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Special Section:

Forecast Model Fidelity for
Extreme Weather

Key Points:

- An improved genesis potential parameter (IGPP) for capturing genesis and daily evolution of cyclones over North Indian Ocean is introduced
- IGPP outperforms the genesis potential parameter (KGPP) implemented by India Meteorological Department (IMD) for real-time prediction
- Results reveal that IGPP successfully capture both cyclogenesis and storm evolution by notably reducing false alarms present in KGPP

Supporting Information:

- Supporting Information S1

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An Improved Cyclogenesis Potential and Storm Evolution Parameter for North Indian Ocean

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Abstract Flawless subseasonal prediction of tropical cyclogenesis and evolution over the narrow basin of North Indian Ocean (NIO) demands accurate rendition of the crucial parameters that influence the development of cyclonic storms. While many genesis potential indices are used for climatological monitoring and prediction of cyclogenesis globally, their skill in subseasonal prediction of individual storm development, especially near coastlines are limited. Thus, an improved genesis potential parameter (IGPP) is introduced in this study which can capture both cyclogenesis and daily evolution of cyclonic systems over NIO. The IGPP is a revised version of Kotal-Genesis Potential Parameter (KGPP) implemented by India Meteorological Department (IMD) for short-range operational cyclogenesis prediction over NIO. Daily averaged ERA-5 and ERA-Interim data sets are used for analysis and comparison of selected cyclonic storms over NIO for the period 1989–2018. Results reveal that false alarms and overestimation of values present in KGPP are remarkably reduced by using IGPP for all the analyzed storms. Moreover, IGPP outperforms KGPP in distinguishing between developing and nondeveloping storms by accurately representing the storm genesis, evolution, rapid intensification and intensity variations. Thus IGPP can be implemented operationally for improving the real-time prediction of cyclogenesis and storm evolution over NIO.

Plain Language Summary Accurate representation of weather parameters that are crucial for the formation and development of tropical cyclones over a small basin like North Indian Ocean (NIO) is critical for biweekly storm predictions. Most studies utilize different cyclogenesis parameters in genesis potential indices to capture annual/interannual frequency of cyclone formations around the globe. While these parameters are successful in studying the average storm genesis and frequencies at longer time scales, forecasts in real-time over a land-locked and narrow basin such as NIO often fail to capture rapid storm development. This study introduces an improved parameter for capturing the genesis and daily evolution of individual storms thus modifying the presently used parameter by India Meteorological Department thus making it more suitable for NIO. Comparison of old and improved parameters using daily averaged reanalysis data sets reveal that new parameter is better than the older one with accurate representation of storm evolution and noticeable reduction in false storm signals present in the old parameter for all the storm cases analyzed here.

1. Introduction

Unlike the vast basins of North Pacific and North Atlantic, prediction of tropical storms in the narrow and land-locked North Indian Ocean basin (NIO) is a major challenge (Lee & Gray, 1984). Intense and long-lived cyclonic systems over the NIO mainly develop over southeast-equatorial Arabian Sea (AS) and east Bay of Bengal (BoB). These systems lead to intense damage to the thickly populated and low-lying peninsular coasts, posing a major threat as they undergo unprecedented intensification close to coastal belts, move along the coast or landfall (Lee et al., 1989). Even if there are seasonal and climatological similarities in cyclogenesis locations, lifespan, and tracks over NIO, each storm is unique and affected by the prevailing seasonal atmospheric and oceanic conditions during its intensification processes.

Genesis potential indices based on W. M. Gray's climatological and seasonally averaged cyclogenesis parameters (Gray, 1968, 1998) has long been considered the standard and widely used for cyclogenesis prediction and monitoring. Thermodynamic parameters, conditional instability, high middle-tropospheric humidity,

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and warm sea surface temperatures (SST) with a deep thermocline, provide the seasonal background for cyclogenesis while dynamic parameters: vorticity, Coriolis force, and vertical wind shear act together under favorable thermodynamic background to enable cyclogenesis and development. While upper ocean heat content is considered vital in capturing cyclogenesis (Ali et al., 2007) and storm frequencies at seasonal and interannual timescales, it may negatively affect the accurate sub-seasonal prediction of daily storm evolution over NIO, as SST is not the major influencing parameter of NIO cyclonic activity (Kikuchi & Wang, 2010; Sebastian & Behera, 2015). This is because the near-equatorial AS and BoB regions are warm throughout the year creating a favorable seasonal thermal state for cyclogenesis such that the dynamical processes as a result of the seasonal shift of intertropical convergence zone or monsoon trough are the major factors behind cyclogenesis over NIO. Monsoon trough shifts over oceanic regions during the monsoon transitional periods, which are the major cyclone seasons of NIO (Lee & Gray, 1984). Warmer SST leads to higher surface latent heat flux which increases the surface wind speed (Liu & Curry, 2006), creating a positive feedback (Li et al., 2011) aiding cyclogenesis under favorable environmental conditions. Thus, it is vital to include the oceanic effect on surface layers of atmosphere. Initial vorticity and vertical wind shear influence the storm before genesis, whereas the initial intensity of the system, the thermodynamic profile of surrounding atmosphere and upper ocean controls storm evolution and intensification (Emanuel, 1999).

Kotal-Genesis Potential Parameter (KGPP) used by India Meteorological Department (IMD) for real-time prediction of daily cyclogenesis uses two dynamic and two thermodynamic atmospheric variables. (Kotal et al., 2009; Kotal & Bhattacharya, 2013). In KGPP, relative vorticity and middle tropospheric humidity terms are taken from Grays' parameters, thermal instability is calculated as difference in air temperature between 850 and 500 hPa, and the magnitude of vertical wind shear between 850 and 200 hPa is employed without scaling (Text S1 in the supporting information). While KGPP is used in operational short-range (1 to 3 days) prediction of daily cyclogenesis, it shows major flaws in medium (up to 10 days) and extended-range (up to 3 weeks) storm predictions. This is due to the improper scaling and usage of its constituent variables. The values of thermal instability term decreases with increasing storm intensity as the air temperature in the middle troposphere increase during storm intensification by latent heat release. KGPP when used for hind-cast study in an ensemble prediction system using nearest initial conditions from cyclogenesis date is found to overestimate the values and produce false alarms (Ganesh et al., 2019).

In this study, the thermal instability term is modified to maintain a positive correlation to storm intensity by using equivalent potential temperature (θ_e). An increase in θ_e at 700 hPa is considered a crucial component of rapid intensification and associated reduction in central pressure of tropical storms (Sikora, 1976) and has been used for operational forecasting of cyclone intensification (Dunnavan, 1981). θ_e is considered the most significant predictor of cyclone intensification after vertical wind shear (Petty & Hobgood, 2000) and is a measure of total thermodynamic energy as it reflects both net heat and moisture fluxes in the lower atmosphere. Higher θ_e values near the ocean surface is a manifestation of higher SSTs that enhance convection and moisture transport (Roxy & Tanimoto, 2007, 2012; Wu, 2010). Thus, the increase of θ_e in the lower troposphere will be higher than that in middle troposphere making it a perfect variable to represent storm evolution rather than the difference in air temperature.

Vertical wind shear is generally measured as the mean magnitude of horizontal wind differences in upper (200 hPa) and lower (850 hPa) troposphere over a radius or an annular region between two radii (Zeng et al., 2010) from the storm center. Intense storms survive under strong vertical shear environment when shear is below 15 m/s while few storms even survive shears higher than 20 m/s (Zeng et al., 2007). Tropical cyclones intensify rapidly when the effective local shear attain a minimum value and rapid dissipation initiates when vertical shear increases to a critical value which may vary for each storm case (DeMaria, 1996; Zhang & Tao, 2013). The vertical wind shear thus determines whether the storm will undergo intensification or dissipation and is inversely correlated with nondeveloping storms. As strong cyclones maintain their strength and undergo intensification even under moderate shear environment, shear term can exhibit both positive and negative correlation with storm intensity, which needs to be accurately represented for flawless prediction.

The selected cases, data sets, and formulation of new GPP are given in section 2. Section 3 describes the major results including climatology analysis, comparison for GPPs for selected cases followed by final conclusions in section 4.

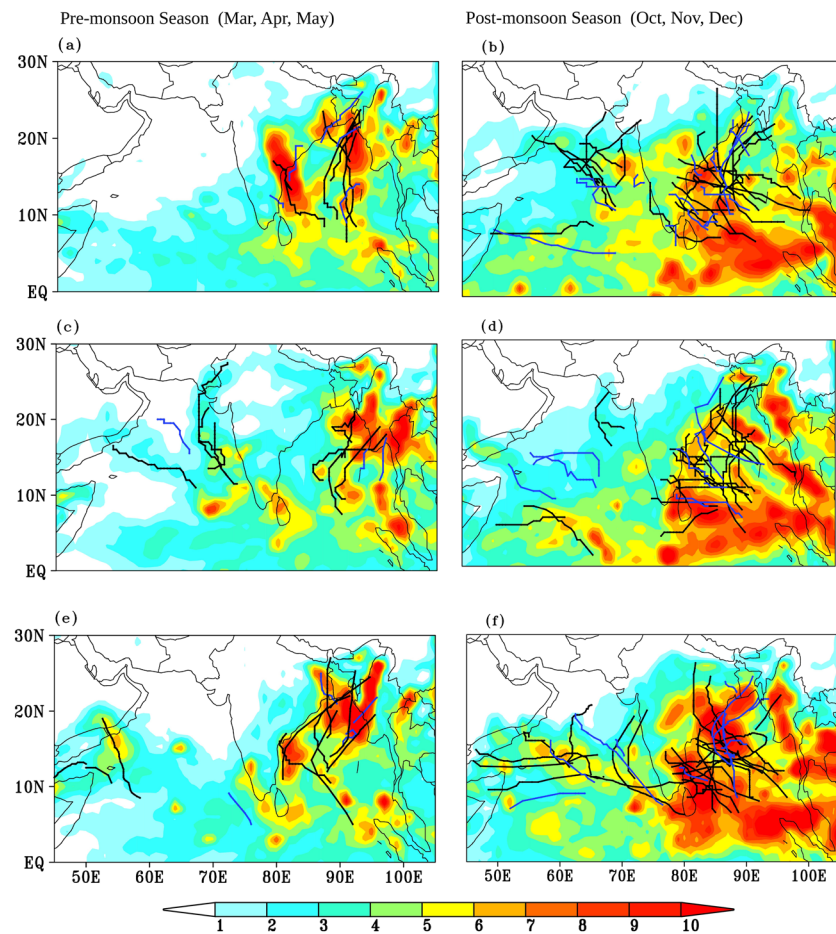


Figure 1. Seasonal climatology for IGPP (shaded) over NIO during premonsoon and postmonsoon seasons of past three decades: (a and b) 1989–1998, (c and d) 1999–2008, and (e and f) 2009–2018 years. IGPP analyses is overlaid with corresponding observed best tracks of developing (black) and nondeveloping (blue) storms during the periods.

2. Data and Methods

2.1. Data

Cyclonic systems recorded by IMD Best Track Data Archive (2019) over NIO for the period 1989–2018 are used in this study (IMD, 2008). Based on IMD mandate, storms are graded by Maximum Surface Windspeeds (MSW) as low-pressure area (L), depression (D), deep depression (DD), cyclonic storm (CS), severe cyclonic storm (SCS), very severe cyclonic storm (VSCS), and extremely severe cyclonic storm (ESCS) (World Meteorological Organization, 2015). Air temperature at 1000, 850 and 500 hPa, relative humidity at 1000, 700 and 500 hPa, u and v components of winds at 850 and 200 hPa are the variables used. Data sets from ERA-Interim and ERA-5 are used to calculate cyclogenesis parameters in KGPP and IGPP. ERA-Interim data sets (Berrisford et al., 2011) at 1° horizontal resolution are daily averaged to calculate decadal climatology of IGPP for the period 1989–2018. ERA-5 three-hourly data sets at 1° horizontal resolution (Copernicus Climate Change Service, 2017) from 2008 to 2017 are daily averaged and used to study genesis and daily evolution of storms using IGPP and KGPP. Details of selected cases for sections 3.2 and 3.3 are provided in Tables S1–S3.

2.2. Improved Cyclogenesis and Evolution Parameter

The IGPP retains vorticity and middle tropospheric humidity terms of KGPP while the vertical wind shear and thermodynamic terms are modified. The scaled mean θ_e between 1,000 and 500 hPa replaces the thermal instability term of KGPP. θ_e at 1000 hPa include the effect of SST and heat fluxes and the midtropospheric θ_e include the effect of latent heat release associated with conditional instabilities and feedbacks

during the storm intensification. The unscaled shear term in KGPP, the magnitude of vertical wind shear between 200 and 850 hPa is replaced in IGPP by the mean vertical wind shear over an annular region between 100 and 200 km radii for each grid point to highlight the effect of background shear and scaled similar to the shear term of widely used genesis potential index (Emanuel & Nolan, 2004). IGPP is formulated as follows: First, θ_e is calculated (Text S2),

$$\text{Thermodynamic term, } I = \frac{(\theta_{e1000} + \theta_{e500})}{2} \quad (1)$$

$$\text{Scaled as, } T = \frac{I - 273.15}{6} \quad (2)$$

Mean middle tropospheric relative humidity,

$$MRH = \frac{(RH_{700} + RH_{500})}{2} \quad (3)$$

$$\text{Scaled as (Gray, 1975), } H = \frac{(MRH - 40)}{30} \quad (4)$$

$$\text{Relative vorticity at 850 hPa, } V = \xi_{850} \times 10^5 \quad (5)$$

Scaled magnitude of vertical wind shear (200–850 hPa) (V_{shear}) averaged over an annular region (Chen & Fang, 2012) between 100 and 200 km from each grid point,

$$S = (1 + 0.1 V_{shear})^{-2} \quad (6)$$

Thus, IGPP is defined as

$$IGPP = V \times H \times T \times S \quad (7)$$

where, $V > 0$, $H > 0$, $T > 0$, $S > 0$.

3. Results

3.1. Climatology of IGPP

Figure 1 depicts the observed climatological maximum of IGPP calculated for the three decades 1989–1998 (a, b), 1999–2008 (c, d), and 2009–2018 (e, f) for the two major cyclone seasons, premonsoon (March to May) and postmonsoon (October to December) over NIO. IMD best-tracks during these periods are overlaid for comparison. Tracks of nondeveloping storms (D, DD) are shown in blue and storms with higher intensities (CS and above) in black.

IGPP climatology patterns closely follow the observed tracks for all three decades and capture both genesis and evolution of cyclonic systems. The seasonal frequency and distribution of cyclones over AS and BoB are also accurately represented by IGPP climatology with higher values and frequencies over BoB that match the frequency of storm tracks. It is also evident that postmonsoon season is the major season of cyclonic activity over NIO. IGPP is dependent on storm intensity and could clearly distinguish between weak and stronger storms, with values less than 4 for D, DDs (blue tracks) and values peaking to more than 10 for intense storms (black tracks).

For the postmonsoon periods of all decades, high IGPP values are present over east-equatorial and central BoB, which may be due to the unrecorded low pressure systems or favorable climatological cyclogenesis conditions. The reduction in frequency of premonsoon storms over AS in Figures 1a and 1e and higher frequency in Figure 1c may be the reflections of interannual oscillations such as negative (positive) effect of El Niño (La Niña) (Landsea, 2000; Singh et al., 2000) with positive Indian Ocean dipole mode (Sumesh & Kumar, 2013).

3.2. Comparison of GPPs for Cyclonic Systems During Different Seasons

Sixteen storm cases with varying intensities and formed in different seasons are selected from the decade of 2008–2017 (Table S1), to examine the spatial distributions and seasonal contrasts between KGPP and IGPP. Figure 2 shows the comparison of observed relative vorticity distribution with the maximum KGPP and IGPP with best tracks overlaid for the evolution of premonsoon CS, Ashobaa, Nanauk, and postmonsoon CS Nilam and Kyant. Further, the GPPs and constituent variables averaged over a region of 1° radius from the storm center for the daily evolution of selected cases are plotted as time series (Figures S4–S7) and compared with observed MSW. The distribution of GPPs for Ashobaa (Figure 2) is almost similar, but KGPP values decrease after the genesis stage as the storm intensifies to cyclone whereas the values are high by almost 50 for the IGPP. Ashobaa reached maximum strength as cyclone just before landfall, which is captured by both GPPs matching the peak of MSW on the fourth day.

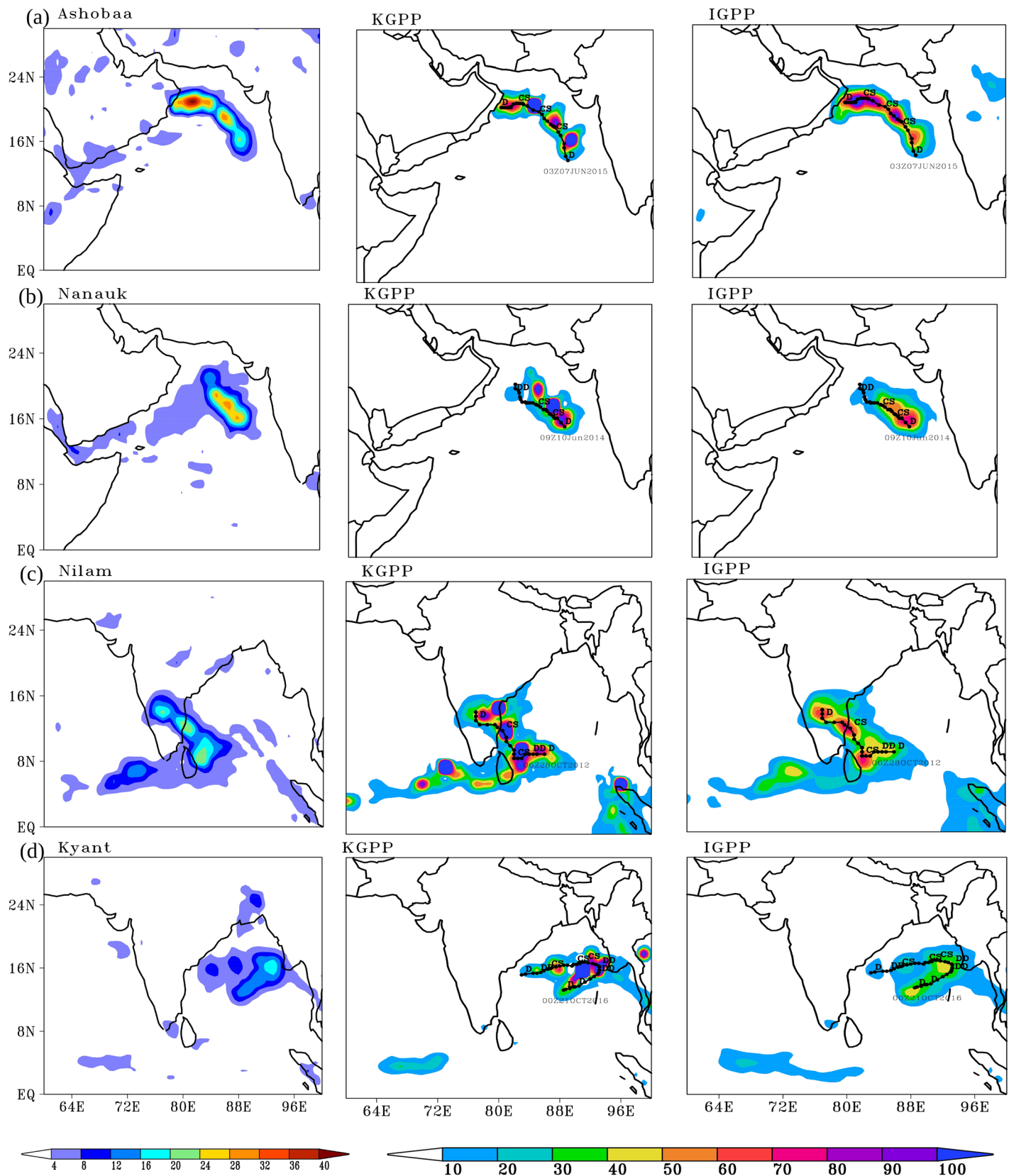
For Nanauk (Figure 2b), the values are higher during genesis and dissipation stages for KGPP. In the time series plot (Figure S8c), KGPP is almost close to IGPP initially and increased to 125 on third day and thereafter matched with IGPP. In the KGPP evolution for Nilam (Figure 2c), false alarm exists over southeast and southwest BoB which is clearly reduced in IGPP analysis. Another false alarm region of KGPP maxima after landfall over southeast peninsular region is also noticeably reduced in IGPP. For Kyant (Figure 2d), a large area of intense false alarm is present in KGPP on the third day and values peaked to almost 400 in corresponding time series (Figure S8c). Timeseries of constituent variables reveal that high shear term peaking to 1.5 is the reason behind this overestimation (Figure S6), while for all the other cases, shear value is always below 0.5. Since KGPP uses inverse of vertical shear without scaling, high value corresponds to wind shear term having values 0.7 m/s or lesser. This fault in KGPP is rectified by IGPP which employ scaled vertical shear term. Thus, CS Kyant is a clear example for the improvement in storm representation by IGPP.

Laila, Aila, Mora, and Phet are the premonsoon severe storms selected for comparison of (Figure S1) maximum GPPs. For Laila and Aila (Figures S1a and S1b), KGPP shows extremely high values during genesis and dissipating stages while IGPP produces better evolution with values increasing linearly with intensification. Here the storm is captured by both GPPs without false alarms. Overestimation of the values is reduced in IGPP analysis with improved values and reduced false alarms. For Mora and Phet (Figures S1c and S1d) also, IGPP captures the spatial evolution better than KGPP. The overestimation observed in KGPP for Mora during the genesis stage is also reduced in IGPP plots. Time series of area averaged GPPs (Figure S8a) show that MSW daily evolution of premonsoon severe storms are followed by both parameters, while the values are little higher for IGPP closely following MSW for most cases.

Ockhi, Hudhud, Vardah, and Chapala are the severe storms during the postmonsoon period selected for comparing KGPP and IGPP (Figure S2). Here also IGPP is perfectly capturing storm evolution with consistent elimination of false alarms present in KGPP. Overestimated KGPP values for a DD over BoB during Ockhi is better represented by IGPP. During Chapala, the pregenesis disturbance that led to the development of VSCS Megh is also visible over southwest AS, which has values less than 50 in IGPP plot, however higher than 100 in KGPP. Time series plots for postmonsoon storms (Figure S8b) show that for Ockhi, the KGPP values are overestimated after the genesis and throughout the storm evolution, but this transformation of intensity is better captured by IGPP.

For Hudhud and Vardah (Figure S8b), IGPP closely follow the storm evolution. For Chapala, the dip in IGPP on 1 November is actually the observed weakening of Chapala before reintensification, even though the change in intensity is minimal. Analysis of four weaker systems (D, DD), two in each season are shown in Figure S3. Similar to previous cases, here also KGPP have higher values before genesis and after dissipation, while IGPP captured the proper evolution of all the systems with values not exceeding 70. Time series (Figure S8d) of mean GPPs show that evolution of premonsoon and postmonsoon DD are almost well captured by both parameters may be because of the smaller spatial size of weak systems.

Time series of constituent parameters (Figures S4–S7) show the evolution of mean constituent parameters with GPPs during the lifespan of each selected cases. Vorticity, humidity, and shear terms show similar patterns for most cases. The problem of inverse relation of thermal instability term of KGPP resolved by the linear relation of thermodynamic term in IGPP with storm intensity and reduction in false alarms by using scaled vertical shear terms are the major highlights from these plots. To understand this



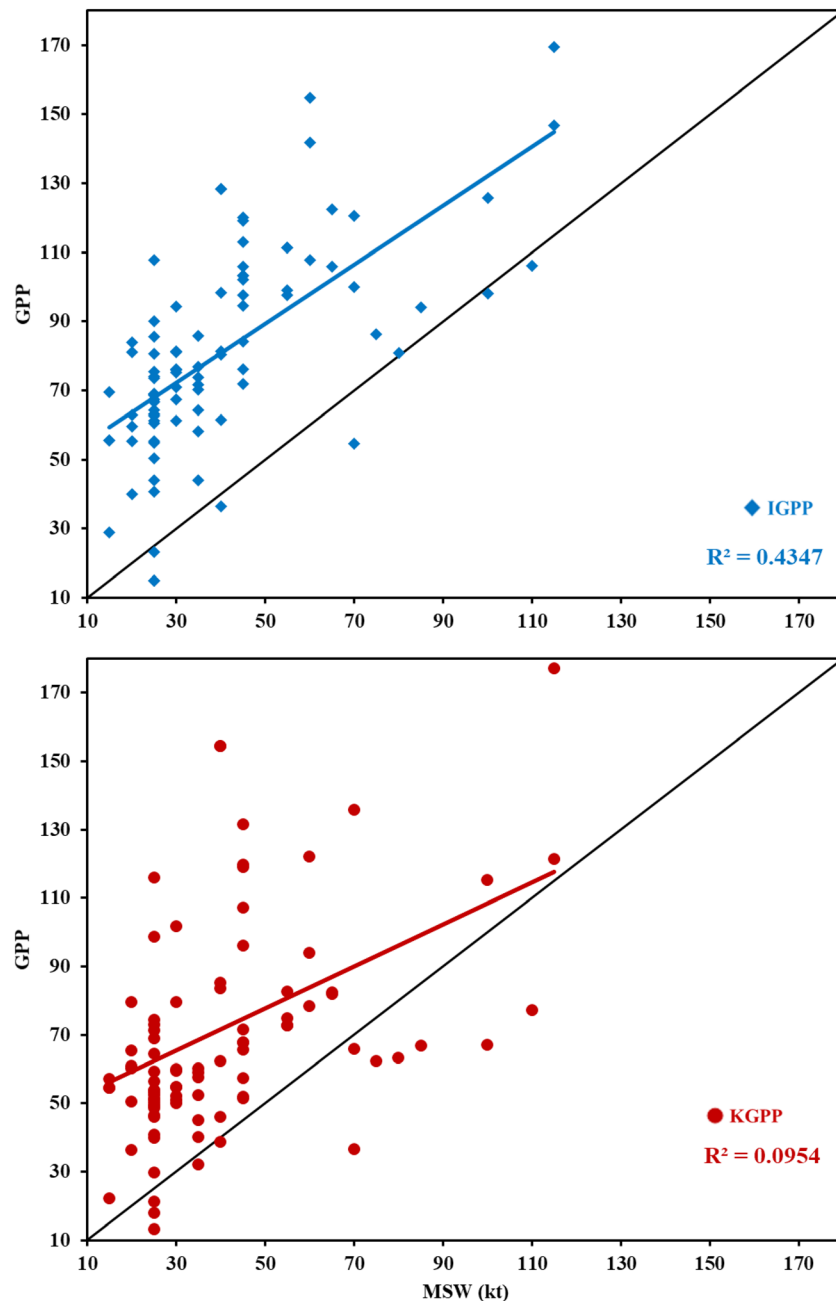


Figure 3. Scatterplot for (a) IGPP and (b) KGPP values compared with MSW (kt) for the intensity evolution of selected cases.

improvement in IGPP, scatterplots for both GPPs comparing them to observed MSW are plotted and the coefficient of determination (R^2) for the selected cases are calculated (Figure 3). It is clear that IGPP has better relationship with the storm intensity ($R^2 = 43.47\%$) as compared to KGPP versus intensity ($R^2 = 9.54\%$). From the R^2 values, the improvement of IGPP relative to KGPP is found to be almost 34% which clearly signifies the better skill of IGPP in capturing the intensity variations and emphasizing the effects of modified thermodynamic and vertical shear terms.

3.3. Comparison of Mean GPPs for Developing and Nondeveloping Storms

The low pressure systems that intensify up to DD stage and dissipate or landfall without further intensification are categorized as nondeveloping storms. Those systems with intensities peaking to CS stage or higher

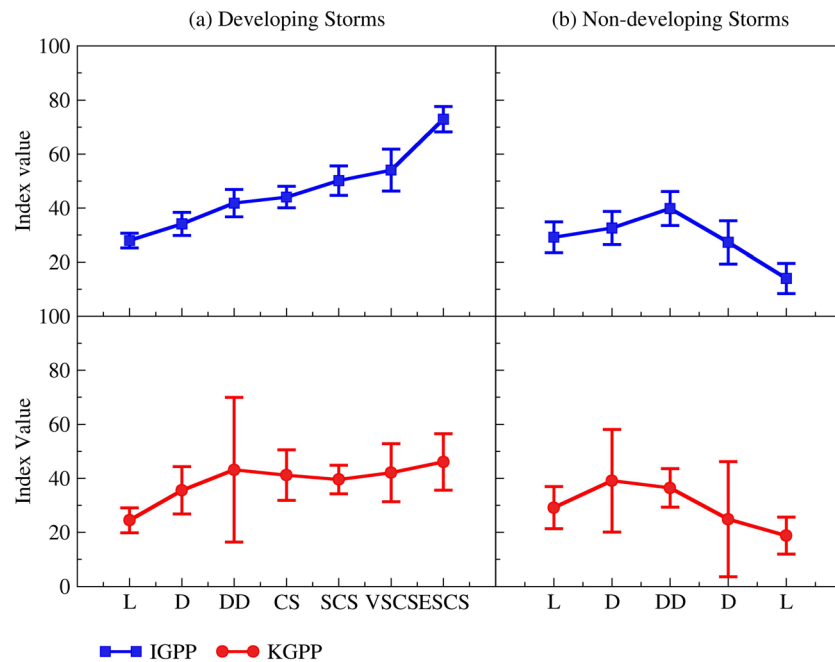


Figure 4. Mean values of IGPP and KGPP with standard deviation for all cases for each stage of evolution for (a) developing storms and (b) nondeveloping storms.

are considered as developing storms. Some major features and differences between developing and nondeveloping storms are provided in Table S2. Fifteen developing storms (Table S3) and 11 nondeveloping storms (Table S4) are considered in this section to evaluate the mean KGPP and IGPP values for each stage of the storm evolution. Here GPPs and constituent terms are area averaged over 2° latitude/longitude from the storm center for each case for stage by stage evolution. Developing storms are sorted from genesis to maximum intensification whereas nondeveloping storms are sorted from genesis to dissipation stages to calculate the mean GPP values (Table S5). Developing storms are graded as L, D, DD, CS, SCS, VSCS, and ESCS, and the nondeveloping cases are graded as L, D, DD, D, and L.

For developing storms (Figure 4a), IGPP shows an increasing curve with intensity unlike KGPP which has two maxima, one during DD stage due to the thermal instability term and the other during ESCS stage. Initially, both KGPP and IGPP values are almost similar, but the standard deviation is larger for KGPP. As the storms intensify, KGPP gradient decrease whereas the IGPP increase linearly and maximum values reach more than 70 for ESCS. For nondeveloping storms (Figure 4b), IGPP follow the intensity changes whereas KGPP have maximum values in initial stage of D similar to previous results and decrease during DD stage, which is clearly due to the inverse relation of thermal instability term to intensification. Both GPP values decrease and coincide at dissipation stages.

For better understanding, mean values of constituent terms of GPPs are calculated (Tables S6 and S7) for the storms and corresponding time series are shown in Figures S9 and S10. Here vorticity and humidity terms are the same for both GPPs and major changes are observed in thermodynamic and shear terms. For developing storms (Figure S9), similar to the IGPP distribution, humidity, and vorticity values show increasing trend with intensification. Kotal-thermal instability term and shear terms show decreasing trend, thus contributing to the reduction in mean KGPP with intensity. It is also evident from the mean shear distributions that it has higher influence during the genesis and dissipating stages and decreases with intensification followed by a slight increase when storms reach maximum intensity of VSCS and ESCS. The standard deviations of both thermodynamic and shear terms of IGPP are less than that of KGPP.

For nondeveloping storms (Figure S10), humidity and vorticity evolution during each stage show that values increase from the genesis stage to DD stages and thereafter decreases as storms dissipate. The thermal instability term of KGPP decreases with increasing intensity thus reducing the KGPP values during DD

stage. This problem is absent in IGPP with new thermodynamic term for both intensifying and weakening storms. Shear terms of KGPP and IGPP exhibit similar evolution, but the modified shear term in IGPP has lower standard deviations during intensification stages in nondeveloping storms.

To quantify the effect of constituent variables on each GPP, linear correlation is calculated for the selected storms (Table S8). Similar to the previous analyses, the thermal instability term is negatively correlated with KGPP for both developing and nondeveloping cases whereas the new thermodynamic term is positively correlated to IGPP with values higher than 0.8 for both developing and nondeveloping storms. For developing systems, shear terms have negative correlation with both GPPs and vice versa. During the stages of rapid intensification and development, due to high lower-level convergence and upper-level divergence, vertical shear surrounding the storms will be higher and correspondingly shear term becomes lower such that influence of vorticity, thermodynamic and humidity terms become more prominent in IGPP. The constituent terms are better correlated with IGPP as compared to the correlation of KGPP with its constituent terms except for the humidity term in the case of developing storms.

4. Conclusions

A new cyclogenesis potential and storm evolution parameter, IGPP, is introduced for improving the daily tropical storm prediction over NIO by modifying the presently implemented KGPP by IMD. This parameter is formulated by using the most suitable variables favoring cyclogenesis and development over NIO by scaling them according to their relative contribution to both cyclogenesis and evolution. IGPP retains the relative vorticity and humidity terms from KGPP, replacing the unscaled vertical shear term and negatively correlated thermal instability terms. The thermodynamic term is modified as the mean θ_e of surface and middle troposphere to include the effect of warm sea surface and middle-tropospheric latent heat release. Vertical wind shear term is modified as scaled and averaged vertical shear for an annular region between 100 and 200 km radii from the storm center. Climatology analysis of IGPP during the premonsoon and post-monsoon seasons for past three decades show the skill of IGPP in accurately representing the cyclogenesis and evolution of NIO cyclonic systems even after landfall. The comparison of daily evolution of IGPP and KGPP for individual storms reveal that IGPP remarkably captures the genesis and evolution of storms without false alarms. The ability of GPPs in differentiating between developing and nondeveloping storms and capturing the storm evolution is also studied. For both developing and nondeveloping storms, the mean IGPP shows better correlation with intensity unlike KGPP which overestimate the values during genesis and dissipation stages and underestimate values during intense stages due to the inverse relation of thermal instability and unscaled shear terms. An improvement of 34% is observed for IGPP versus MSW over KGPP versus MSW which signifies better linear relation of IGPP to storm intensity. The new thermodynamic term closely follows intensification and storm evolution and is positively correlated to IGPP. The improved shear term also reduce false alarms over both land and ocean regions present in KGPP analyses. Thus, IGPP outperforms KGPP in every aspect by accurately representing intensity changes during cyclogenesis and evolution and having better correlation with its constituent variables. Thus IGPP is extremely appropriate to be implemented operationally for improving the real-time prediction of cyclogenesis and storm evolution over NIO on short to medium range and seasonal to subseasonal time scales.

Data Availability Statement

All details of storms are accessed from <http://www.rsmcnwdelhi.imd.gov.in/images/pdf/archive/best-track/best%20track%20ecscsuc-2018.xls> website. ERA-Interim data sets used are available at <https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=pl/> and documented in Berrisford et al. (2011). ERA-5 data sets used (Copernicus Climate Change Service, 2017) are downloaded from <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form> and documented in <https://confluence.ecmwf.int/display/CKB/ERA5%3AA+dataA+documentation> website.

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