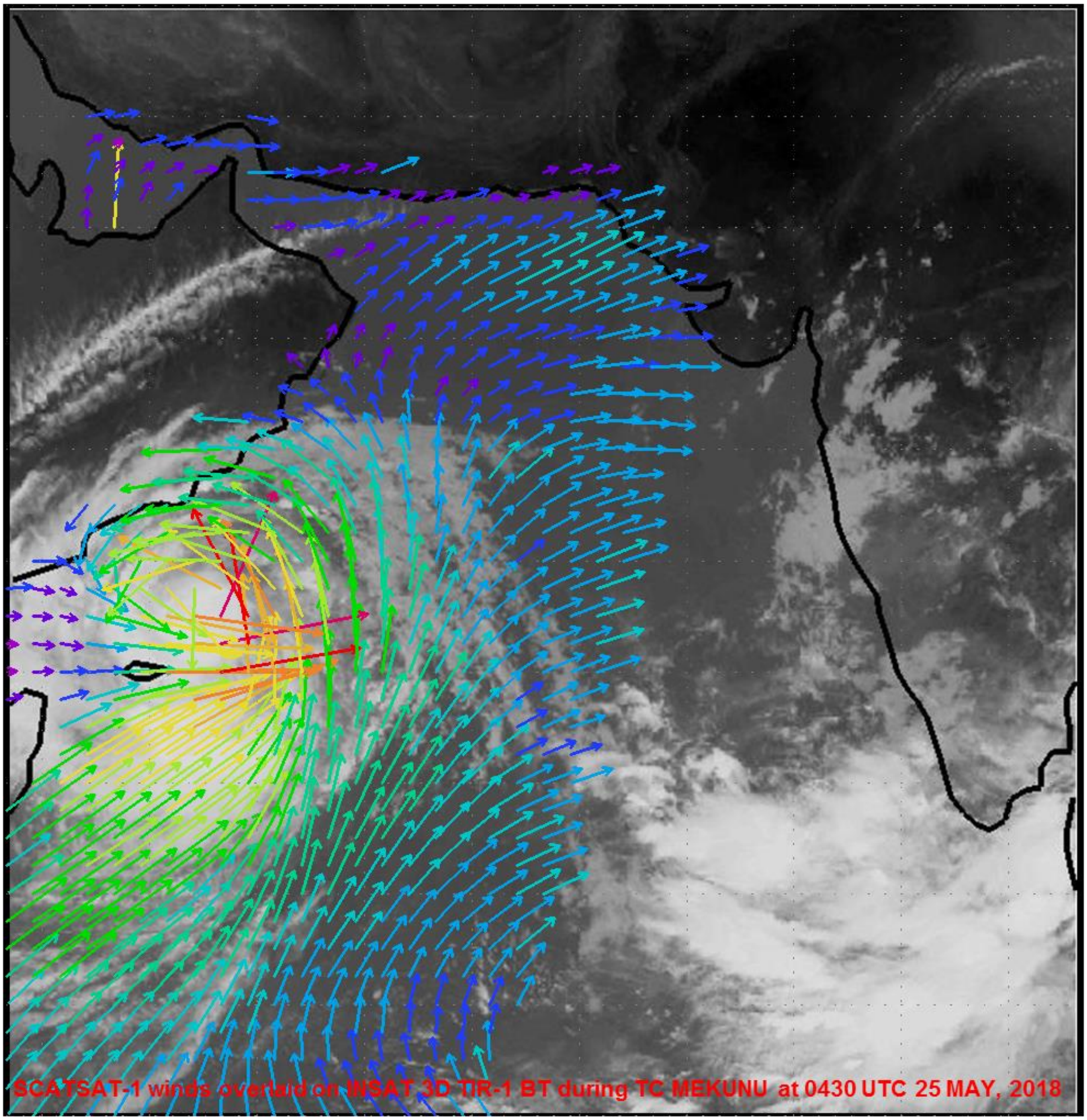
Real-time monitoring and prediction of tropical cyclone MEKUNU

SAC/EPSA/AOSG/ASD/SR- 35/2018


SCATSAT-1 winds overlaid on INSAT 3D TIR-1 BT during TC MEKUNU at 0430 UTC 25 MAY, 2018

October, 2018

Atmospheric and Oceanic Sciences Group
Space Applications Centre (ISRO)
Ahmedabad-380015

Document Control and DATA Sheet

Report No.	SAC/EPSA/AOSG/SR/ 05/2018
Date	October, 2018
Title	Real-time monitoring and prediction of tropical cyclone MEKUNU
Type of Report	Scientific Report
No. of Pages	24
Authors	Neeru Jaiswal, C. M. Kishtawal, and R. M. Gairola
Number of Figures	10
Number of Tables	4
Number of References	16
Originating Unit	ASD/AOSG/EPSA/SAC
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 low pressure system is formed, it is continuously monitored by satellite observations. Possibility of its cyclogenesis, and after its development into tropical cyclone its track is predicted and updated. These forecasts are disseminated through web-portal SCORPIO linked to MOSDAC. The real-time prediction of cyclone MEKUNU 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, cyclogenesis prediction, track prediction, center determination, satellite observations
Security classification	Unrestricted

Acknowledgements

The authors are thankful to the Director, Space Applications Centre (ISRO), Ahmedabad and the Deputy Director of EPSA, SAC-ISRO. The authors acknowledge the Joint Typhoon Warning Centre (JTWC) and Regional Specialized Meteorological Centre (RSMC) for tropical cyclones over North Indian Ocean, India Meteorological Department (IMD), Delhi for providing real time cyclone track through their websites. IMD Delhi is also acknowledged from providing best track of tropical cyclone MEKUNU. The satellite observations of SCATSAT, INSAT-3D, INASAT-3DR and SAPHIR were obtained from MOSDAC (www.mosdac.gov.in).

Table of contents

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). 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 “MEKUNU” in NIO during 21-26 May, 2018, which has been discussed in the present report.

1.1 Overview of Tropical cyclone MEKUNU (21 -26 May, 2018)

The cyclone name “MEKUNU”, which meant “mullet” in Dhivehli, the language of Maldivians was provided by Maldives, in the comprehensive nomenclature list for cyclones in the Arabian Sea and Bay of Bengal. Extremely Severe Cyclonic Storm (ESCS) Mekunu originated from a low pressure area which formed over southeast

Arabian Sea (AS) in the morning (0300 UTC) of 20th May. It became a well marked low pressure area over southwest & adjoining southeast AS in the early morning (0000 UTC) of 21st May. Under favourable environmental conditions, it concentrated into a Depression (D) over southwest AS in the evening (1200 UTC) of 21st May. Moving westnorthwestwards it intensified into a deep depression (DD) in the morning (0300 UTC) of 22 nd May. It then moved north-northwestwards and intensified into a cyclonic storm (CS) “Mekunu” in the evening (1200 UTC) of same day over southwest AS. It further continued to move north-northwestwards, intensified into a Severe Cyclonic Storm (SCS) in the morning (0300 UTC) and into a Very Severe Cyclonic Storm (VSCS) in the afternoon (0900 UTC) of 23rd May over Westcentral AS. Moving further north-northwestwards, it intensified into an Extremely Severe Cyclonic Storm (ESCS) in the morning (0300 UTC) of 25th and crossed south Oman coast near 16.85^0 N/53.75^0 E around midnight (between 1830-1930 UTC) of 25th May as an ESCS with an estimated wind speed of 170-180 kmph gusting to 200 kmph. It moved north-northwestwards and weakened into a VSCS over Oman in the early hours of 26th May (2100 UTC of 25th May). Continuing to move northnorthwestwards, it weakened into an SCS in the early morning (0000 UTC), into a CS in the afternoon (0900 UTC) and into a DD around midnight (1800 UTC) of 26 th May. It further weakened into a D in the early morning (0000 UTC) and into a well marked low pressure area over Saudi Arabia and adjoining Oman & Yemen in the morning (0300 UTC) of 27th May (IMD report, 2018).

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

The IMD classification of cyclone categories has been given in the Table 1. IMD best track of cyclone with its intensity category have been shown in the Figure 1.

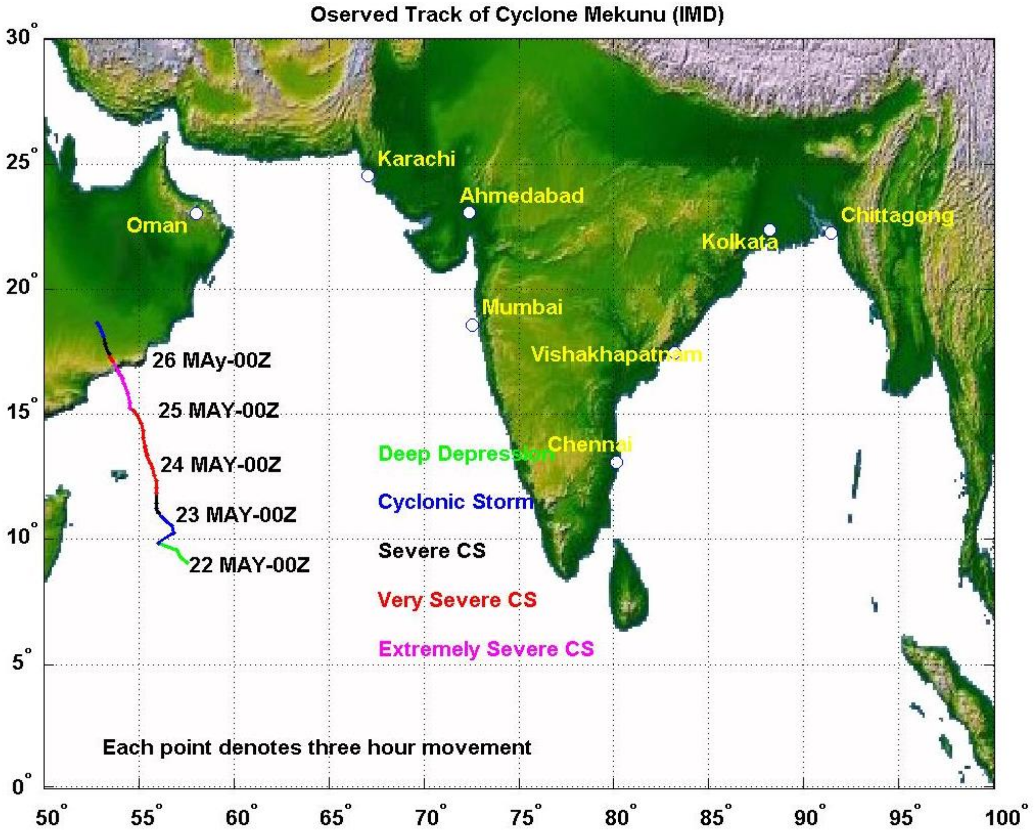


Figure 1: IMD best track of cyclone MEKUNU with its intensity categories.

Developments of the cyclone MEKUNU were continuously monitored by the visible and infrared observations from geo-stationary satellites viz., INSAT-3D and high resolution microwave satellite viz., SAPHIR onboard Megha-Tropiques. SCATSAT 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.

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 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) were being used in the real-time prediction of TCG in NIO at SAC. SCATSAT1 (Scatterometer Satellite1) satellite was launched on 26th September, 2016 to provide weather forecasting, cyclone prediction, and tracking services to India. It is being developed by ISRO Satellite Centre, Bangalore whereas its payload is being developed by Space Applications Centre, Ahmedabad. The satellite will has taken place of Oceansat2 which has become dysfunctional after its life span of four and a half years.

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 0.5^0x0.5^0 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 MEKUNU.

3. Results: Prediction of TC MEKUNU

Real-time cyclogenesis and track prediction of TC MEKUNU 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 MEKUNU

The development of any cyclonic activity is regularly monitored by the satellite observations and in-house developed algorithms.

3.1.1 Tropical cyclogenesis prediction using SCATSAT winds

The wind pattern matching based technique indicated a strong signal of cyclogenesis using the SCATSAT data, on 1600 Z 21 May, 2018. The wind matching index value was found as 0.76 which was higher than the threshold value 0.6. The surface winds obtained by SCATSAT are shown in the Fig. 3, where the cyclogenesis region has been marked with the box. Cyclone MEKUNU was declared as tropical cyclone on 12 UTC 22 May, 2018. Thus, the wind pattern matching based technique predicted the cyclogenesis of TC approximately 1 days (~20 hours) before the official declaration of the system as a cyclonic storm by IMD. The passes over the system during its genesis stage i.e. 19-21 May, 2018 have been shown in the Fig. 3.

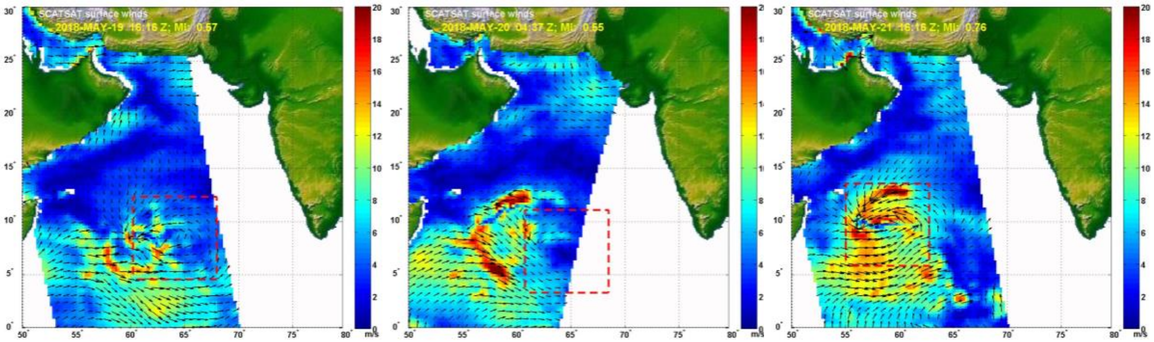


Figure 2: SCATSAT winds during the cyclogenesis of TC MEKUNU. The earliest cyclogenesis signature was detected on 1600 UTC 21st May 2018.

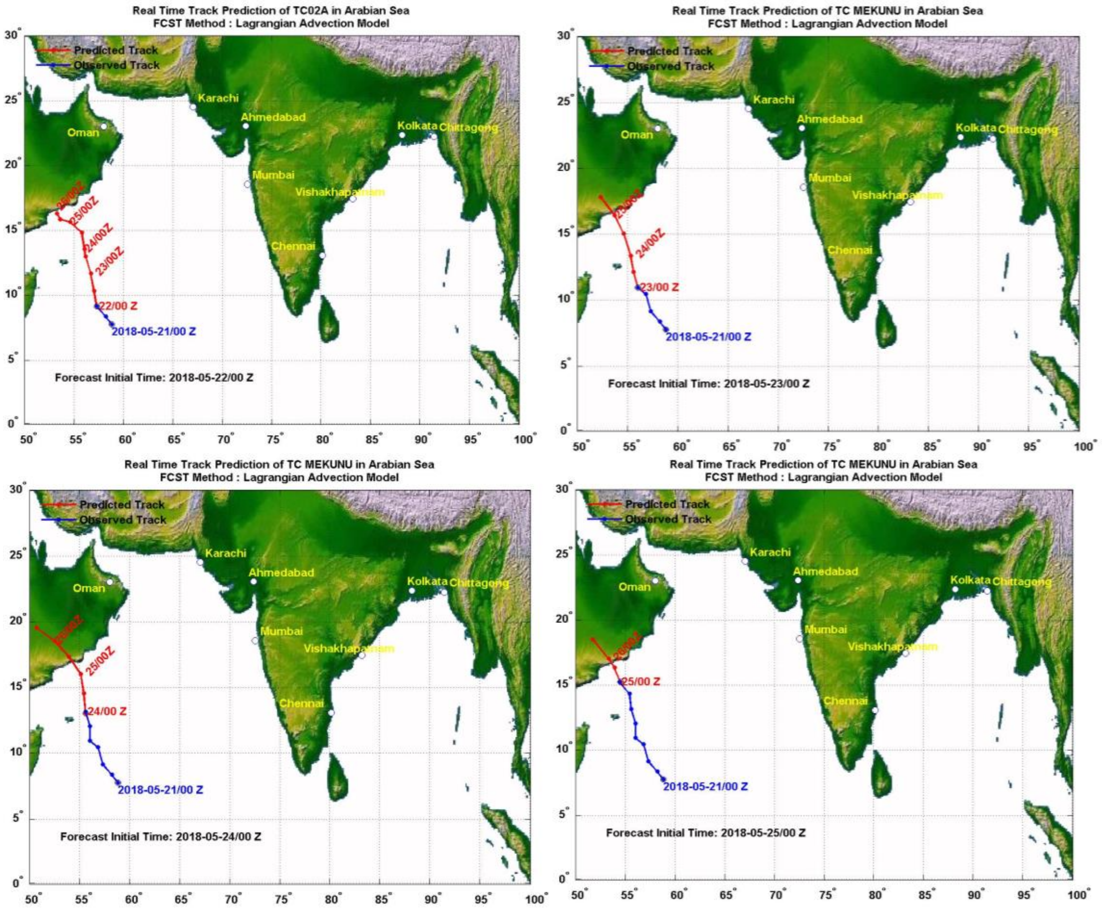
3.2 Real-time track prediction of TC MEKUNU

After the formation of TC MEKUNU (designated as tropical storm by JTWC or IMD) its track was predicted using the SAC-Lagrangian Advection model.

3.2.1 Track prediction using SAC-Lagrangian model

The cyclone track forecasts using SAC-Lagrangian model were generated on 00Z of 22-25 May, 2018. All the real-time predicted tracks along with the observed best track of IMD have been shown in the Fig. 3. Each point in the figure is representing the six hours' movement of the cyclone. The forecasts generated on different initial conditions have been shown in different colors.

Each point in the figure is representing the six hours' movement of the cyclone.


Real Time Track Prediction of TC02A in Arabian Sea
FCST Method : Lagrangian Advection Model

Real Time Track Prediction of TC MEKUNU in Arabian Sea
FCST Method : Lagrangian Advection Model

Real Time Track Prediction of TC MEKUNU in Arabian Sea
FCST Method : Lagrangian Advection Model

Real Time Track Prediction of TC MEKUNU in Arabian Sea
FCST Method : Lagrangian Advection Model

Figure 3a: Real-time predicted track of TC MEKUNU at 00Z on 22-25 May, 2018.

It can be seen from the figure that all the tracks generated on different initial conditions are showing the system making landfall over the Oman coast. All these forecasted tracks have been plotted together with IMD best track and the error of track forecast has been estimated.

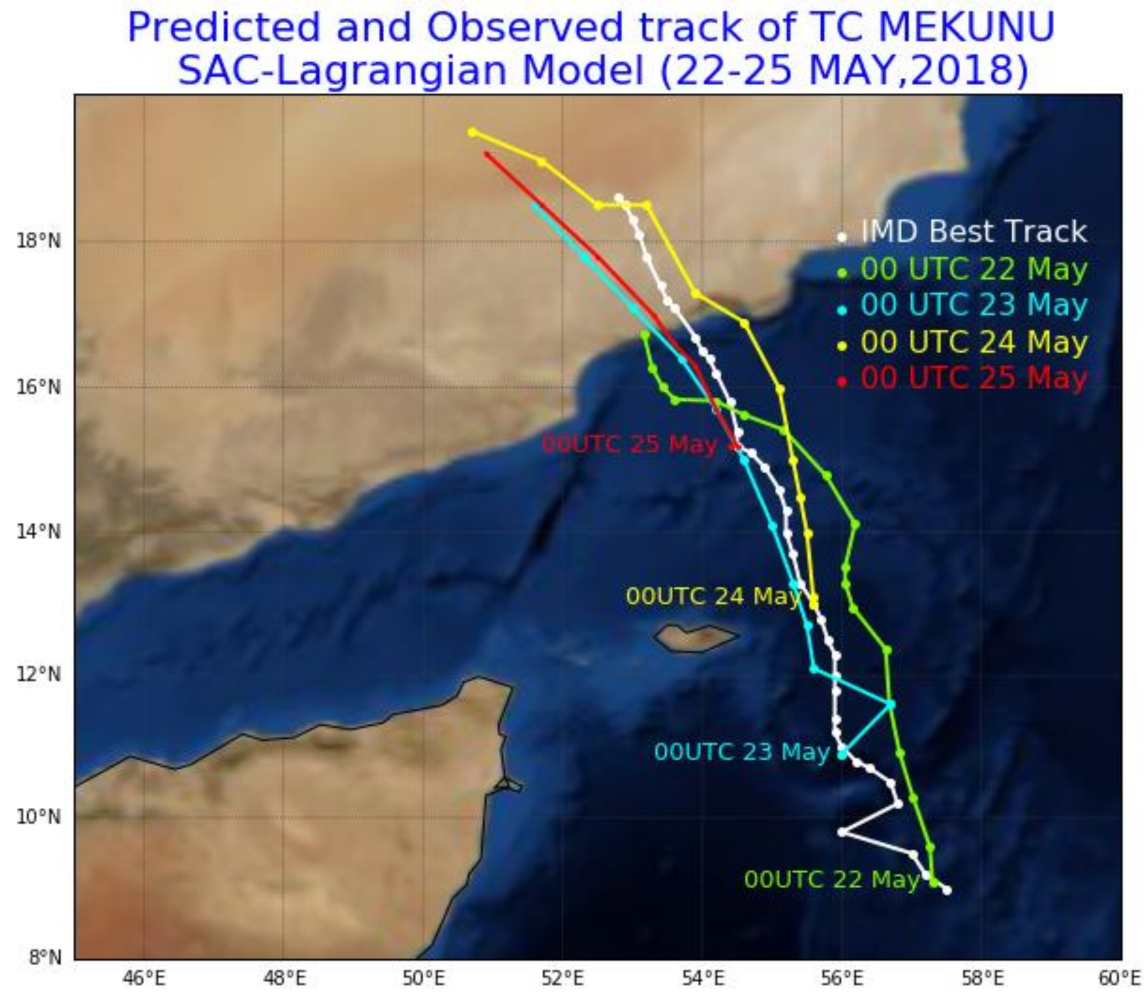


Figure 3b: Comparison of real-time predicted track of TC TC MEKUNU at 00Z on 22-25 May, 2018 and the IMD best track.

The direct position error (DPE), cross track (CT) and along track (AT) component of track forecast error were calculated with respect to IMD best 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. 6.

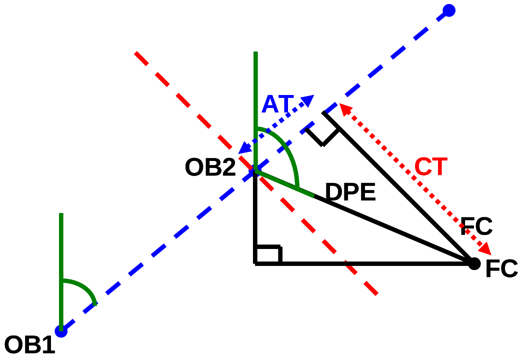


Figure 4: Schematic showing the positional forecast errors (Heming, 1994).

Average track forecast error (DPE) for TC MEKUNU was found as 82 km at 24 hrs. Average along track forecast error (AT) for was found as 25 km at 24 hrs and Average cross track forecast error (CT) was found as 72 km at 24 hrs. It can be seen that in 24 average along track error was less than the average cross track error but in 48 hours forecast along track error was higher than the cross track error value.

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

FCST Initial time → Lead time↓	22 May 00Z	23 May 00Z	24 May 00Z	25 May 00Z	Average track error(km)
6	30.64	90.06	39.78	70.15	57.66
12	26.10	34.50	30.99	80.81	43.10
18	52.51	39.47	44.44	54.84	47.81
24	101.35	46.61	109.86	70.10	81.98
30	134.10	55.08	124.30	116.01	107.37
36	109.46	101.23	102.43	148.42	115.38
42	92.03	116.53	213.69	200.82	155.77
48	76.54	158.70	179.35		138.20
54	106.93	208.04	214.54		176.50
60	82.14	246.90			164.52
66	64.75	315.75			190.25
72	48.83				48.83
78	22.60				22.60
84	81.44				81.44
90	91.76				91.76
96	105.06				105.06
102	116.96				116.96

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

FCST Initial time → Lead time↓	22 May 00Z	23 May 00Z	24 May 00Z	25 May 00Z	Average track error (km)
6	12.44	0.00	21.73	62.00	24.04
12	2.87	0.00	18.02	59.57	20.11
18	11.48	27.91	9.64	18.25	16.82
24	18.94	42.84	0.00	38.08	24.97
30	84.39	53.52	116.97	43.93	74.70
36	0.00	86.64	99.37	1.98	47.00
42	80.59	112.76	208.67	102.46	126.12
48	35.77	149.65	179.32		121.58
54	3.85	164.70	198.18		122.24
60	42.58	222.74			132.66
66	38.05	299.85			168.95
72	20.67				20.67
78	5.81				5.81
84	30.83				30.83
90	34.45				34.45
96	64.53				64.53
102	102.54				102.54

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

FCST Initial time → Lead time↓	22 May 00Z	23 May 00Z	24 May 00Z	25 May 00Z	Average track error (km)
6	27.99	90.06	33.32	32.82	46.05
12	25.94	34.50	25.22	54.60	35.07
18	51.24	27.91	43.38	51.72	43.56
24	99.57	18.36	109.86	58.86	71.66
30	104.21	13.02	42.04	107.38	66.66
36	109.46	52.35	24.84	148.41	83.76
42	44.43	29.41	46.03	172.72	73.15
48	67.66	52.82	3.42		41.30
54	106.86	127.10	82.17		105.38
60	70.24	106.53			88.39
66	52.38	98.95			75.67
72	44.24				44.24
78	21.84				21.84
84	75.37				75.37
90	85.05				85.05
96	82.91				82.91
102	56.25				56.25

The forecasts from SAC model can be further improved by including the high resolution (17km x 17 km) first guess conditions provided by NCMUM model from National Centre of Medium Range Weather Forecast (NCMRWF) in place of currently being used 50 km x 50 km gfs initial conditions.

3.3 Intensity Prediction of TC MEKUNU

Intensity of TC MEKUNU was predicted using output of HWRF model which is operationally run at NCEP. Real-time generated intensity products are shown in the figures.

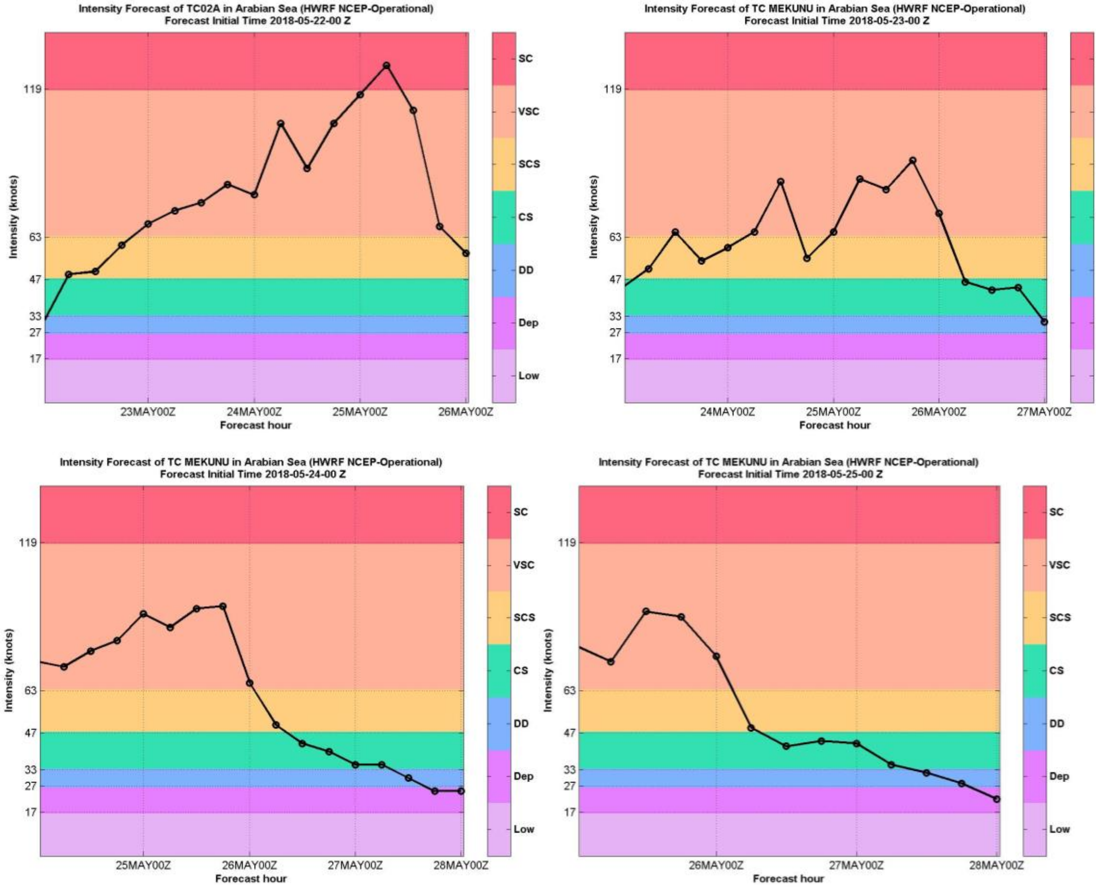


Figure 5: Real-time generated intensity prediction of TC MEKUNU during 00 UTC of 22-26 May, 2018

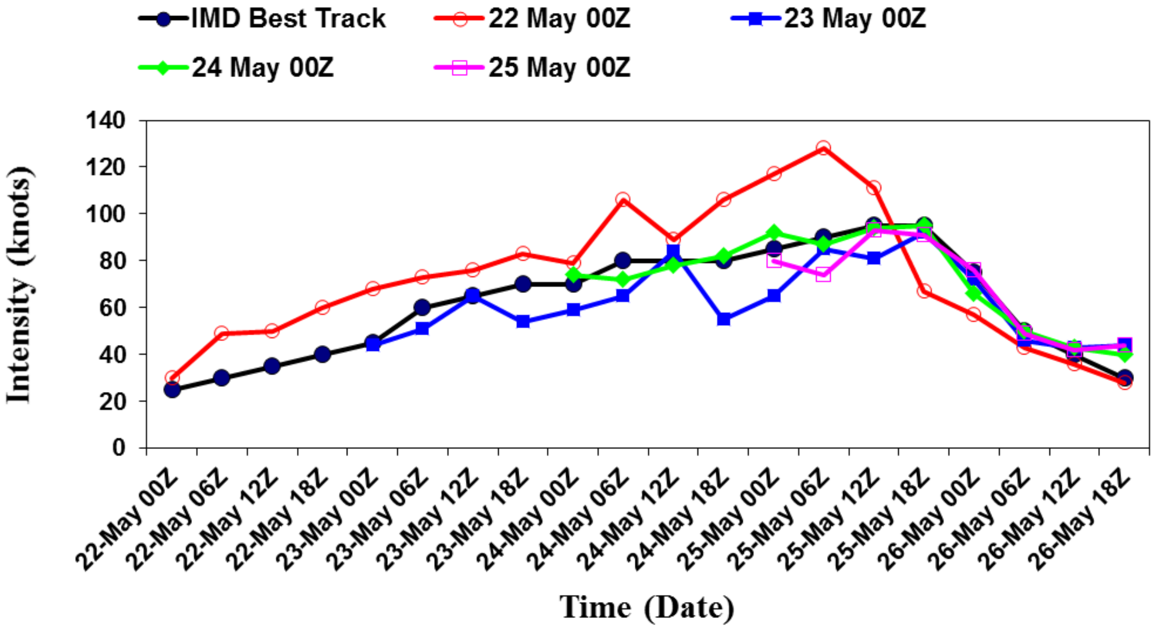


Figure 6: Comparison of Intensity predicted by HWRF model (NCEP Operational Run) and IMD best track estimates for TC MEKUNU for different initial conditions during 00 UTC 22-25 May, 2018

The figure shows that The HWRF model predicted intensity values were over-estimated for 00 UTC 22 May 2018 forecasts for all the time steps. IMD best track shows that the TC had maximum intensity of 95 knots during 12-18 UTC 25 May, 2018. This was over estimated by HWRF model forecast generated on 22 May as 120 knots. This shows that model need to further investigated for the Indian Ocean cyclone intensification processes.

4. Satellite Observations over TC MEKUNU

Different sensors onboard 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 geo-location of the system and retrieve its structural parameters. Different satellite observations over TC MEKUNU have been discussed in this section.

4.1 INSAT 3D

Cyclone Geo-location

TC MEKUNU was continuously observed by the half hourly acquisition of INSAT-3D satellite. In half hourly TIR imageries of INSAT 3D satellite the center location of cyclone was estimated by center determination algorithm developed at SAC. 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.

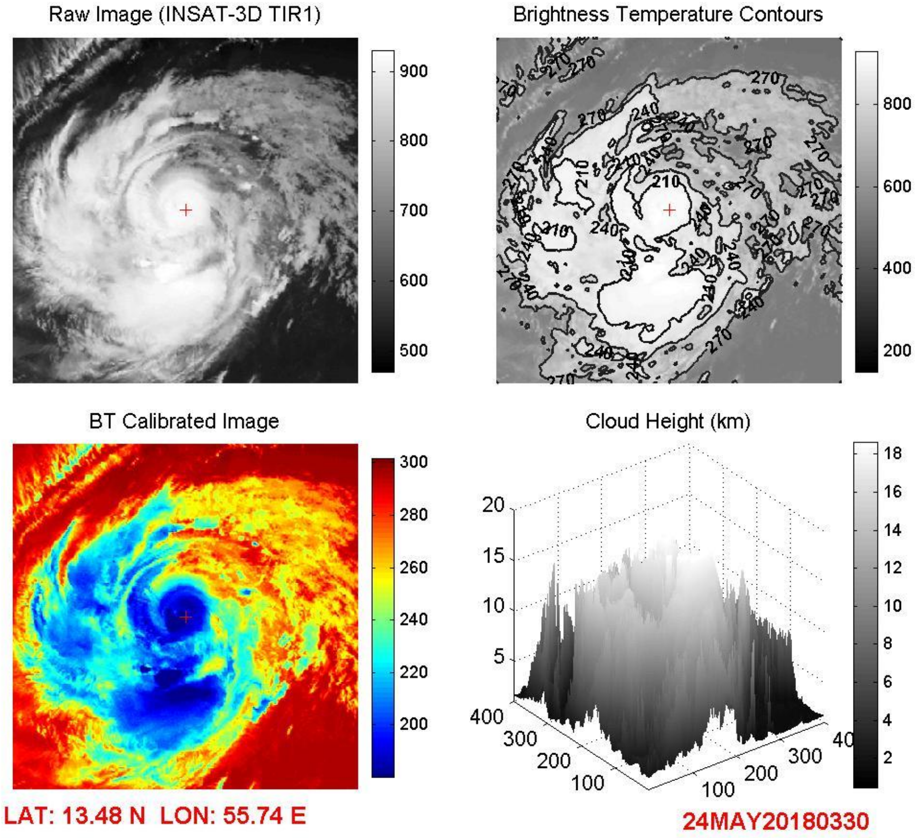


Figure 7: Center of TC estimated using INSAT 3D TIR image (0330Z 24 May, 2018).

Cyclone centric products of INSAT3D satellite

A procedure has been developed to produce cyclone centric products from each half hourly image of INSAT3D satellite. These images are very useful to study the structural changes in the core of tropical cyclone. A sample product generated on 0330 Z 23 May, 2018 have been presented in the figure 8.

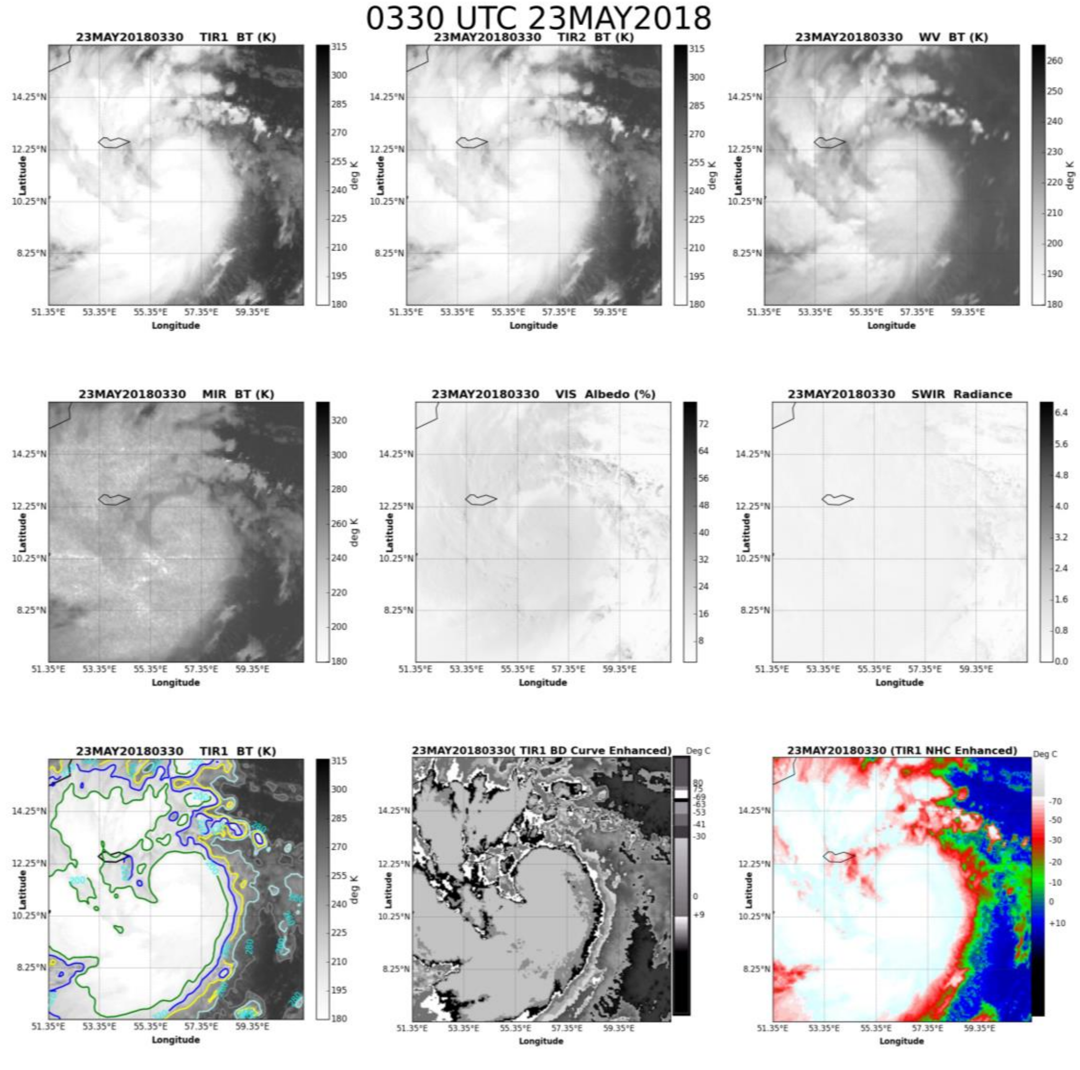


Figure 8: Cyclone centric products of INSAT3D imager channels

4.2 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. 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.

The BT values observed from SAPHIR 21-22 May, 2018 have been shown in the Fig. 9. Such images are very useful to determine the lower level structure of cyclone and its geo-location.

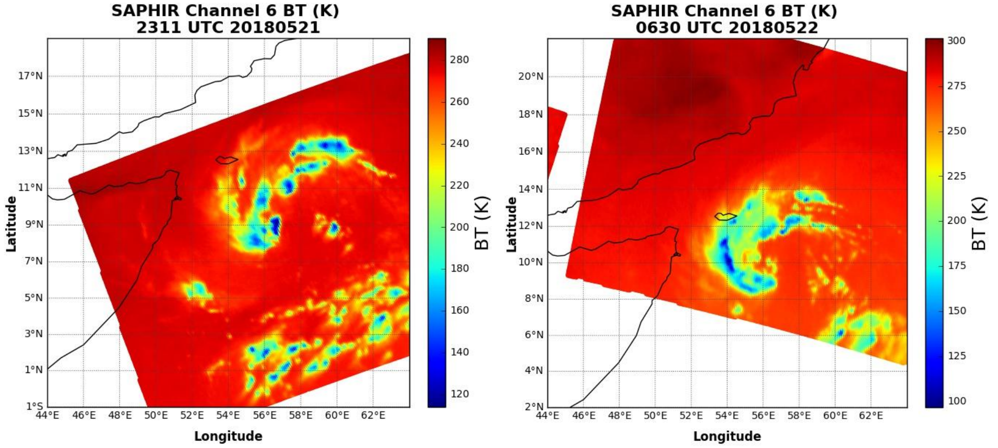


Figure 9: BT values observed by SAPHIR channel-6 over the tropical cyclone MEKUNU

4.3 SCATSAT-1

The observations of surface wind vectors over TC MEKUNU by SCATSAT-1 have been analyzed. The TC MEKUNU was fully covered by two passes i.e. during 22 and-24 May, 2018 as shown in the Figure 10. During this period cyclone was categorized as extremely severe cyclone category by the IMD best track measurements. The maximum winds estimated by SCATSAT-1 over the above fully covered cyclone pass of 24th May was found as 28.86 m/s, however the IMD best track estimated wind speed during this time was 75 kt (38.58 m/s). Thus the maximum sustained wind speed measurements were underestimated by SCATSAT-1 during cyclone intense categories.

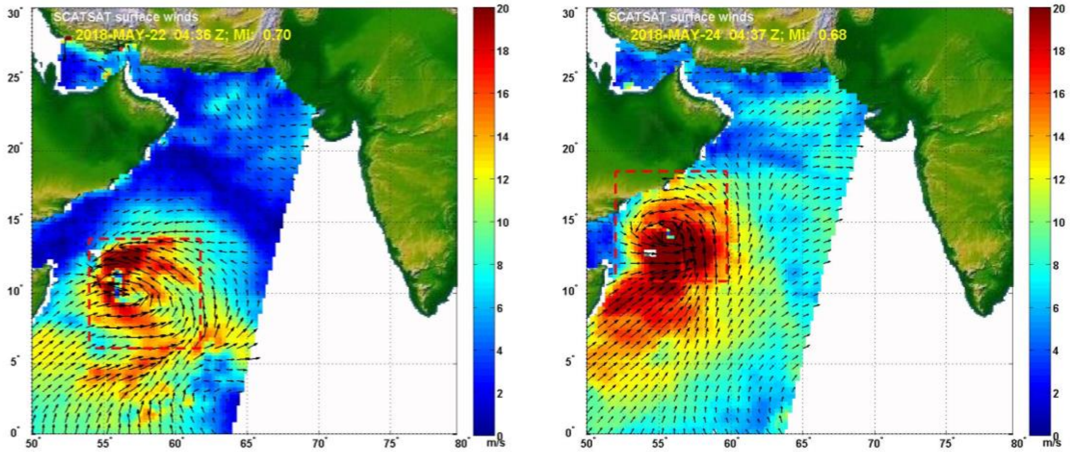


Figure 10: SCATSAT-1 wind vector products over the TC MEKUNU (22nd and 24th May, 2018)

References

1. Brand, S., Buenafe, C. A. and Hamilton, H. D. (1981). Comparison of tropical cyclone motion and environmental steering. Mon Wea Rev 108:908-909.

2. Chan, J.C.L. and Williams, R.T. (1987). Analytical and numerical studies of the beta-effect in tropical motion. J Atmos Sci 44:1257-1265.

3. Frank, Neil L., Husain, S. A., 1971. The Deadliest Tropical Cyclone in History. *Bull. Amer. Meteor. Soc*., 52, 438–445.

4. Heming J. T. (1994). Keeping an eye on the hurricane -Verification of tropical cyclone forecast tracks at the UK Meteorological Office. NWP Gazette,1, No.2, pp.3 -8.

5. Hoover, B.T. and Morgan M.C. (2006). Effects of cumulus parameterization on tropical cyclone potential vorticity structure and steering flow. Preprints of the 27th AMS Conference on Hurricanes and Tropical Meteorology. April 23-28 Monterey, CA, paper 8B.5.

6. IMD Report, (2015a). Cyclonic Storm, ASHOBAA over the Arabian Sea (07-12 June 2015): A Report. Cyclone Warning Division, India Meteorological Department, New Delhi. June 2015.

7. IMD Report, (2015b). Extremely Severe Cyclonic Storm, CHAPALA over the Arabian Sea (28 October - 4 November, 2015): A Report. Cyclone Warning Division, India Meteorological Department, New Delhi. December 2015.

8. IMD Report, (2015c). Extremely Severe Cyclonic Storm, MEGH over the Arabian Sea (05 - 10 November, 2015): A Report. Cyclone Warning Division, India Meteorological Department, New Delhi. December 2015.

9. IMD Report, (2018c). Extremely Severe Cyclonic Storm, “MEKUNU” over the Arabian Sea (21 – 27 May 2018): A Report: A Report. Cyclone Warning Division, India Meteorological Department, New Delhi. June 2018.

10. Jaiswal, N., Kishtawal, C. M., Bhomia, S. and Pal, P. K. (2016). Multi-model ensemble based probabilistic prediction of tropical cyclogenesis using TIGGE Model Forecasts. Meteorology and Atmospheric Physics. DOI 10.1007/s00703-016-0436-2.

11. Jaiswal, N., and Kishtawal, C. M., (2011a). Prediction of Tropical Cyclogenesis Using Scatterometer Data. IEEE Transaction on Geoscience and Remote Sensing, vol. 49, Issue 12, pp. 4904 – 4909.

12. Jaiswal, N., and Kishtawal, C. M., (2011b). Automatic Determination of Center of Tropical Cyclone in Satellite-Generated IR Images. IEEE Geoscience and Remote Sensing Letters. vol. 8, No. 3, pp. 460-463.

13. Jaiswal, N., and Kishtawal, C. M., (2012). Objective Detection of Center of Tropical Cyclone in Remotely Sensed Infrared Images. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. DOI.10.1109/JSTARS.2012.2215016

14. Jaiswal, N., Kishtawal, C. M., and Pal, P. K., (2013). Prediction of Tropical Cyclogenesis in North Indian Ocean using OSCAT Data. Meteorology Atmospheric Physics, vol. 119, pp. 137–149

15. Singh, Sanjeev Kumar, Kishtawal, C.M, and Pal, P. K. (2012a). Track prediction of Indian Ocean cyclones using Lagrangian advection model. Nat. Hazards, Vol.63, no.3, 62:745-778.

16. Singh, S. K., Kishtawal, C. M., Jaiswal, N., Singh, R. and P. K. Pal, (2012b). Impact of Vortex-Removal from Environmental Flow in Cyclone Track Prediction using Lagrangian Advection Model. Meteorology Atmospheric Physics, vol. 117, pp. 103–120.