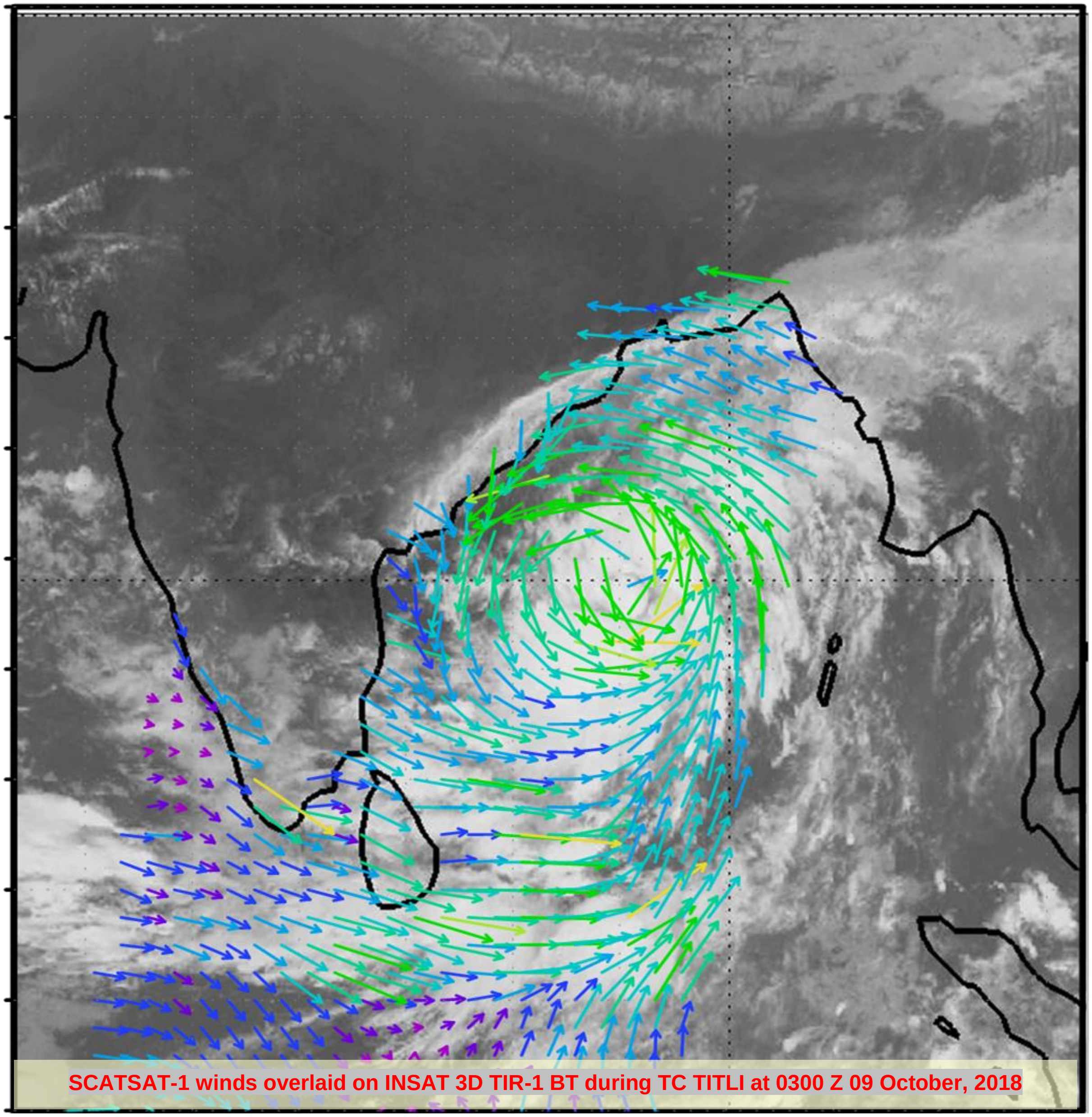
Real-time Monitoring and Prediction of Tropical Cyclone TITLI

SAC/EPSA/AOSG/ASD/SR- 45/2018



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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 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 TITI 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
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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). 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 "TITLI" in NIO during 08 -12 October, 2018, which has been discussed in the present report.

1.1 Overview of Tropical cyclone TITLI (07 - 13 October, 2018)

Tropical cyclone "TITLI" was originated from a low pressure area over south east Bay of Bengal (BoB) and adjoining north Andaman Sea in the morning (0830 IST) of 7th October, 2018 which laid as a well marked low pressure system over the same region till 1730 UTC same day. Under favourable environmental conditions, it concentrated into a depression over eastcentral BoB in the morning (0830 IST) of 8th October. Moving nearly west-northwestwards, it intensified into a deep depression over eastcentral BoB in the mid-night (2330 IST) of 8th October and further into a cyclonic storm "Titli" around noon (1130 IST) of 9th October. It then moved northwestwards and intensified , into a severe cyclonic storm (SCS) in the early hours (0230 IST) of 10th. It then moved north-northwestwards and further intensified into a very severe cyclonic storm (VSCS) around noon (1130 IST) of 10th. It crossed north Andhra Pradesh and south Odisha coasts near Palasa (18.8^{0}N/84.5^{0}E) to the southwest of Gopalpur during 0430-0530 IST of 11th as a VSCS with the wind speed of 140-150 gusting to 165 kmph. Moving further west-northwestwards, it weakened into an SCS around noon (1130 IST) of 11th and a cyclonic storm in the same evening (1730 IST). Under the influence of southwesterly winds at middle and upper tropospheric levels, the system recurved northeastwards from 11th evening. It weakened into a deep depression over south Odisha in the mid-night (2330 IST) of 11th. It further weakened into a depression in the afternoon (1430 IST) of 12th , into a WML over Gangetic West Bengal and adjoining Bangladesh & north BoB in the early hours (0530 IST) of 13th and into an low pressure area over the same region in the morning (0830 IST) of 13th. (ref. IMD report on TC TITLI, 2018). The best track of TC TITLI provided by IMD has been shown in the Figure 1.

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.

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 (VSCS)	64-85
Extremely SCS (ESCS)	86-119
Super Cyclonic Storm(SuC)	>119

The cyclone name “TITLI”, was given by Pakistan. As per global convention, the eight countries that make up the Indian Ocean Region—India, Bangladesh, Sri Lanka, Thailand Pakistan, Maldives, Myanmar, Oman—have drawn up a list of names for tropical cyclones, which are assigned serially with the alphabetic order of the nation’s name.

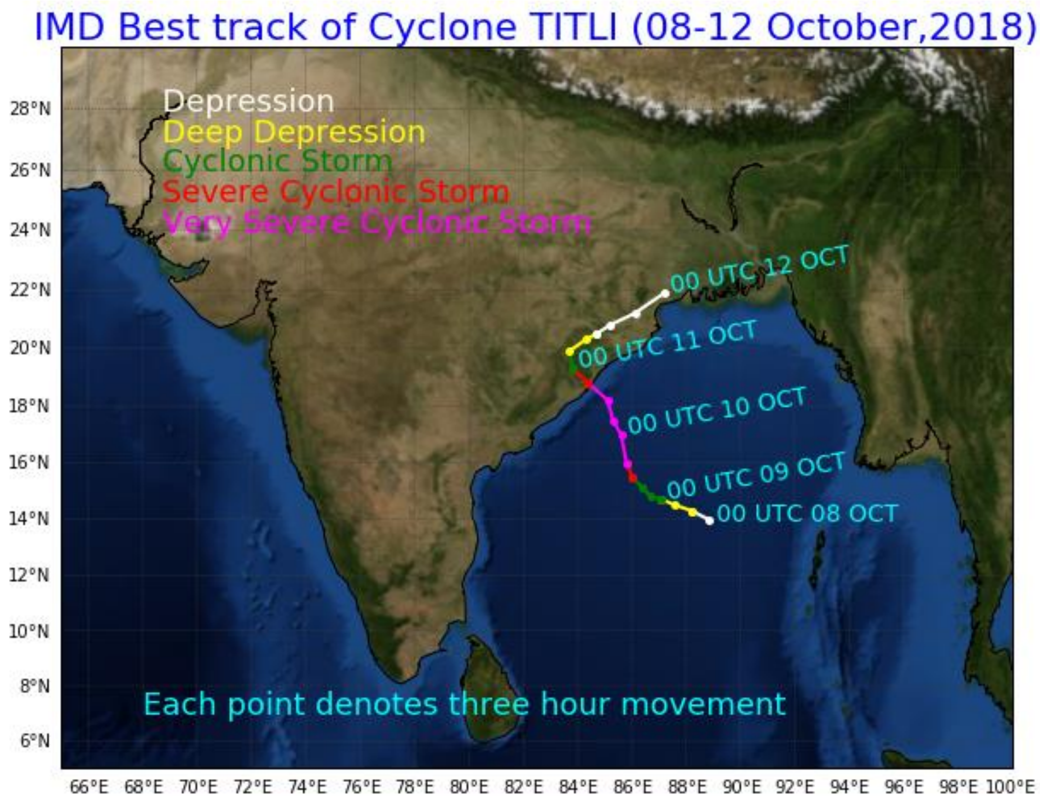


Figure 1: IMD best track of cyclone TITLI with its intensity categories.

Development stages of the cyclone TITLI 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.

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

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 TITLI.

3. Results: Prediction of TC TITLI

Real-time cyclogenesis and track prediction of TC TITLI 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 TITLI

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 15 UTC 06 OCT, 2018. The wind matching index value was found as 0.63 which was higher than the threshold value 0.6. The surface winds obtained by SCATSAT are shown in the Fig. 2, where the cyclogenesis region has been marked with the box. Cyclone TITLI was declared as tropical cyclone on 06 UTC 09 OCT, 2018. Thus, the wind pattern matching based technique predicted the cyclogenesis of TC approximately 3 day (~62 hours) before the official declaration of the system as a cyclonic storm by IMD.

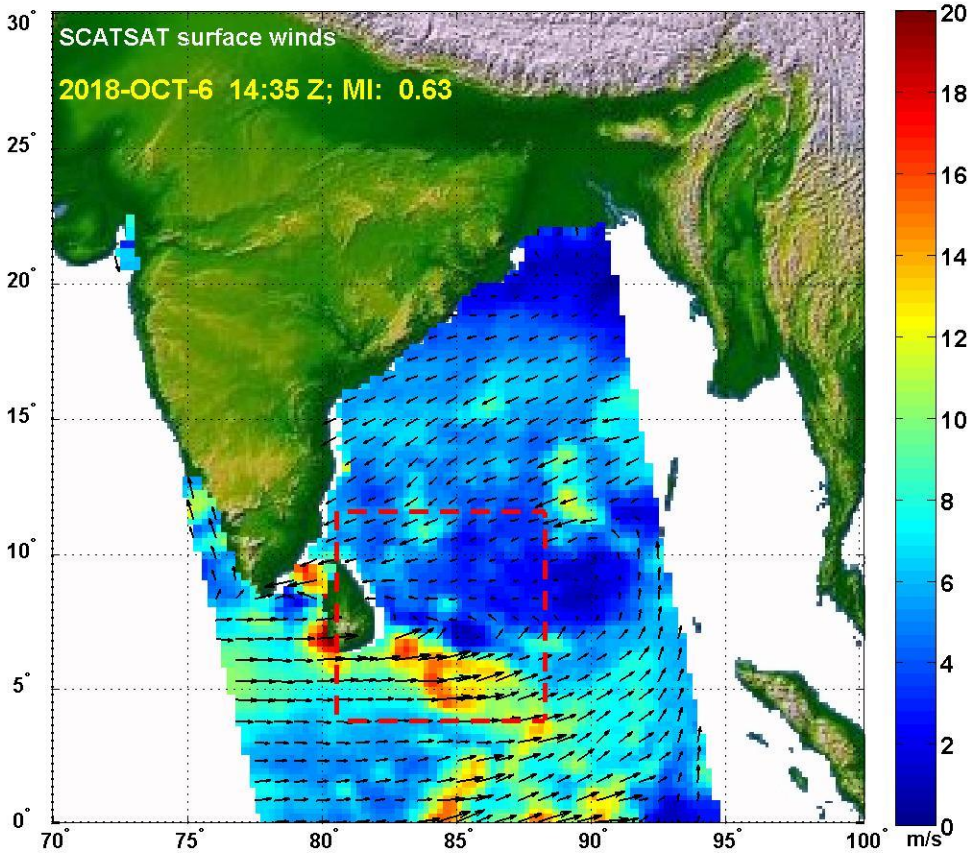


Figure 2: SCATSAT winds during the cyclogenesis of TC TITLI. The earliest cyclogenesis signature was detected on 1435 UTC 06th October, 2018.

3.2 Real-time track prediction of TC TITLI

After the formation of TC TITLI its track was predicted using the SAC-Lagrangian Advection model.

3.2.1 Track prediction using SAC-Lagrangian model

The cyclone track forecast using SAC-Lagrangian model was generated on 00, 06, 12 and 18 UTC of 09th -10th October, 2018 and have been shown in the Fig. 3. Each point in the figure is representing the six hours' movement of the cyclone. Shaded region along the track shows the cone of uncertainty based on the past track error statistics. In the real-time only 00 UTC track were disseminated over the website.

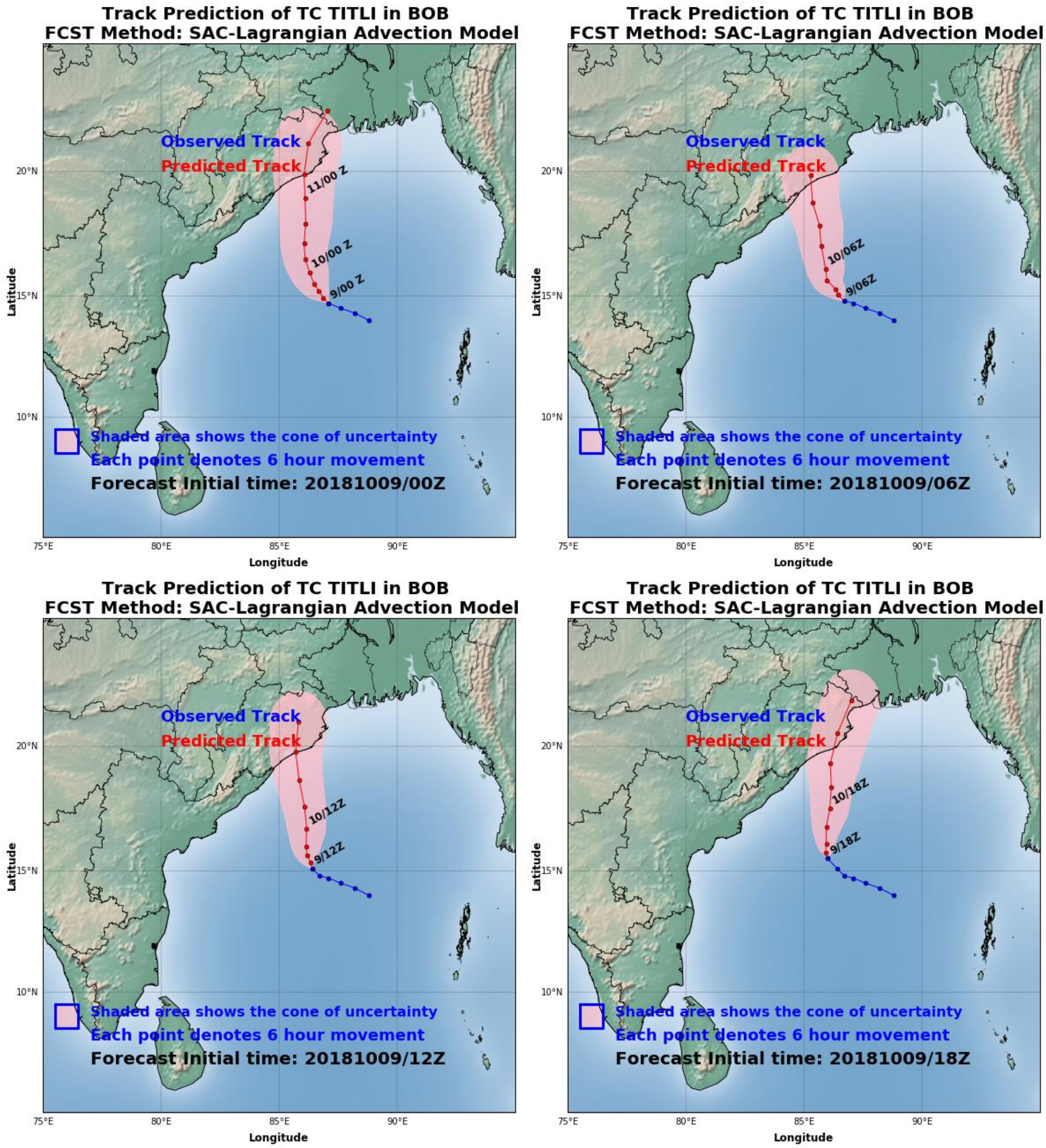


Figure 3: Real-time predicted track of TC TITLI at 00,06,12,18 UTC 09 October, 2018.

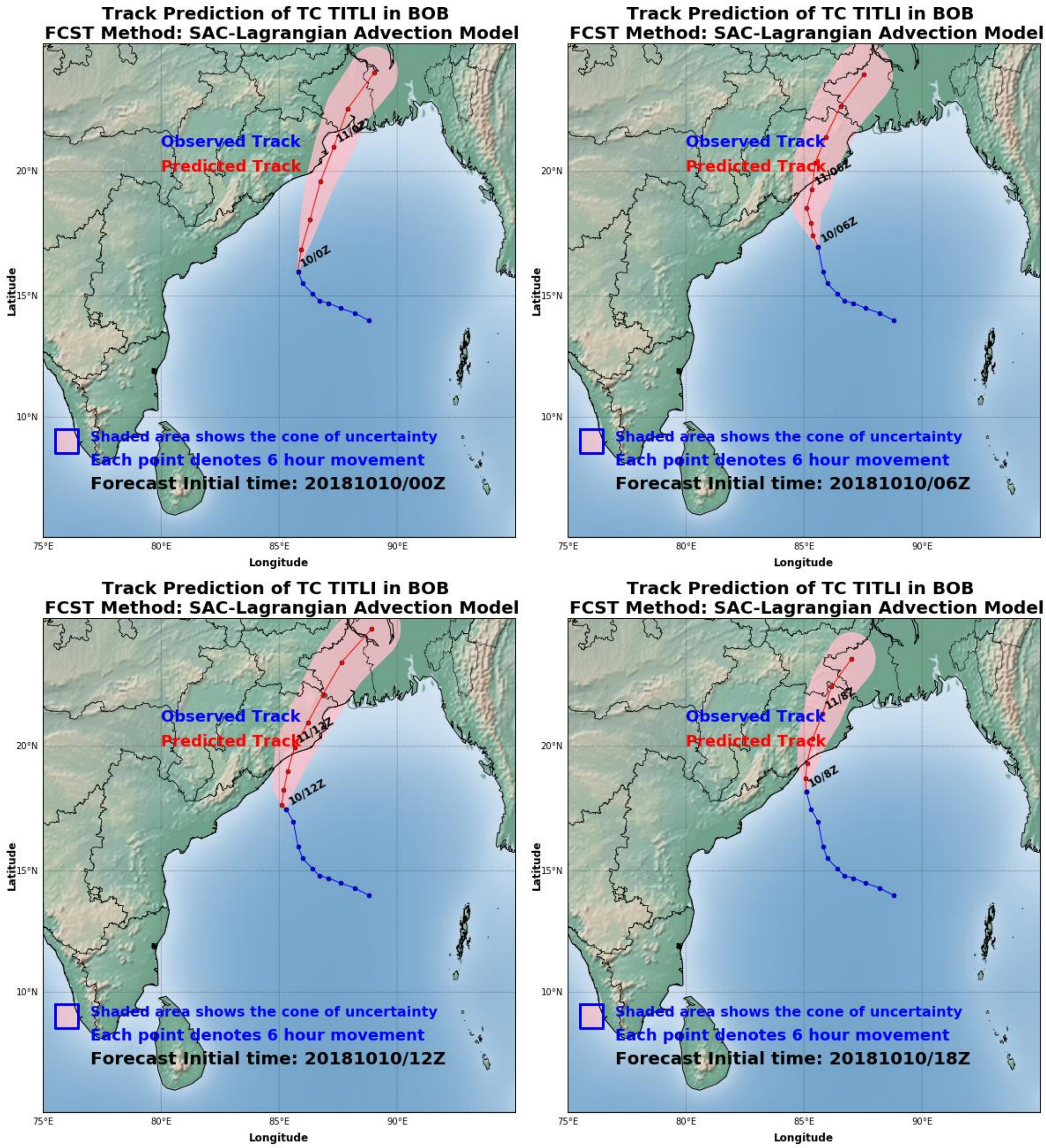


Figure 4: Real-time predicted track of TC TITLI at 00,06,12,18 UTC 10 October, 2018.

It can be seen from the figure that all the track generated is showing the system making landfall over the east coast of India near Odisha region. The forecasted track was plotted together with IMD best track and the error of track forecast has been estimated. 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. 5.

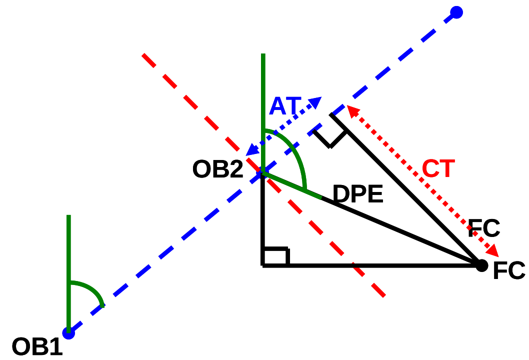


Figure 5: Schematic showing the positional forecast errors (Heming, 1994).

Table 2: Along track error (km) of SAC-Lagrangian advection track prediction model for TC TITLI

FCST Initial time → Lead time↓	09 OCT 00Z	09 OCT 06Z	09 OCT 12Z	09 OCT 18Z	10 OCT 06Z	10 OCT 12Z	10 OCT 18Z	Average track error (km)
6	16.31	9.28	37.41	31.62	10.01	58.1	59.86	31.80
12	13.74	43.77	51.87	104.22	31.17	103.71	104.65	64.73
18	38.69	44.32	119.84	102.9	75.26	146.53	12.59	77.16
24	24.45	103.65	123.2	98.92	125.65	26.5	190.23	98.94
30	66.5	67.11	93.03	169.63	14.83	204.86	232.21	121.17
36	76.92	52.67	125.73	186.57	205.73	277.26	316.81	177.38
42	59.69	78.99	121.34	16.2	278.51	362.3	387.76	186.40
48	126.41	83.61	74.77	325.36	385.71	427.17	498.74	274.54

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

FCST Initial time → Lead time↓	09 OCT 00Z	09 OCT 06Z	09 OCT 12Z	09 OCT 18Z	10 OCT 06Z	10 OCT 12Z	10 OCT 18Z	Average track error (km)
6	15.26	0	14.51	1.64	4.08	15.44	38.8	12.82
12	30.53	8.45	23.91	18.67	13.79	11.07	92.68	28.44
18	35.65	3.69	36.77	20.95	29.58	80.96	179.72	55.33
24	46.72	15.43	36.34	83.69	101.97	203.54	0.29	69.71
30	43.41	14.39	82.99	88.26	191.82	55.87	108.11	83.55
36	48.95	47.51	88.32	156.84	1.77	43.28	143.39	75.72
42	96.76	64.93	166.91	291.7	110.53	94.49	243.8	152.73
48	127.78	143.94	239.79	26.38	148.49	210.03	160.69	151.01

Table 4: Direct position track error (km) of SAC-Lagrangian advection track prediction model for TC TITLI

FCST Initial time → Lead time↓	09 OCT 00Z	09 OCT 06Z	09 OCT 12Z	09 OCT 18Z	10 OCT 06Z	10 OCT 12Z	10 OCT 18Z	Average track error (km)
6	22.34	9.28	40.12	31.67	10.81	60.12	71.33	35.10
12	33.48	44.58	57.12	105.88	34.08	104.3	139.78	74.17
18	52.61	44.47	125.35	105.01	80.87	167.41	180.16	107.98
24	52.73	104.79	128.45	129.57	161.82	205.26	190.23	138.98
30	79.41	68.64	124.66	191.22	192.39	212.34	256.14	160.69
36	91.18	70.94	153.65	243.74	205.74	280.62	347.75	199.09
42	113.69	102.25	206.36	292.15	299.64	374.42	458.03	263.79
48	179.74	166.46	251.17	326.42	413.3	476.01	523.99	333.87

IMD reported that cyclone crossed north Andhra Pradesh and south Odisha coasts near 18.8 N/84.5 E during 2300 UTC of 10th and -0000 UTC of 11th October. The landfall point and time error of SAC model has been comp[uted with respect to IMD estimated landfall position.

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

Forecast initial time	Forecast Lead Time (hr)	Landfall point Error (km)	Landfall Time Error
00Z 09 Oct, 2018	48	187.2	+ 6 hours
06Z 09 Oct, 2018	42	109.7	+ 5 hours
12Z 09 Oct, 2018	36	153.1	+ 6 hours
18Z 09 Oct, 2018	30	179.9	+ 9 hours
06Z 10 Oct, 2018	18	118.9	+ 9 hours
12Z 10 Oct, 2018	12	124.5	+ 5 hours
18Z 10 Oct, 2018	6	91.9	+ 6 hours

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 TITLI

Intensity of TC TITLI was predicted using output of HWRF model which is operationally run at NCEP. Real-time generated intensity product is shown in the figure.

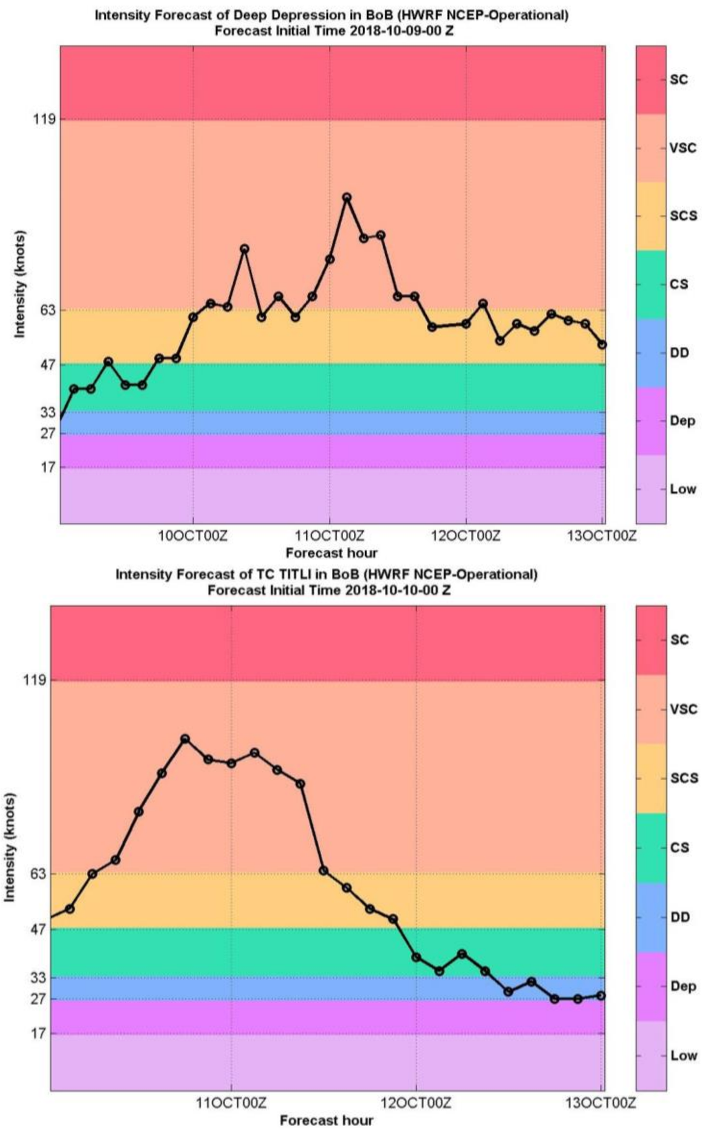


Figure 6: Real-time generated intensity prediction of TC TITLI during 00 UTC of 09-10 October, 2018.

4. Satellite Observations over TC TITLI

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 TITLI have been discussed in this section.

4.1 INSAT 3D

Cyclone Geo-location

TC TITLI 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.

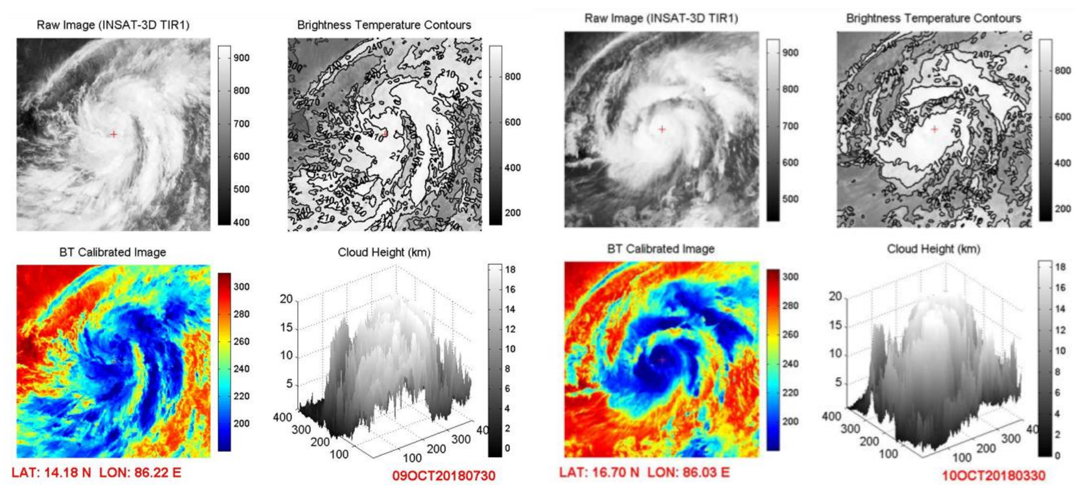


Figure 7: Center of TC estimated using INSAT 3D TIR image (0730Z 09 Oct, 2018 and 0330 10 Oct 2018).

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 0930 Z 10 OCT, 2018 have been presented in the figure 8.

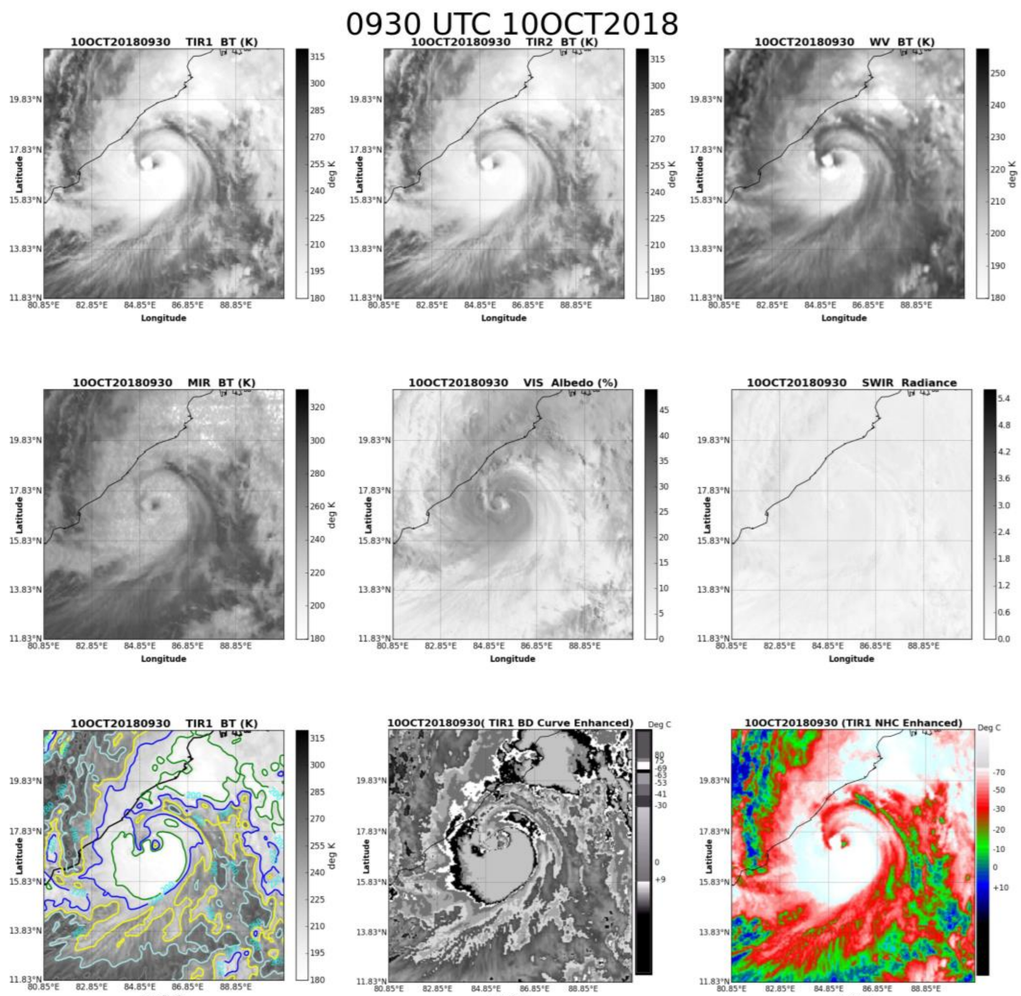
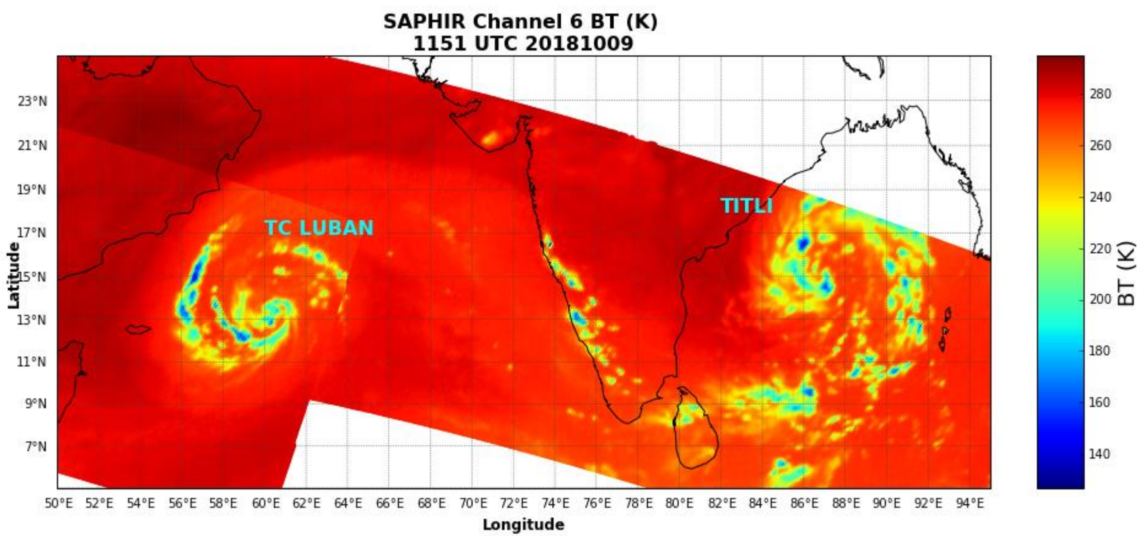


Figure 8: Cyclone centric products of INSAT3D imager channels

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 1200 UTC 09 October, 2018 and 10 UTC 10 October, 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.



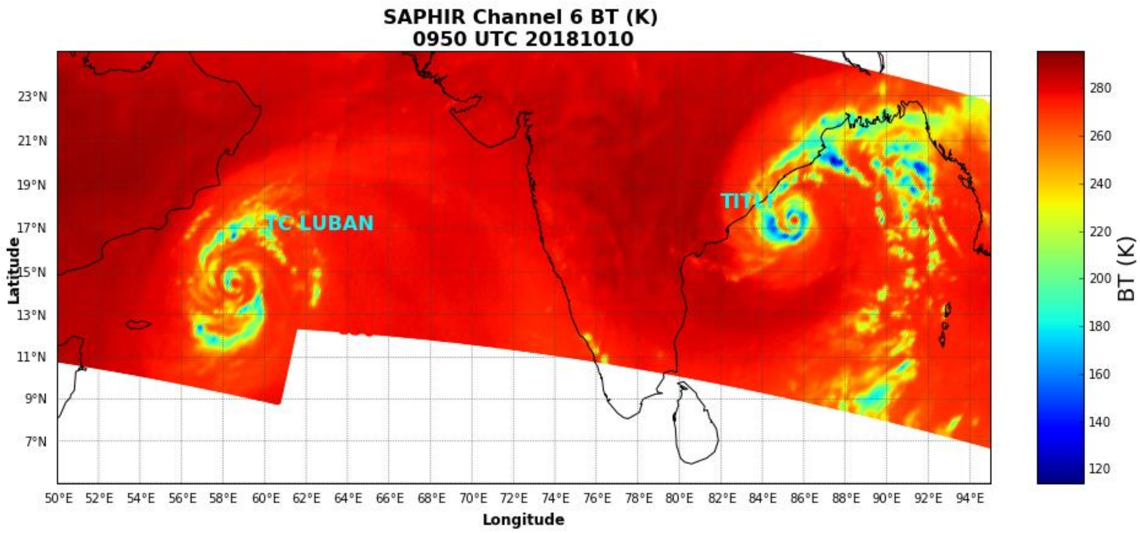


Figure 9: BT values observed by SAPHIR channel-6 over the tropical cyclone TITLI

4.3 SCATSAT-1

The observations of surface wind vectors over TC TITLI by SCATSAT-1 have been analyzed. All of the pass covering the cyclonic winds have been shown in the following figure.

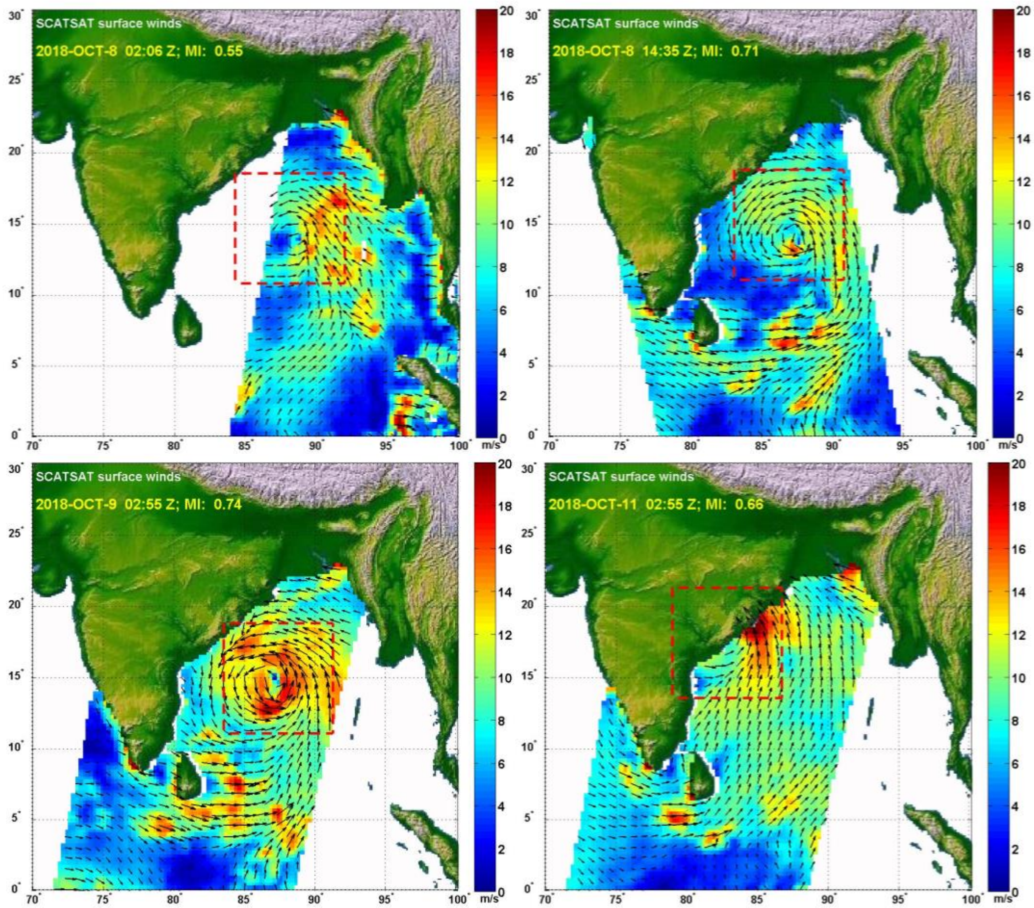


Figure 10: SCATSAT-1 wind vector products over the TC TITLI (08th -11th October, 2018)

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, (2018). Cyclonic Storm “Daye” over eastcentral Bay of Bengal and adjoining Myanmar (19-22 September 2018): Summary. Regional Specialised Meteorological Centre-Tropical Cyclones, New Delhi, India Meteorological Department, New Delhi. October 2018.

10. IMD Report, (2018). Very Severe Cyclonic Storm “Titli” over eastcentral Bay of Bengal (08-13 October 2018): Summary. Regional Specialised Meteorological Centre-Tropical Cyclones, New Delhi, India Meteorological Department, New Delhi. October 2018.

11. 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.

12. 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.

13. 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.

14. 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

15. 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

16. 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.

17. 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.