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Tropical cyclone Genesis Potential Parameter (GPP) and it's application over the north Indian Sea

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सार – इस शोध पत्र में उत्तरी हिन्द महासागर में उष्णकटिबंधीय चक्रवात के बनने के विभव प्राचल (जी. पी. पी.) का विश्लेषण किया गया है। कोटल द्वारा विकसित (2009) चक्रवात बनने के विभव प्राचल का आकलन चार परिवर्तिताओं के आधार पर किया गया है जो इस प्रकार है : 850 हैक्टापास्कल पर भ्रमिलता, मध्य क्षोभमंडलीय सापेक्षिक आर्द्रता, मध्य क्षोभमंडलीय अस्थिरता और उस स्थान के सभी ग्रिड प्वाइंटों पर उर्ध्वाधर पवन अपरूपण। इन स्थितियों में ग्रिड प्वाइंट पर जी.पी.पी. पर यह विचार किया गया कि सभी परिवर्ती भ्रमिलता, मध्य क्षोभमंडलीय सापेक्षिक आर्द्रता, मध्य क्षोभमंडलीय स्थिरता और उर्ध्वाधर पवन अपरूपण शून्य से बड़ा है और यह माना गया है कि जब इनमें से कोई भी परिवर्ती शून्य से कम या बराबर हो तो वह शून्य ही माना जाएगा। यूरोपीय मध्यावधि मौसम पूर्वानुमान केन्द्र (इ.सी.एम.डब्ल्यू.एफ.) निदर्श आँकड़ों का उपयोग करते हुए इन परिवर्तिताओं का आकलन किया गया हैं। इ. सी. एम. डब्ल्यू. एफ. निदर्श की सूचनाओं (http://www.imd.gov.in/section/nhac/dynamic/analysis.htm पर उपलब्ध) का वास्तविक समय का उपयोग करते हुए सात दिनों तक के लिए जेनेसिस प्राचल के पूर्वानुमान भी तैयार किए गए। उस क्षेत्र में जी.पी.पी. के उच्चतर मानों से उस स्थान के जेनिसिस के उच्चतर विभव का पता चला है। उस स्थान पर जी.पी.पी. के मान 30 के बराबर अथवा अधिक होने की स्थिति में चक्रवात उत्पत्ति के लिए उच्च विभव क्षेत्र पाया गया है। प्राचल के विश्लेषण और 2010 में चक्रवाती विक्षोभों के दौरान इनकी प्रभावशीलता से उत्तरी हिन्द महासागर में चक्रवात उत्पत्ति के लिए पूर्वानुमान सूचक सिंगनल (4–5 दिन पहले) के रूप में और विकास की आरंभिक अवस्थाओं में विकसित और गैर–विकसित प्रणालियों के व्रीवीकरण के लिए विभव का निर्धारण हेतु इनकी उपयोगिता की पुष्टि हुई है।

ABSTRACT. An analysis of tropical cyclone genesis potential parameter (GPP) for the North Indian Sea is carried out. The genesis potential parameter developed by Kotal *et al.* (2009) is computed based on the product of four variables, namely: vorticity at 850 hPa, middle tropospheric relative humidity, middle tropospheric instability and the inverse of vertical wind shear at all grid points over the area. The GPP at a grid point is considered under the conditions that all the variables vorticity, middle tropospheric relative humidity, middle tropospheric instability and the vertical wind shear are greater than zero and it is taken as zero when any one of these variables is less or equal to zero. The variables are computed using the European Centre for Medium Range Weather Forecast (ECMWF) model data. Forecast of the genesis parameter up to seven days is also generated on real time using the ECMWF model output (available at http://www.imd.gov.in/section/nhac/dynamic/Analysis.htm). Higher value of the GPP over a region indicates higher potential of genesis over the region. Region with GPP value equal or greater than 30 is found to be high potential zone for cyclogenesis. The analysis of the parameter and its effectiveness during cyclonic disturbances in 2010 affirm its usefulness as a predictive signal (4-5 days in advance) for cyclogenesis over the North Indian Sea and for determining potential for intensification of developing and non-developing systems at the early stages of development.

Key words – Tropical cyclone, Cyclogenesis, Genesis potential parameter, Vorticity, Moisture variable, Instability and vertical wind shear.

1. Introduction

Forecast demonstration project on cyclone (FDP-cyclone) has been conducted since 2009 for the North Indian Sea. During the FDP, cyclone genesis and their movement are monitored. Prediction of cyclogenesis has been a most challenging task in the day to day cyclone monitoring work in FDP, particularly to declare a IOP (intense observation period). The tropical cyclone genesis has been attributed to both thermodynamic and dynamical factors. Palmen (1948) showed that hurricanes form over regions where Sea Surface Temperature (SST) is greater than 26° C. In addition to SST, other important factors for genesis of tropical cyclones are: large Coriolis force, high low level relative vorticity, weak vertical wind shear, moisture in the middle troposphere and convective instability (Gray 1975).

Gray (1978) defined a tropical cyclone genesis parameter as the product of three thermodynamic and three dynamical parameters. The three thermodynamic parameters are: SST above 26° C to a depth of 60 m, middle troposphere relative humidity and vertical gradient of equivalent potential temperature. The three dynamical parameters are: the Coriolis parameter, inverse of vertical wind shear and relative vorticity in the lower troposphere.

DeMaria *et al.* (2001) developed a genesis parameter to evaluate the potential of tropical cyclone formation in the North Atlantic between Africa and the Caribbean islands. They used scaled 5-day running mean vertical wind shear, instability, and moisture variables to define the genesis parameter. This genesis parameter can also explain intra and interseasonal variability in tropical cyclone formation.

Camargo *et al.* (2007) developed a Genesis Potential Index to evaluate the variations of tropical cyclone number with the annual cycle and El Nino-Southern Oscillation (ENSO) in various basins. The genesis potential index consists of four factors: low-level vorticity (850 hPa), relative humidity at 600 hPa, the magnitude of vertical wind shear from 850 to 200 hPa and potential intensity.

McBride (1981), McBride and Zehr (1981) examined the thermodynamic and dynamical fields around tropical systems. In their work they developed a Daily Genesis Potential parameter (DGP) which is defined as the difference of vorticity between 900 hPa and 200 hPa. The study showed that DGP is three times greater for developing systems than for non-developing systems, when averaged over 0 - 6° radius around the centre of cyclonic systems.

Zehr (1992) used vorticity at 850 hPa, divergence at 850 hPa and vertical wind shear to derive a genesis parameter (GP). He showed that this genesis parameter was useful in differentiating between non-developing and developing tropical disturbances in the western North Pacific. Roy Bhowmik (2003) observed that a low pressure system with GP value around 20×10^{-12} at T. No. 1.5 has the potential to intensify into a severe cyclonic storm, while one with GP value greater than 45×10^{-12} at T. No. 2.0 have the potential to intensify into a very severe cyclonic storm over the Indian Sea.

Kotal *et al.* (2009) developed a Genesis Potential Parameter (GPP) consisting of both dynamical as well as thermodynamic variables for differentiating non-developing and developing low pressure systems over the Indian Sea at their early development stages from T. No 1.0.

Among the genesis parameters described in various studies as stated in above, Zehr’s (1992) genesis parameter (GP) and the Daily genesis potential (DGP) parameter of McBride and Zehr (1981) used in differentiating between developing and non-developing tropical disturbances are consisting of dynamical parameters only. The area averaged genesis potential parameter (GPP) developed by Kotal *et al.* (2009) consisting of both dynamical as well as thermodynamical parameters in differentiating between developing and non-developing tropical disturbances over the north Indian Sea. Therefore, in this paper, grid point analysis and forecasts of the GPP is carried out on real time to identify the potential zone for cyclogenesis and area averaged GPP for determining potential for intensification of non-developing and developing low pressure systems in 2010 over the north Indian Sea at their early development stages.

Data and methodology is described in section 2. Applications of genesis potential (GPP) are illustrated in section 3. Threshold grid point GPP and its predictability are discussed in section 4. Concluding remarks are given in section 5.

2. Data and methodology

Every year a good number of low pressure systems form over the Indian Sea, but only a few of them intensify into a cyclonic storm. For the operational practice there is need to specify a genesis parameter for the Indian Sea, which could indicate (at early stages of development) the potential of the system for intensification into a cyclonic storm. The new insight in this study is the real time analysis of the GPP (consisting of both dynamical as well as thermo dynamical parameters) at the early stages (T. No. 1.0, 1.5, 2.0) of a cyclone to understand the potential for intensification (Developing or Non-developing system) of the system and the grid point analysis of the parameter for locating the most potential zone for cyclogenesis.

Kotal *et al.* (2009) developed a genesis potential parameter (GPP) using the variables vorticity at 850 hPa, middle tropospheric relative humidity, middle tropospheric instability and vertical wind shear variables. It was found from their analysis that all the variables used in GPP have distinct contribution to the intensification process of a low pressure system. The first three variables

TABLE 1

The details of tropical disturbances in 2010 used in this study

S. No.	Period	Year	Maximum intensity (kt)	Coast of Landfall
1	LAILA (17-21 May)	2010	55	Andhra Pradesh
2	BANDU (19-23 May)	2010	40	Gulf of Aden
3	PHET (31 May-7 June)	2010	85	Pakistan
4	GIRI (20-23 October)	2010	105	Myanmar
5	JAL (4-8 November)	2010	60	Tamilnadu
6	Depression (7-9 October)	2010	25	West Bengal -Bangladesh
7	Deep Depression (13-16 October)	2010	30	Orissa
8	Depression (7-8 December)	2010	25	Andhra Pradesh

TABLE 2

Area average GPP analysis of cyclone LAILA

Date/Time	16 May 2010 (1200 UTC)	17 May 2010 (0000 UTC)	17 May 2010 (1200 UTC)
T. No.→	1.0	1.0	2.0
Developing	11.1	11.1	13.3
Non-Developing	3.4	3.4	4.6
LAILA	17.4	13.5	16.5

contribute directly and fourth one contributes inversely to the intensification processes. The GPP was defined as:

$$GPP = \frac{\xi_{850} \, x \, \mathrm{M} x \mathrm{I}}{\mathrm{S}} \quad \text{if} \quad \xi_{850} > 0, \mathrm{M} > 0 \text{ and } \mathrm{I} > 0$$

$$= 0 \quad \text{if} \quad \xi_{850} \leq 0, \mathrm{M} \leq 0 \text{ or } \mathrm{I} \leq 0$$

Where, ξ_{850} = Low level relative vorticity (at 850 hPa) in 10^{-5} s^{-1}

S = Vertical wind shear between 200 and 850 hPa (ms^{-1})

$\mathrm{M} = \frac{[\mathrm{RH} - 40]}{30}$ = Middle troposphere relative humidity

Where RH is the mean relative humidity between 700 and 500 hPa

$\mathrm{I} = (T_{850} - T_{500})$ °C = Middle-tropospheric instability (Temperature difference between 850 hPa and 500 hPa).

Kotal *et al.* (2009) used the NCEP (National Center for Environmental Prediction) re-analysis data, which is available at 2.5° latitude-longitude grid for the comparison of GPP between developing and non-developing tropical disturbances. The variables were averaged over an area of radius 2.5° around the centre of cyclonic system and GPP was calculated from the stage T. No. 1.0 to T. No. 3.0. They found that the area average of GPP value equal or greater than 8.0 for developing systems and less than 8.0 for non-developing systems. In the present study, analysis and forecast fields at resolution 0.25° × 0.25° of ECMWF (European Centre for Medium Range Weather Forecast) are used to compute the GPP at each grid point. GPP is analyzed for cyclonic disturbances (LAILA, BANDU, PHET, GIRI, JAL and 3 Depressions) in 2010 over the North Indian Sea. Observed data of tropical cyclones in 2010 are obtained from annual report of the Regional Specialized Meteorological Centre (RSMC) at India Meteorological Department (IMD), New Delhi. The data table for the cyclones includes date, time, position in latitude and longitude, T. No. and maximum sustained winds in knots. These are estimated from post storm synoptic analysis based on all available observations and also by the analysis of cloud patterns in visible and

TABLE 3

Area average GPP analysis of cyclone PHET

Date/Time	31 May 2010 (0000 UTC)	31 May 2010 (1200 UTC)	01 June 2010 (0000 UTC)
T. No.→	1.0	1.5	2.0
Developing	11.1	12.3	13.3
Non-Developing	3.4	4.2	4.6
PHET	09.7	14.2	17.3

TABLE 4

Area average GPP analysis of cyclone GIRI

Date/Time	20 Oct 2010 (0000 UTC)	20 Oct 2010 (1200 UTC)	21 Oct 2010 (0000 UTC)
T. No.→	1.0	1.5	2.0
Developing	11.1	12.3	13.3
Non-Developing	3.4	4.2	4.6
GIRI	16.1	16.2	15.9

TABLE 5

Area average GPP analysis of cyclone JAL

Date/Time	03 Nov 2010 (0000 UTC)	04 Nov 2010 (0000 UTC)	05 Nov 2010 (0000 UTC)
T. No.→	1.0	1.5	2.0
Developing	11.1	12.3	13.3
Non-Developing	3.4	4.2	4.6
JAL	12.7	13.5	17.4

TABLE 6

Area average GPP analysis of Depression (7-9 October)

Date/Time	07 Oct 2010 (0000 UTC)	07 Oct 2010 (1200 UTC)	08 Oct 2010 (0000 UTC)
T. No.→	1.0	1.5	1.5
Developing	11.1	12.3	12.3
Non-Developing	3.4	4.2	4.2
Depression	18.4	14.3	14.5

infrared imagery of satellite (INSAT) following Dvorak (1975) technique. The life period, year, maximum intensity (T. No.) and coast of landfall of the cyclonic systems are summarized in the Table 1.

3. Applications of GPP

In this section, two applications of GPP are discussed namely, area average of GPP for determining potential for intensification of developing and non-developing systems at their early development stages as explained by Kotal *et al.* (2009) and grid point analysis of GPP as predictive signal to identify the potential cyclogenesis zone over the North Indian Sea.

3.1. *Area averaged GPP*

In this Section, the GPP were averaged over an area of radius 2.5° around the centre of cyclonic system as proposed by Kotal *et al.* (2009) from the stage T. No. 1.0

TABLE 7

Area average GPP analysis of Deep Depression (13-16 October)

Date/Time	13 Oct 2010 (0000 UTC)	14 Oct 2010 (0000 UTC)	15 Oct 2010 (0000 UTC)
T. No.→	1.0	1.5	1.5
Developing	11.1	12.3	12.3
Non-Developing	3.4	4.2	4.2
Deep Depression	16.7	23.4	15.7

TABLE 8

Area average GPP analysis of Depression (7-8 December)

Date/Time	07 Dec 2010 (0000 UTC)	08 Dec 2010 (0000 UTC)
T. No.→	1.0	1.5
Developing	11.1	12.3
Non-Developing	3.4	4.2
Depression	21.6	15.4

to T. No. 2.0 for cyclonic storms in 2010. They found that the area average of GPP value equal or greater than 8.0 for developing systems and less than 8.0 for non-developing systems. GPP for cyclonic storms LAILA, PHET, GIRI and JAL are presented in Table 2, Table 3, Table 4 and Table 5 respectively and GPP for one Deep Depressions and two Depressions are presented in Table 6, Table 7 and Table 8. GPP above the threshold value for all the cyclones clearly indicated the potential for intensification at their early stages of development. Although the GPP (above the threshold) of the three Depressions (Tables 6- 8) show enough potential for intensification but did not intensify. Previous study (Kotal *et al*., 2009) showed that 85% cases GPP values are less than threshold value for non-developing systems those form over the high sea. The plausible reasons for non-intensification of these systems into cyclone are, the systems were formed near the coast and therefore track over the sea was less, less life time over sea and also due to encounter with the coastal land mass. Further study is needed to estimate the critical lifetime and sea track of depressions to intensify into cyclone those form near coast.

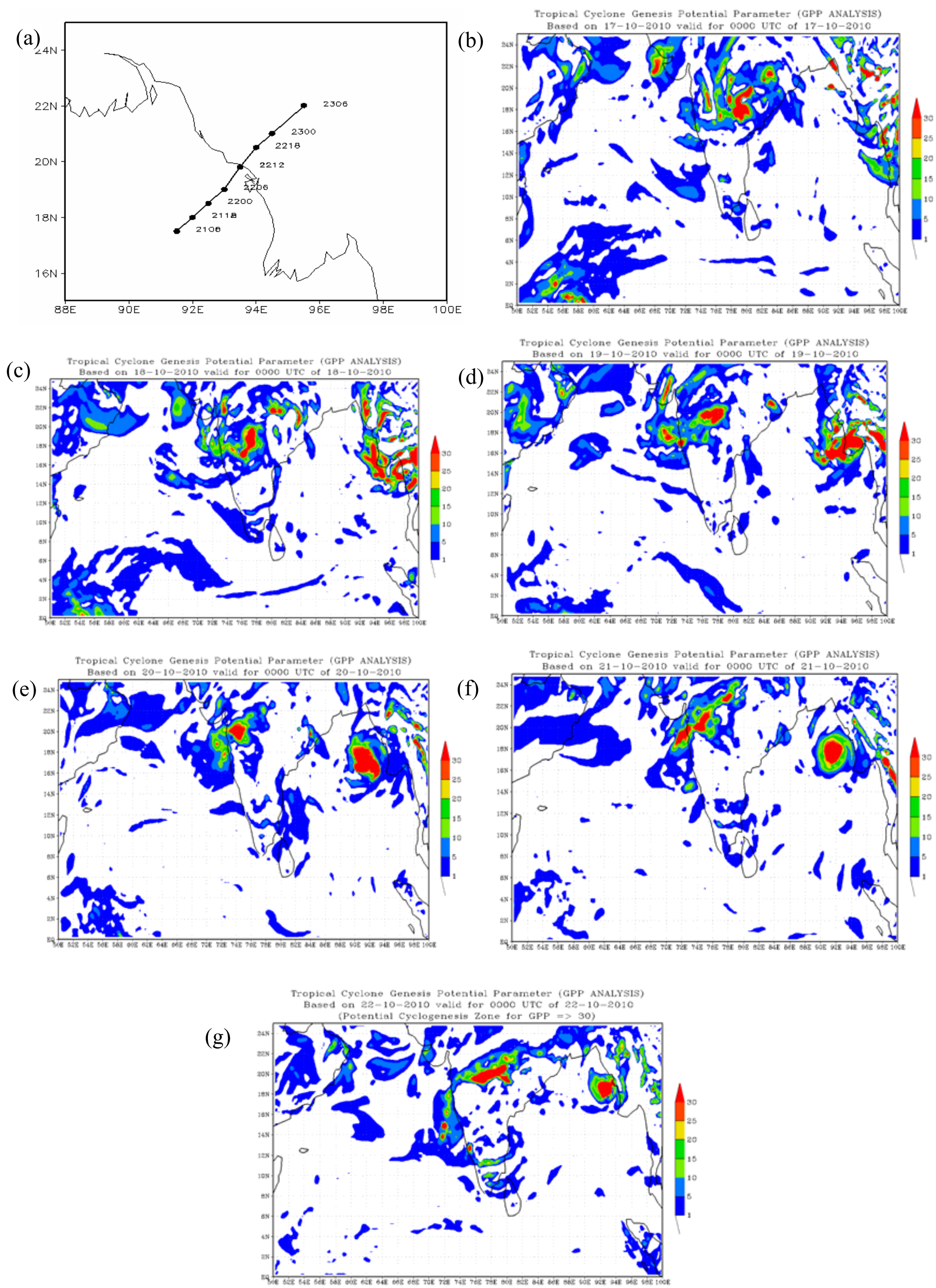
3.2. *Grid point analysis of GPP*

In this Section, case studies of grid point analysis of GPP associated with two very severe cyclonic storms (VSCS), two severe cyclonic storms (SCS), one cyclonic storm (CS), one deep depression (DD) and two depression (D) those formed over the north Indian Sea in 2010 are presented and discussed.

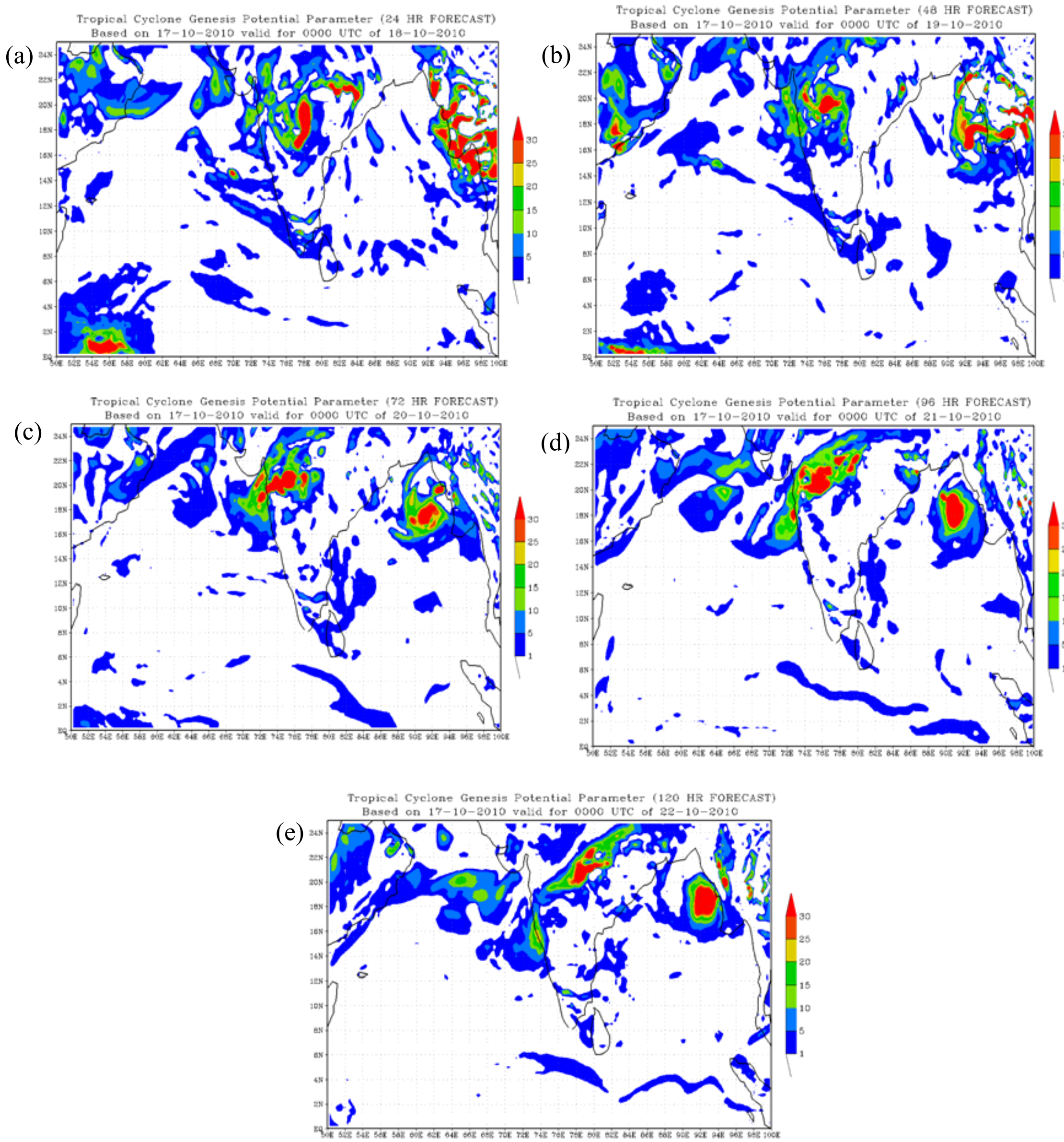
Case I : Very severe cyclonic storm GIRI (20-23, October 2010)

A low pressure area formed over the east central Bay of Bengal on 19 October 2010. It intensified into a deep depression and into a cyclonic storm, GIRI on 21 October. It then moved northeastwards and intensified into a severe cyclonic storm on 22 October and into a very severe cyclonic storm on the same day. The system crossed Myanmar coast around 1400 UTC of 22 October 2010 with estimated sustained maximum wind speed 105 knots.

The track of the cyclone GIRI is shown in Fig 1(a). Analyses of genesis potential parameter (GPP) at 0000 UTC from 17 October 2010 to 21 October 2010 are shown in Figs. 1(b-f). Gradual organization of GPP zone is noticed during the period. At 0000 UTC of 17 October no zone of GPP greater than 30 is noticed over the region north of latitude 5° N in the North Indian Sea. At 0000 UTC of 18 October cluster of GPP greater than 30 appeared over the East central Bay of Bengal primarily indicated development of a potential zone of cyclogenesis. Organization of the GPP cluster on the next day (0000 UTC of 19 October) affirmed the formation of a low pressure area over the area. Subsequent organization (circular in structure) of the GPP cluster on 0000 UTC of 20 October and 21 October at the stage of depression fairly indicated further intensification of the low pressure system in the subsequent hours.



Figs. 1 (a-g). Track and analysis of Genesis Potential Parameter (GPP) for cyclone GIRI: (a) Track of GIRI (b) 0000 UTC 17 October 2010, (c) 0000 UTC 18 October 2010, (d) 0000 UTC 19 October 2010, (e) 0000 UTC 20 October 2010, (f) 0000 UTC 21 October 2010, (g) 0000 UTC 22 October 2010

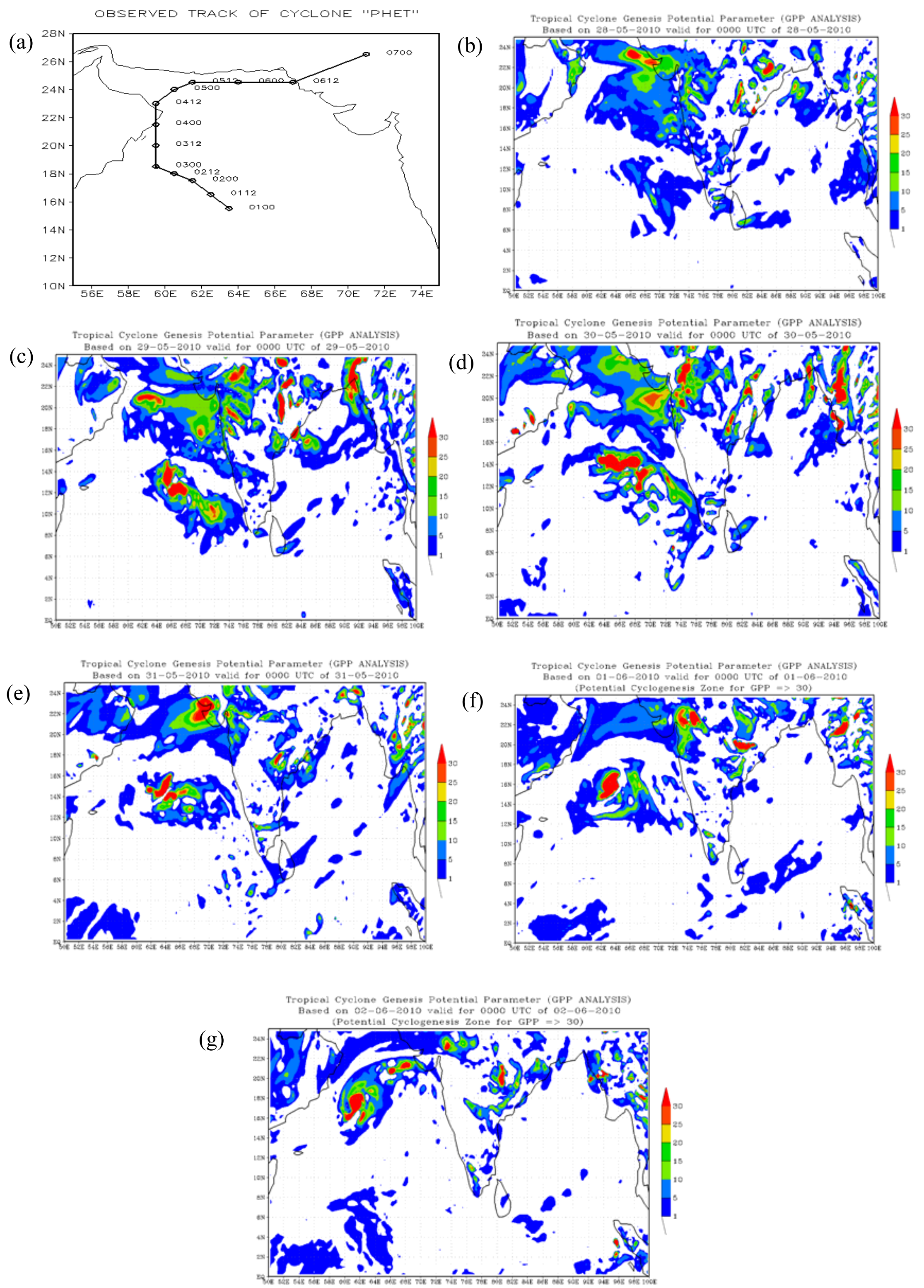


Figs. 2(a-e). Forecasts of Genesis Potential Parameter (GPP) for cyclone GIRI based on 0000 UTC of 17 October 2010: (a) 24 hrs, (b) 48 hrs, (c) 72 hrs, (d) 96 hrs and (e) 120 hrs

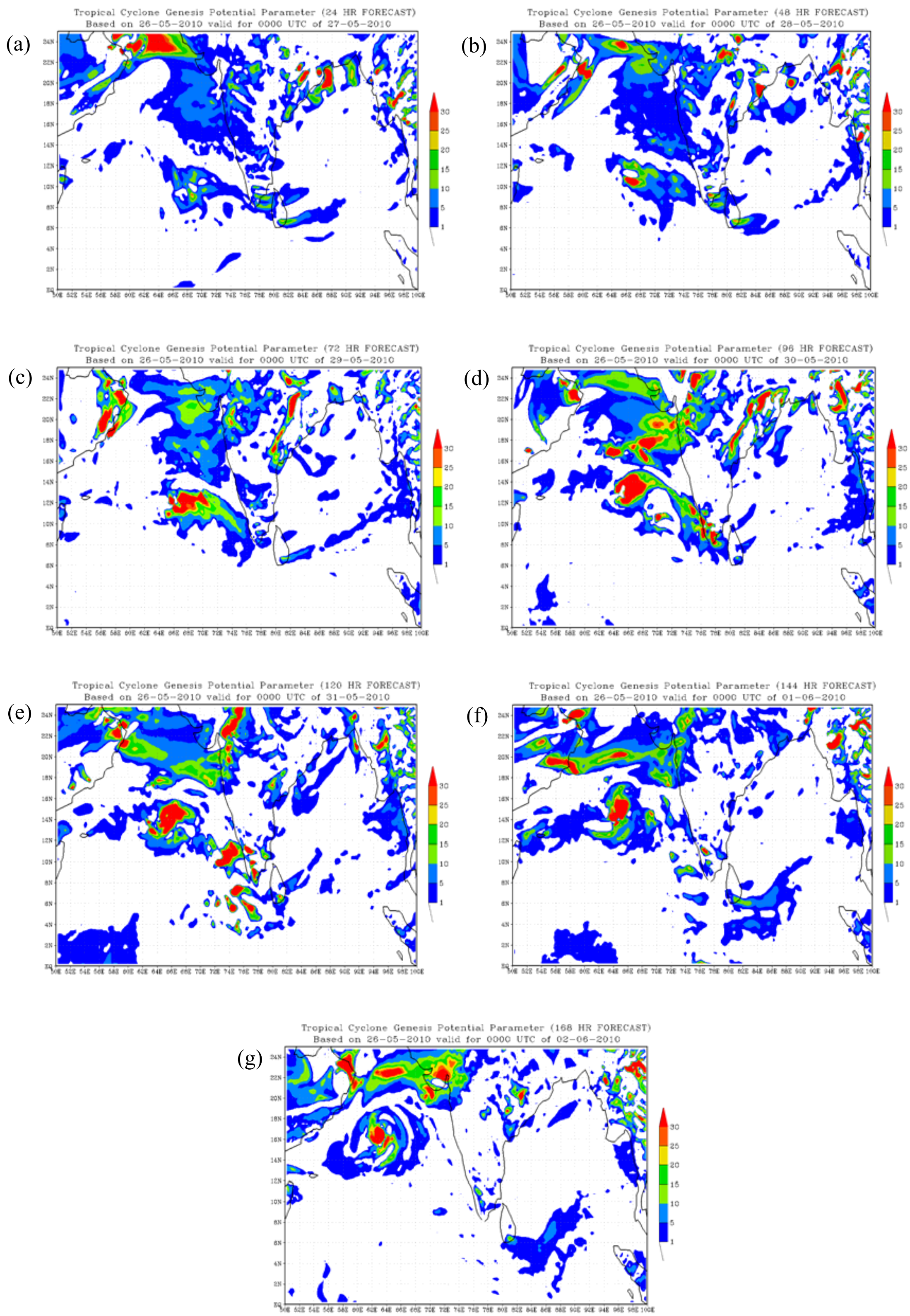
Five days forecasts at 24 hour intervals based on 0000 UTC of 17 October 2010 as shown in Figs. 2(a-e) also indicated the development of potential cyclogenesis zone(GPP $\geq$ 30). Rapid organization of GPP clearly indicated the formation of a low pressure area and its potential of significant intensification into very severe cyclonic storm over the East central Bay of Bengal. The analysis and corresponding forecasts GPP as shown in Figs. 1(b-f) and Figs. 2(a-e) shows that forecasts could captured the organization of GPP as well as their location fairly well.

Case II : Very severe cyclonic storm PHET (31 May-7 June, 2010)

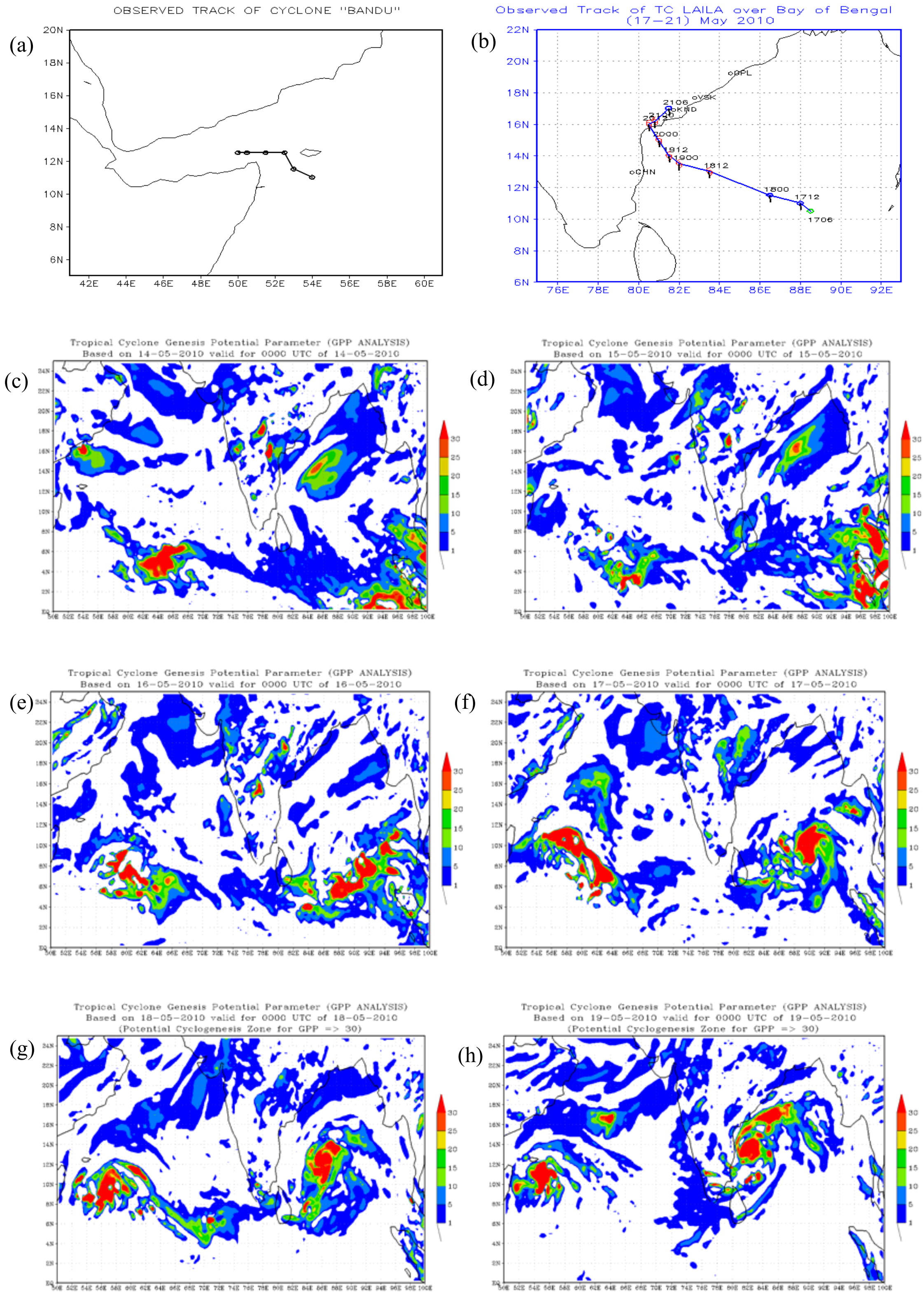
A low pressure area formed over the east central Arabian Sea on 30 May 2010 and concentrated into a depression on 31 May 2010. Subsequently it intensified into a deep depression and thereafter a cyclonic storm, PHET on 1 June 2010. The system intensified into a severe cyclonic storm on 2 June, and further intensified into a very severe cyclonic storm on the same day over the same region. The system moved north-westwards and



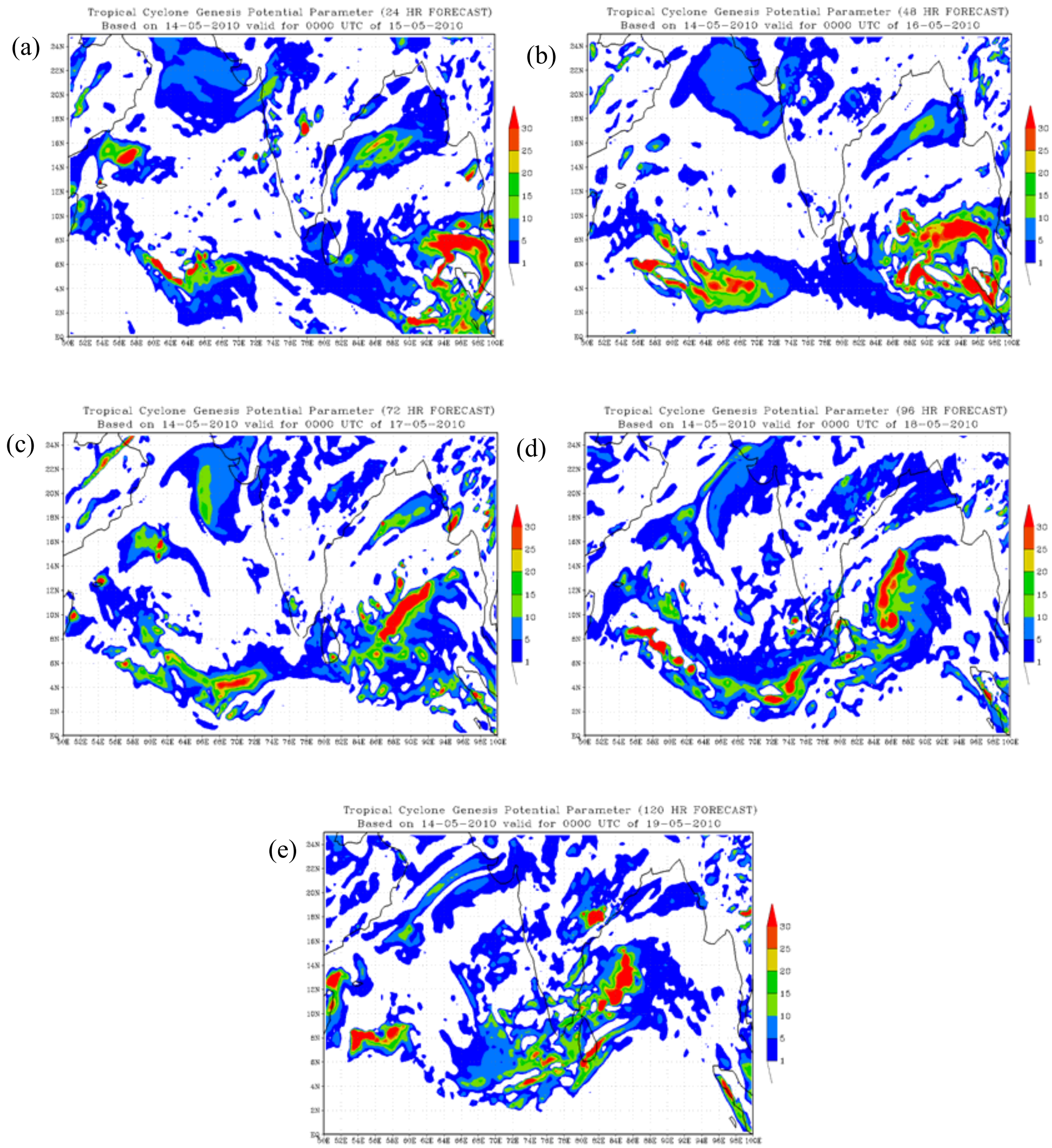
Figs. 3(a-g). Track and analysis of Genesis Potential Parameter (GPP) for cyclone PHET: (a) Track of PHET (b) 0000 UTC 28 May 2010, (c) 0000 UTC 29 May 2010, (d) 0000 UTC 30 May 2010, (e) 0000 UTC 31 May 2010, (f) 0000 UTC 1 June 2010, (g) 0000 UTC 2 June 2010



Figs. 4(a-g). Forecasts of Genesis Potential Parameter (GPP) for cyclone PHET based on 0000 UTC of 26 May 2010 : (a) 24 hrs, (b) 48 hrs, (c) 72 hrs, (d) 96 hrs, (e) 120 hrs, (f) 144 hrs and (g) 168 hrs



Figs. 5(a-h). Track and analysis of Genesis Potential Parameter (GPP) for cyclone LAILA and BANDU: (a) Track of BANDU (b) Track of LAILA (c) 0000 UTC 14 May 2010, (d) 0000 UTC 15 May 2010, (e) 0000 UTC 16 May 2010, (f) 0000 UTC 17 May 2010, (g) 0000 UTC 18 May 2010, (h) 0000 UTC 19 May 2010

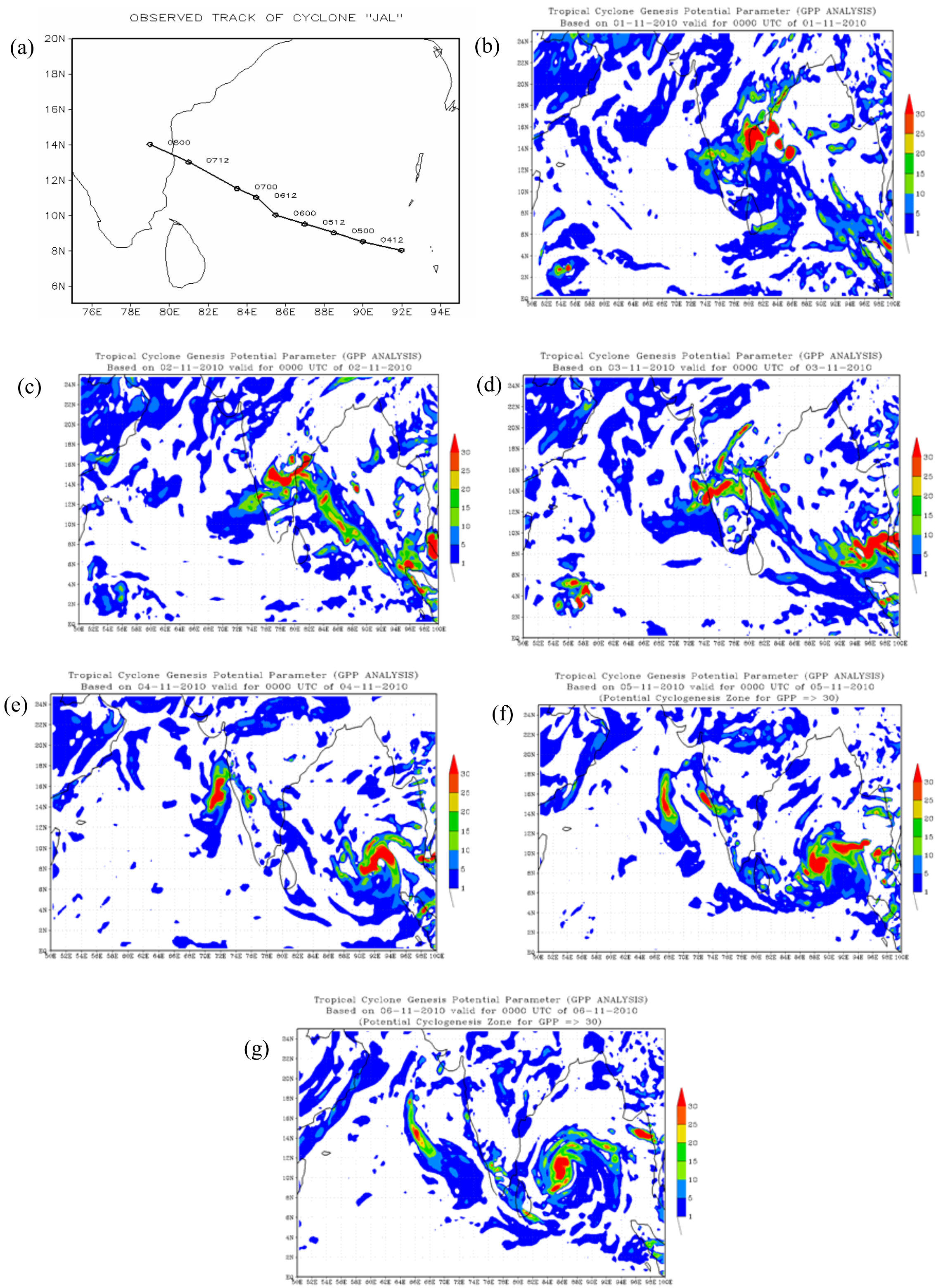


Figs. 6(a-e). Forecasts of Genesis Potential Parameter (GPP) for cyclone LAILA based on 0000 UTC of 14 May 2010: (a) 24 hrs, (b) 48 hrs, (b) 72 hrs, (c) 96 hrs and (d) 120 hrs

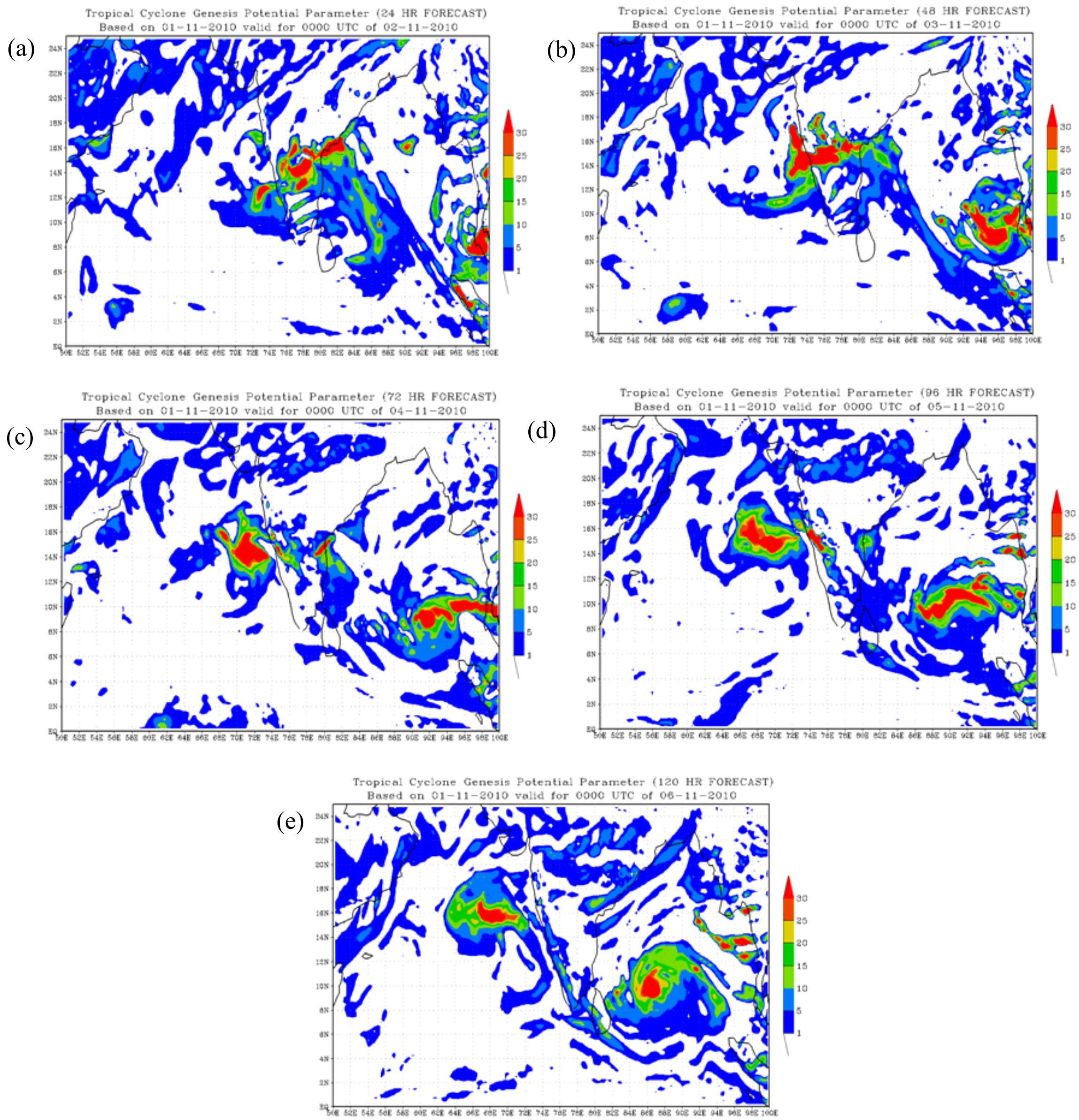
crossed Oman coast between 0000 & 0200 UTC of 3 June near Lat. 21.50° N.

Track of the cyclone PHET is shown in Fig. 3(a). Analyses of GPP at 0000 UTC from 28 May to 31 May 2010 are shown in Figs. 3 (b-e). The figures show that there was no signal of cyclogenesis over the east central Arabian Sea at 0000 UTC of 28 May 2010 [Fig. 3(b)]. Development of GPP cell (≥ 30) over the east central Arabian Sea at 0000 UTC of 29 May 2010 [Fig. 3(c)] was the initial indication of a potential zone of cyclogenesis. Persistent GPP cell over the region on the next day (0000 UTC of 30 May) indicated the formation of a low pressure area over the area.

Seven days forecasts at 24 hrs intervals based on 0000 UTC of 26 May 2010 are shown in Figs. 4(a-g). The forecasts show the development of GPP cell and its organization. The development of GPP cell and its subsequent organization in the form of spiral structure [Figs. 4(f-h)] indicated well in advance the potential



Figs. 7(a-g). Track and analysis of Genesis Potential Parameter (GPP) for cyclone JAL: (a) Track of JAL (b) 0000 UTC 1 November 2010, (c) 0000 UTC 2 November 2010, (d) 0000 UTC 3 November 2010, (e) 0000 UTC 4 November 2010, (f) 0000 UTC 5 November 2010 and (g) 0000 UTC 6 November 2010



Figs. 8(a-e). Forecasts of Genesis Potential Parameter (GPP) for cyclone JAL based on 0000 UTC of 1 November 2010: (a) 24 hrs, (b) 48 hrs, (c) 72 hrs, (d) 96 hrs and (e) 120 hrs

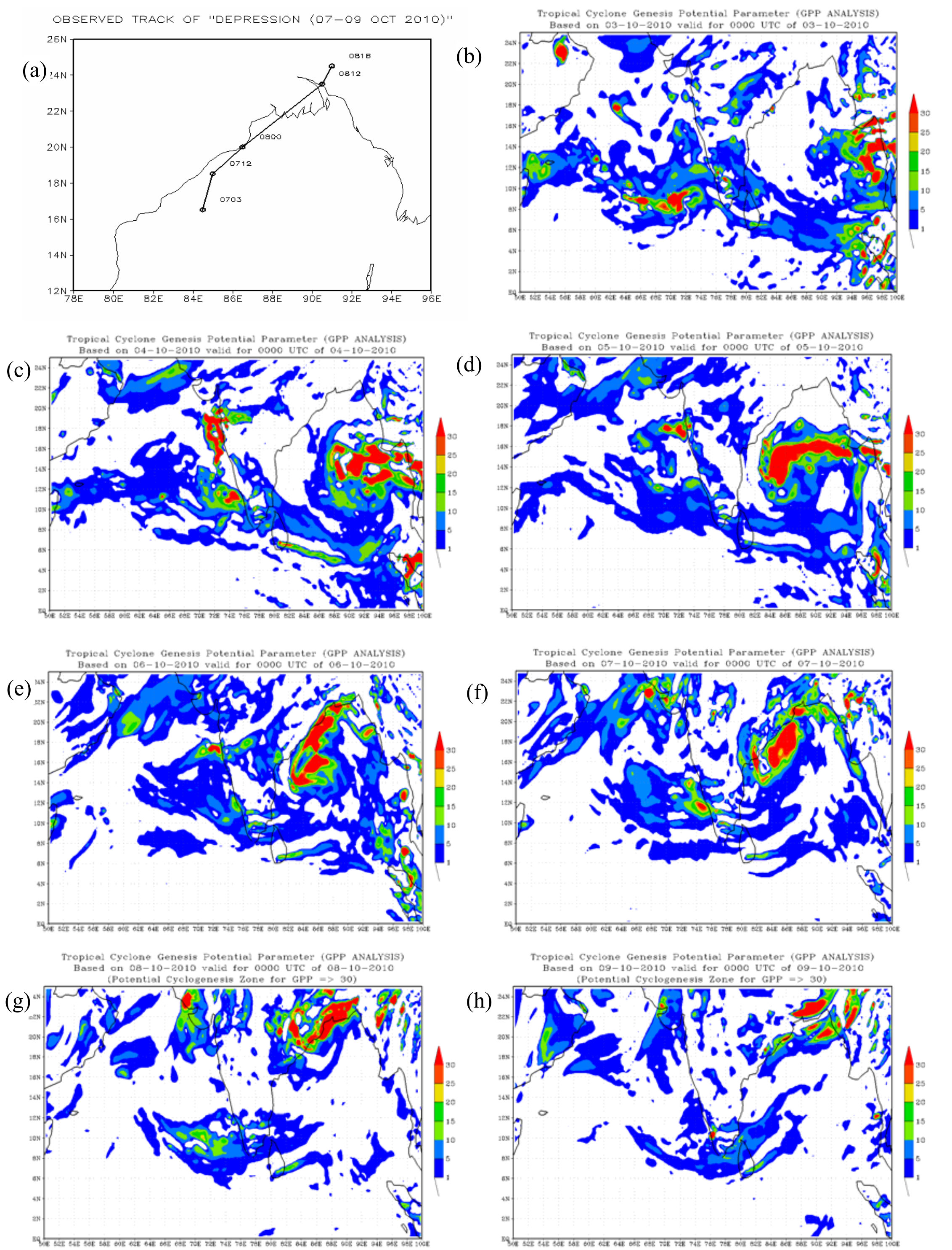
cyclogenesis zone and its intensification into cyclonic storm over the Arabian Sea.

Case III : Severe cyclonic storm LAILA (17-21 May, 2010) & cyclonic storm BANDU (19-23, May 2010)

(a) *LAILA*

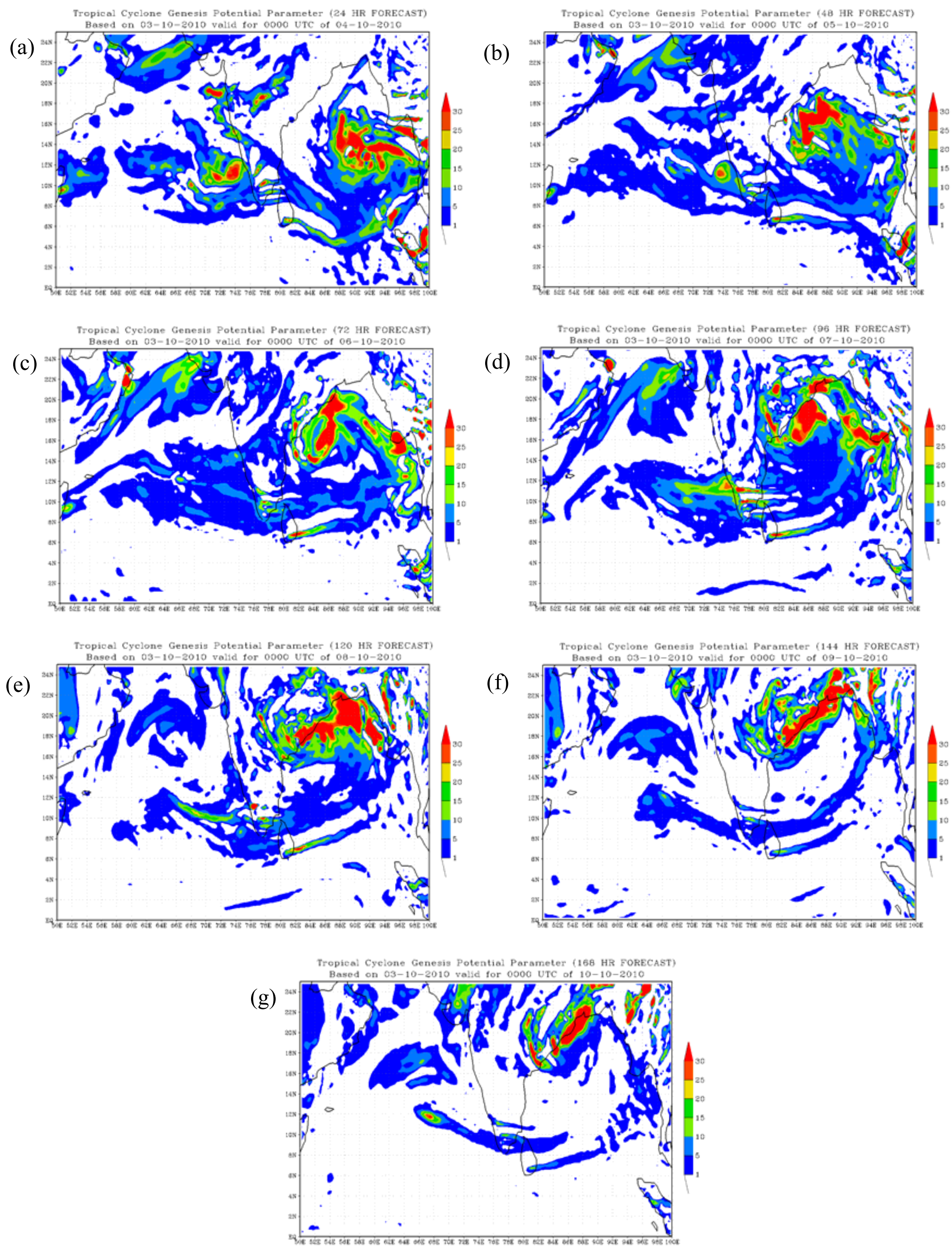
A low pressure area developed over the southeast Bay of Bengal at 1200 UTC of 16 May 2010 and concentrated into a depression on 17 May. The development of the system was very fast and moving northwestwards the system intensified into a cyclonic storm, LAILA on 18 May, 2010 over southeast and adjoining southwest Bay of Bengal. It further intensified into a severe cyclonic storm on 19 May, 2010 over southwest and southeast Bay of Bengal and crossed Andhra Pradesh coast near Bapatla between 1100 and 1200 UTC of 20 May, 2010.

The track of the cyclone LAILA is shown in Fig 5(a). Analyses of GPP at 0000 UTC from 14 May 2010 to 17 May 2010 are shown in Figs. 5(c-f). Gradual organization and northwesterly movement of GPP zone



Figs. 9(a-h). Track and analysis of Genesis Potential Parameter (GPP) for Depression (7-8) October 2010: (a) Track of Depression (b) 0000 UTC 3 October 2010, (c) 0000 UTC 4 October 2010, (d) 0000 UTC 5 October 2010, (e) 0000 UTC 6 October 2010, (f) 0000 UTC 7 October 2010, (g) 0000 UTC 8 October 2010, (h) 0000 UTC 9 October 2010

over the south Andaman Sea and southeast Bay of Bengal is noticed during the period. At 0000 UTC of 14 May isolated cell of GPP greater than 30 is appeared over the south Andaman Sea. At 0000 UTC of 15 May the GPP cell greater than 30 enlarged over the same area. Further development and its movement towards southeast Bay of



Figs. 10(a-g). Forecasts of Genesis Potential Parameter (GPP) for Depression (7-8) October, 2010 based on 0000 UTC of 3 October 2010: (a) 24 hrs, (b) 48 hrs, (c) 72 hrs, (d) 96 hrs, (e) 120 hrs, (f) 144 hrs and (g) 168 hrs

Bengal primarily indicated a potential zone of cyclogenesis over the area. Circular organization of the GPP cluster on the next day (0000 UTC of 17 May) fairly indicated further intensification of the system in the subsequent hours at the stage of Depression.

Five days forecasts at 24-hour intervals based on 0000 UTC of 14 May 2010 as shown in Figs. 6(a-e) also indicated the development of potential cyclogenesis zone (GPP ≥ 30). Spiral band type organization of GPP at 0000 UTC of 18 May [Fig. 4(d)] as found in the analysis field also clearly indicated the potential of intensification into cyclonic storm over the southeast and adjoining southwest Bay of Bengal four days in advance.

(b) *BANDU*

During onset phase of monsoon, a low pressure area formed over the southwest Arabian Sea on 18 May. The low pressure area concentrated into a depression at 0900 UTC of 19 May 2010 over southwest Arabian Sea. The depression moved northwestwards and intensified into a cyclonic storm BANDU over west central Arabian Sea on 21 May 2010. Thereafter it weakened into a deep depression and into a low pressure area at 0000 UTC of 23 may 2010 over the Gulf of Aden.

The track of the cyclone BANDU is shown in Fig 5(a). Analyses of GPP at 0000 UTC from 14 May 2010 to 17 May 2010 are shown in Figs. 5(c-f). Development and west northwesterly movement of GPP zone over the southeast Arabian Sea is noticed during the period. At 0000 UTC of 14 May a wide cell of GPP greater than 30 is appeared over the southeast Arabian Sea. Subsequent enlargement of the GPP zone at 0000 UTC of 16 May clearly indicated the potential zone of cyclogenesis over the area.

Five days forecasts at 24-hour intervals based on 0000 UTC of 14 May 2010 as shown in Figs. 6(a-e) also indicated the development of potential cyclogenesis zone (GPP ≥ 30) over the southeast Arabian Sea four days in advance.

Case IV : Severe cyclonic storm JAL (4-8, November 2010)

A low pressure area from West Pacific Ocean emerged as a low pressure area over the south Andaman Sea on 2 November. The system intensified into a Cyclonic Storm JAL on 5 November. The cyclonic storm intensified further into a severe cyclonic storm in the early hours of 6 November. The severe cyclonic storm, JAL moved to the southwest Bay of Bengal weakened into a deep depression and crossed north Tamilnadu-south Andhra Pradesh coast, close to the north of Chennai around 1600 UTC of 07 November, 2010.

The track of the cyclone JAL is shown in Fig 7(a). Analyses of GPP at 0000 UTC from 1 November 2010 to 4 November 2010 are shown in Figs. 7(b-e). Gradual organization of GPP zone is noticed during the period. An isolated cell of GPP greater than 30 is noticed over the south Andaman Sea at 0000 UTC of 1 November. At 0000 UTC of 2 November a larger cluster of GPP greater than 30 appeared over the area. Subsequent organization (circular in structure) of the GPP cluster on 0000 UTC of 4 November at the stage of depression fairly indicated further intensification of the low pressure system in the subsequent hours.

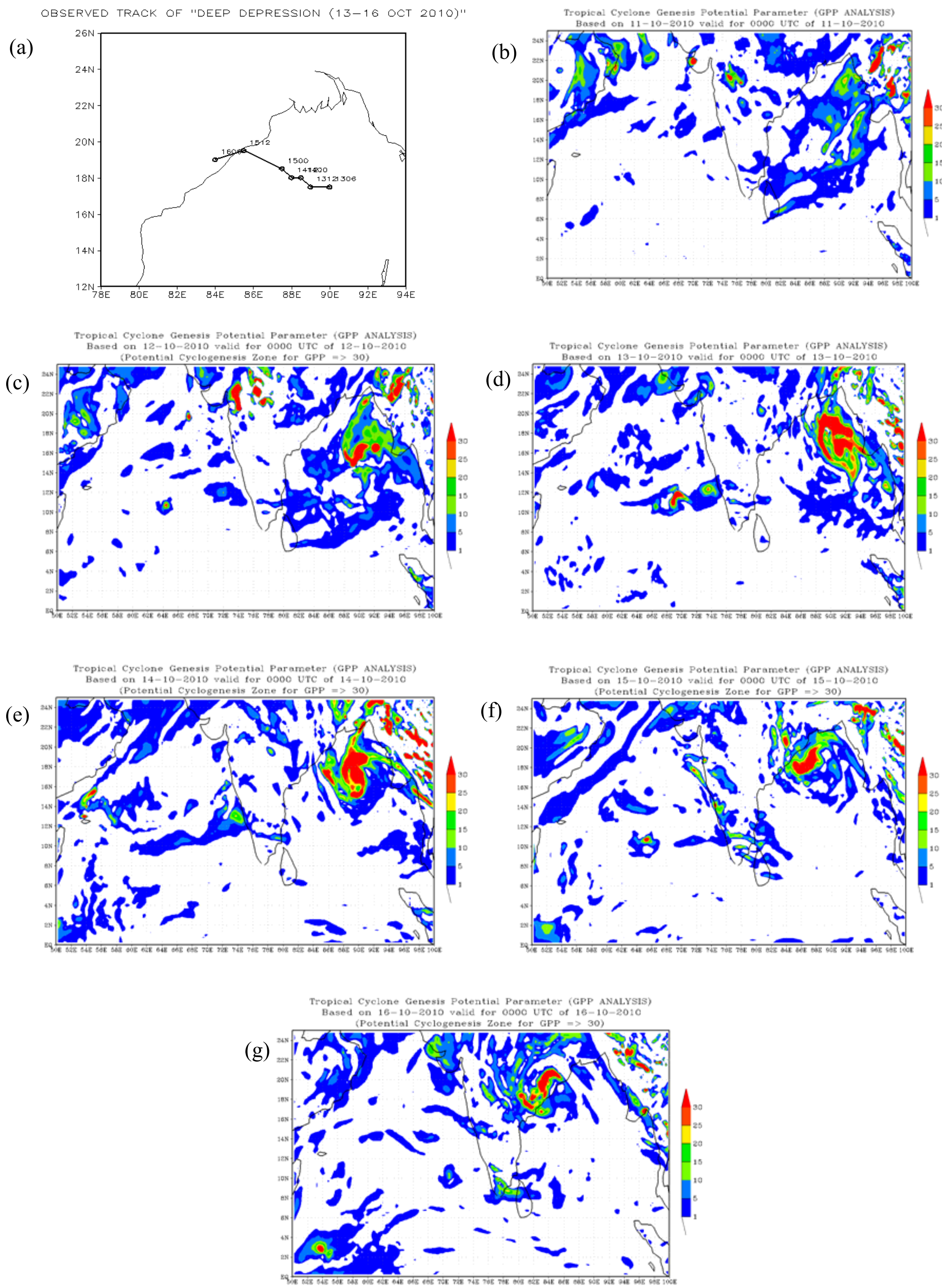
Five days forecasts at 24 hrs intervals based on 0000 UTC of 1 November 2010 as shown in Figs. 8(a-e) also indicated the development of potential cyclogenesis zone (GPP ≥ 30) and subsequent organization of GPP from 4 November (also found in the analysis field) clearly indicated the formation of a low pressure area and its potential for intensification over the south east Bay of Bengal.

Case V : Depression (7-8 October, 2010)

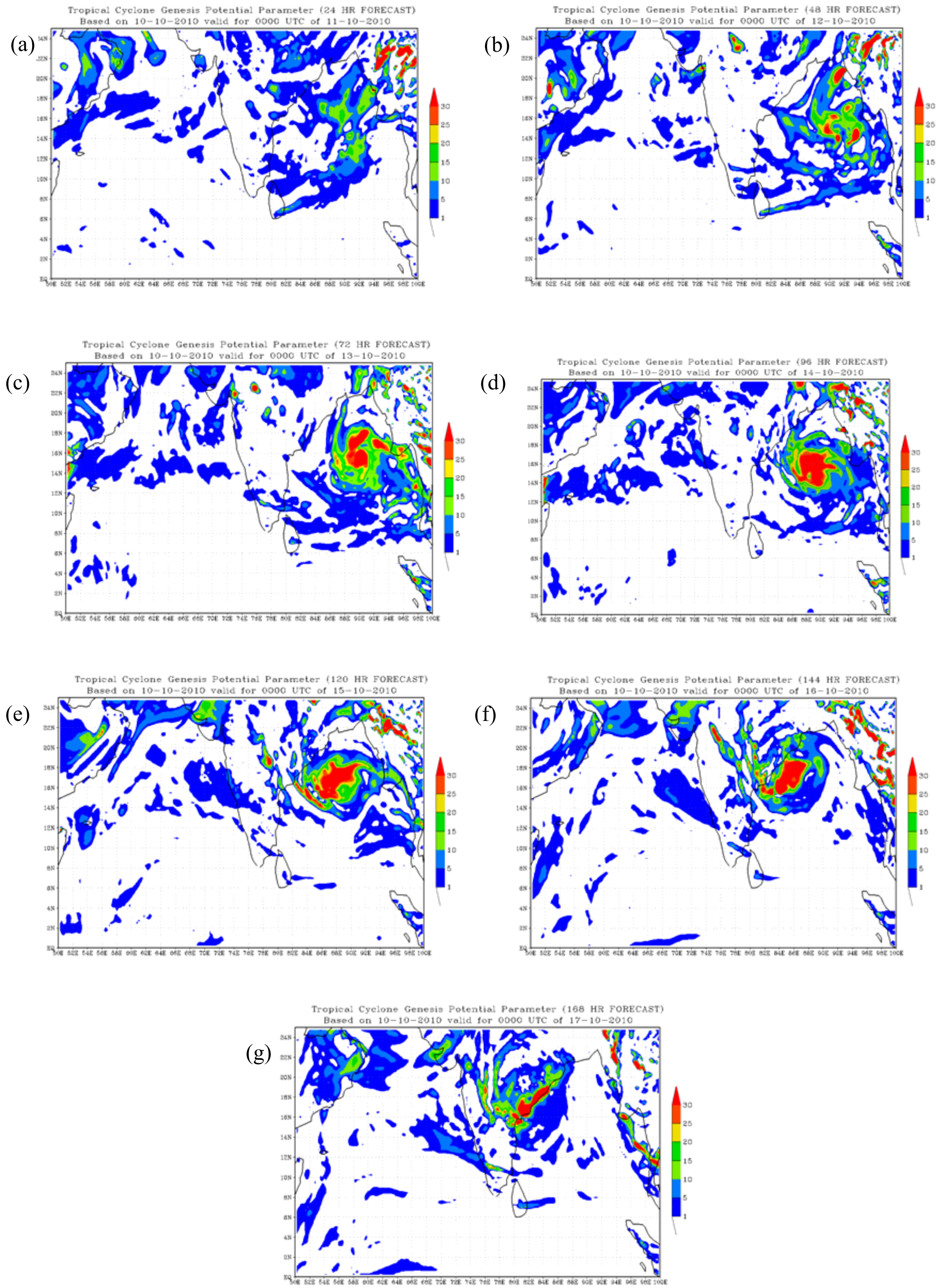
A low pressure area formed over the west-central Bay of Bengal on 5 October evening. The system concentrated into a depression and lay centred at 0300 UTC of 7 October over west-central Bay of Bengal near Lat. 16.50° N and Long. 84.50° E. Moving north-northeastwards and subsequently northeastwards the system crossed West Bengal-Bangladesh coast near Long. 88.50° E between 0500 and 0600 UTC of 8 October as a depression.

The track of the Depression is shown in Fig 9(a). Analyses of GPP at 0000 UTC from 3 October 2010 to 9 October 2010 are shown in Figs. 9(b-h). Isolated cell of GPP greater than 30 is noticed over the west-central Bay of Bengal at 0000 UTC of 4 October indicating formation of genesis potential zone over the area. Some organization occurred on 5 and 6 October 2010 indicating its intensification, thereafter disorganization started as it moved closer to coast. Subsequent movement of the GPP zone along the Orissa coast indicated the movement of the system. Although the organization of GPP zone indicated its potential for intensification as shown by area average GPP also (above threshold) but subsequent disorganization along the Orissa coast indicated its weakening due to encounter with the coastal land mass.

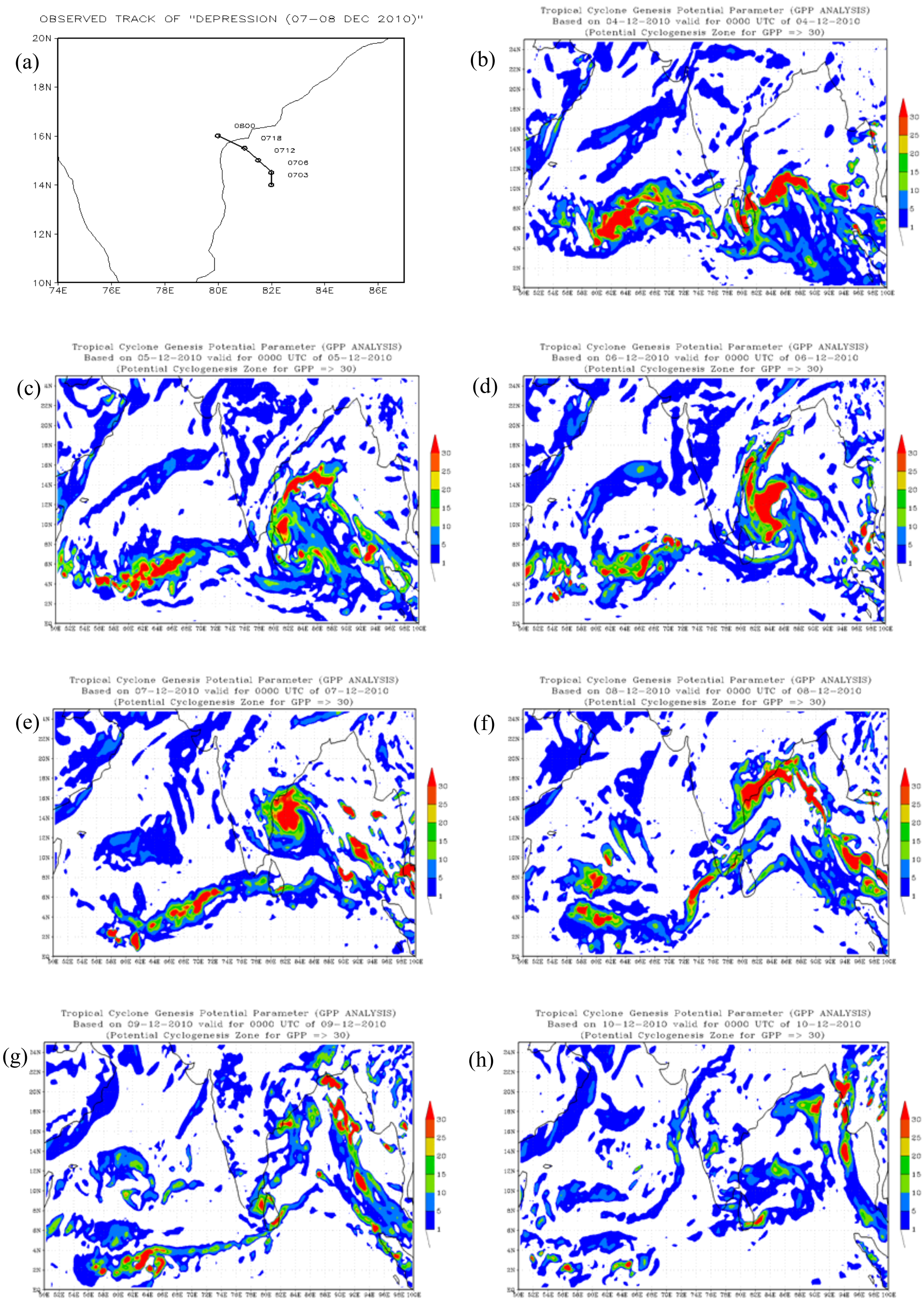
Seven days forecasts at 24 hrs intervals based on 0000 UTC of 3 October 2010 as shown in Figs. 10(a-g) also indicated the development of potential cyclogenesis zone (GPP ≥ 30) and subsequent movement and disorganization of GPP along the Orissa coast as found in the observed fields.



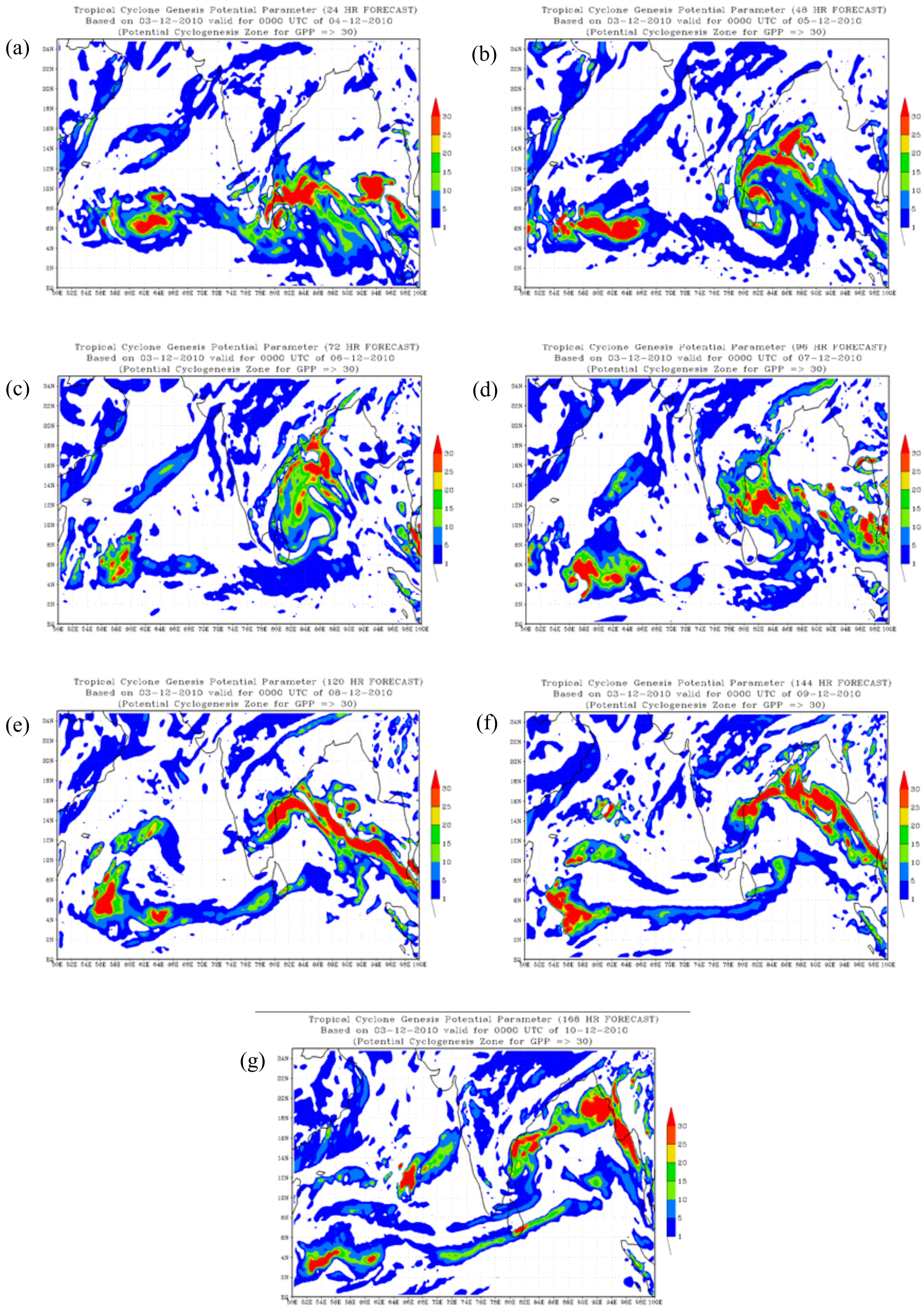
Figs. 11(a-g). Track and analysis of Genesis Potential Parameter (GPP) for Deep Depression 13-16 October, 2010: (a) Track of Deep Depression (b) 0000 UTC 11 October 2010, (c) 0000 UTC 12 October 2010, (d) 0000 UTC 13 October 2010, (e) 0000 UTC 14 October 2010, (f) 0000 UTC 15 October 2010 and (g) 0000 UTC 16 October 2010



Figs. 12(a-g). Forecasts of Genesis Potential Parameter (GPP) for Deep Depression (13-16) October 2010 based on 0000 UTC of 10 October 2010: (a) 24 hrs, (b) 48 hrs, (c) 72 hrs, (d) 96 hrs, (e) 120 hrs, (f) 144 hrs and (g) 168 hrs



Figs. 13(a-h). Track and analysis of Genesis Potential Parameter (GPP) for Depression 7-8 December, 2010: (a) Track of Depression (b) 0000 UTC 4 December 2010, (c) 0000 UTC 5 December 2010, (d) 0000 UTC 6 December 2010, (e) 0000 UTC 7 December 2010, (f) 0000 UTC 8 December 2010, (g) 0000 UTC 9 December 2010 and (h) 0000 UTC 10 December 2010



Figs. 14(a-g). Forecasts of Genesis Potential Parameter (GPP) for Depression (7-8) December, 2010 based on 0000 UTC of 3 December 2010: (a) 24 hrs, (b) 48 hrs, (c) 72 hrs, (d) 96 hrs, (e) 120 hrs, (f) 144 hrs and (g) 168 hrs

Case VI : Deep depression (13-16 October, 2010)

A low pressure area formed over east-central Bay of Bengal on 12 October. The low pressure area concentrated into a depression on 13 October over east-central Bay of Bengal and intensified into a deep depression on 15 October over northwest Bay of Bengal. It then moved west-northwestwards and crossed Orissa coast near Gopalpur between 1500 and 1600 UTC of 15 October.

The track of the Deep Depression is shown in Fig. 11(a). Analyses of GPP at 0000 UTC from 11 October 2010 to 16 October 2010 are shown in Figs. 11(b-g). Scattered cell of GPP greater than 30 was formed over the east-central Bay of Bengal at 0000 UTC of 11 October indicating formation of genesis potential zone over the area. Organization of spatial distribution of GPP started from 13 October 2010 indicating its intensification. The system intensified into Deep depression on the same day. Subsequent movement of the GPP zone towards northwest direction indicated the movement of the system and dis-organization near the coast.

Seven days forecasts at 24 hrs intervals based on 0000 UTC of 10 October 2010 as shown in Figs. 12(a-g) also shows the development of potential cyclogenesis zone and subsequent movement towards northwest direction and disorganization near the coast.

Case VII : Depression (7-8 November, 2010)

A low pressure area formed over southwest Bay of Bengal on 4 December 2010. It concentrated into a depression on 7 December 2010 over west-central Bay of Bengal. The depression moved northwestward and crossed south Andhra Pradesh coast near Baptla around 2000 UTC of 7 December 2010.

The track of the Depression is shown in Fig 13(a). Analyses of GPP at 0000 UTC from 4 December 2010 to 10 December 2010 are shown in Figs. 13(b-h). Scattered cell of GPP greater than 30 was formed over the southwest Bay of Bengal at 0000 UTC of 4 October indicating formation of genesis potential zone over the area. Subsequent organization of spatial distribution of GPP from 6 December 2010 indicated its intensification. The system intensified into Depression on 7 December 2010. The movement of the GPP zone towards northwest direction indicated the movement of the system and disorganization near the coast.

Seven days forecasts at 24 hrs intervals based on 0000 UTC of 3 December 2010 as shown in Figs. 14(a-g) also shows that it was able to capture the development of potential cyclogenesis zone and subsequent movement towards northwest direction and disorganization near the coast.

The above analyses for cyclonic disturbances in 2010 show that scattered GPP distribution over the area at the early development stages (Low, Depression) and the relative organization of the distribution in the form of circular or spiral during their intensification phases. The qualitative assessment of the analysis and corresponding forecasts of each case shows that the spatial and temporal distribution (forecasts) of the parameter could indicate the potential zone for formation of a system and its probable intensification. The estimation of the rate of intensification is beyond the scope of this study. A critical study is needed using a considerable number of cases to estimate the rate of intensification of a system from the spatial and temporal distribution of GPP.

4. Threshold grid point GPP and predictability

Kotal *et al.* (2009) showed that at T. No.1.0, GPP of 86% developing cases are equal and above 8.0 and 100% non-developing cases are below 8.0. At T. No.1.5, GPP of 87% developing cases are equal and above 8.0 and 100% non-developing cases are below 8.0 and at T. No. 2.5, 86% developing cases are above 8.0 and 87% non-developing cases below 8.0. They determined the threshold value using a considerable number of systems. The above analysis shows that there is a distinction in GPP (based on area averaged) values for developing and non-developing systems in more than 85% of cases at all stages. Therefore, in this study, the area averaged GPP (with threshold 8.0) is used on real time to understand the potential for intensification of the cyclonic disturbances over the north Indian Sea in 2010.

In addition, the grid point analysis and forecasts of GPP is mainly used to find the most potential zone for cyclogenesis at a lead time 4-5 days. The above case studies in Section 3.2 reveal that the higher value of the GPP over a region indicates higher potential of genesis over the region. Region with GPP value equal or greater than 30 is found to be high potential zone for cyclogenesis where all the systems were formed and no system were formed over the region of GPP less than 30. The studies also reveal that before the formation of a low pressure area, a GPP zone of 30 developed over the area two to three days in advance. The development of GPP zone of 30 before formation of a system and its gradual organization is found to be a useful predictive signal for cyclogenesis. Therefore, it appears that the combined effect of all the variables used in GPP started becoming favourable over a region before formation of a system over that region. Four to five days forecasts of GPP could able to capture the development and organization of GPP zone (scattered to circular or spiral band) and can provide a greater lead time of cyclogenesis over a region. Although results of the case studies for cyclonic disturbances in 2010 are very encouraging, more case studies are required to calibrate threshold value (30) of grid point GPP.

5. Concluding remarks

Every year a good number of low pressure systems form over the Indian Sea and a few of them intensify into a cyclonic storm. For the operational practice there is need to specify a genesis parameter for the Indian Sea, which could indicate the potential cyclogenesis zone and potential for intensification of a system well in advance. An analysis of tropical cyclone genesis potential parameter (GPP) (Kotal *et al.*, 2009) is carried out for tropical disturbances in 2010 over the North Indian Sea. The area averaged GPP for tropical disturbances in 2010 shows that GPP was well above the threshold value 8.0 for all the cyclones. Therefore, it could able to indicate their potential for intensification at the early stages of development. Although the GPP of the three Depressions show enough potential for intensification but did not intensify. The plausible reasons for non-intensification of these systems into cyclone are they were formed near the coast and therefore, track over the Sea was less as well as less lifetime over the Sea and also due to encounter with the coastal land mass. Further study is needed to estimate the critical lifetime and sea track of depressions to intensify into cyclone those form near coast.

The grid point distribution of the parameter shows that the higher value of the GPP over a region indicates higher potential zone of cyclogenesis. Primary analysis shows that the region with GPP value equal or greater than 30 is found to be high potential zone for cyclogenesis, where all the systems were formed in 2010 and no system was formed over the region of GPP less than 30. The study also shows that before the formation of a low pressure area, a GPP zone of 30 developed over the area two to three days in advance. The combined effect of all the variables used in GPP is found to be started becoming favourable over a region before formation of a system over that region. Four to five days forecasts of GPP could able to capture the organization of GPP zone (scattered to circular or spiral band) and can provide a greater lead time of cyclogenesis over a region. Therefore, this product could provide useful predictive signal (4-5 days in advance) for day to day monitoring of cyclogenesis over the north Indian Sea as found during FDP-Cyclone. Analysis and forecasts of parameter up to seven days is generated twice a day on real time using ECMWF model output (available at http:// www.imd.gov.in/section/nhac/dynamic/Analysis.htm). Although results of the case studies are very encouraging, more case studies are required to calibrate threshold value 30 and to estimate the rate of intensification of a system from the spatial and temporal distribution of GPP. Our future study will focus on these subjects.

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