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Analysis of cyclogenesis parameter for developing and nondeveloping low-pressure systems over the Indian Sea

S. D. Kotal · P. K. Kundu · S. K. Roy Bhowmik

Abstract A cyclone genesis parameter, termed the genesis potential parameter (GPP), for the Indian Sea is proposed. The parameter is defined as the product of four variables, namely vorticity at 850 hPa, middle tropospheric relative humidity, middle tropospheric instability, and the inverse of vertical wind shear. The variables are calculated using the National Centers for Environmental Prediction (NCEP), USA, reanalysis data, averaged within a circle of 2.5° radius around the centre of cyclonic system. The parameter is tested with a sample dataset of 35 nondeveloping and developing low-pressure systems that formed over the Indian Sea during the period 1995–2005. The result shows that there is a distinction between GPP values for nondeveloping and developing systems in more than 85% cases. The composite GPP value is found to be around three to five times greater for developing systems than for nondeveloping systems. The analysis of the parameter at early development stage of a cyclonic storm appears to provide a useful predictive signal for intensification of the system.

1 Introduction

Tropical cyclone genesis has been attributed to both thermodynamic and dynamical factors. Palmen (1948) showed that hurricanes form over regions where sea surface temperatures (SST) are 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).

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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. Mandal et al. ([1981](#)) evaluated the values of this genesis parameter for a cyclonic storm in the Arabian Sea. They showed that the values are comparable with Gray's estimate for disturbances in the Pacific Ocean, but greater than those of the Atlantic Ocean.

Previous studies (Royer et al. [1998](#); Camargo et al. [2007](#)) showed that threshold value of SST (26°C) limits the use of Gray's parameter in different climate. Royer et al. ([1998](#)) developed a yearly genesis parameter (YGP) to study the future changes of tropical cyclogenesis frequency by replacing the thermal potential part of Gray's seasonal genesis parameter (SGP) with "convective potential," defined as: $k \times P_c$ over the oceans and for latitude less than or equal to 35°, where $k = 0.145$ and P_c is the seasonal mean convective precipitation in mm/day.

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 Niño-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](#)) and McBride and Zehr ([1981](#)) examined the thermodynamic and dynamical fields around tropical systems. In their extensive work they developed a daily genesis potential (DGP) parameter, which is defined as the difference of vorticity between 900 and 200 hPa. The study showed that DGP is three times greater for developing systems than for nondeveloping 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 nondeveloping 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 has the potential to intensify into a very severe cyclonic storm over the Indian Sea.

The genesis parameter (GP) of Zehr ([1992](#)) and the daily genesis potential (DGP) parameter of McBride and Zehr ([1981](#)) used for differentiating between nondeveloping and developing tropical disturbances consist of dynamical parameters only. Herein, a genesis potential parameter (GPP) is proposed, which consists of both dynamical as well as thermodynamic variables, for differentiating between nondeveloping and developing low-pressure systems over the Indian Sea. Finally the GPP values for 35 nondeveloping and developing systems that formed over the Indian Sea during the period 1995 to 2005 are compared.

Data and methodology is described in Sect. [2](#) and genesis variables are discussed in Sect. [3](#). The genesis potential parameter (GPP) is described in Sect. [4](#) and an intercomparison of GPP for developing and nondeveloping systems is presented in Sect. [5](#). The skill

scores of the GPP are presented in Sect. 6 and GPP analysis for individual cases is discussed in Sect. 7. Concluding remarks are given in Sect. 8.

2 Data and methodology

For the present study, a sample of 35 tropical disturbances that formed over the Indian Sea during the period 1995–2005 (11 years) has been considered. The dataset used to develop the GPP of tropical disturbances was obtained from Annual Reports of the Regional Specialized Meteorological Centre (RSMC) at India Meteorological Department (IMD), New Delhi. The World Meteorological Organization (WMO) recognizes this office as an RSMC for providing cyclone warning advisories over the region. 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 poststorm synoptic analysis based on all available observations and also by the analysis of cloud patterns in visible and infrared imagery of satellite (INSAT) following the technique of Dvorak (1975). The dataset available in the Annual Reports of RSMC are used in various studies (Roy Bhowmik et al. 2003, 2007; Kalsi and Srivastava 2006, etc.). The position and intensity of cyclones are available from 1990 to 1994 at 6-h intervals. Since 1995, this information is available at 3-h intervals. Classifications of tropical disturbances (based on intensity), as per the convention of IMD, are given in Table 1.

The life period, year, maximum intensity (T. No.), and coast of landfall of the 35 sample cyclonic systems are summarized in Table 2. The term "dissipated" in the last column of Table 2 indicates that the cyclone did not make landfall but dissipated over the sea. The coastal states referred to in the table are shown in Fig. 1.

Table 1 T. No. classification of cyclonic systems and corresponding wind speed	Classification of cyclonic system	T. No.	Wind speed in knots	Wind criteria (knots)
	Low (L)	1.0	–	<17
	Depression (D)	1.5	25	17–27
	Deep depression (DD)	2.0	30	28–33
	Cyclonic storm (CS)	2.5	35	34–47
	Cyclonic storm (CS)	3.0	45	34–47
	Severe cyclonic storm (SCS)	3.5	55	48–63
	Very severe cyclonic storm (VSCS)	4.0	65	64–119
	Very severe cyclonic storm (VSCS)	4.5	77	64–119
	Very severe cyclonic storm (VSCS)	5.0	90	64–119
	Very severe cyclonic storm (VSCS)	5.5	102	64–119
	Very severe cyclonic storm (VSCS)	6.0	115	64–119
	Super cyclonic storm (SUCS)	6.5	127	≥ 120
	Super cyclonic storm (SUCS)	7.0	140	≥ 120
	Super cyclonic storm (SUCS)	7.5	155	≥ 120
	Super cyclonic storm (SUCS)	8.0	170	≥ 120

S. No.	Period	Year	Maximum intensity (T. No.)	Coast of landfall
1	7–10 November	1995	4.5	Andhra Pradesh
2	21–25 November	1995	5.5	Bangladesh
3	12–16 June	1996	3.0	Andhra Pradesh
4	17–20 June	1996	3.5	Gujarat
5	22–28 October	1996	3.5	Dissipated
6	23–27 September	1997	3.5	Bangladesh
7	17–20 May	1998	3.5	Bangladesh
8	13–16 November	1998	4.5	Andhra Pradesh
9	13–17 December	1998	3.5	Dissipated
10	25–31 October	1999	7.0	Orissa
11	26–30 November	2000	5.5	Tamil Nadu
12	23–28 December	2000	5.0	Sri Lanka
13	11–16 December	2003	3.5	Andhra Pradesh
14	15–19 October	2000	2.5	Dissipated
15	25–28 October	2000	2.5	Bangladesh
16	24–27 September	2001	2.5	Dissipated
17	8–10 October	2001	2.5	Dissipated
18	14–17 October	2001	2.5	Andhra Pradesh
19	23–28 November	2002	2.5	Dissipated
20	7–8 May	1996	2.0	Bangladesh
21	27–29 October	1996	2.0	West Bengal
22	10–13 November	1997	2.0	Dissipated
23	13–15 June	1998	2.0	Andhra Pradesh
24	6–9 October	1998	2.0	Dissipated
25	13–15 October	1998	2.0	Andhra Pradesh
26	26–29 October	1998	2.0	Dissipated
27	8–10 December	1999	1.5	Dissipated
28	11–12 November	2001	1.5	Dissipated
29	22–23 October	2002	1.5	Dissipated
30	26–28 October	2003	2.0	Andhra Pradesh
31	10–13 June	2004	2.0	Dissipated
32	11–13 June	2004	2.0	Orissa
33	2–4 October	2004	1.5	Andhra Pradesh
34	26–29 October	2005	2.0	Andhra Pradesh
35	20–22 November	2005	1.5	Sri Lanka

Table 2 The details of 35 tropical cyclonic systems

In order to compare the GPP, the 35 systems considered in this study are placed in two classes, namely nondeveloping systems and developing systems. According to the convention of IMD (Table 1), the wind speed of a cyclonic system of T. No. 2.5 is marginally stronger (5 knots) than the system of T. No. 2.0. The analysis of GPP also shows that the GPP values of cyclonic systems of peak intensity T. No. 2.5 are comparable to that of cyclonic systems of peak intensity T. No. 2.0. In view of this, distinction is made between the cyclonic systems that reached peak intensity up to T. No. 2.5 (nondeveloping) and that exceeded
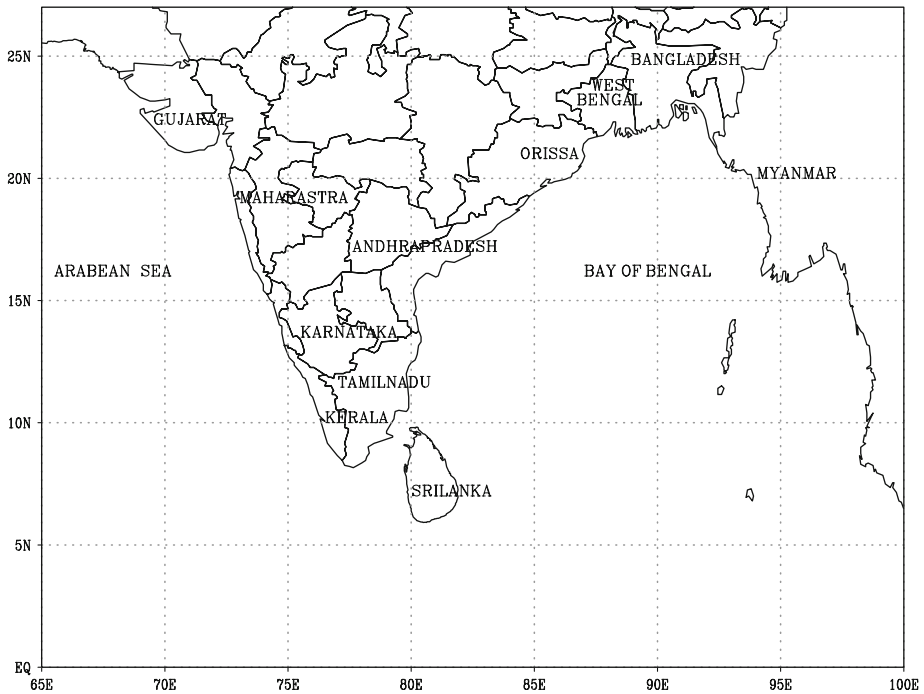
Fig. 1 Indian Sea and adjoining coastal states

T. No. 2.5 (developing) (Roy Bhowmik 2003). The dataset includes 13 cases of developing systems and 22 cases of nondeveloping systems. Out of the 13 developing systems 1 remained cyclonic storm, 6 attained severe cyclonic storm intensity, 5 became very severe cyclonic storm, and 1 became super cyclonic storm. Among 22 nondeveloping systems 5 remained depression, 11 became deep depression, and 6 reached intensity up to T. No. 2.5.

All the variables used to compute the GPP parameter are derived from the NCEP reanalysis data which is available at 2.5° latitude–longitude grid. The variables are averaged over an area of radius 2.5° around the centre of cyclonic system and GPP is calculated from the stage T. No. 1.0 to 3.0.

The area used in the average of parameters varied in different studies; for example, McBride and Zehr (1981) used a radius of 6°, Franklin et al. (1993) used a radius of 6°, Elsberry and Jeffries (1996) used an area within a radius of 3°, Zeng et al. (2007) used a radius of 5°, and Kotal et al. (2008) used a radius of 2.5° around storm centre for averaging the parameters. In this study, all the variables are estimated by averaging of all grid points within a circle of radius 2.5° around the centre of cyclonic system. In all cases, there will be more than one grid point in the area of radius 2.5° around the centre of cyclonic systems; for example, if the centre of a cyclonic system coincides with a grid point there will be five grid points in the area of radius 2.5°. On the other hand, when the centre of a cyclonic system lies within the grid box of 2.5° × 2.5° there will be four grid points in the area of radius 2.5°. Since, in most cases, the systems lie within the grid box of 2.5° × 2.5°, four grid points are generally used for the area average. As the NCEP reanalysis data is available at 6-hourly intervals (00, 06, 12, 18 UTC) the GPP is calculated at 6-hourly intervals.

3 Analysis of genesis potential variables

As described in the "Introduction," many studies have shown that intensification of a pre-existing disturbance depends on favorable environmental conditions. In this section, we examine the contribution of two dynamical variables and two thermodynamic variables to the development of a pre-existing disturbance (developing or nondeveloping) over the Indian Sea.

Two dynamical variables considered are:

(i)   Low-level relative vorticity (ξ_{850})
(ii) Vertical wind shear (S)

The two thermodynamic variables are:

(i)   Middle tropospheric relative humidity (M)
(ii) Middle tropospheric instability (I)

Generally tropical cyclone forms on the leading edge of equatorial low in both the hemispheres when there is sufficient low-level relative vorticity. Gray (1978) and McBride and Zehr (1981) showed that low-level relative vorticity is one of the important dynamical variables for the formation of tropical cyclones. To investigate its impact on the two classes of tropical disturbances, the relative vorticity (ξ_{850}) at 850 hPa is averaged over an area of radius 2.5° around the storm centre for all the storms. The average relative vorticity (ξ_{850}) at each T. No. for developing and nondeveloping systems is displayed in Fig. 2a. Initially, vorticity increases and reaches its maximum value at T. No. 2.5 for developing systems and at T. No. 2.0 for nondeveloping systems and subsequently decreases. The vorticity variable is found to be persistently greater at all T. No. for developing systems compared with that of nondeveloping systems. The value of the variable ranges from 3.9×10^{-5} to 4.9×10^{-5} s^{-1} for developing systems and from 2.7×10^{-5} to 3.5×10^{-5} s^{-1} for nondeveloping systems.

Another dynamical parameter which is important for development of tropical disturbances is the low vertical wind shear (Gray 1968; McBride and Zehr 1981). Zeng et al. (2007) estimated the vertical wind shear from the NCEP reanalysis data, defined as the difference of winds between 200 and 850 hPa averaged over an area of radius 5° around the storm centre. They showed that there is negative effect of the vertical wind shear on storm intensity. Following Zeng et al. (2007), in the present case, the vertical wind shear variable (S) is computed as the magnitude of vertical wind shear between 200 and 850 hPa averaged over an area of radius 2.5° around the centre of cyclonic system. The average wind shear variable (S) at each T. No. for developing and nondeveloping systems is displayed in Fig. 2b. Wind shear variable remains between 9.1 and 10.9 m s^{-1} for developing systems. On the other hand, it varies from 13.4 to 15.7 m s^{-1} for nondeveloping systems.

The third variable considered is the middle tropospheric relative humidity. The development phase of a tropical disturbance is characterized by latent heat release due to convection. Moistening of the middle troposphere is an important factor for tropical cyclone intensification. Following Gray (1978), a scaled middle troposphere relative humidity variable (M) is used, defined as follows:

$$M = \frac{[\text{RH} - 40]}{30},$$

where RH is the mean relative humidity between 700 and 500 hPa averaged over an area of radius 2.5° around the centre of cyclonic system. The relative humidity variable M is taken as zero when RH is equal or less than 40%.
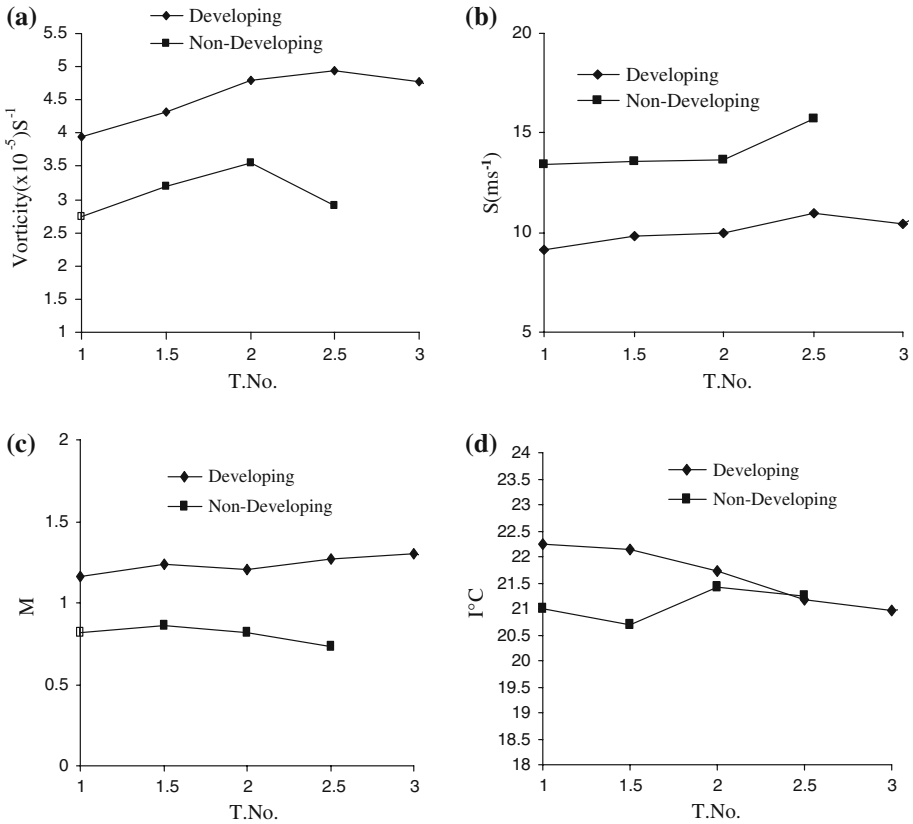
Fig. 2 Comparison of genesis variables between developing and nondeveloping systems: **a** low-level relative vorticity (ξ_{850}), **b** vertical wind shear (S), **c** middle tropospheric relative humidity (M), and **d** middle tropospheric instability (I)

Figure 2c shows the average value of M at each T. No. for developing and nondeveloping systems. Initially M increases slightly and then becomes stable for developing systems and decreases further for nondeveloping systems. The value of the variable ranges from 1.1 to 1.3 for developing systems and from 0.7 to 0.9 for nondeveloping systems.

The fourth variable whose impact on development of tropical disturbances has been analyzed is the instability parameter (I). The development phase of a tropical disturbance is characterized by intense convective activity, which is associated with middle tropospheric instability. The temperature difference between 850 and 500 hPa measures the middle tropospheric instability (George 1960). This difference is averaged over an area of radius 2.5° around the centre of a cyclonic system and is used as instability parameter (I). Figure 2d shows that the instability variable ($T_{850} - T_{500}$) is greater by 0.4–1.3°C for developing systems than for nondeveloping systems. The difference is more in the initial stage of the disturbances and becomes zero at T. No. 2.5. The decreasing trend of instability curve of developing systems indicates that latent heat release due to convection in the middle troposphere is more during the developing stage.

The analysis above indicates that all the variables selected here have distinct contribution to the intensification process of a low-pressure system.

4 Formulation of the genesis potential parameter

The vorticity at 850 hPa, middle tropospheric relative humidity, middle tropospheric instability, and vertical wind shear variables are used to derive the GPP. The proposed GPP is defined as:

$$\text{GPP} = \frac{\xi_{850} \times M \times I}{S} \quad \text{if } \xi_{850} > 0, M > 0 \text{ and } I > 0$$
$$= 0 \quad \text{if } \xi_{850} \leq 0, M \leq 0 \text{ or } I \leq 0 \tag{1}$$

where ξ_{850} = low-level relative vorticity (at 850 hPa) in 10^{-5} s^{-1}

S = vertical wind shear between 200 and 850 hPa (m s^{-1})

$$M = \frac{[\text{RH} - 40]}{30} = \text{Middle tropospherere relative humidity,}$$

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

$I = (T_{850} - T_{500})$ °C = middle tropospheric instability (temperature difference between 850 and 500 hPa)

Each of the four variables are estimated by averaging of all grid point values within a circle of radius 2.5° around the centre of cyclonic system for the computation of GPP value.

5 Genesis potential parameter for developing versus nondeveloping systems

The average value of GPP at each T. No. for developing systems and nondeveloping systems is shown in Fig. 3. The values of the composite GPP are also listed in Table 3. Figure 3 shows that GPP value increases during early development stages for both systems, then becomes stable for developing systems and decreases for nondeveloping systems. The slope of the developing curve is higher at T. No. 1.0 to 2.0.

For convenience of description, we express GPP with numeric part only (scaled by 10^{-5}). Following this convention, the GPP values are around 11.1, 12.3, 13.3, and 13.5 with standard deviation 3.7, 4.1, 5.9, and 2.3 for T. No. 1.0, 1.5, 2.0, and 2.5, respectively,

Fig. 3 Comparison of composite genesis potential parameter (GPP × 10^{-5}) between developing and nondeveloping systems
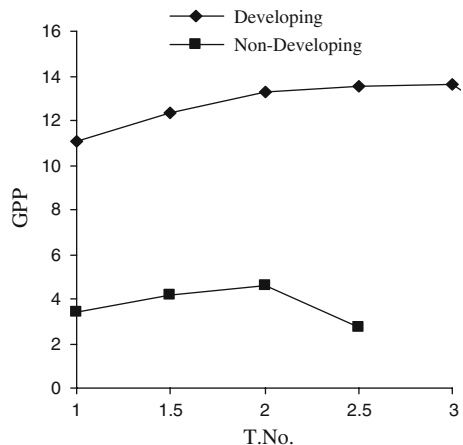
Table 3 Composite genesis potential parameter (GPP) and standard deviation (σ) for developing and nondeveloping systems

T. No.	1.0	1.5	2.0	2.5	3.0
GPP for developing	11.1	12.3	13.3	13.5	13.6
GPP for nondeveloping	3.4	4.2	4.6	2.7	–
Standard deviation (σ) for developing	3.7	4.1	5.9	2.6	2.3
Standard deviation (σ) for nondeveloping	1.3	4.2	4.6	2.7	–

for developing systems and 3.4, 4.2, 4.6, and 2.7 with standard deviation 1.3, 1.6, 4.6, and 1.2, respectively, for nondeveloping systems. It is very encouraging to see that GPP values are three to five times greater for developing systems than for nondeveloping systems.

6 Skill score

It is important to examine if there are some nondeveloping cases with high GPP that are as high or higher than the lower cases of the developing sample. Figure 4a–e shows the variations of GPP for developing systems and nondeveloping systems at T. No. 1.0, 1.5, 2.0, 2.5, and 3.0, respectively. In the figures, line with solid square and solid circle indicates variations of individual GPP and composite GPP, respectively, for developing systems; line with solid triangle and open circle indicates variations of GPP for individual cases and composite GPP respectively for nondeveloping systems; and line with plus sign indicates constant GPP line of 8.0. Figure 4a shows that there is a clear distinction in GPP for developing and nondeveloping systems at T. No. 1.0. Figure 4a shows that there is no case when the GPP value for a nondeveloping system exceeds the GPP value of a developing system. Tables 4 and 5 present the skill score based on GPP <8.0 or ≥8.0 for developing and nondeveloping systems, respectively. At T. No. 1.0, the GPP of 86% of developing cases was ≥8.0 and that of 100% of the nondeveloping cases was <8.0. Figure 4b shows that there were four developing cases whose GPP was as low as the highest value of the nondeveloping cases at T. No. 1.5 and that the GPP of 87% of the developing cases was ≥8.0 and 100% of the nondeveloping cases had GPP <8.0. Variations in GPP were highest at T. No. 2.0 for both developing and nondeveloping cases (Fig. 4c), with standard deviation of 5.9 and 4.6, respectively. Out of 28 developing cases 4 cases were below 8.0, with 86% cases above 8.0; out of 67 nondeveloping cases 9 cases were >8.0, with 87% cases <8.0. Figure 4d shows that GPP of all the developing cases were above 8.0 and GPP of all the nondeveloping cases were below 8.0 at T. No. 2.5. GPP of one developing case was found to be below 8.0 at T. No. 3.0 (Fig. 4e).

The above analysis shows that there is a distinction in GPP values for developing and nondeveloping systems in more than 85% of cases at all stages. This could be useful information regarding the intensification of tropical disturbances.

7 Genesis potential parameter for individual cases

As averaging of a parameter for many events smoothens its internal variation, it is worthwhile to compare the composite characteristics with individual cases to verify consistency. In this section, we examine the GPP value associated with the Orissa super cyclone of October 1999. We also examine the GPP associated with two cyclonic storms.
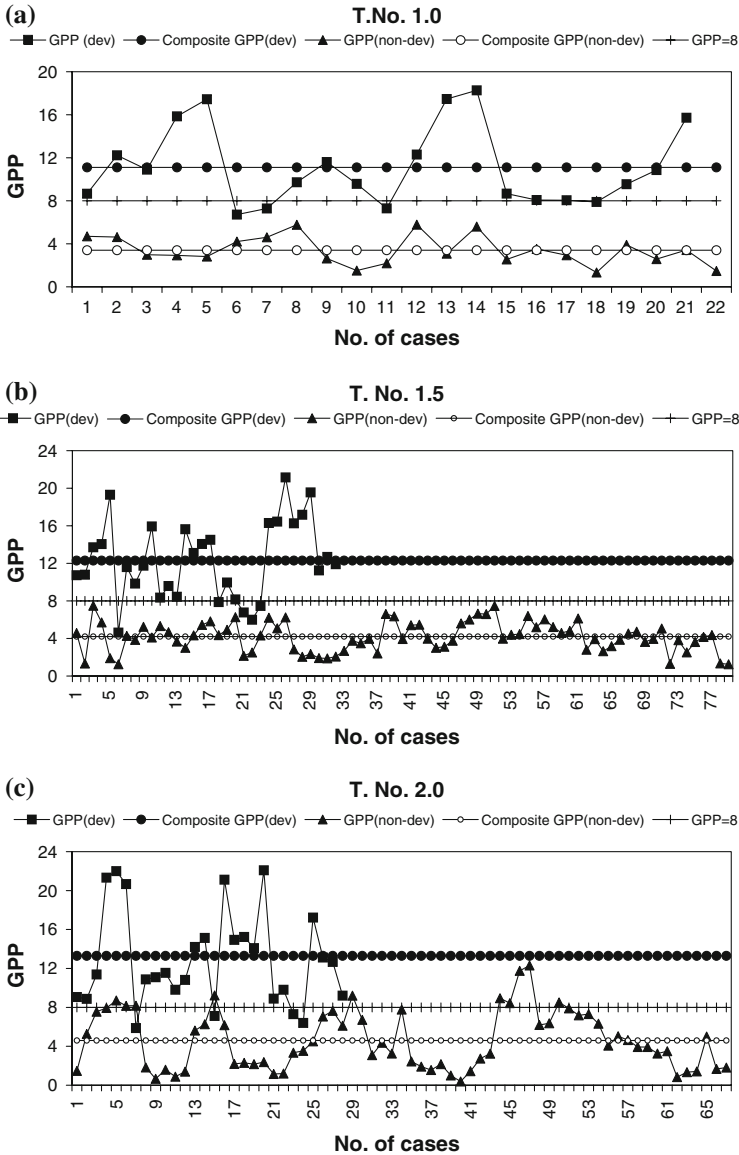
(a)

(b)

(c)

Fig. 4 Variations of GPP for developing systems and nondeveloping systems at (**a**) T. No. 1.0, (**b**) T. No. 1.5, (**c**) T. No. 2.0, (**d**) T. No. 2.5, and (**e**) T. No. 3.0

Case 1: super cyclone over the Bay of Bengal of 25–31 October 1999

Orissa super cyclone of October 1999 was one of the most intense tropical cyclones in the history of the Indian Sea over the last 100 years. The system emerged in the North Andaman Sea as a well-marked low pressure in the morning of 25 October when the GPP value was 12.7 against T. No. 1.0. Figure 5 shows comparison of its GPP with composite GPP of developing systems. The system attained T. No. 1.5 at 0600 UTC and maintained the same intensity until 1800 UTC of the same day. The average GPP during this period

(d) T.No.2.5

(e) T.No. 3.0
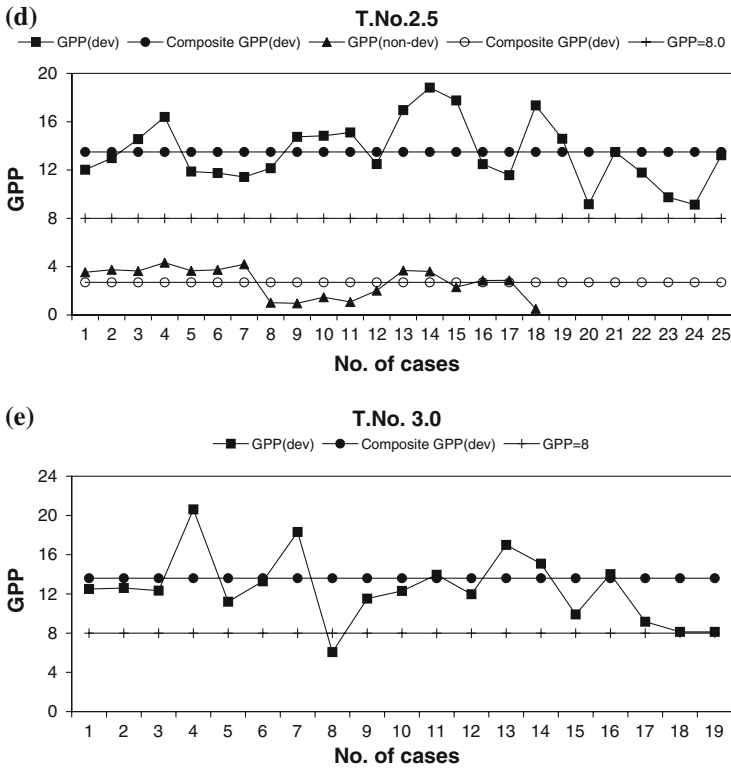
Fig. 4 continued

Table 4 Skill scores for developing cases

T. No.	1.0	1.5	2.0	2.5	3.0
Number of cases of GPP ≥ 8.0	18	28	24	25	18
Number of cases of GPP <8.0	3	4	4	0	1
Total number of cases	21	32	28	25	19
Percentage of cases in developing group	86	87	86	100	95

Table 5 Skill scores for nondeveloping cases

T. No.	1.0	1.5	2.0	2.5
Number of cases of GPP ≥ 8.0	0	0	9	0
Number of cases of GPP <8.0	22	79	58	18
Total number of cases	22	79	67	18
Percentage of cases in nondeveloping group	100	100	87	100

was 14.4. The system further intensified and reached T. No. 2.0 at 0000 UTC of 26 October. The system attained T. No. 2.5 at 0600 UTC and T. No. 3.0 at 1200 UTC of the same day. It maintained the same intensity until 0000 UTC of 27 October. The GPP values during these stages were 14.9, 13.1, and 12.7, respectively. The system reached its severe

stage T. No. 3.5 at 0300 UTC of 27 October and maintained the same intensity until 1200 UTC of that day. The system was in the very severe stage (T. No. 4.0) from 1500 UTC of 27 October to 0000 UTC of 28 October. Subsequently the system further intensified and reached its super cyclonic stage at 1500 UTC of 28 October (T. No. 6.5).

GPP values of this system are found to be persistently higher compared with the composite GPP of developing systems during the stages from T. No. 1.0 to 2.0 and nearly equal at T. No. 2.5. During the early stages of development, the higher values of GPP compared with the composite GPP value for developing systems could be an indication of the system having enough potential to reach higher intensity.

Case 2: cyclonic storm over the Bay of Bengal of 12–16 June 1996

This is a rare case in the history of occurrence of tropical cyclones over the Indian Sea, when a system formed and intensified into a cyclone in the month of June (Monsoon season) at low latitude. The initial vortex was spotted at 0500 UTC of 12 June at 10.0°N 87.5°E. The comparison of GPP for the system with the composite GPP of developing systems is illustrated in Fig. 6. The system concentrated into a depression (T. No. 1.5) at 1200 UTC of 12 June and remained at the same stage until 0000 UTC of 13 June. The mean GPP during this stage was 11.9. Then the system intensified to T. No. 2.0 and continued to be so until 1800 UTC of the same date, while the GPP value remained 11.3. The system lay as a cyclonic storm (T. No. 2.5) during the period from 0000 UTC of 14 June to 1800 UTC of 15 June. Thereafter GPP value decreases to 9.7. It further intensified to T. No. 3.0 at 1200 UTC of 15 June and remained at this stage until landfall on 0500 UTC of 16 June. The GPP value during this stage further decreased to 8.3.

Fig. 5 Comparison of composite genesis potential parameter (GPP × 10^{-5}) and genesis potential parameter of super cyclone over the Bay of Bengal of 25–31 October 1999

Fig. 6 Comparison of composite genesis potential parameter (GPP × 10^{-5}) and genesis potential parameter of cyclonic storm over the Bay of Bengal of 12–16 June 1996
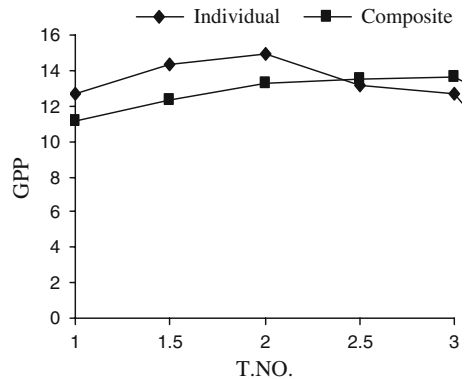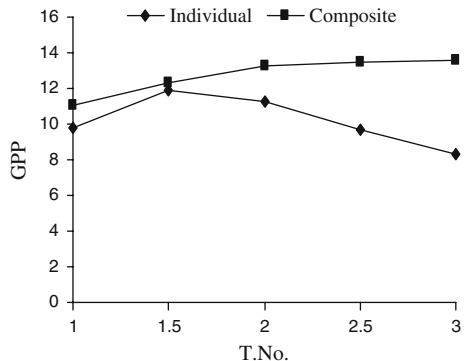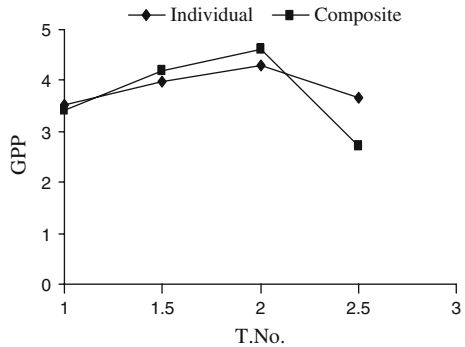
Fig. 7 Comparison of composite
genesis potential parameter
(GPP $\times 10^{-5}$) and genesis
potential parameter of cyclonic
storm over the Bay of Bengal of
15–19 October 2000

GPP values of this system are found to be persistently lower than the composite GPP of developing systems but higher than the threshold value (8.0). This indicates the potential of the system to intensify into a developing system.

Case 3: cyclonic storm over the Bay of Bengal of 15–19 October 2000

The initial low-pressure system formed over the central and adjoining south Bay of Bengal and intensified into a depression (T. No. 1.5) on 0000 UTC of 15 October. This system persisted over the Bay of Bengal for more than 4 days, but maximum intensity never exceeded T. No. 2.5. Finally it weakened over the sea. The GPP values of this system are found to be closely matching with the composite GPP of nondeveloping systems (Fig. 7).

These case studies illustrate that the composite characteristics of GPP for developing or nondeveloping cases is consistent with the corresponding individual GPP.

8 Concluding remarks

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. In operational practice there is a 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. A genesis parameter (GPP) is proposed, which consists of two thermodynamic and two dynamical variables. The dynamical variables used in the computation are low-level relative vorticity and vertical wind shear. The thermodynamic variables are middle tropospheric relative humidity and instability. The variables are derived from the NCEP reanalysis data. The result shows that composite GPP values are 11.1, 12.3, 13.3, and 13.5 for developing systems and 3.4, 4.2, 4.6, and 2.7 for nondeveloping systems at T. No. 1.0, 1.5, 2.0, and 2.5, respectively. During the early development stages of storms at T. No. 1.0, 1.5, and 2.0, the GPP values are found to be around three times greater for developing systems than for nondeveloping systems. It becomes five times greater at T. No. 2.5. The skill score analysis based on GPP <8.0 or ≥8.0 reveals that in more than 85% of cases GPP values are ≥8.0 for developing systems and <8.0 for nondeveloping systems. The genesis parameter described in this study is found to provide useful predictive signals for intensification of a tropical disturbance over the Indian Sea. The result of the study appears to be very promising for operational cyclone forecasting.

References

Camargo SJ, Emanuel KA, Sobel AH (2007) Use of a Genesis Potential Index to diagnose ENSO effects on tropical cyclone genesis. J Clim 20:4819–4834. doi:10.1175/JCLI4282.1

DeMaria M, Knaff JA, Bernadette HC (2001) A tropical cyclone genesis parameter for the tropical Atlantic. Weather Forecast 16:219–233. doi:10.1175/1520-0434(2001)016<0219:ATCGPF>2.0.CO;2

Dvorak VF (1975) Tropical cyclone intensity analysis and forecasting from satellite imagery. Mon Weather Rev 103:420–430. doi:10.1175/1520-0493(1975)103<0420:TCIAAF>2.0.CO;2

Elsberry RL, Jeffries R (1996) Vertical wind shear influences on tropical cyclone formation and intensification during TCM-92 and TCM-93. Mon Weather Rev 124:1374–1387. doi:10.1175/1520-0493(1996)124<1374:VWSIOT>2.0.CO;2

Franklin JL, Lord SJ, Feuer SE, Marks FD (1993) The kinematic structure of Hurricane Gloria (1985) determined from nested analysis of dropsonde and Doppler radar data. Mon Weather Rev 121:2433–2451. doi:10.1175/1520-0493(1993)121<2433:TKSOHG>2.0.CO;2

George JJ (1960) Weather forecasting For aeronautics. Academic Press, USA, p 673

Gray WM (1968) Global view of the origin of tropical disturbances and storms. Mon Weather Rev 96:669–700. doi:10.1175/1520-0493(1968)096<0669:GVOTOO>2.0.CO;2

Gray WM (1975) Tropical cyclone genesis. Dept. of Atmos. Sc., Paper No. 232, Colorado State University, Port Collins Co., USA, p 121

Gray WM (1978) Hurricane and their formation structure and likely role in the tropical circulation. Prepared for the RMS/AMS conference on met. over the tropical oceans, London, August 21–25 1978 and RMS conference volume

Kalsi SR, Srivastava KB (2006) Characteristic features of Orissa super cyclone of 29th October, 1999 as observed through CDR Paradip. Mausam (New Delhi) 57:21–30

Kotal SD, Roy Bhowmik SK, Kundu PK, Das AK (2008) A Statistical Cyclone Intensity Prediction (SCIP) Model for Bay of Bengal. J Earth Syst Sci 117:157–168. doi:10.1007/s12040-008-0006-1

Mandal GS, Rao AVRK, Gupta SC (1981) Characteristics of an Arabian Sea cyclone. Mausam (New Delhi) 32:139–144

McBride JL (1981) Observational analysis of tropical cyclone formation. Part III: budget analysis. J Atmos Sci 38:1152–1166. doi:10.1175/1520-0469(1981)038<1152:OAOTCF>2.0.CO;2

McBride JL, Zehr RM (1981) Observational analysis of tropical cyclone formation. Part II: comparison of non-developing versus developing systems. J Atmos Sci 38:1132–1151. doi:10.1175/1520-0469(1981)038<1132:OAOTCF>2.0.CO;2

Palmen EN (1948) On the formation and structure of the tropical hurricane. Geophysica 3:26–38

Roy Bhowmik SK (2003) An evaluation of cyclone genesis parameter over the Bay of Bengal using model analysis. Mausam (New Delhi) 54:351–358

Roy Bhowmik SK, Kotal SD, Kalsi SR (2007) An empirical model for predicting intensity of tropical cyclone over the Bay of Bengal. Nat Hazards 41:447–455. doi:10.1007/s11069-006-9053-6

Royer J-F, Chauvin F, Timbal B, Araspin P, Grimal D (1998) A GCM study of the impact of greenhouse gas increase on the frequency of occurrence of tropical cyclone. Clim Change 38:307–343. doi:10.1023/A:1005386312622

Zehr RM (1992) Tropical cyclogenesis in the western north Pacific. NOAA Tech. Rep. NESDIS 61, 181pp

Zeng Z, Wang Y, Wu CC (2007) Environmental dynamical control of tropical cyclone intensity—an observational study. Mon Weather Rev 135:38–59. doi:10.1175/MWR3278.1