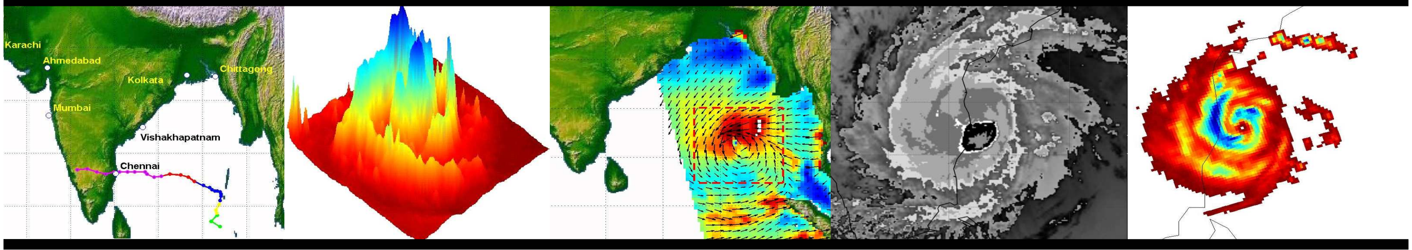
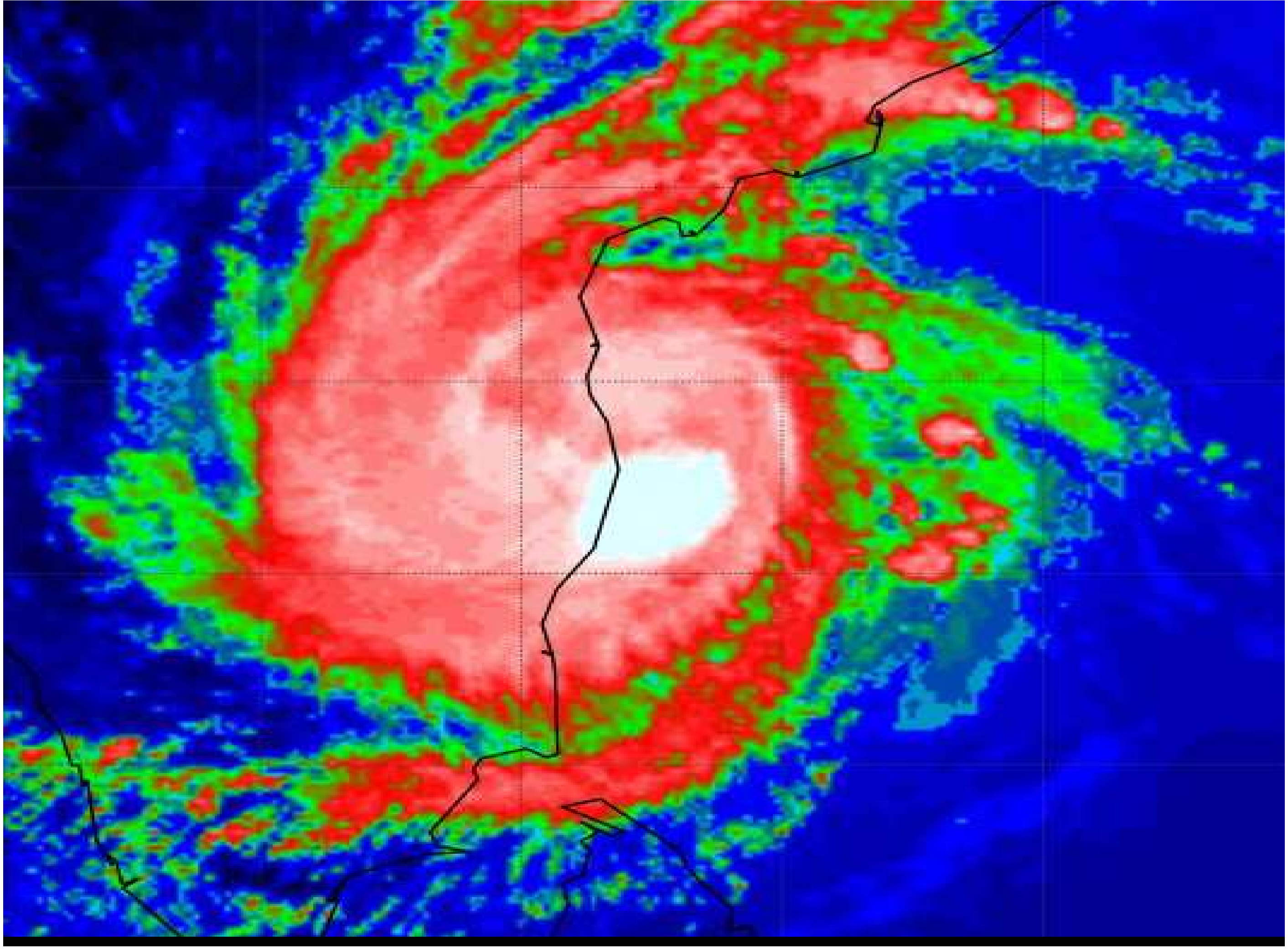
Real-time monitoring and prediction of tropical cyclone VARDAH

SAC/AOSG/ASD/SR-01/2017





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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 VARDAH 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 “VARDAH” in NIO during 6-13 December, 2016, which has been discussed in the present report.

1.1 Overview of Tropical cyclone VARDAH (6-13 December, 2016)

The cyclone name “VARDAH” which meant “rose” in Arabic, was provided by Pakistan, in the comprehensive nomenclature list for cyclones in the Arabian Sea and Bay of Bengal. Tropical cyclone “VARDAH” was the most intense cyclone over the NOI in

2016, which struck Andaman and Nicobar Islands as well as south east coastal region of India.. Vardah was the fourth cyclonic storm of the annual cyclone season. It was the strongest storm to form in the BoB since cyclone Hudhud in 2014 and the strongest cyclone to affect south India since cyclone Nilam in 2012. Originating as a low pressure area near the Malay Peninsula on 3rd December, the storm was classified as depression BOB 06 on 6th December by the IMD, as it had sufficiently organized itself with winds of 30 mph. Owing to low wind shear and favorable sea surface temperatures, the storm gradually intensified into a deep depression the following day. BOB 06 was upgraded to a cyclonic storm by the IMD and JTWC in the early hours of 8th December, assigning it the name Vardah, suggested by Pakistan. With conditions favorable for further development, Vardah intensified into a severe cyclonic storm on 9th December following west northwards track. Gradually intensifying as it moved westwards, Vardah reached its peak intensity on 11 December with winds of 80 mph and a minimum central pressure of 982 mbar.

Vardah weakened into a severe cyclonic storm before making landfall on 12th Dec over the eastern coast of India close to Chennai with winds of 65 mph. Thereafter, it rapidly weakened into a depression due to land interaction on 13th Dec. The depression caused overnight rainfall in Southern Karnataka on December 13. Due to frictional forces it degenerated into a well-marked low pressure area around midday on 13th Dec and moved out of Karnataka into the Arabian Sea as a low pressure area in the evening. The observed track of cyclone has been shown in the Fig.1. More than 1,400 tourists were stranded on the Havelock and Neil islands of the archipelago, they were evacuated by the Indian Navy on December 9nth. The cyclone claimed over 18 lives, uprooted 12,000 trees in Chennai and its suburbs, and caused extensive damage to road, supplies and power infrastructure: over 10,000 electric poles have been mangled and 800 transformers damaged. More than 16,000 people were evacuated from low lying areas as a result of Vardah. The IMD classification of cyclone categories has been given in the Table 1.

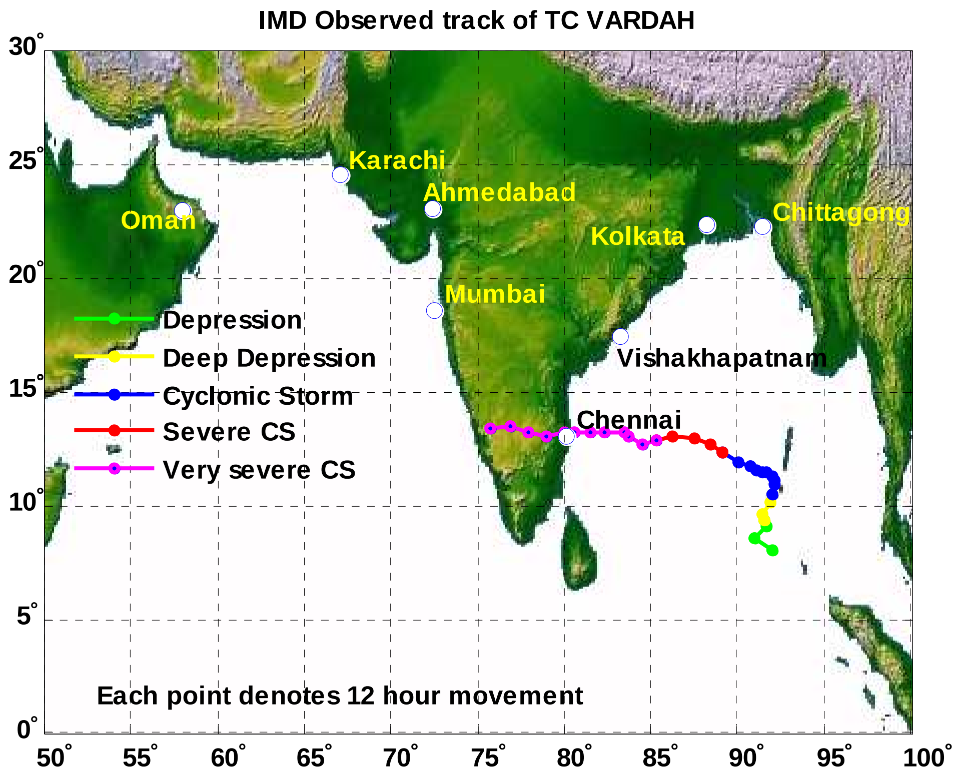


Figure 1: Observed track of cyclone VARDAH.

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

Developments of the cyclone VARDAH 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 Extended range TCG prediction based on multi-model ensemble technique

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., CMA, 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) 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 $0.5^0 x 0.5^0$ 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 VARDAH.

3. Results: Prediction of TC VARDAH

Real-time cyclogenesis and track prediction of TC VARDAH 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 VARDAH

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 1 Dec and 2 Dec, 2016 using the initial conditions from 29 Nov and 30 Nov, 2016 respectively, 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 1 Dec, indicates a low possibility (30%) of formation of tropical cyclone in the next 4 days, in the BoB that is developing near Andaman and Nicobar Islands and moving north westwards of India. The forecast generated on 3 Dec indicated the medium possibility (50%) of formation of tropical cyclone in the same area.

The earliest prediction of cyclogenesis of cyclone VARDAH was given on 1st Dec by MME based cyclogenesis prediction technique. However, the system was designated as tropical cyclone on 8th Dec, 2016 by IMD. Thus, the multi-model based cyclogenesis technique predicted the development of tropical cyclone 7 days before its formation.

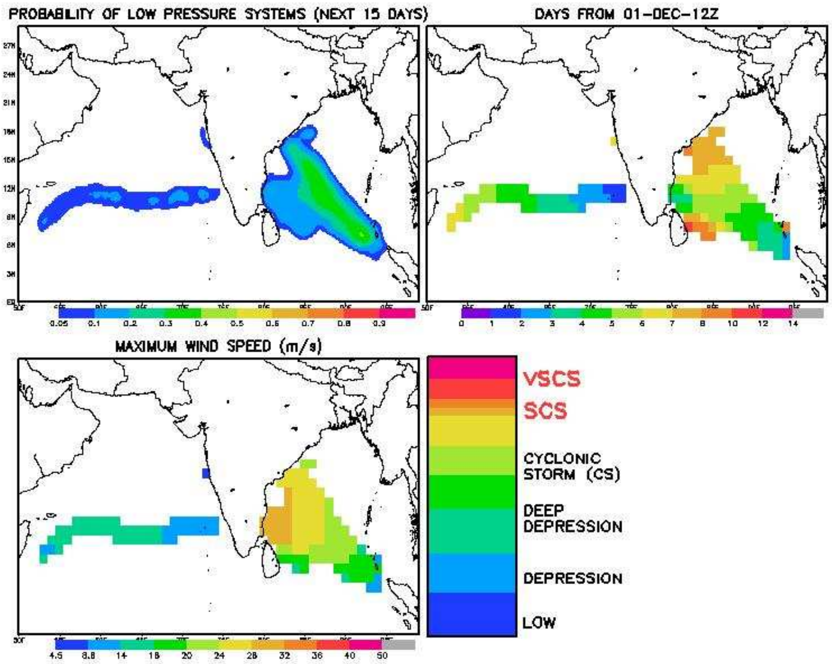


Figure 2a: Real-time forecast generated on 12Z 01 Dec showing the development of cyclone in Bay of Bengal (on 5th Dec), which is making landfall near Chennai (in the next 10 days).

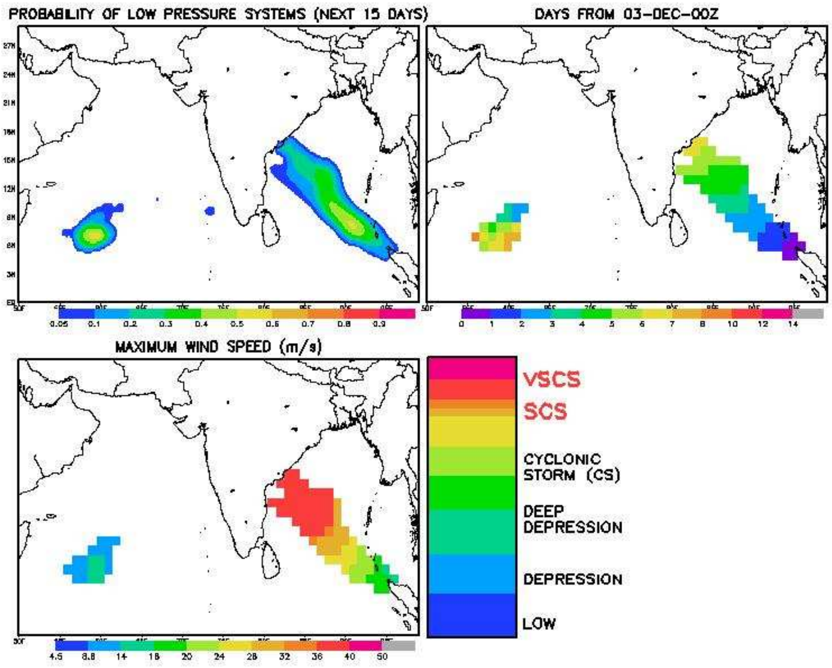


Figure 2b: Real-time forecast generated on 00Z 03 Dec showing the development of cyclone in Bay of Bengal, which is making landfall at Chennai (in the next 7 days).

The wind pattern matching based technique indicated a strong signal of cyclogenesis using the SCATSAT data, on 02:39 Z 5 Dec, 2016. 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 VARDAH was declared as tropical cyclone on 8 Dec, 2016. Thus, the wind pattern matching based technique predicted the cyclogenesis of TC approximately 3 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. 4-8 Dec have been shown in the Fig. 3.

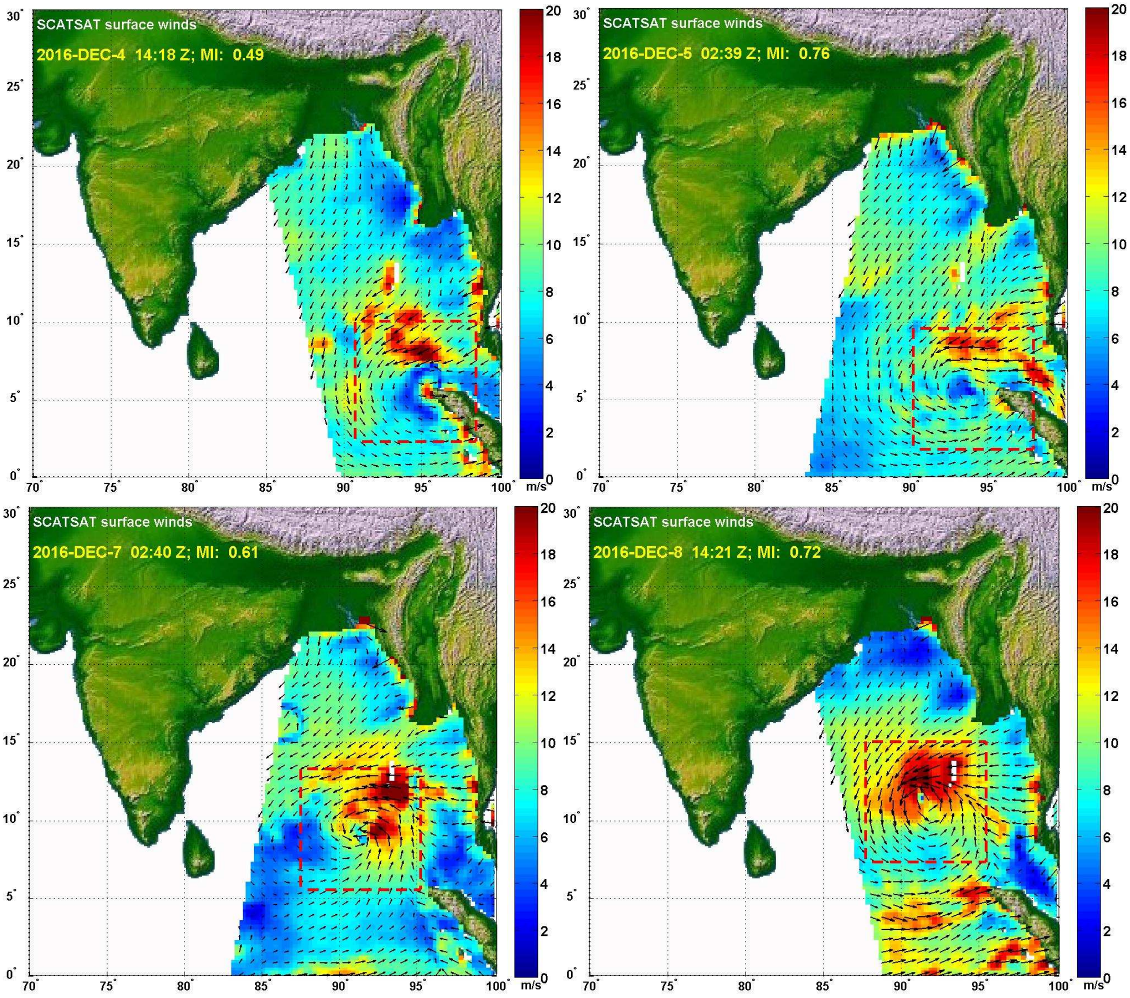


Figure 3: SCATSAT winds during the cyclogenesis of TC VARDAH. The earliest cyclogenesis signature was detected on 5th Dec 2016.

3.2 Real-time track prediction of TC VARDAH

After the formation of TC VARDAH (designated as tropical storm by JTWC or IMD) its track was predicted using the SAC-Lagrangian Advection model. The forecasts were generated on 00Z of 8-12 Dec, 2016. All the real-time predicted tracks along with the observed best track of IMD 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.

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

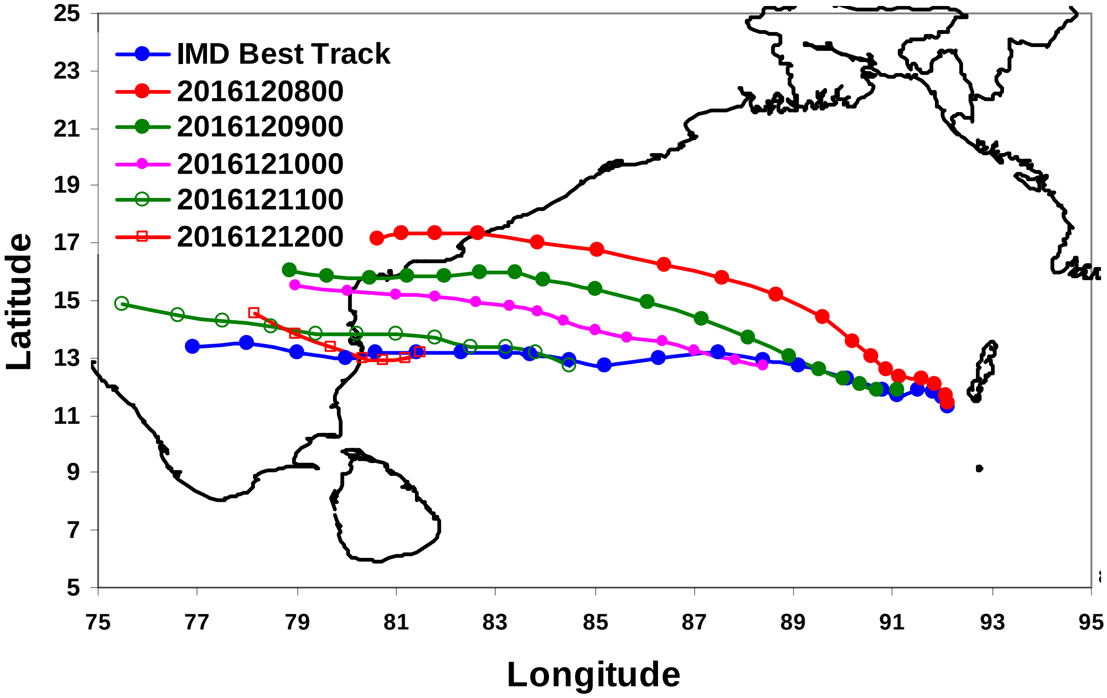


Figure 4: Real-time predicted track of TC VARDAH at 00Z on 8 -12 Dec 2016.

It can be seen from the figure that all the tracks generated on different initial conditions are showing the system making landfall over the east coast of India.

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.

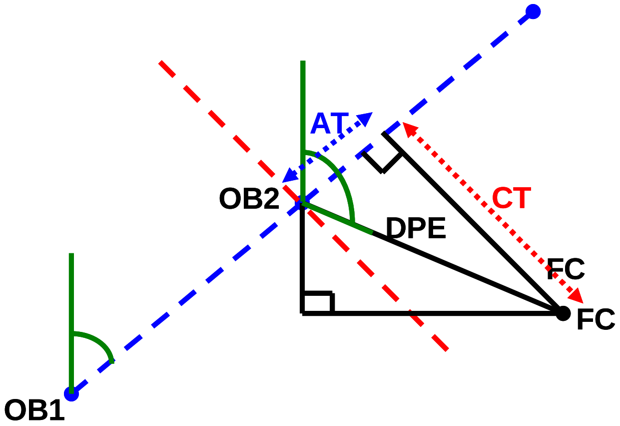


Figure 5: Schematic showing the positional forecast errors (Heming, 1994).

Average track forecast error (DPE) for TC Vardah was found as 100.25 km at 24 hrs, 265.5 km at 48 hrs and 393.58 km at 72 hrs. Average along track forecast error (AT) for was found as 77.34 km at 24 hrs, 157.4 km at 48 hrs and 182.77 km at 72 hrs. Average cross track forecast error (CT) was found as 50.62 km at 24 hrs, 188.01 km at 48 hrs and 347.62 km 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 12 Dec was found as 11 km with 7 hrs delay.

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

FCST Initial time → Lead time↓	08DEC 00Z	09DEC 00Z	10DEC 00Z	11DEC 00Z	Average track error (km)
12	53.28	32.74	78.31	33.39	49.43
24	48.95	120.39	167.24	64.44	100.25
36	134.42	204.08	180.95		173.15
48	232.47	299.29	264.72		265.49
72	452.73	334.44			393.58
96	463.14				463.14

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

FCST Initial time → Lead time↓	08DEC 00Z	09DEC 00Z	10DEC 00Z	11DEC 00Z	Average track error (km)
12	41.75	21.18	74.99	0.00	34.48
24	6.72	109.51	159.98	33.15	77.34
36	14.69	176.77	72.22		87.89
48	19.57	255.79	196.85		157.40
72	232.85	132.69			182.77
96	40.94				40.94

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

FCST Initial time → Lead time↓	08DEC 00Z	09DEC 00Z	10DEC 00Z	11DEC 00Z	12DEC 00Z	Average track error (km)
12	33.10	24.97	22.56	33.39	28.51	33.10
24	48.48	50.01	48.73	55.26	50.62	48.48
36	133.61	101.99	165.91		133.84	133.61
48	231.65	155.39	176.99		188.01	231.65
60	388.26	306.99			347.62	388.26
72	461.33				461.33	461.33

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

Forecast based on	Forecast Lead Time (hr)	Landfall point Error (km)	Landfall Time Error
08 Dec 00Z	106	534.66	-20 hrs
09 Dec 00Z	82	298.16	+8 hrs
10 Dec 00Z	58	245.78	+11 hrs
11 Dec 00Z	34	78.02	+1 hrs
12 Dec 00Z	10	11.12	+7 hrs

4. Satellite Observations over TC VARDAH

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 VARDAH have been discussed in this section.

4.1 <u>INSAT 3D</u>

Cyclone Geo-location

TC VARDAH 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. 6.

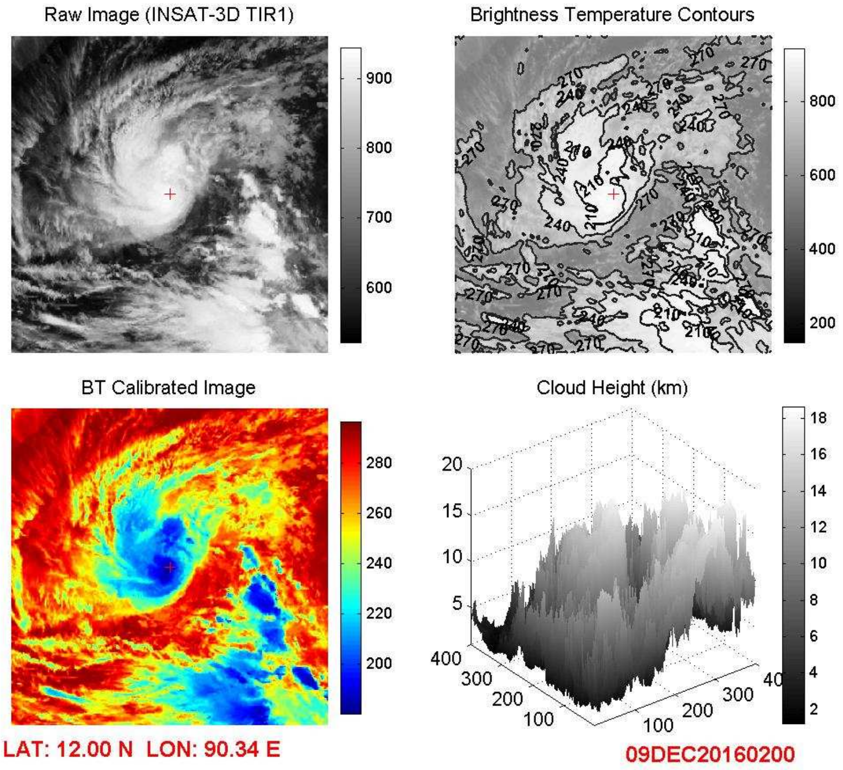


Figure 6: Center of TC estimated using INSAT 3D TIR image (0200Z 12 Dec, 2016).

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 0700 Z 12 DEC, 2016 have been presented in the figure 7.

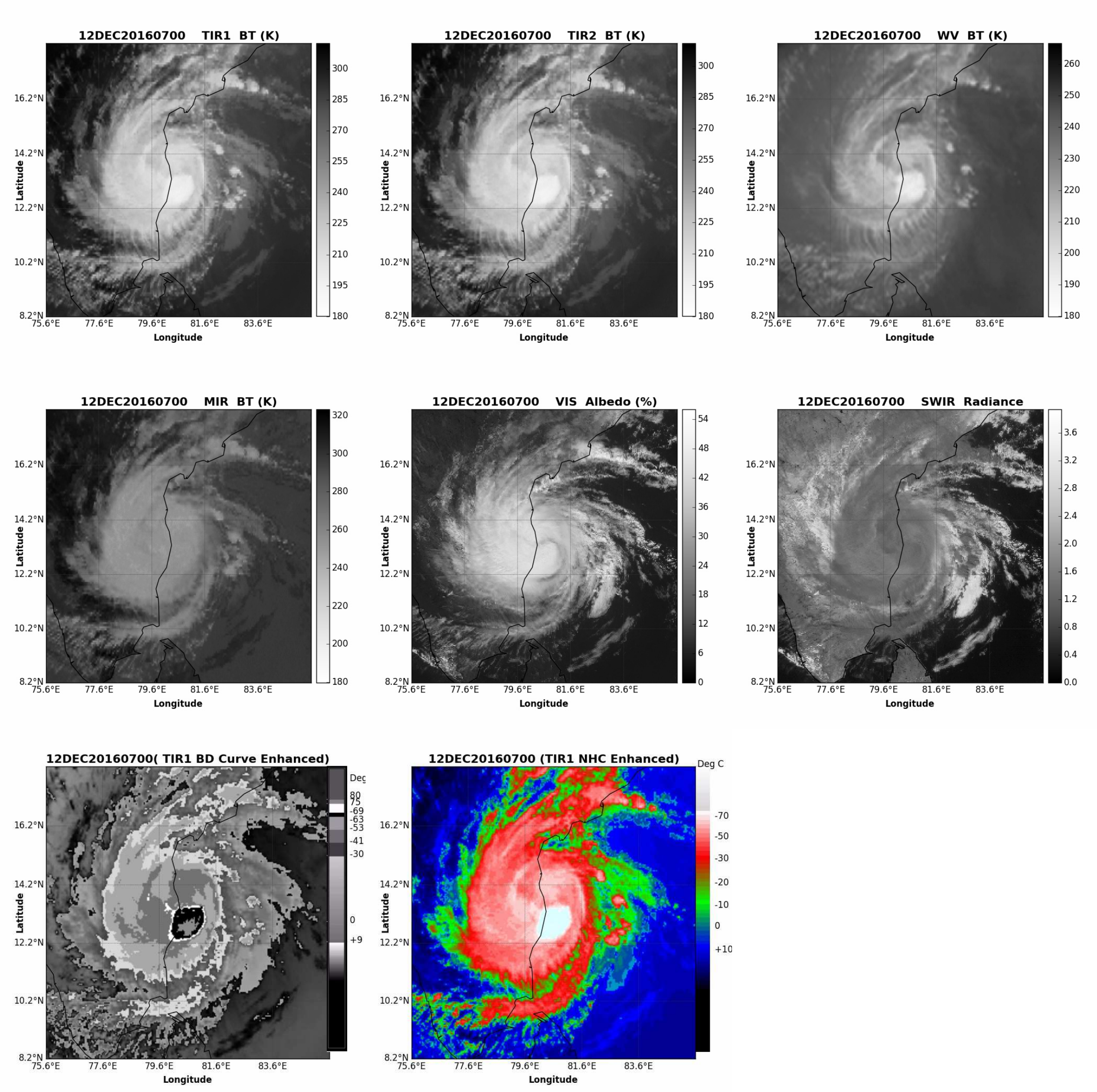
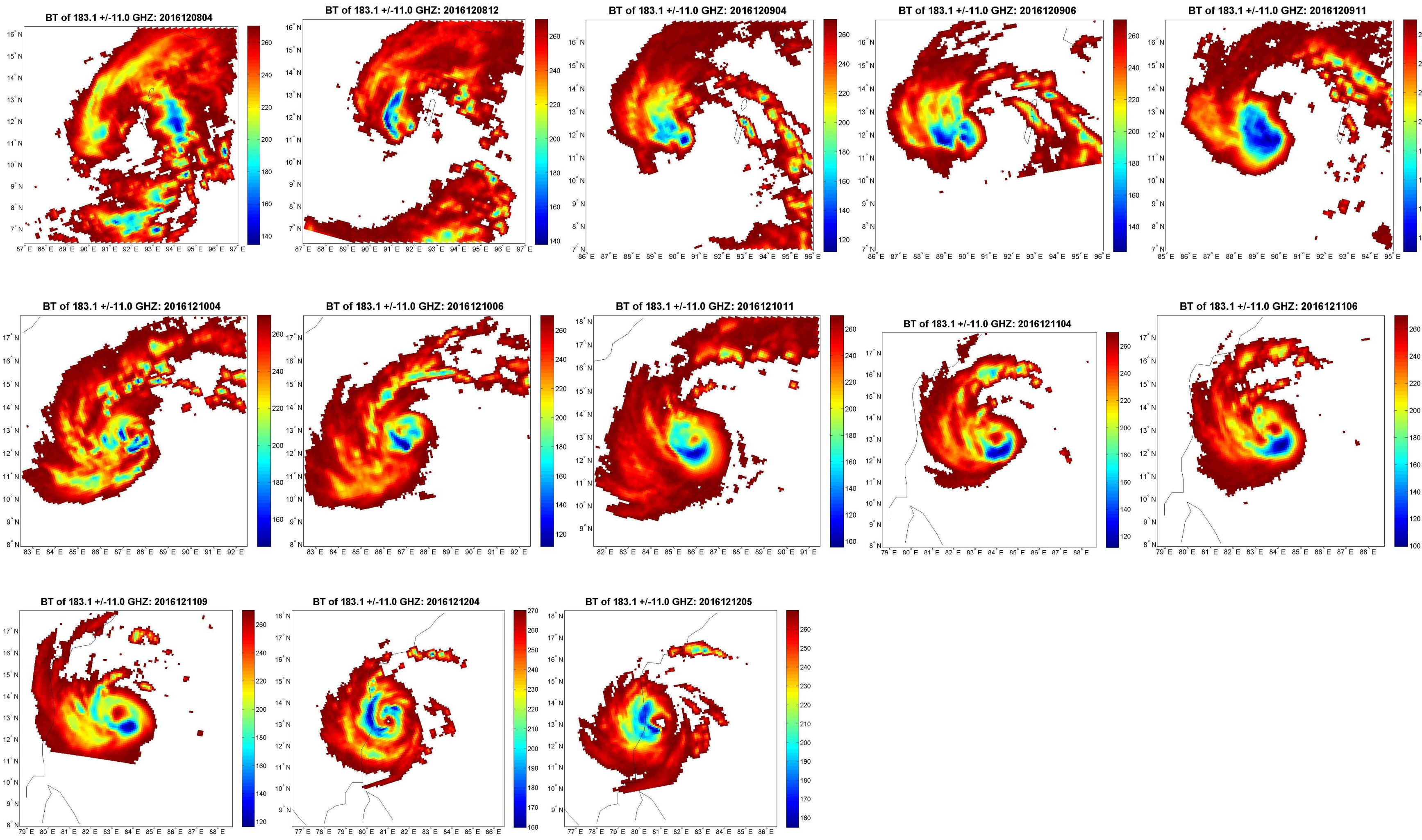


Figure 7: Cyclone centric products of INSAT3D imager channels

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 on 02Z 09 Dec, 12Z 10 Dec and 12Z 11 Dec have been shown in the Fig. 8. Such images are very useful to determine the lower level structure of cyclone and its geo-location.



BT of 183.1 +/-11.0 GHZ: 2016120804

BT of 183.1 +/-11.0 GHZ: 2016120812

BT of 183.1 +/-11.0 GHZ: 2016120904

BT of 183.1 +/-11.0 GHZ: 2016120906

BT of 183.1 +/-11.0 GHZ: 2016120911

BT of 183.1 +/-11.0 GHZ: 2016121004

BT of 183.1 +/-11.0 GHZ: 2016121006

BT of 183.1 +/-11.0 GHZ: 2016121011

BT of 183.1 +/-11.0 GHZ: 2016121104

BT of 183.1 +/-11.0 GHZ: 2016121106

BT of 183.1 +/-11.0 GHZ: 2016121109

BT of 183.1 +/-11.0 GHZ: 2016121204

BT of 183.1 +/-11.0 GHZ: 2016121205

Figure 8: BT values observed by SAPHIR channel-6 over the tropical cyclone VARDAH

5. Rainfall observed by INSAT-3D and 3DR over TC VARDAH

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 important 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 three successive days of IMSRA rainfall distribution over land and oceanic regions is shown in Fig. 9.

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-3DR 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).

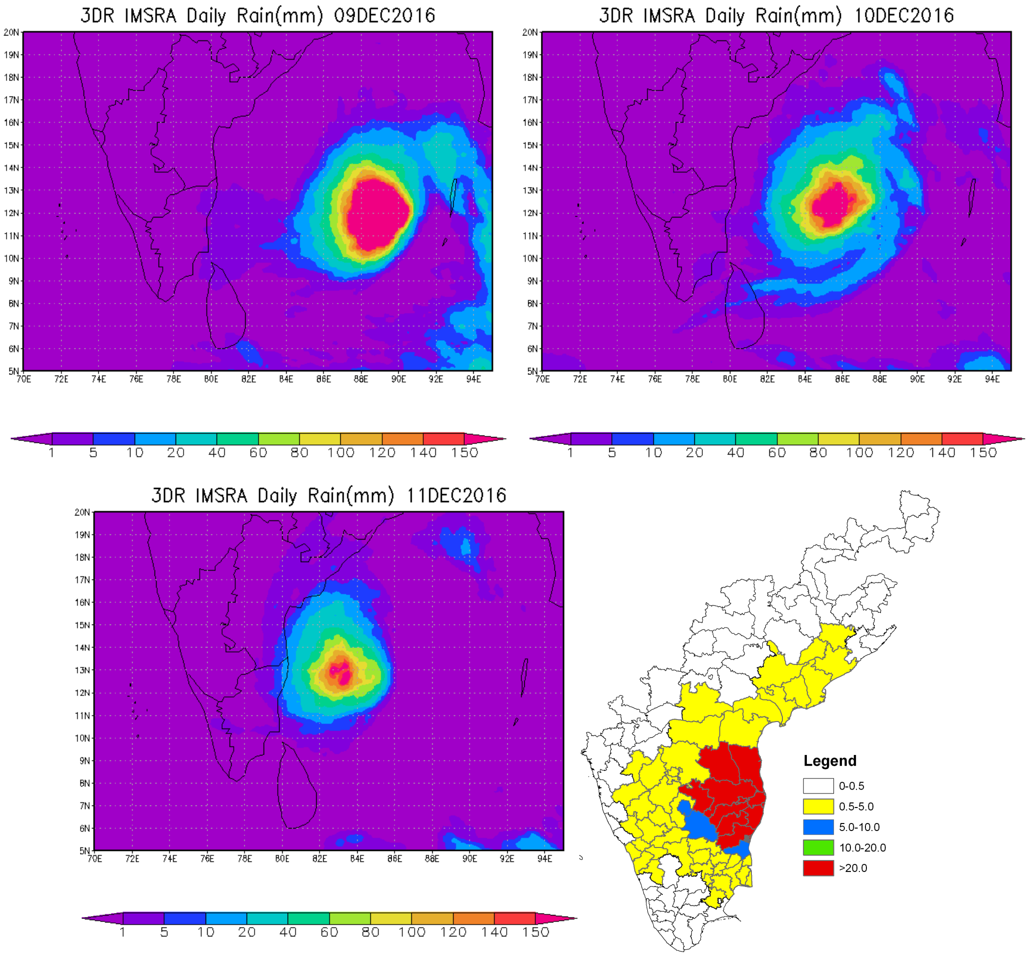


Figure 9: IMSRA rainfall distribution over land and oceanic regions and district wise IMSRA rainfall distribution over Indian region.

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