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# Large-scale characteristics of rapidly intensifying tropical cyclones over the Bay of Bengal and a Rapid Intensification (RI) index

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**सार** – बंगाल की खाड़ी में उष्णकटिबंधीय चक्रवातों के लिए एक द्रुतगति तीव्रीकरण सूचकांक (आर.आई. आई.) विकसित किया गया। आर. आर. आई. 24 घंटों और उसके बाद के द्रुतगति तीव्रीकरण (आर. आई.) की संभावना का आकलन करने के लिए उष्णकटिबंधीय चक्रवातों के अभिलक्षणों का बड़े पैमाने पर उपयोग करता है। 24 घंटों के दौरान आर. आई. को 30 नॉट (15.4 एम.एस.$^{-1}$) पर तीव्रता की वृद्धि के रूप में परिभाषित किया गया है जो 1981–2010 के दौरान बंगाल की खाड़ी में बने उष्णकटिबंधीय चक्रवातों के 24 घंटे की तीव्रता के परिवर्तनों के 93वें शतमक को दर्शाता है। इसमें यह देखा गया है कि 32 प्रतिशत अति प्रचंड सभी चक्रवाती तूफान (वी. एस. सी. एस.) और सभी महाचक्रवाती तूफान (एस. यू. सी. एस.) अपने–अपने जीवनचक्र में कम से कम एक बार आर. आई. चरण से जरूर गुजरते है। आर. आई. स्थितियों से संबद्ध बड़े पैमाने पर विभिन्न परिवर्तनों की गैर आर. आई. स्थितियों के साथ तुलना की गई है। इन तुलनाओं से यह पता चला है कि आर. आई. की स्थितियाँ सामान्यतः उच्च अक्षांश पर घटित होती है और गैर आर. आई. स्थितियों की अपेक्षा 12 घंटे पहले अत्यंत तेजी से तीव्र हो जाती हैं। सांख्यिकीय विश्लेषण से भी यह पता चलता है कि आर. आई. की स्थितियाँ उन क्षेत्रों से जुड़ी हुई होती है जहाँ पर उपरितन स्तर के अपसरण, निचले स्तर की सापेक्षिक भ्रमिलता और सापेक्षिक आर्द्रता अधिक होती है तथा जिसमें अपनी–अपनी परिवर्तिताओं के सुनिश्चित आरंभिक मानों की अपेक्षा उर्ध्वाधर पवनों के अपरूपण कम होते हैं। अततः आर. आई. की पवन गति आरंभ में अधिक होती है और गैर आर. आई. स्थितियों की अपेक्षा तीव्र गति से स्थानांतरित होती हुई आगे बढ़ती है। आर. आई. आई. तकनीक को आठ परिवर्तिताओं के संयुक्त आरंभिक (सूचकांक) मानों द्वारा विकसित किया गया है। जिनके लिए आर. आई. और गैर आर. आई. स्थितियों के मध्य सांख्यिकीय रूप से उल्लेखनीय भिन्नताओं का पता चला है। जिस समय अक्षांश की कुल संख्या शून्य से आठ तक पहुँचती है उस समय आर. आई. की संभाव्यता में 0 प्रतिशत से 100 प्रतिशत तक की वृद्धि देखी गई है।

**ABSTRACT.** A rapid intensification index (RII) is developed for tropical cyclones over the Bay of Bengal. The RII uses large-scale characteristics of tropical cyclones to estimate the probability of rapid intensification (RI) over the subsequent 24 hrs. The RI is defined as an increase of intensity 30 kt (15.4 ms$^{-1}$) during 24 hrs, which represents approximately the 93$^{rd}$ percentile of 24 hrs intensity changes of tropical cyclones that developed over the Bay of Bengal during 1981-2010. It is found that 32% of all very severe cyclonic storms (VSCS) and all super cyclonic storms (SUCS) underwent RI phase at least once during their lifetime. Various large-scale variables associated with the RI cases are compared to those of non-RI cases. These comparisons show that the RI cases generally occur at higher latitude and are intensifying at a faster rate during the previous 12 hrs than the non-RI cases. The statistical analysis also shows that the RI cases are embedded in regions where the upper-level divergence, lower-level relative vorticity and relative humidity are more and vertical winds shear is less than certain threshold values of the respective variables. Finally, the initial wind speed of RI cases is higher and tends to move with a faster translational speed than the non-RI cases. The RII technique is developed by combining threshold (index) values of the eight variables for which statistically significant differences are found between the RI and non-RI cases. The probability of RI is found to be increases from 0% to 100% when the total number of indices satisfied increases from zero to eight.

**Key words** – Tropical cyclone, Rapid intensification, Probability, Vorticity, Divergence, Vertical wind shear, Bay of Bengal.

## 1. Introduction

Tropical cyclones are well known for their destructive character and impact on human activities. The massive destruction caused by strong winds, storm surge and torrential rains associated with a storm. With the availability of sophisticated Numerical Weather Prediction (NWP) models though some progress has been made in tropical cyclone track prediction, the skill of intensity prediction is still remains a difficult task to forecasters (Elsberry *et al.*, 2007 and Houze *et al.*, 2007). Gross (2001) also showed that the operational forecast models are substantially more skillful in predicting a tropical cyclone's track than its intensity. DeMaria *et al.*, (2002) showed that the official National Hurricane Center (NHC) intensity forecasts are much less skillful than the official NHC track forecasts. While the forecasting of tropical cyclone (TC) intensity has been quite difficult, the forecasting of rapid intensification (RI) has been more challenging. The inability to forecast RI is due to our limited understanding of physical mechanism responsible for RI in general.

In the previous studies, many researchers have examined the role of the ocean, inner-core processes, and environmental interactions on tropical cyclone intensity. Some of these studies have also discussed possible physical mechanisms responsible for RI. The results of some important studies on TC intensity change relevance to RI are discussed below.

Many studies (Byers, 1944; Miller, 1958; Malkus and Riehl, 1960; DeMaria and Kaplan, 1994a; Whitney *et al.,* 1997; Zeng *et al.,* 2007) stressed the positive impact of the ocean on TC intensity. Their results show that the maximum intensity of a tropical cyclone is more sensitive to warmer sea surface temperature (SST). Many other studies (Sutyrin and Khain, 1979; Bender *et al.*, 1993; Bender and Ginis, 2000) have also shown negative feedback between the ocean and atmosphere due to upwelling and vertical mixing of the cool underlying ocean by the TC. The importance of inner-core processes has been linked to changes in TC intensity. Latent heat release contributes to intensification through a range of mechanisms. The most commonly used theory to explain TC growth has been conditional instability of the second kind (CISK) (Charney and Eliassen, 1964; Ooyama, 1964; Rasmussen, 1979; Fraedrich and Mcbride, 1989; Mcbride and Fraedrich, 1995). During the intensification period, low level convergence coupled with upper level divergence gives rise to vertical motion taking moist air upwards. This moist air condenses at higher levels (middle troposphere) and releases latent heat of condensation which warms up the air column. This results in further fall in surface pressure and increase in surface wind speed. This process continues and a low pressure system gradually intensifies into a cyclonic storm. Willoughby *et al.,* (1982) noted concentric eyewalls are characterized by the development of a secondary ring of convection around an existing inner eyewall. This secondary (outer) eyewall may contract and replace the inner eyewall and can produce significant changes in TC intensity. They also showed that a TC can weaken significantly due to the collapse of an inner eyewall and contraction of an outer eyewall can produce significant intensification of a TC.

Montgomery and Kallenbach (1997) suggested that a TC vortex can intensify due to the axisymmetrization of a convectively induced positive potential vorticity (PV) region near the radius of maximum wind (RMW). Davis *et al.*, (1993) showed that positive PV anomalies produced by latent heating in the lower troposphere can greatly increase the intensity of surface cyclones. On the rapid pressure fall of Hurricane Elena (1985), Molinari *et al.,* (1995) hypothesized that the superposition of an upper level positive PV anomaly above Hurricane Elena may have initiated the wind-induced surface heat exchange (WISHE) mechanism (Emanuel, 1986). They speculated that the initiation of the WISHE mechanism might have triggered the rapid pressure falls of Elena.

Previous studies (Gray, 1968; Merrill, 1988) have shown that vertical wind shear plays a significant role in modulating TC intensity. They showed that storm development is associated with low vertical wind shear. Holliday and Thompson (1979) examined the characteristics of rapidly intensifying typhoons in the Northwest Pacific Ocean. They found that RI of TCs occurs over the region of sufficiently deep layer of warm water. They also found that RI was more likely to occur for TCs with smaller eye diameter than average eye diameters and was more prevalent during the night. Kaplan and Demaria (2003) showed that the RI cases are developed in regions of warmer water and higher lower-tropospheric relative humidity than the non-RI cases. Also, the RI cases were in the regions of lower vertical shear and more easterly upper-tropospheric flow than the non-RI cases. They also showed that the RI was more likely to occur in an environment where forcing from upper-level troughs or cold lows was weaker than average.

The aim of this study is to examine the various environmental conditions that appear to be favourable for RI of TCs over the Bay of Bengal for a large dataset. The conditions associated with the cases that underwent RI are evaluated to determine if they are significantly different from those that existed for non-RI cases. The article is organized as follows. The data sample used in this study is described in Section 2. Climatology of 24 hrs intensity changes over the Bay of Bengal is presented in Section 3. A comparison of the environmental conditions that were present for cases that underwent RI to those that existed for non-RI cases during 24 hrs time periods is presented in Section 4. An estimate of probability of RI is described in Section 5. Finally, some concluding remarks are presented in Section 6.

TABLE 1

Classification of tropical disturbances

| T. No. | Classification of Cyclonic Disturbance | Wind speed (kt) | Wind criteria (kt) |
|---|---|---|---|
| T1.0 | Low (L) | - | <17 |
| T1.5 | Depression (D) | 25 | 17-27 |
| T2.0 | Deep Depression (DD) | 30 | 28-33 |
| T2.5 | Cyclonic storm (CS) | 35 | 34-47 |
| T3.0 | Cyclonic storm (CS) | 45 | 34-47 |
| T3.5 | Severe Cyclonic Storm (SCS) | 55 | 48-63 |
| T4.0 | Very Severe Cyclonic Storm (VSCS) | 65 | 64-119 |
| T4.5 | Very Severe Cyclonic Storm (VSCS) | 77 | 64-119 |
| T5.0 | Very Severe Cyclonic Storm (VSCS) | 90 | 64-119 |
| T5.5 | Very Severe Cyclonic Storm (VSCS) | 102 | 64-119 |
| T6.0 | Very Severe Cyclonic Storm (VSCS) | 115 | 64-119 |
| T6.5 | Super Cyclonic Storm (SuCS) | 127 | ≥120 |
| T7.0 | Super Cyclonic Storm (SuCS) | 140 | ≥120 |
| T7.5 | Super Cyclonic Storm (SuCS) | 155 | ≥120 |
| T8.0 | Super Cyclonic Storm (SuCS) | 170 | ≥120 |

## 2. Data and analysis

A sample database of 88 cyclones that developed over the Bay of Bengal during the period 1981-2010 is used in this study. As per the convention of India Meteorological Department (IMD), the classification of tropical disturbances is given in Table 1 (available at http://www.imd.gov.in/section/nhac/dynamic/faq/FAQP.htm#q62).

Dvorak's technique based on pattern recognition in the cloud imagery of satellite observation is used to determine the intensity of cyclonic storm. For this purpose a T. No. where T stands for tropical cyclone is assigned to the system. This scale of T Nos. varies from T 1.0 to T 8.0 at the interval of 0.5. Five different T. Nos between T 4.0-T 6.0 corresponds to the different intensity between 64-119 kts of a VSCS are assigned based on pattern recognition in the cloud imagery as described by Dvorak (1975). The cyclone Atlas of IMD contains only track positions and classification of cyclonic disturbances. Regional Meteorological Centre (RMC), New Delhi started functioning as Regional Specialised Meteorological Centre (RSMC)-Tropical Cyclones from the year 1988. The track and intensity of cyclones are available in the IMD's RSMC report from the year 1990. The database of this study is considered during the period 1981 to 2010. In view of this, cyclone data such as intensity, tracks etc. obtained from the Joint Typhoon Warning Center (JTWC) "best track" database (Chu *et al.*, 2002) from 1981 are used in this study. The data table includes date and time, position in latitude, longitude and intensity (maximum sustained surface winds in knots). The maximum sustained surface wind of a tropical cyclone is a common indicator of the intensity of a storm. According to the convention of Joint Typhoon Warning Center (JTWC), maximum sustained surface wind is the average winds over a period of one minute. In this study, unit of wind speed knots is used instead of standard unit metres per second as winds are forecast in knots, rounded to the nearest 5 (1 kt = 0.5144 ms$^{-1}$). Various environmental conditions, which appear to be responsible for intensification are derived from European Centre for Medium Range Weather Forecasting (ECMWF) ERA 40 Re-Analysis daily fields available at 2.5° latitude-longitude grid. As ECMWF (ERA-40) reanalysis data is available freely on the Internet up to August 2002, for this exercise NCEP (National Center for Environmental Prediction) reanalysis data has been used after August 2002 available at 2.5° latitude-longitude grid to derive the environmental variables. Sea surface temperature (Reynolds SST) is obtained from National Center for Environmental Prediction (NCEP) reanalysis data (Reynolds *et al.*, 2002), which are available at 1° latitude-longitude grid. These data are freely available on the Internet.

**TABLE 2**

**Climatological, persistence and synoptic variables**

| S. No. | Variables | Symbol of Variables | Unit |
|---|---|---|---|
| 1. | Previous 12-h intensity change | IC12 | kt |
| 2. | Vorticity at 850 hPa | V850 | $10^{-5}$ $s^{-1}$ |
| 3. | Storm motion speed | SMS | $ms^{-1}$ |
| 4. | Divergence at 200 hPa | D200 | $10^{-5}$ $s^{-1}$ |
| 5. | Initial Storm intensity | ISI | kt |
| 6. | Initial Storm latitude position | ISL | °N |
| 7. | 850-700 hPa average relative humidity | LTRH | % |
| 8. | 850-200 hPa vertical wind shear | SHR | $ms^{-1}$ |
| 9. | Sea Surface Temperature | SST | °C |

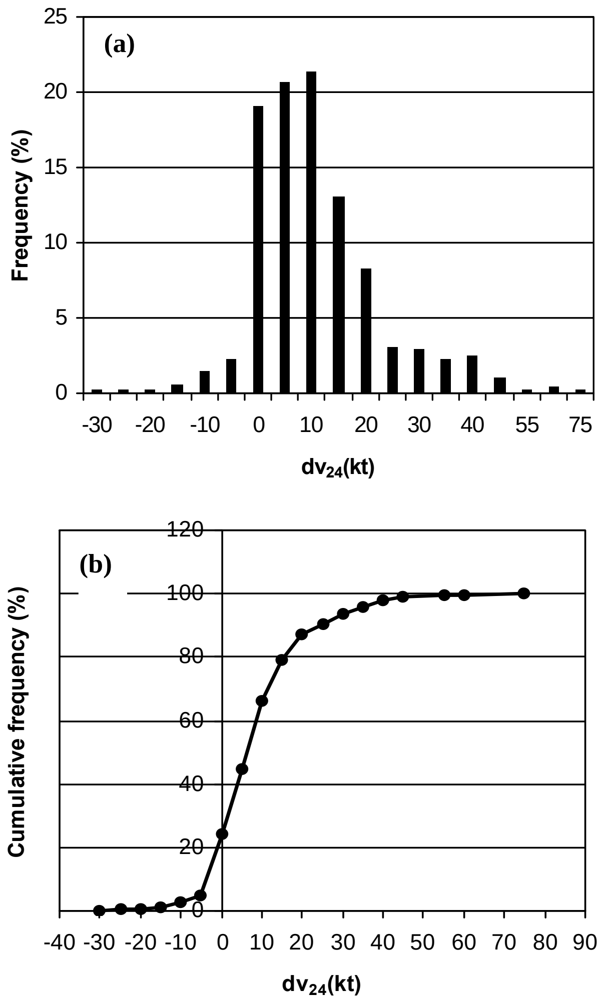
The climatological and persistence, and large-scale variables that were evaluated for each TC are shown in Table 2. Most of the variables in Table 2 are used as predictors in the SCIP model (Kotal *et al.*, 2008) for TC intensity prediction; however, lower tropospheric relative humidity (LTRH) that was not employed in SCIP is included in the table. The methodology currently used to compute the variables is identical to that described in SCIP. Each of the variables in Table 2 was evaluated for the total number of 88 TCs [5 Deep Depression, 24 cyclonic storms (CS), 26 severe cyclonic storms (SCS), 25 very severe cyclonic storms (VSCS), and 8 super cyclonic storms (SUCS)] those formed during 1981-2010. The 88 TCs contributed a total of 483 cases of 24 hrs time periods intensity changes, since lifetime of a TC could be more than 24 hrs. These 483 cases were employed in the statistical analyses of 24 hrs period of rapid intensification phases discussed in Sections 3 and 4.

## 3. Climatology of rapid intensification

The frequency distribution of 24 hrs intensity change ($dv_{24}$) of all 483 cases under study is shown in Fig.1(a). The figure shows that the frequency of slow intensification ($dv_{24}$ = 0 to 10 kt) was higher. Fig. 1(b) shows the cumulative frequency distributions of 24 hrs intensity change ($dv_{24}$). In this study, rapid intensification (RI) is defined as an increase of tropical cyclone intensity 30 kt (15.4 $ms^{-1}$) during 24 hrs. The 24 hrs intensity change 30 kt represents the 93.4th percentile of $dv_{24}$ for all 483 sample cases employed in this study [Fig. 1(b)]. A percentile is the value of a variable below which a certain percent of observations fall. For example, the pth percentile is a value so that roughly p% of the data is smaller and (100-p)% of the data is larger. The 24 hrs intensity change 30 kt represents the 93.4th percentile of $dv_{24}$ for all 483 sample cases indicate that the 93.4th percentile is the value below which 93.4 per cent of the 483 observations ($dv_{24}$) of value less than 30 kt are found. It is to note that, the Kaplan and Demaria (2003) definition for RI of a 24 hrs intensity change of 30 kt is equivalent to the 95th percentile of all of the 24 hrs intensity changes of the TCs in the North Atlantic basin from 1989 to 2000.

Out of the sample total of 88 TCs, 16 TCs (8 VSCS, 8 SUCS) underwent RI phase at least once during their lifetime. These 16 TCs contributed a total of 46 RI phases of 24 hrs period, since a TC could undergo RI phase more than once during its lifetime. The sample total of 46 RI cases represents 9.5% of the sample total of 483 cases. Fig. 2 indicates that 32% of TCs that attained VSCS, and all the SUCSs underwent RI at least once during their lifetime. No cyclonic storms (CS) and severe cyclonic storm (SCS) underwent RI during their lifetime. Overall, 18% of all TCs underwent RI. The RI cases as a function of the initial TC intensity shows that 4.7%, 10.9%, 26.7%, and 30.5% of the DD, CS, SCS, and VSCS samples among all 483 samples underwent RI respectively.

Fig. 3 shows the 24 hrs tracks of the RI cases of 16 TCs. Some of the tracks overlap because RI may occur for consecutive 24 hrs time periods. The figure indicates that RI frequently occurred north of latitude 10° N. Also, it appears that there is a tendency for more RI cases in the central Bay of Bengal. The figure also suggests that the lack of RI tracks in the southwestern, southeastern, Andaman Sea, and northern portion of the Bay of Bengal. Clearly, the large-scale environment plays a role in determining favourable regions for RI. In the subsequent section, the large-scale conditions that are conducive to RI will be examined in more detail.



**Figs.1 (a&b).** (a) Frequency distribution and (b) cumulative freq. distribution of 24 hr intensity change ($dv_{24}$)

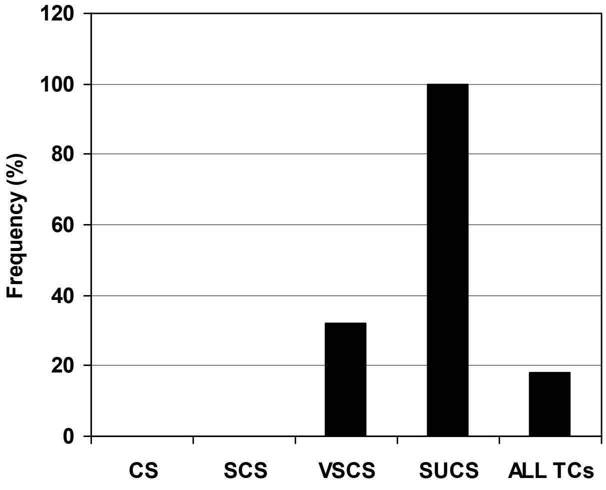


**Fig. 2.** The percentage distribution of systems that underwent RI at least once during their lifetime as a function of the maximum intensity attained by each system

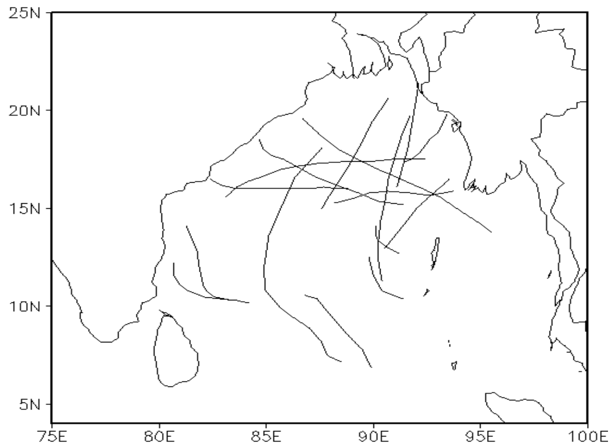


**Fig. 3.** The tracks of the RI cases during 1981-2010

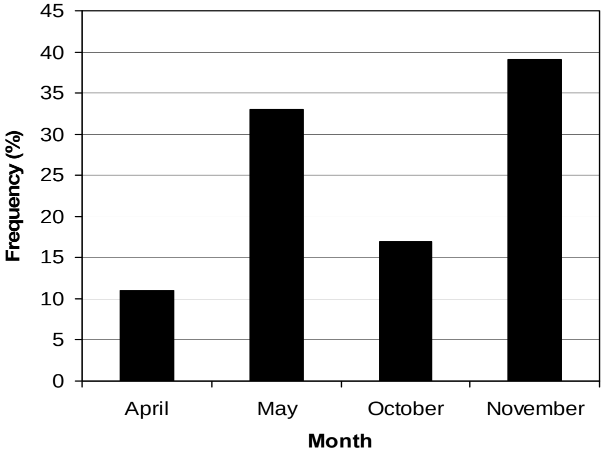


**Fig. 4.** The percentage distribution of the RI cases by month

The seasonal distribution of the RI cases is shown in Fig. 4. The majority of the RI cases (72%) occurred in later months (May, November) of pre-monsoon season (March, April, May) and post-monsoon season (October, November, December). A much larger fraction of the RI cases occurred in November (39%) and May (33%) than in April (11%) and October (17%). Interestingly, no RI cases occurred in March and December. This is consistent with the climatology which showed that tropical cyclones occur more frequently in the months of May and November than March, April, October and December.

## 4. Large-scale conditions associated with the RI and non-RI cases

### 4.1. *Comparison of large scale conditions and their physical link with RI*

In this section, the large-scale conditions (Table 2) associated with each of the 46 cases of RI are compared to

**TABLE 3**

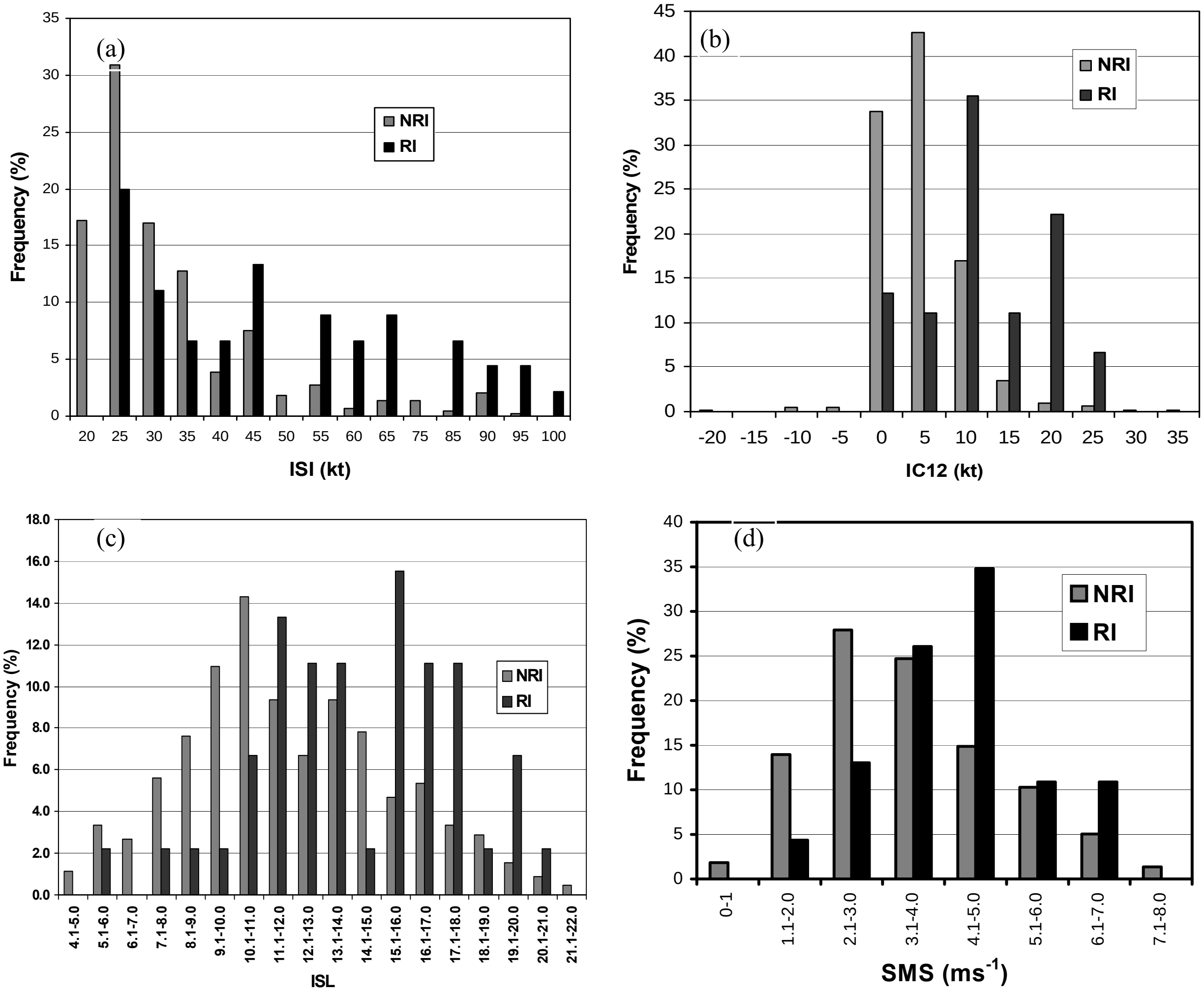
**The variables (as in Table 2) with the mean magnitudes of the RI and non-RI samples, the differences between these mean values (D = RI - non-RI) and the threshold values are shown. A single or double asterisk was placed beside the D value if the difference was statistically significant (two-sided t-test) at either the 95% (*) or 99.9% (**) level. The RI (N = 46) and non-RI (N = 437) sample sizes that were used to perform significance tests are also shown**

| Variables | Unit | RI (N=46) | Non-RI (N=437) | D = RI -Non-RI | Threshold |
|---|---|---|---|---|---|
| IC12 | kt | 11.6 | 4.8 | $6.8^{**}$ | 8.2 |
| SMS | $ms^{-1}$ | 4.1 | 3.5 | $0.6^{**}$ | 3.8 |
| SHR | $ms^{-1}$ | 10.1 | 11.8 | $-1.7^{**}$ | 10.9 |
| D200 | $10^{-5}$ $s^{-1}$ | 1.8 | 1.4 | $0.4^{*}$ | 1.6 |
| V850 | $10^{-5}$ $s^{-1}$ | 5.0 | 4.1 | $0.9^{**}$ | 4.5 |
| ISL | °N | 14.3 | 12.0 | $2.3^{**}$ | 13.1 |
| ISI | kt | 50.0 | 32.4 | $17.6^{**}$ | 41.2 |
| LTRH | % | 86.9 | 84.8 | $2.1^{**}$ | 85.8 |
| SST | °C | 29.0 | 28.9 | 0.1 | 28.95 |

those of the 437 non-RI cases to determine if the large-scale conditions for these two sets of sample were significantly different. The variables selected have certain physical significance with the change of intensity. The distribution of these conditions is discussed in Section 4.2. The mean values of each of the variables for both the RI and non-RI samples and the differences between the mean values of the RI and non-RI samples are presented in the Table 3. The differences between the mean values of the variables for RI and non-RI samples are statistically significant at greater than or equal to the 95% confidence level except SST. Asterisk marks were placed beside those differences that were found to be statistically significant at the 95% (*) and 99.9% (**) level using a two-sided t-test that assumes unequal variances (Dowdy and Wearden, 1991).

Table 3 indicates that differences between the RI and non-RI samples are statistically significant for all of the variables except SST. Interestingly, these differences are most significant (at 99.9% level) for seven variables (IC12, ISI, SMS, ISL, SHR, V850, LTRH) and it is significant at 95% level for variable D200 (as shown in the Table 3). It is surprising that statistically significant differences were not found between the SST value of the RI and non-RI samples. One plausible explanation for this result is that the mean SST values of the RI and non-RI samples are both well above the threshold value of SST ($\geq$ 26.5 °C) for intensification of tropical cyclone.

The larger LTRH values (evaluated from 850 to 700 hPa in this study) for the RI cases is consistent with physical reasoning, as shown by Schade and Emanuel (1999). They found that lower boundary layer relative humidity in the initial undisturbed environment produced the most intense storms in their model simulations. They speculated that this was due to a stronger imbalance at the sea surface for drier boundary layers. The lower values of SMS for the non-RI cases is consistent with results of Geisler (1970) who showed that sea surface temperature (SST) gets cool due to upwelling for a slow moving or stationary system. This feature can also be explained by previous studies (Schade and Emanuel, 1999; Schade, 2000; Peng *et al.*, 1999) that if TCs move too slow, oceanic cooling induced by turbulent mixing generated by surface wind stress curl under the TC will disrupt the intensification. The importance of inner-core processes has been linked to changes in TC intensity. Willoughby *et al.*, (1982) noted that concentric eyewalls are characterized by the development of a secondary ring of convection around an existing inner eyewall. This secondary (outer) eyewall may contract and replace the inner eyewall and can produce significant changes in TC intensity. This result justifies the higher values of ISI for the RI cases. This finding may be attributed to the fact that the higher ISI may intensify more because of their better initial organization. The preference for RI to occur in the higher latitude (ISL) may simply be a reflection of systems getting organized and intensifying prior to RI at higher latitude as TCs in the Bay of Bengal generally move towards north and northwest direction. The findings of higher values of V850 hPa and D200 hPa for the RI cases is consistent with the study of Kotal *et al.*, (2008) who showed that systems were more likely to experience high rates of intensification for higher values of V850 and D200. They explained that more cyclonic environment at



**Figs. 5(a-d).** The percentage frequency distributions of the climatological and persistence variables for the RI and non-RI (NRI) samples

850 hPa and more anticyclonic environment at 200 hPa are favorable for intensification. They also showed that these two variables are the most stable and maintained almost same significance for all forecast hour (12 hrs to 72 hrs). The finding of higher values of SHR for the non-RI cases is due to the fact that the higher vertical wind shear disrupts the circulation pattern and latent heat released within the system due to condensation advected away from the system. This is consistent with results of DeMaria and Kaplan (1994b), Kaplan and DeMaria (2003). It is also consistent with the three-dimensional modeling simulations of Frank and Ritchie (1999). They showed that a TC embedded in an environment with no shear intensified rapidly. Finally, the RI cases were generally intensifying at a faster rate than the non-RI cases during the 12 hrs period prior to the start of RI phase. The result shows that intensity changes during the past 12 hrs can indicate the future rate of intensification and if intensity increases in the past 12 hrs, the same environmental condition likely to prevail for shorter intervals.

### 4.2. *Distribution of large-scale conditions*

As discussed in Section 4.1, statistically significant differences exist between the mean of large-scale conditions of the RI and non-RI samples for all of the variables listed in Table 2 except SST. In this section, the frequency distributions of the eight variables (Table 3) for which statistically significant differences were found between the RI and non-RI samples are shown together so that comparisons can be made between the relative chances of RI for a given range of predictor's magnitude.

The distributions for all the climatological and persistence variables listed in Table 2 are shown in Figs. 5(a-d). The Fig. 5(a) shows an increase in the

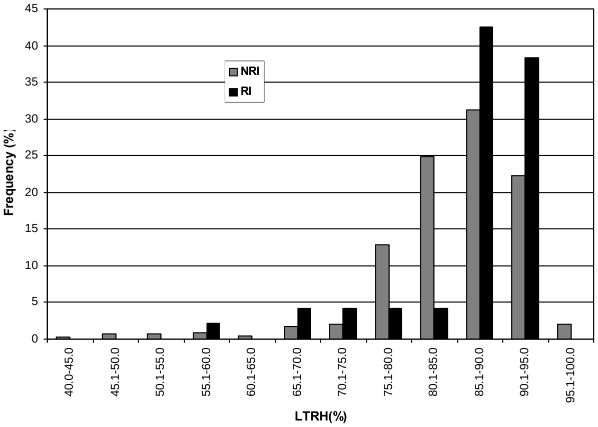


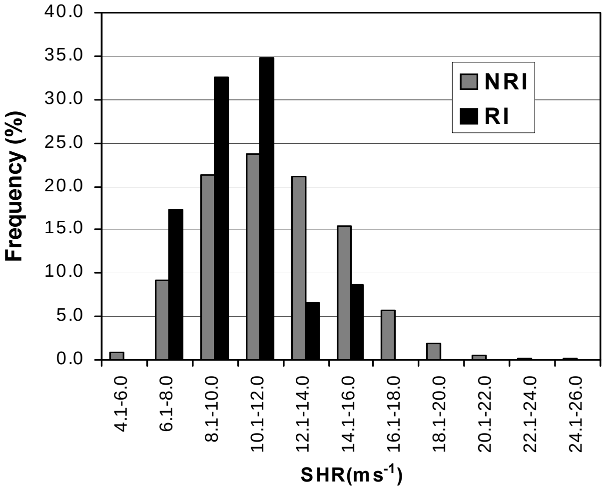
**Fig. 6.** Same as in Fig. 5 except for the thermodynamic variable (LTRH)

fraction of RI cases than non-RI cases for large ISI values with 62% of all RI cases having ISI exceeding 35 kt compared with only 22% of non-RI cases. Also, approximately 5 times as many RI cases than non-RI cases had ISI values above 50 kt. The distributions of IC12 [Fig. 5(b)] for the RI and non-RI samples show that a larger fraction (87%) of the RI cases than non-RI cases (65%) intensifying during the previous 12 hr. Also, the fraction of RI cases that were intensifying at high rates (≥ 10 kt) during previous 12 hr was much larger (76%) than that for the non-RI cases (22%).

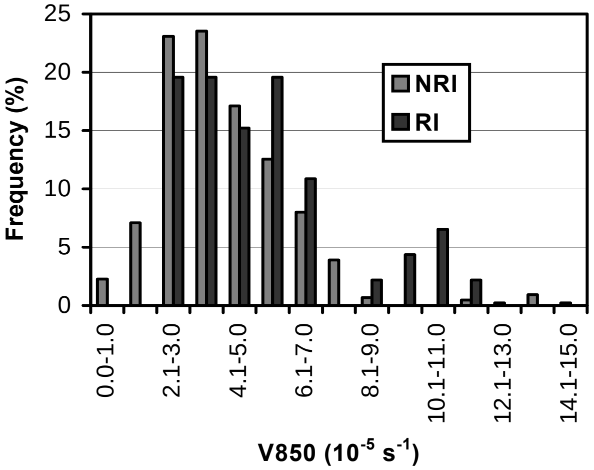
Fig. 5(c) shows notable differences between the distributions of ISL for the RI and non-RI samples. Rapid intensification occurs mostly over the central Bay of Bengal from 11° N to 21° N. A large fraction of 87% of all RI cases compared to 52% of non-RI cases occurred over north of 11° N. Fig. 5(d) indicates that a notable increase in the fraction of RI cases to non-RI cases for large SMS values with nearly 83% of all RI cases having SMS exceeding 3 ms$^{-1}$ compared with about 56% of non-RI cases. Furthermore, the figure suggests that RI was less likely for slow storm speeds (SMS ≤ 3 ms$^{-1}$). Also, more than 2 times as many RI cases than non-RI cases had storm motion speed values between 4 to 5 ms$^{-1}$. This is consistent with the results of Wang and Wu (2004) and Zeng *et al.*, (2007) who showed that either too fast motion or too slow motion inhibit intensification of TC.

Fig. 6 shows the distribution of RI and non-RI cases for the thermodynamic variable LTRH listed in Table 2. An increase in the fraction of RI cases to non-RI cases was observed for large LTRH values. There are nearly 81% of all RI cases compared with about 55% of non-RI cases having LTRH values exceeding 85%. Also, approximately 2 times as many RI cases than non-RI cases had relative humidity values above 90%.

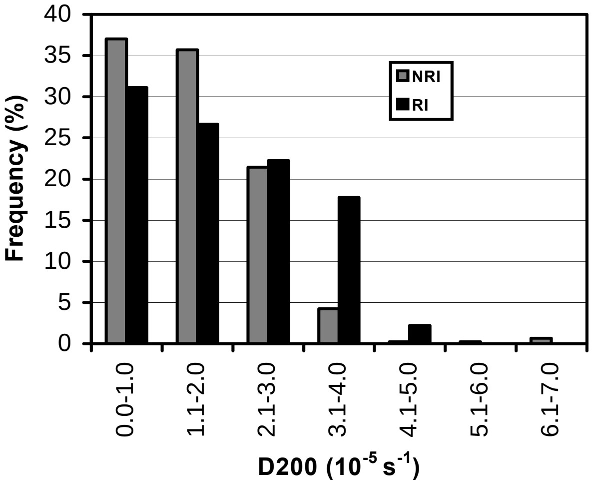
(a) SHR



(b) V850



(c) D200



**Figs. 7(a-c).** Same as in Fig. 5 except for the kinematic variables

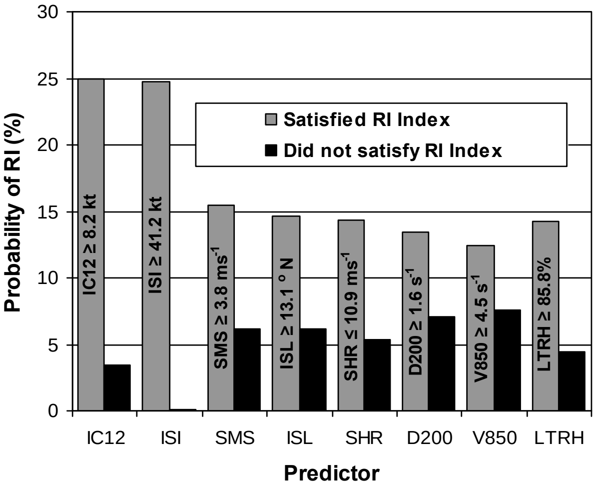


**Fig. 8.** The probability of RI when the individual RI predictors were satisfied for the RI and non-RI samples. The RI Indices (thresholds) of each of the predictors are also presented

Figs. 7(a-c) show the distribution of RI and non-RI cases for the kinematic variables listed in Table 2. The distribution of SHR [Fig. 7(a)] of the RI and non-RI cases shows that 85% of the RI cases occurred when the SHR was less than 12 ms$^{-1}$ compared to 55% of the non-RI cases and 2 times as many RI cases than non-RI cases had SHR values below 8 ms$^{-1}$. This suggests that low SHR is an important factor for RI. However, RI cases for moderate SHR values indicate that other factors may compensate for increased SHR.

The distributions of V850 [Fig. 7(b)] of the RI and non-RI cases shows that 73% of the non-RI cases occurred when the V850 was less than 5 s$^{-1}$ compared to 54% of the RI cases. But, 46% of the RI cases compared to 27% of the non-RI cases occurred for V850 greater than 5 s$^{-1}$. The distributions of D200 [Fig. 7(c)] of the RI and non-RI cases shows that 73% of the non-RI cases occurred when the D200 was less than 2 s$^{-1}$ compared to 58% of the RI cases. But, 42% of the RI cases compared with 27% of the non-RI cases occurred for D200 greater than 2 s$^{-1}$. Furthermore, approximately 4 times as many RI cases than non - RI cases had D200 values above 3 s$^{-1}$. This suggests that more cyclonic environment at 850 hPa and more anticyclonic environment at 200 hPa is favourable for rapid intensification.

## 5. RI-Index and Probability of Rapid Intensification

In this section, the probabilities of RI are computed for each of the 8 variables (as in Table 3) of the 483 cases for which statistically significant differences between the RI and non - RI samples were at the 95% level or greater (Section 4.1). The RI threshold for each variable was defined as the mid value between the means of the RI and non-RI samples. A threshold was said to be satisfied if a value was greater than or equal to the specified RI threshold, except for wind shear (SHR) for which it is less than or equal to the specified RI threshold for favourable for RI. Fig. 8 shows the probability of RI for each of the 8 variables for which statistically significant differences between the means of the RI and non-RI samples were found to exist. These RI probabilities were computed by dividing the number of RI cases that satisfied the RI threshold by the number of all cases in the entire sample (483 cases) that satisfied that same threshold. To illustrate, RI occurred 34 times when the threshold for the variable IC12 was satisfied, but the IC12 threshold was satisfied 134 times in the entire sample. Thus, the probability of RI was 25% (34 × 100/134) when the RI threshold for IC12 was satisfied. Fig. 8 shows that the probability of RI ranged from 12.4% when the threshold for V850 was satisfied to 25% when the threshold for IC12 was satisfied. Where as, the sample mean probability of RI is 9.5% (46 RI cases × 100/483 total cases). It is worth to note that the probability of RI when an RI threshold was satisfied exceeded the probability of RI when an RI threshold was not satisfied for each of the 8 predictors (Fig. 8). Also, these RI probabilities of all variables were larger than the sample mean probability of RI (9.5%). This suggests that this simple technique could provide additional information over climatology.

Since the probability of RI for any individual predictor was not more than 25%, all the 8 predictors were combined to provide improved probability of RI estimates. The predictors that were statistically significant at the 95% levels or more were employed to obtain a composite estimate of the probability of RI.

The composite probability of RI ($P_n$) is defined as:

$$P_n = \left( \frac{n_1}{(n_1 + n_2)} \right) \times 100\%$$

Where,

$P_n$ = RI probability for $n$ number of variables that satisfied their respective thresholds

$n_1$ = Number of RI cases that satisfied the $n$ number thresholds

$n_2$ = Number of non-RI cases that satisfied the $n$ number thresholds

$n$ = 0, 1, 2, 3, 4, 5, 6, 7, 8 (number of variables)

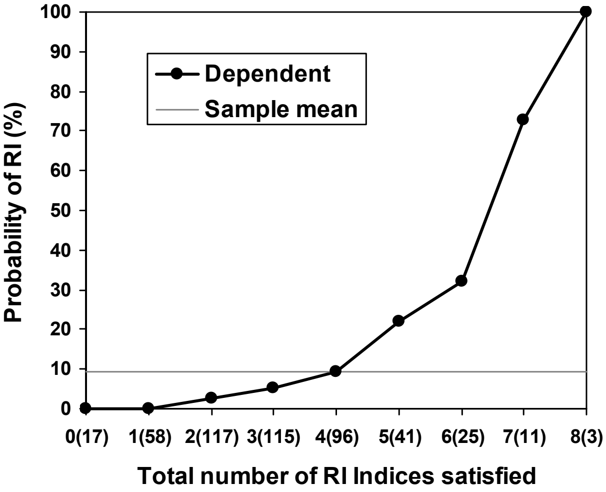


**Fig. 9.** The composite probability of RI determined for the 1981-2010 dependent sample. The probabilities are provided as a function of the total number of the eight (ISI, IC12, ISL, SMS, LTRH, SHR, V850, D200) RI predictor indices that were satisfied. The sample mean probability of RI is also shown for reference. The number of cases is shown in parentheses beside the total number of RI indices satisfied

To illustrate, the threshold for 5 variables was satisfied 9 times for RI cases and 32 times for non-RI cases. Thus, the probability of RI was 21.9% [9/(9+32)] when the RI threshold for 5 variables was satisfied. Fig. 9 shows the variation of the probability of RI as a function of the total number of thresholds satisfied for the dependent dataset of 88 TCs over the Bay of Bengal during the period 1981–2010. Composite estimate of the probability of RI is obtained using the eight predictors (IC12, ISI, SMS, ISL, SHR, D200, V850, LTRH). It is found that the probability of RI increased from 0% to 100% when the total number of RI thresholds satisfied increased from zero to eight, and was close to the sample mean value (climatological) of 9.5% when four thresholds (out of eight) were satisfied. It is interesting to note that the rate of increase of probability of RI increased with the increase of number of RI thresholds satisfied when number of RI thresholds satisfied exceeds four (*i.e.*, climatological value). The probability increased from around 9.5% to 22% when the number of RI thresholds satisfied increased from four to five and these are around 32%, 73% and 100% for number of RI thresholds satisfied six, seven and eight respectively. The figure also indicates that all eight RI thresholds were satisfied for 3 cases only, which suggests that TCs are rarely formed in an environment where all the favourable conditions for RI are satisfied simultaneously. The highest probability of RI was only 25% when any single predictor was satisfied (Fig. 8), whereas the probability of RI increased to 100% when all eight of the RI predictors were satisfied (Fig. 9). This emphasizes the need to include the effects of a wide range of physical processes for predicting RI. The results are very encouraging and suggest that this simple technique has the potential to provide useful information (probability of RI) to operational forecasters.

## 6. Concluding remarks

A probabilistic rapid intensification (RI) index is developed using large-scale characteristics of rapidly intensifying tropical cyclones over the Bay of Bengal. Rapid intensification (RI) is defined as an increase of tropical cyclone intensity 30 kt (15.4 $ms^{-1}$) during 24 hrs. The 24 hrs intensity change of 30 kt represents the 93.4th percentile of 24 hrs intensity changes of tropical cyclones that developed over the Bay of Bengal during the period 1981 to 2010. Various climatological and persistence, and large-scale variables associated with the cases that underwent RI are compared to those of the non-RI cases. The variables are: Storm latitude position, previous 12 hrs intensity change, initial storm intensity, vorticity at 850 hPa, divergence at 200 hPa, vertical wind shear, lower tropospheric relative humidity, and storm motion speed. The primary findings of this study are as follows.

(*i*) Of the data sample of 88 tropical cyclones that formed during 1981-2010, 18% of all tropical cyclones, 32% of all very severe cyclonic storms (VSCS) and all super cyclonic storms (SUCS) underwent RI at least once during their lifetime. No cyclonic storms (CS) and severe cyclonic storm (SCS) underwent RI during their lifetime.

(*ii*) The RI cases generally occurred at higher latitudes as compared to non-RI cases. Central Bay of Bengal is found to be the region of higher likelihood for RI. No significant differences were found between the Sea surface temperatures (SSTs) of the RI and non-RI cases.

(*iii*) The RI cases were developed in regions of higher lower-tropospheric relative humidity and higher lower-tropospheric relative vorticity than the non-RI cases. Also, the RI cases were formed in the regions of lower vertical shear and higher upper-level divergence than the non-RI cases. The RI cases are typically intensifying at a faster rate during the previous 12 hrs with a higher initial wind speed than the non-RI cases. Interestingly, the RI cases generally move with a faster translational speed than the non-RI cases. There are certain threshold value for each of the variables is found to exist for RI.

(*iv*) The rapid intensification (RI) index technique was developed to estimate the probability of RI. This technique compares the magnitudes of the eight predictors to previously determined RI indices (thresholds) using the 88 tropical cyclones under this study. It was found that the probability of RI increased from 0% to 100% for the dependent sample when the total number of RI indices satisfied increased from zero to eight. The rate of increase of probability of RI increases with the increase of total number of RI indices satisfied when number of RI indices satisfied exceeds four, which is equivalent to climatological probability value 9.5%. It was also found that TCs are rarely formed in an environment where all the favourable conditions for RI are present simultaneously.

The results of this study to estimate the probability of RI are very encouraging and suggest that this simple technique has a potential to provide useful information to forecasters. However, the contribution of each predictor to RI should be determined which may provide better predictive tool for RI. Other predictors, such as Ocean heat content, latent heat due to convection should be examined to determine if there is similar significant forecasting ability for this rare event. RI indices for higher $dv_{24}$ (*e.g.*, 35 kt, 40 kt etc) could also be developed. Similar study could be extended for the Arabian Sea basin. Our future research will focus on these subjects.

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## **References**

Bender, M. A. and Ginis, I., 2000, "Real-case simulations of hurricane ocean interaction using a high-resolution coupled model: Effects on hurricane intensity", *Monthly Weather Review*, **128**, 917-943.

Bender, M. A., Ginis, I. and Kurihara, Y., 1993, "Numerical simulations of tropical cyclone–ocean interaction with a high-resolution coupled model", *Journal of Geophysical Research*, **98**, 23245-23263.

Byers, H. R., 1944, "*General Meteorology-McGraw-Hill*", p645.

Charney, J. G. and Eliassen, A., 1964, "On the growth of hurricane depression", *Journal of Atmospheric Sciences*, **21**, 68-75.

Chu, J. H., Sampson, C. R., Levine, A. S. and Fukuda, E., 2002, "The Joint Typhoon Warning Center Tropical Cyclone Best-Tracks 1945-2000", NRL Reference No. NRL/MR/7540-02-16.

Dvorak, V. F., 1975, "Tropical cyclone intensity analysis and forecasting from satellite imagery", *Mon. Wea. Rev.*, **103**, 420-430.

DeMaria, M. and Kaplan, J., 1994a, "Sea Surface Temperature and the Maximum Intensity of Atlantic Tropical Cyclones", *Journal of Climate*, **7**, 1324-1334.

DeMaria, M. and Kaplan, J., 1994b, "A Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic basin", *Weather Forecasting*, **9**, 209-220.

DeMaria, M., Zehr, R. M., Kossin, J. P. and Knaff, J. A., 2002, "The use of GOES imagery in statistical hurricane intensity prediction", 25th Conference on Hurricanes and Tropical Meteorology, 29 April-3 May, San Diego, CA. *American Meteorological Society*, 120-121.

Dowdy, S. and Wearden, S., 1991, "Statistics for Research", 2nd ed. *Wiley-Interscience*, p555.

Davis, C. A., Stoelinga, M. T. and Kuo, Y. H., 1993, "The integrated effect of condensation in numerical simulations of extratropical cyclogenesis", *Monthly Weather Review*, **121**, 2309-2330.

Elsberry, R. L., Lambert, T. D. B. and Boothe, M. A., 2007, "Accuracy of Atlantic and eastern North Pacific tropical cyclone intensity forecast guidance", *Weather Forecasting*, **22**, 747-762.

Emanuel, K. A., 1986, "An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance", *Journal of Atmospheric Sciences*, **43**, 585-604.

Fraedrich, K. and McBride, J. L., 1989, "The physical mechanism of CISK and the free ride balance", *Journal of Atmospheric Sciences*, **46**, 2642-2648.

Frank, W. M. and Ritchie, E. A., 1999, "Effects of environmental flow upon tropical cyclone structure", *Monthly Weather Review*, **127**, 2044-2061.

Geisler, J. E., 1970, "Linear theory on response of a two layer ocean to a moving hurricane", *Geophysical Fluid Dynamics*, **1**, 249-272.

Gray, W. M., 1968, "Global view of the origin of tropical disturbances and storms", *Monthly Weather Review*, **96**, 669-700.

Gross, J. M., 2001, "North Atlantic and east Pacific track and intensity verification for 2000", Minutes of the 55th Interdepartmental Hurricane Conf., Miami, FL, Office of the Federal Coordinator for Meteorological Services and Supporting Research, NOAA, B12-B15.

Holliday, C. R. and Thompson, A. H., 1979, "Climatological characteristics of rapidly intensifying typhoons", *Monthly Weather Review*, **107**, 1022-1034.

Houze, R. A., Chen, S. S., Smull, B. F., Lee, W. C. and Bell, M. M., 2007, "Hurricane intensity and eyewall replacement", *Science*, **315**, 1235-1238.

Kaplan, J. and DeMaria, M. 2003, "Large scale characteristics of rapidly intensifying tropical cyclones in the North Atlantic Ocean", *Weather Forecasting*, **18**, 1093-1108.

Kotal, S. D., Roy Bhowmik, S. K., Kundu, P. K. and Das, A. K. 2008, "A Statistical Cyclone Intensity Prediction (SCIP) Model for Bay of Bengal", *Journal of Earth System Science*, **117**, 157-168.

Malkus, J. S. and Riehl, H., 1960, "On the dynamics and energy transformations in steady-state hurricanes", *Tellus*, **12**, 1-20.

McBride, J. L. and Fraedrich, K., 1995, "CISK: A theory for the response of tropical convective complexes to variations in sea surface temperature", *Quarterly Journal of Royal Meteorological Society*, **121**, 783-796.

Merrill, R. T., 1988, "Environmental influences on hurricane intensification", *Journal of Atmospheric Sciences*, **45**, 1678-1687.

Miller, B. I., 1958, "On the maximum intensity of hurricanes", *Journal of Meteorology*, **15**, 184-195.

Molinari, J., Skubis, S. and Vollaro, D., 1995, "External influences on hurricane intensity. Part III: Potential vorticity structure", *Journal of Atmospheric Sciences*, **52**, 3593-3606.

Montgomery, M. T. and Kallenbach, R. J. 1997, "A theory for vortex Rossby waves and its application to spiral bands and intensity changes in hurricanes", *Quarterly Journal of Royal Meteorological Society*, **123**, 435-465.

Ooyama, K., 1964, "A dynamical model for the study of tropical cyclone development", *Geofisica Internacional*, **4**, 187-198.

Peng, M. S., Jeng, B .F. and Williams, R. T., 1999, "A numerical study on tropical cyclone intensification. Part I: Beta effect and mean flow effect", *Journal of Atmospheric Sciences*, **56**, 1404-1423.

Rasmussen, E., 1979, "The polar low as an extra tropical CISK disturbance", *Quarterly Journal of Royal Meteorological Society*, **105**, 531-549.

Reynolds, R. W., Rayner N. A., Smith, T. M., Stokes, D. C. and Wang, W., 2002, "An improved in situ and satellite SST analysis for climate", *Journal of Climate*, **15**, 1609-1625.

Schade, L. R. and Emanuel, K. A., 1999, "The Ocean's effect on the intensity of tropical cyclones: Results from a simple coupled atmosphere–ocean model", *Journal of Atmospheric Sciences*, **56**, 642-651.

Schade, L. R., 2000, "Tropical cyclone intensity and sea surface temperature", *Journal of Atmospheric Sciences*, **57**, 3122-3130.

Sutyrin, G. G. and Khain, A. P., 1979, "Interaction of the ocean and the atmosphere in the area of moving tropical cyclone", *Doklady Akademii Nauk S S S R*, **249**, 467-470.

Willoughby, H. E., Clos, J. A. and Shoreibah, M. G., 1982, "Concentric eyewalls, secondary wind maxima, and the evolution of the hurricane vortex", *Journal of Atmospheric Sciences*, **39**, 395-411.

Wang, Y. and Wu, C. C., 2004, "Current understanding of tropical cyclone structure and intensity changes - A review", *Meteorology and Atmospheric Physics*, **87**, 257-278.

Whitney, L. D. and Hobgood, J. S., 1997, "The Relationship between Sea Surface Temperatures and Maximum Intensities of Tropical Cyclones in the Eastern North Pacific Ocean", *Journal of Climate*, **10**, 2921-2930.

Zeng, Z., Wang, Y. and Wu, C. C., 2007, "Environmental Dynamical Control of Tropical Cyclone Intensity - An Observational Study", *Monthly Weather Review*, **135**, 38-59.