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Investigation of Tropical Cyclogenesis Using NWP Model Analysis and Forecasts over the Bay of Bengal

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Abstract
A tropical cyclone is a warm core intense low pressure system around which air circulates in anti-clockwise direction in northern hemisphere and in clockwise direction in the southern hemisphere. Tropical Cyclones (TCs)are one of the most devastating hazardous weather events in the world. In the present study, Genesis Potential Parameter (GPP) has been used to predict the tropical cyclogenesis using the Numerical Weather Prediction (NWP) model analysis as well as forecasts (up to 96-h). The National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) high resolution (0.25º ×0.25º) data is used to detect the genesis and its location of tropical cyclone before classified as a tropical cyclone (intensity ≥ 34 kt.) by India Meteorological Department(IMD). To identify the genesis, a threshold value of the GPPis determined by maximizing the Probability of Detection (POD) and minimizing the False Alarm Ratio (FAR). The threshold value has been computed using the data during the period 2015-2017 and it applied to predict for tropical cyclogenesis which formed over the Bay of Bengal (BoB) in the year 2018. The threshold value 60 is found as an optimum threshold to predict the cyclogenesis using GFS forecast fields. To ensure that the model wind fields are realistic, the GFS wind fields is compared with the scatterometer SCATSAT-1 wind fields also.The Megha-Tropiques SAPHIR Brightness Temperature (BT) values of tropical cyclones have been also analyzedbefore the tropical cyclone formation. The result shows that the tropical cyclogenesis can be predicted priorto 24 to 60-h of tropical cyclone formation.

Keywords*: Cyclogenesis, GFS, GPP, FAR and POD.*

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I. Introduction

Tropical Cyclones (TCs) are one of the most devastating hazardous weather events in the world due to its serious ecological, economical and human life damages. The prediction of genesis of TCs has been a great challenge to the operational forecasters. It creates strong winds and intenseprecipitation in the regions around the system. There are seven global basins that conceive TCs, viz. North Atlantic Ocean, eastern and western parts of North Pacific Ocean, south-western Pacific, south-western and south-eastern Indian Ocean and North Indian Ocean (NIO). The BoBlocated in the northeast of the Indian Ocean, is familiar and responsible for the formation of some of the strongest and deadliest TCs in the world. The BoB is a potentially energetic region for the development of cyclonic storms, accounting for about 7% of the global annual total number of tropical storms (Gray 1968). The BoBscoast is surrounded by among the countries of India, Bangladesh, Myanmar, Sri Lanka and the western part of Thailand. The average frequency of occurrence, season and intensity of TCs vary from basin to basin. TCs usually form over NIO basin in two seasons, which is in pre-monsoon (March-April-May) and post-monsoon (October–November) period. In the NIO basin with maximum frequency during post-monsoon period are comparatively stronger than pre-monsoon ones. Though the size of the TCs is relatively smaller and intensity is comparatively less over NIO basin as compared to the other global basins, but this region is quite important due to long and low line coast and highly dense populated area with poor socioeconomic conditions. Hence, this region is significant for the loss of life and property. Generally, BoB generating more numbers of cyclonic systems compared to Arabian Sea (AS) as BoB generally more stratified than AS because its upper-ocean part is relatively warmer resulting in higher Sea Surface Temperature(SST) and availability of more middle tropospheric moisture. Moreover,the shallow waters of the BoB, the low flat coastal terrain, and the funneling shape of the coast line can also lead to devastating losses of life and property.Whenever, any low-level circulation forms over the sea, meteorologists of the nearby countries show keen interest to know the possibility of cyclogenesis. The characterized of cyclogenesis by a decrease in the sea level pressure and an intensification of low-level circulation leading to increase in maximum sustained surface wind speed. Based on the intensity, TCs formed over NIO basin can be classified into (i) Depression if the associated 10-min Maximum Sustained Wind (MSW) is in between 17 and 33 kt; (ii) Cyclonic Storm (CS) if MSW is in between 34 and 47 kt; (iii) Severe Cyclonic Storm (SCS) if it has MSW of 48–63 kt; (iv) Very Severe Cyclonic Storm (VSCS) if the MSW is within the range 64–90 kt, and Extremely Severe Cyclonic Storm (ESCS) if the MSW is in range of 91–119 kt; and (v) Super Cyclonic Storm (SuCS) if it has MSW of 120 kt or more (http://www.rsmcnewdelhi.imd.gov.in). In this work, GPP has been used to predict the tropical cyclogenesis using the high-resolution GFS model analysis and forecast fields.

The following six environmental conditions are important for TC formation: warm SST, high Relative Humidity (RH), conditional instability, high low-level relative vorticity, weak vertical wind shear and enough Coriolis force (Gray 1968; Anthes 1982). Among these factors, high SST is favorable for TC genesis and intensification, whereas strong vertical wind shear is unfavorable for genesis and leads to weaken the intensity of the storm. TCs generally originate in tropics and thereafter, travel westward (Simpson, 1946) or turn pole ward and re-curve towards eastward direction (Elsberry, 1995; Sampson *et al.* 1995) or suffers extra-tropical transition over land or water (Jones *et al.*2003) before dissipation. The most common way of dissipation of a TC is its landfall. When the storm enters in land, it deprives itself from warm water and the available moisture over ocean and turns into a remnant low pressure area due to quick loss of energy. Also weakening can occur if it encounters a vertical wind shear that causes the heat engine and convection shift away from the center. During the past several decades, it has been shown that tropical cyclogenesis statistics at long time scales (e.g., seasonal) are closely related to the above discussed conditions (e.g., Gray 1975, 1979, Gray 1968; Anthes 1982). A technique based on wind pattern matching in low-level wind circulation among the developing systems has been discussed by Jaiswal and Kishtawal, (2011) to predict tropical cyclogenesis. A GPP was developed by Kotal *et al.* (2009) which consists of two thermodynamic and two dynamical variables. The dynamical variables which used in the computation are low-level relative vorticity and vertical wind shear. The thermodynamic variables are middle tropospheric relative humidity and instability. GPP is used to identify the potential cyclogenesis zone and also to understand the potential of cyclogenesis of a low pressure system (Kotal *et al.*2009; Kotal and Bhattacharya,2013). Hence, the early detection and prediction of cyclogenesis over the NIO can provide more lead time and also accurate early warning. The NIO being the data sparse region with limited ground observations and buoys/ships (Mohapatra *et al.* 2012), satellite plays a dominant role for early detection and prediction of cyclogenesis. The satellite data which are used to monitor TC genesis by infrared (IR) and visible imageries from Kalpana-1 and INSAT-3D and the microwave scatterometer onboard polar-orbiting satellites have helped to study the early stages of cyclogenesis (Liu *et al.* 1995) as they provide sea surface winds. The sea-winds scatterometer, onboard the QuikSCAT satellite that infers surface wind speed and direction, has encouraged various studies regarding early identification of tropical disturbances (Katsaros *et al.* 2001; Sharp *et al.* 2002). The analysis and forecasting of TCs may also suffer from inadequate model resolution. The outputs of NWP models are not uniform. So, there are bound to be wide variations in predictions of track and landfall point of any system.

The main objective of this study is to access the forecast skill of the high resolution GFS model to predict the tropical cyclogenesis and its location over the BoB. And also estimationof the optimal threshold value of GPP for cyclogenesis prediction over the BoB. Four cyclones which formed over the BoB in the year 2018 have taken for case study.

II. Description of the Selected Cyclones for NWP Study

The brief life history of the selected cyclones are as follows:

2.1 Cyclonic Storm 'Daye'over east-centralBay of Bengal and adjoining Myanmar (19-22 September 2018)

The initial stage low pressure area was formed over BOB on 18 September. A Depression (D)formed over east-central BoB at 1500 UTC of 19September. It intensified into a Deep Depression (DD) over west-central BoB in the morning (0300 UTC) of 20th and further into a Cyclonic Storm (CS)Daye in the same night (1500 UTC). It crossed south Odisha and north Andhra Pradesh coast close to Gopalpur (Odisha) as a CS with a wind speed of 60-70 kmph gusting to 80 kmphof 20September. It continued to move west-northwestwards, weakened into DD in the early morning of 21 September, into a D in the same evening (1200 UTC) and into a low pressure over west Madhya Pradesh and adjoining east Rajasthan in the evening of 22 September.It is the first cyclonic storm to develop over the NIO in the month of September after 2005. The system had intensification close to the coast 4 hours prior to landfall. According to IMD,the peak MSW of the cyclone was 60-70 kmph gusting to 80 kmph (35 knots gusting to 45 knots) during 1500-2100 UTC of 21September (IMD Preliminary Report, 2018). The lowest Estimated Central Pressure (ECP) was 992 hPa.

2.2Very Severe Cyclonic Storm 'Titli' over east-central Bay of Bengal (08-13 October 2018)

Very Severe Cyclonic Storm (VSCS) Titli originated from a low pressure area formed over southeast BoB and adjoining north Andaman Sea in the morning (0300 UTC) of 7 October. It concentrated into a D over east-centralBoB in the morning (0300 UTC) of 8 October. Moving west-northwestwards, it intensified into a DD over east-central BoB in the midnight (1800 UTC) of 8 October and further into a CS Titli around noon (0600 UTC) of 9 October. It moved north-westwards and intensified into a Severe Cyclonic Storm (SCS) in the late hours (2100 UTC)of09 October. Continuous moved north-northwestwards and further intensified into a VSCS around noon (0600 UTC) of 10 October. It crossed north Andhra Pradesh and south Odisha coasts near Palasa (18.8˚ N/84.5˚ E) to the southwest of Gopalpur of 11 October as a VSCS with the wind speed of 140-150 gusting to 165 kmph. Moving west-northwestwards, it weakened into an SCS around noon of 11th and as a CS in the same evening. It weakened into a DD over south Odisha in the midnight of 11 October. It further weakened into a D in the afternoon of 12 October, into a low pressure over Gangetic West Bengal and adjoining Bangladesh & north BoB in the early hours of 13 October. Titli was the most destructive cyclonic storm to strike Indian coast during 2018. The genesis of VSCS, Titli over BoB took place 45 hours after the genesis of VSCS, Luban over AS. It was one of the rarest of rare events that simultaneously two VSCSs developed over AS and BoB. According to IMD, the peak MSW of the cyclone was 140-150 kmph gusting to 165 kmph (80 knots) during 10 to 11October (IMD Preliminary Report, 2018). The lowest ECP was estimated as 972 hPa on 11 October.

2.3 Very Severe Cyclonic Storm 'Gaja'over east-central Bay of Bengal (10-19 November 2018)

Gaja originated as a Very Severe Cyclonic Storm (VSCS) from a low pressure area which formed over Gulf of Thailand and adjoining Malay Peninsula in the morning (0300UTC)of 8November**.** It lay as a well-marked low pressure area over north Andaman Sea and neighborhood in the evening (1200 UTC)of 9 November. It concentrated into a D over southeast BoB in the morning (0300UTC)of 10 November. Moving west-northwestwards, it intensified into a DD over southeast & adjoining central BoB in the same evening (1200 UTC). Further moving west-northwestwards, it intensified into CS Gaja over east-central and adjoining west-central & southeast BoB in the early morning (0000 UTC) of 11 November. After 12 November it recurved south-southwestwards and followed an anti-clockwise looping track till 13 November morning. It was then move west-southwestwards and intensified into a SCS over southwest BoB in the morning of 15 November and into a VSCS in the same night. It crossed Tamilnadu & Puducherry coast between Nagapattinam and Vedaranniyam near latitude 10.45° N and longitude 79.8° E with wind speed of 130 kmph gusting to 145 kmphof 16 November. Thereafter, it moved nearly westwards, and weakened rapidly into an SCS in the early morning, a CS in the morning and into a DD over interior Tamil Nadu in the forenoon of 16 November. It then moved west-southwestwards and weakened into a D in the same evening over central Kerala. Moving nearly westwards, it emerged into southeast AS in the same midnight. Moving westwards, it intensified into a DD over southeast AS in the early morning of 17 November and crossed as a DD Lakshadweep Islands in the 17th afternoon. It continued to move west-northwestwards and weakened into a Dover southeast AS around noon on 19th& into a low pressure over southwest & adjoining southeast AS in the same midnight.It was the first ever looping track cyclone over the BoB after 1996. The system had one of the longest track. Despite unfavorable environmental conditions, the system intensified into a VSCS just prior to landfall near to coast. According to IMD, the peak MSW of the cyclone was 130 kmph gusting to 145 kmph during 15 November (IMD Preliminary Report, 2018). The lowest ECP was estimated as 975 hPa.

2.4Severe Cyclonic Storm 'Phethai'over Southeast Bay of Bengal(13-18 December 2018)

Phethai originated from a low pressure area which formed over Equatorial Indian Ocean (EIO) and adjoining central parts of south BoB in the evening (1200 UTC)of 9 December. It lay as a well-marked low pressure area over central parts of south BoB and adjoining EIO in the morning of 11 December. It concentrated into D over southeast BoB in the early morning (0000 UTC) of 13 December. Moving north-northwestwards, it intensified into a DD over southeast BoB in the same midnight (1800UTC) of 13 December. It intensified into a CS Phethai in the evening (1200UTC) of 15 December and into a SCS in the afternoon of 16 December. It maintained its intensity of SCS till early morning of 17December and weakened into a CS in the same morning. Move north-northwestwards and then northwards it crossed Andhra Pradesh coast during 17December afternoon as a CS with MSW of 70-80 kmph gusting to 90 kmph. After landfall, it moved north-northeastwards and weakened rapidly into a DD over west-central BoB. According to IMD, the peak MSW of the cyclone was 100-110 kmph gusting to 120 kmph (55 knots) on16 December (IMD Preliminary Report, 2018). The lowest ECP was 992 hPa during the same period with pressure drop of 15 hPa.

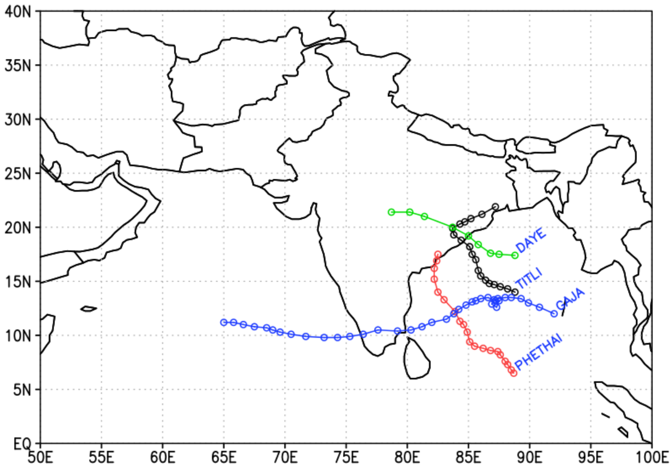


Fig. 1. The track of 4 cyclones formed over the BoB on 2018 (source: IMD)

III. Experimental Set up, Data Used and Methodology

The study area used in this work is BoB region that covers 5˚N-25˚ N, 80ºE-100˚ E. The NCEP-GFS high resolution (0.25˚ ×0.25˚) datasets are used in the present study. GFS is the global NWP model runs by NCEP (four times per day at 0000, 0600, 1200 and 1800 UTC) to generate forecasts up to 16 days in advance. It consists of a global forecasting model and initial conditions for the global forecasts are obtained through the Global Data Assimilation System (GDAS). GDAS uses a hybrid four-dimensional ensemble variational formulation (Hybrid 4DEnVar, Buehneret al. 2013). GFS is a global spectral model with a triangular spectral horizontal coordinate truncated after wave number T1534 (T574) for days 0-10 (days 10-16) forecasts and a hybrid sigma-pressure vertical coordinate implemented with 64 levels with the top layer centered around 0.27 hPa (approximately 55 km). The horizontal resolution is approximately 13 km (34km) at the equator for days 0-10 (days 10-16) forecasts. The basic data for this study is obtained from the GFS 6-hourly forecasted fields over the BoB domain (5ºN-25º N, 80ºE-100º E) for 0 to 96 hours forecast during the cyclogenesis period i.e. T0 to T0-3 (where T0 is the day when cyclone was identified as tropical storm by IMD and T0-3 is the 3 day before T0). In this work four TCs formed in the BoB during the period 2018 are analyzed. The details of these cyclones including the location and time of formation and maximum attained intensity have been given in the Table 1. The historical information of cyclones i.e., formation day and location is taken from IMD best track data. The GPP has been estimated using the 850 hPa wind fields, deep vertical wind shear (850-200 hPa), warm core (850-500 hPa) and mean relative humidity (700-500 hPa). In order to verify, GFS forecasted wind fields is compared with the SCATSAT-1 wind fields. The Megha-Tropiques SAPHIR BT values of TCs have been also analyzed before the TC formation. These products are available on Meteorological & Oceanographic Satellite Data Archival Centre (MOSDAC) cyclone web page (https://www.mosdac.gov.in/scorpio).

Table 1. Formation locations and time of 4 cyclones formed over BoB on2018.

No.	Cyclone Name	Life duration	IMD classification time as tropical storm	Maximum Intensity (knots)	Location of cyclone formation
1	Daye	19-22 September (04 days)	20/09/2018 1500 UTC	35	Lat. 18.7^0 N, Long. 85.6^0 E
2	Titli	08-13 October (06 days)	09/10/2018 0600 UTC	80	Lat. 14.8 ^{0}N, Long. 86.7^0 E
3	Gaja	10-19 November (10 days)	11/11/2018 0000 UTC	70	Lat. 13.4^0 N, Long. 89.3^0 E
4	Phethai	13-18 December (06 days)	15/12/2018 1200 UTC	55	Lat. 10.3^0 N, Long. 84.9^0 E

3.1 Estimation of Genesis Potential Parameter(GPP)

In this study, forecast skill of high resolution GFS data to predict the cyclogenesis and its location over the BoB domain is evaluated. For this purpose, the approach based on GPP has been used. The GPP value has computed at every grid point from following equation which is adapted from that of the study by Kotal *et al.* (2009):

$$GPP = \begin{cases} \dfrac{\zeta_{850} \times M \times I}{S} & if \quad \zeta_{850} > 0, M > 0, and \quad I > 0 \\ 0 & otherwise \end{cases} \qquad (1)$$

$$M = \frac{(RH - 40)}{30}$$

Where, ζ_{850} is low-level relative vorticity (at 850 hPa in $10^{-5}\,s^{-1}$), S is vertical wind shear (between 200 and 850 hPa in s^{-1}), RH is the mean relative humidity (between 700 and 500 hPa) and I is middle-tropospheric instability (temperature difference between 850 hPa and 500 hPa). The maximum GPP values have been determined at every 6-h interval up to 96 h forecasts initiated at 0000 UTC of T0 to T0-3 for all the 4 TCs which formed over the BoB in the year 2018.

3.2 Threshold Determination

The threshold value of the above discussed parameter is determined by maximizing the POD and minimizing the FAR. POD is the ratio of the total number of detected TC formation and total number of formed cases and FAR is the ratio of the total number of predicted TC formation that does not occur (develop) and total number of non-developed cases. To compute the POD, the TC formation has been determined by varying the different threshold values of the discussed parameter which is obtained by minimum of the all maximum values of GPP using GFS analysis fields on the day of TC formation of 8 cyclones (formed during the period 2015-17).

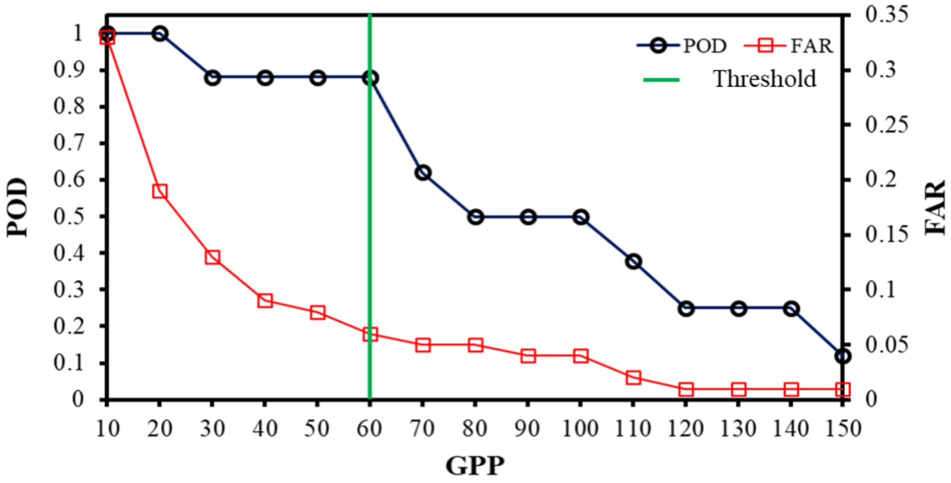


Fig. 2. Estimation of GPP threshold for the identification of tropical cyclogenesis.

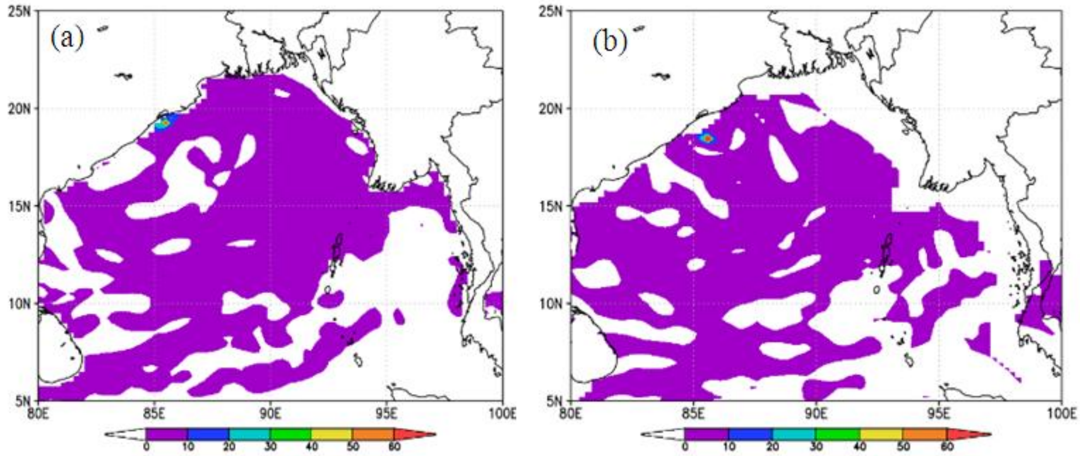
An important aspect of the GFS forecasted fields is to predict the cyclone formation that does not become TC. This allows assessment of false alarm. In order to determine the false alarms in NCEP GFS model 134 non-developed GFS model analysis fields were taken during the period 2015-17 for the months which are prone to the cyclonic activities. POD and FAR for different values of threshold of GPP has been shown in the Fig.2. For the GPP threshold value 60, the POD is maximum and FAR is minimum. Hence, the value 60 is chosen as a threshold for GPP to identify the cyclogenesis in GFS analysis as well as forecast fields.

IV. Results and Discussion

The skill of GFS model to predict the tropical cyclogenesis and its location is evaluated using the threshold value of GPP. The above discussed detection parameter is used to examine the forecasts of GFS model associated with TC formation during the period 2018 over the BoB. In this study, the forecasts (up to 96 hours) of GFS model for 4 TCs before the cyclone formation from T0 to T0-3 are analyzed. The formation time for each TC is taken as a time when the system was identified as tropical storm by IMD (shown in Table 1). The results of 4 TCs are discussed below.

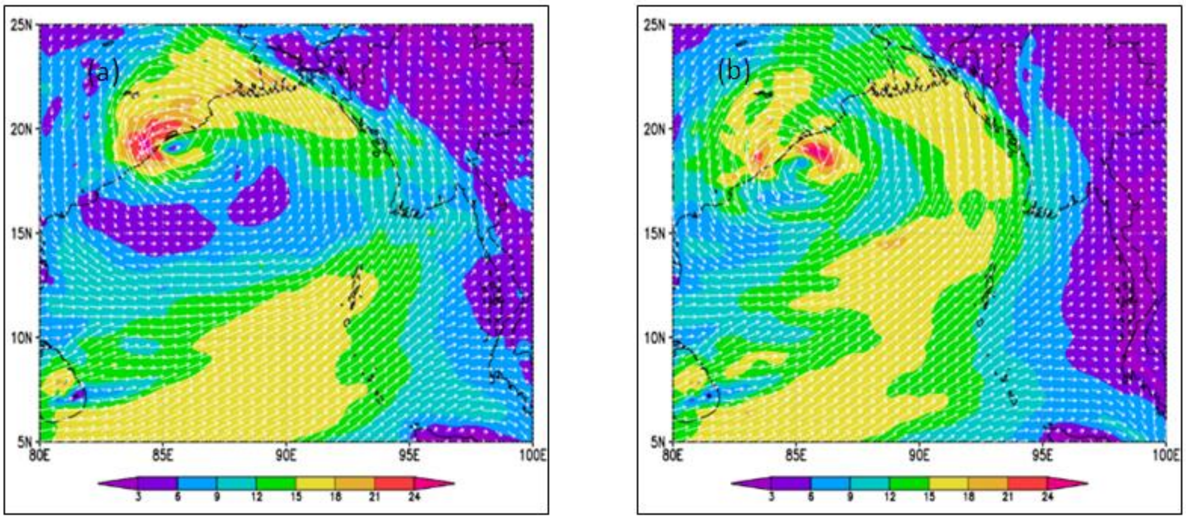
4.1 Case study of Cyclonic Storm Daye

The maximum value of GPP has been calculated for cyclone Daye from T0 to T0-3 at every 6-h interval up to 96-h forecast, where T0is the day when cyclone was identified as tropical storm by IMD and T0-3 is the 3-day before T0. However, figures have been shown only those forecasts where maximum GPP has crossed the threshold value i.e., 60. According to IMD, system converted into tropical cyclone at 1500 UTC of 20 September 2018 near latitude 18.7º N and longitude 85.6º E. So, that day is denoted as T0. The GPP value has been estimated up to 96 hours (6-hourly) forecasts generated from initial condition at 0000 UTC of 17-20 September2018. The maximum GPP value was found greater than the threshold value at 60-h forecast near the latitude 19.5º N and longitude 85.5º E generated from initial condition at 0000 UTC of 18 September 2018as shown in Fig.3(a), which is valid on formation time. At this forecast, the distance of the genesis position was found 90 km away from the observed. Further, maximum GPP was exceeded at 36-h forecast near latitude 19.0º N and longitude 85.25º E generated from initial condition at 0000 UTC of 19 September 2018as shown in Fig.3(b). For this, predicted genesis distance was found 50 km away from observed. The result analysis reveals that, using the GPP parameter, system has detected before 60- and 36-h priorto the formation using the GFS forecast fields. The wind fields of 850 hPa show the maximum magnitude greater than 24 m/s near the cyclone center are shown in Figs. 4(a-b)at 60- and 36-h forecast generated from initial condition at 0000 UTC of 18 and 19 September 2018. A new technique based on wind circulation pattern matching index (MI) developed by Jaiswal and Kishtawal, (2011) has been used to detect the tropical cyclone genesis signature using the scatterometer data. In this technique, if MI is found to be higher than a pre-determined threshold value i.e.,0.5, the tropical cyclogenesis is predicted. This technique is used to predict the early signature of tropical cyclone formation using the Indian scatterometer SCATSAT-1 (hereafter, SCATSAT) data in real time and products are available on Space Applications Centre (SAC), ISRO, MOSDAC. To ensure that the model wind fields are realistic, the wind fields of GFS model is compared with SCATSAT. The SCATSAT wind fields have been taken when tropical cyclogenesis is predicted using the technique Jaiswal and Kishtawal, (2011). SCATSAT wind fields at 13:46 UTC of 19 September 2018 are used to validate model wind fields. Since, GFS wind fields is not available at same time, so nearest time has been taken for verification. Hence, 12-h wind fields forecast initiated at 0000 UTC of 19 September 2018 is compared with SCATSAT as shown in Figs. 5(a-b).

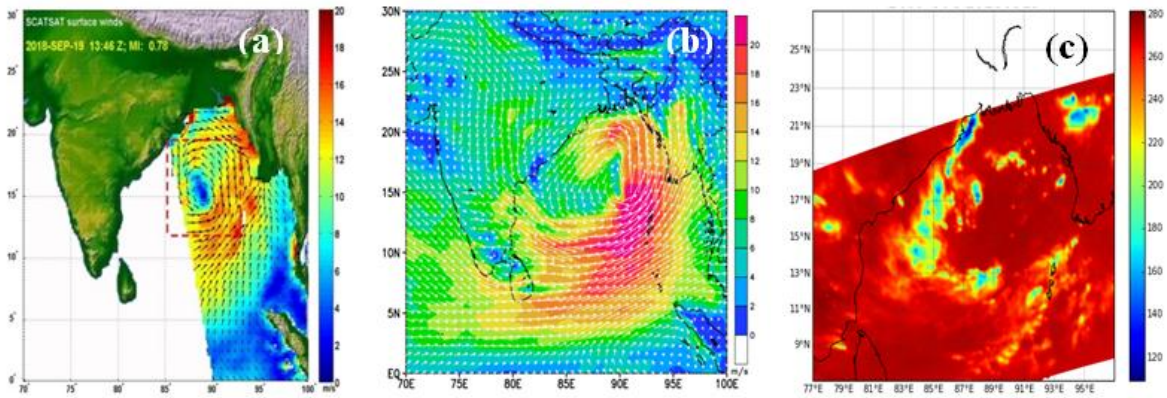


Figs. 3(a-b).(a) The maximum GPPat 60-h forecast generated from initial condition at 0000 UTC of 18 September 2018 and (b) GPP at 36-h forecast generated from initial condition at 0000 UTC of 19 September 2018.

The comparison shows that model able to capture the cyclonic circulation over the same area with maximum wind speed greater than 20 m/s near the center. The Megha-Tropiques SAPHIR BT of channel-6 has been shown about 24-h before the system identified as TC by IMD which is shown in Fig. 5(c). Low value of BT can be seen in the area of TC formation.



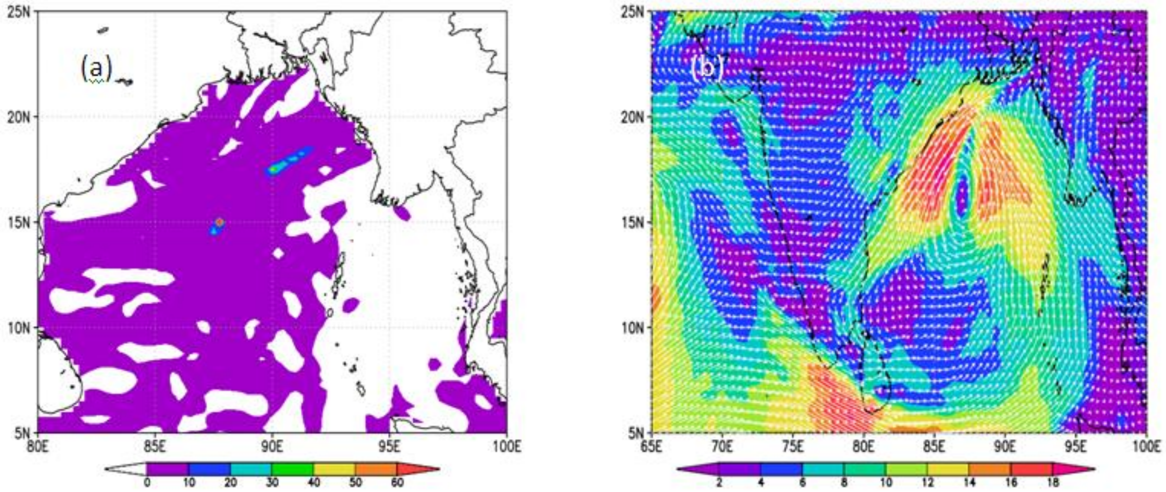
Figs. 4(a-b).(a) The 850 hPa wind fields at 60-h forecast generated from initial condition at 0000UTC of 18 September 2018 and (b) The 850 hPa wind fields at 36-h forecast generated from initial condition at 0000 UTC of 19 September 2018.



Figs. 5(a-c).(a) SCATSAT wind fields at 13:46 UTC of 19 September2018 for cyclone Daye. (Source: https://mosdac.gov.in/scorpio), (b) The 850 hPa wind fields of GFS for 12-h forecast based on 0000 UTC of 19 September 2018 for cyclone Daye and (c) The Megha-Tropiques SAPHIR BT(K) of channel-6 at 14:07 UTC of 19 Septe0ber2018. (Source: https://mosdac.gov.in/scorpio)

4.2 Case study of Cyclonic Storm Titli

The maximum value of GPP has been calculated for cyclone Titli from T0 to T0-3 at every 6-h interval up to 96-h forecast, where T0is the day when cyclone was identified as tropical storm by IMD and T0-3 is the 3-day before T0. According to IMD, system converted into tropical cyclone at 0600 UTC of 09 October 2018 nearlatitude 14.8º N and longitude 86.7º E. So, that day is denoted as T0. The GPP value hasbeen estimated up to 96 hours (6-hourly) forecasts generated from initial condition at 0000 UTC of 06-09October2018. The maximum GPP was found greater than the threshold value at 30-h forecast near latitude 15.25º N and longitude 87.5º E generated from initial condition at 0000 UTC of 08 October 2018 as shown in Fig. 6(a), which is valid on formation time. At this forecast, the distance of the genesis position was found 99 km away from the observed. The result analysis reveals that, using the GPP parameter, system has detected before 30-h prior to the formation of the system. The wind fields of 850 hPa show the maximum magnitude greater than 16 m/s near the cyclone center shown in Fig. 6(b)at 30-h forecast generated from initial condition at 0000 UTC of 08October2018.

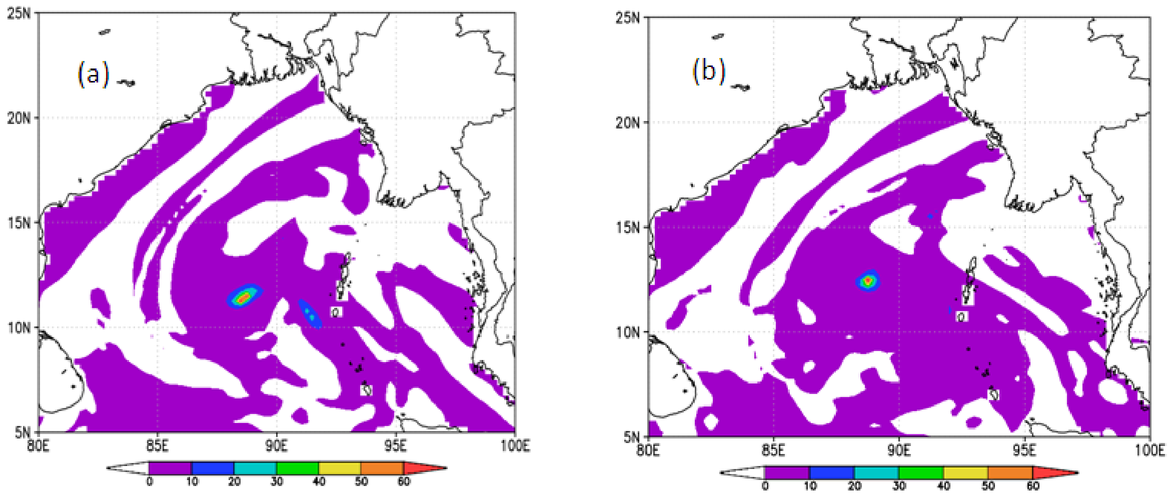


Figs. 6(a-b).(a) The maximum GPP at 30-h forecast generated from initial condition at 0000 UTC of 08 October 2018 and (b) The 850 hPa wind fields at 30-h forecast generated from initial condition at 0000UTC of 08 October 2018.

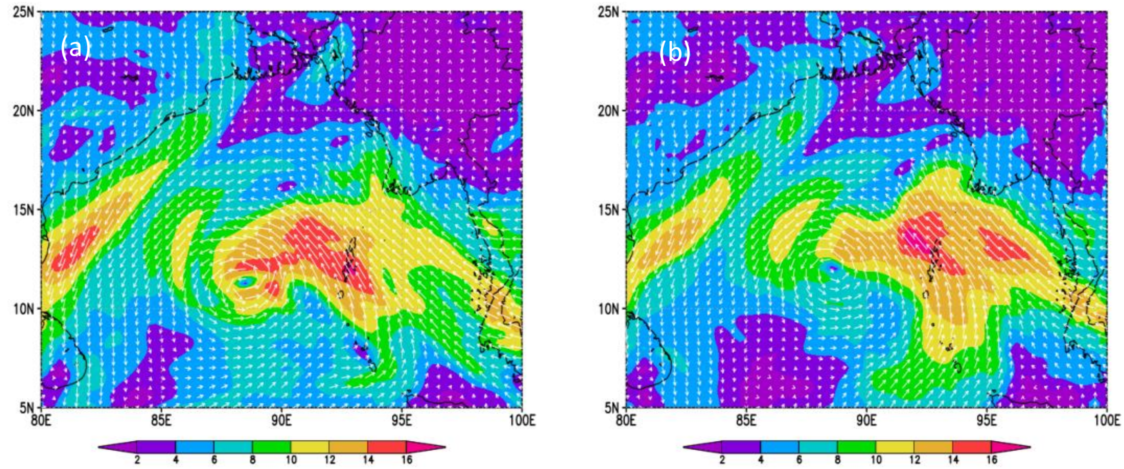
The SCATSAT wind fields and Megha-Tropiques SAPHIR BT of channel-6 data was not available during that time.

4.3 Case Study of Cyclonic Storm Gaja

The maximum value of GPP has been calculated for Gaja cyclone from T0 to T0-3 at every 6-h interval up to 96-h forecast. According to IMD, system converted into tropical cyclone at 0000 UTC of 11 November 2018 near latitude 13.4º N and longitude 89.3º E. Here, figures have been shown only those forecasts where maximum GPP has crossed the threshold value 60.The GPP value has been estimated up to 96-h (6-hourly) forecasts generated from initial condition at 0000 UTC of 08-11 November 2018. The maximum GPP value was found greater than the threshold value at 48-h forecast generated near latitude 12.0º N and longitude 88.5º E from initial condition at 0000 UTC of 09 November 2018 as shown in Fig. 7(a), which is valid on formation time. At this forecast, the distance of the genesis position was found 178 km away from the observed. Further, maximum GPP was found higher than threshold at 24-h forecast near the latitude 12.75º N and longitude 88.75º E generated from initial condition at 0000 UTC of 10 November 2018 is shown in Fig. 7(b). For this forecast, distance of the genesis position was found 94 km away from the observed.

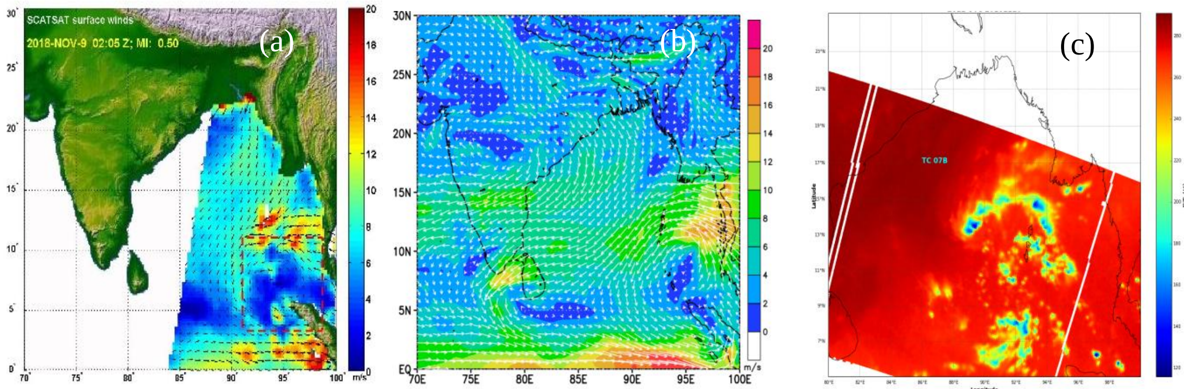


Figs. 7(a-b).(a)The maximum GPP at 48-h forecast generated from initial condition at 0000 UTC of 09 November 2018 and (b) GPP at 24-h forecast generated from initial condition at 0000 UTC of 10 November 2018.



Figs.8(a-b).(a) The 850 hPa wind fields at 48-h forecast generated from initial condition at 0000 UTC of 09 November 2018 and (b) The 850 hPa wind fields at 24-h forecast generated from initial condition at 0000 UTC of 10 November 2018.

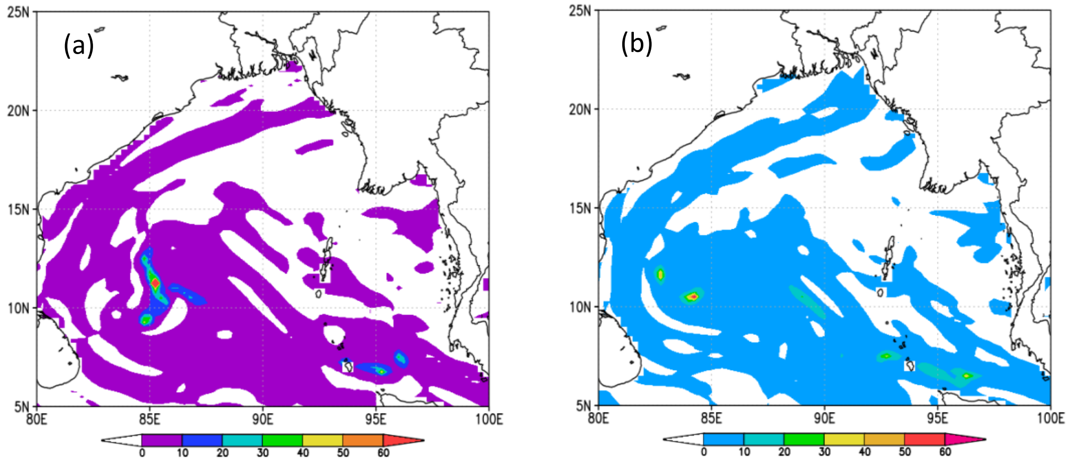
The result analysis reveals that, using the GPP parameter, system has detected before 48- and 24-h prior to the formation using the GFS forecast fields. The wind fields of 850 hPa show the maximum magnitude greater than 14 m/s and 12 m/snear the cyclone center are shown in Figs.8(a-b) at 48- and 24-h forecast generated form initial condition at 0000 UTC of 09 and 10 November 2018. To ensure that the model wind fields are realistic, the wind fields of GFS model is compared with SCATSAT. The comparison shows that model able to capture the cyclonic circulation over the same area are shown in Figs. 9(a-b). The Megha-Tropiques SAPHIR BT of channel-6 has been shown about 4-h before the system identified as TC as shown in Fig. 9(c). Low value of BT can be seen in the area of TC formation.



Figs.9(a-c).(a) The SCATSAT surface wind fields at 02:05 UTC of09 November 2018 for cyclone Gaja (Source: https://mosdac.gov.in/scorpio), (b) The 850 hPa wind fields of GFS at 0000 UTC of 09 November 2018 for cyclone Gaja and (c) The Megha-Tropiques SAPHIR BT(K) of channel-6 at 20:11 UTC of 10 November 2018 (Source: https://mosdac.gov.in/scorpio).

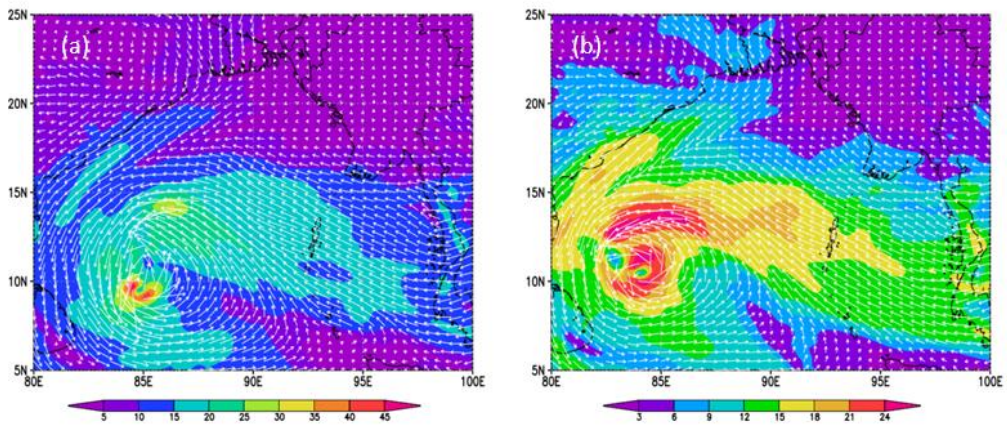
4.4 Case Study of Cyclonic Storm Phethai

The maximum value of GPP has been calculated and shown only those forecasts where maximum GPP has crossed the threshold.According to IMD, system hasconverted into tropical cyclone at 1200 UTC of 15 December 2018 near latitude 10.3º N and longitude 84.9º E. The GPP value has been estimated up to 96 h (6-hourly) forecasts generated from initial condition at 0000 UTC of 12-15 December 2018. The maximum GPP value was found greater than the threshold value at 60-h forecast near latitude 11.5º N and longitude 85.25º E generated from initial condition at 0000 UTC of 13 December 2018 as shown in Fig. 10(a). At this forecast, the distance of the genesis position was found 139 km away from the observed.

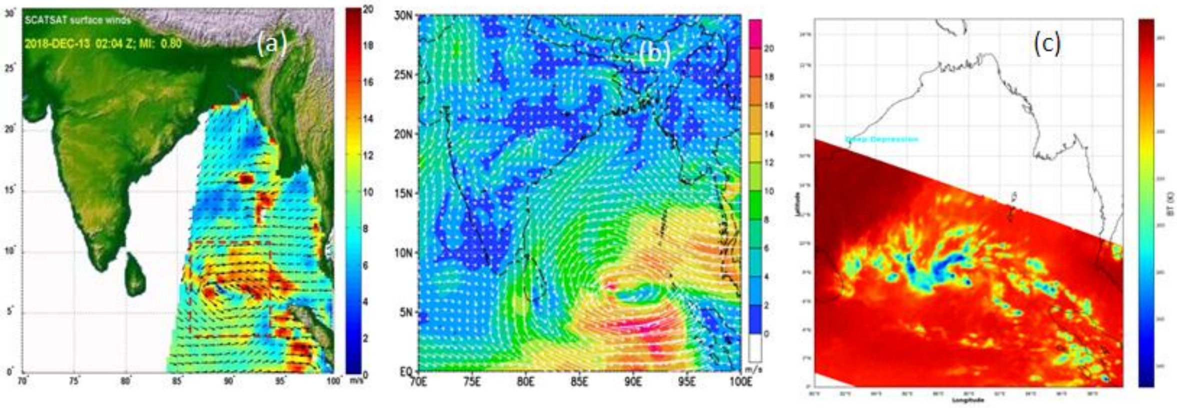


Figs. 10 (a-b).(a) The maximum GPP valueat 60-h forecast generated from initial condition at 0000 UTC of 13 December 2018 and (b) GPP at 36-h forecast generated from initial condition at 0000 UTC of 14 December 2018.

Further, maximum GPP was exceeded from the threshold at 36-h forecast near latitude 10.75º N and longitude 84.25º E generated from initial condition at 0000 UTC of 14 December 2018 is shown in Fig.10(b). The distance of the genesis position was found 87 km away from the observed. The result analysis reveals that, using the GPP, system has detected before 60- and 36-h priorto the formation using the GFS forecast fields. The wind fields of 850 hPa show the maximum magnitude greater than 45 and 24 m/s near the cyclone center are shown in Figs.11(a-b)) at 60- and 36-h forecasts generated form initial conditions at 0000 UTC of 13 and 14 December 2018. At 0000 UTC wind field of 13 December 2018 is compared with SCATSAT are shown in Figs.12(a-b).



Figs. 11(a-b).(a) The 850 hPa wind fields at 60-h forecast generated from initial condition at 0000 UTC of13 December 2018 and (b) The 850 hPa wind fields at 36-hforecast generated from initial condition at 0000 UTC of 14 December 2018.



Figs. 12(a-c).(a) The SCATSAT surface wind fields at 02:04 UTC of 13 December 2018 for cyclone Phethai (Source: https://mosdac.gov.in/scorpio),(b) The 850 hPa wind fields of GFS at 0000 UTC of 13 December 2018 for cyclone Phethai and (c) The Megha-Tropiques SAPHIR BT (K) of channel-6 at 06:25 UTC of13 December 2018 (Source: https://mosdac.gov.in/scorpio).

The comparison shows that model able to capture the cyclonic circulation over the same area with maximum wind speed greater than 20 m/s near the center. The Megha-Tropiques SAPHIR BT of channel-6 has been shown about 54-h before the system identified as TC by IMD as shown in Fig.12(c). Low value of BT can be seen in the area of TC formation.

V. Conclusion

In this work, the skill of GFS model to predict the tropical cyclogenesis and its location over the BoB has been examined using the GPP. For this purpose, an optimal threshold value of GPP has been determined by maximizing the POD and minimizing the FAR using the analysis fields of developed and non-developed cases during the period 2015-17. Hence, the threshold value 60 is found as an optimal threshold of GPP for genesis prediction. Thereafter, it is used to identify the tropical cyclogenesis of 4 TCs which formed over the BoB in the year 2018. The GPP have been computed at every 6-h interval up to 96-h forecasts before the formation of cyclone. The grid point where GPP is exceeded from threshold value is considered as location of the cyclogenesis. To ensure that the model wind fields are realistic, the wind fields of GFS model is compared with the SCATSAT. The Megha-Tropiques SAPHIR BT values of tropical cyclones have been also analyzed before the tropical cyclone formation. The result analysis of 4 TCs reveals that using GPP based parameter tropical cyclogenesis can be predicted 24-60 h prior tothe system identified as a TC over the BoB region.

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