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RESEARCH ARTICLE

Estimation of tropical cyclone intensity and location over the north Indian Ocean – a challenge

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Maximum wind speeds associated with tropical cyclones are estimated operationally by a very widely used tool, the satellite-based Dvorak technique (SDT) of cloud pattern matching and infrared cloud-top temperature analyses, but it still has its own limitations. To make a good forecast and its proper verification it is essential to estimate the location and current intensity of a cyclone accurately. This study compares intensity estimates of tropical cyclones over the north Indian Ocean by the Joint Typhoon Warning Center (JTWC) and the Regional Specialized Meteorological Centre, New Delhi (RSMCND). The results show that, except for super cyclones, the differences in intensity estimates are a function of intensity, the 12 hr intensity trend and the translation speed. The intensity estimates by the JTWC are often higher than RSMCND estimates. The mean absolute difference (MAD) and the root mean square difference (RMSD) are 9.7 kt and 13.3 kt respectively. The MAD ranges from 5.9 kt to 15.6 kt and the RMSD ranges from 7.6 kt to 19.0 kt. The average difference in location estimation and the corresponding standard deviation are found to be 67 km and 54 km respectively. In view of the subjectivity in SDT-based intensity estimation which largely depends on the skill of the individual analyst, a robust objective method should be adopted to achieve uniformity in intensity estimates across agencies. The results of this study and the factors affecting intensity estimates quantified in the study will help operational forecasters for better monitoring of tropical cyclones and better post storm best-track data analysis.

KEYWORDS

cyclone intensity, Dvorak technique, north Indian Ocean, tropical cyclone

1 | INTRODUCTION

Analyses and forecasts of tropical cyclone (TC) intensity remain a challenging task to meteorologists. The use of satellite pictures with about one picture *per* day became operational in the mid-1960s to locate cyclonic storms over the oceans, where surface data were not available (Fett, 1964; Timchalk *et al*., 1965). By the early 1970s a method for using satellite pictures to determine current intensity, the Dvorak technique (SDT), was developed (Dvorak, 1973) with the availability of more frequent satellite pictures. In this technique, the current intensity in terms of T numbers of TCs is estimated by analysing satellite image patterns (e.g. eye, shear, banded, central dense overcast) (Dvorak, 1972, 1975, 1984) and infrared cloud-top temperatures (Dvorak, 1984, 1995). The SDT has become an important operational tool. It estimates intensity by assigning a T number which ranges from 1 to 8 with increments of 0.5. A unit T number corresponds to the climatological rate of TC intensity. The T number and corresponding maximum wind speed are shown in Table 1. In the table, the T number *versus* maximum wind speed and mean sea level pressure depth (the difference between the value of the outermost closed isobar and the minimum pressure value at the centre of the cyclonic

TABLE 1 Classification of tropical disturbances over the north Indian Ocean

Serial no.	T number	Classification of cyclonic disturbance	Wind speed (kt)	Wind criteria (kt)	Pressure depth Δp (hPa)
1	T1.0	Low (L)	—	<17	—
2	T1.5	Depression (D)	25	17–27	—
3	T2.0	Deep depression (DD)	30	28–33	4.5
4	T2.5	Cyclonic storm (CS)	35	34–47	6.1
5	T3.0	Cyclonic storm (CS)	45	34–47	10.0
6	T3.5	Severe cyclonic storm (SCS)	55	48–63	15.0
7	T4.0	Very severe cyclonic storm (VSCS)	65	64–89	20.9
8	T4.5	Very severe cyclonic storm (VSCS)	77	64–89	29.4
9	T5.0	Extremely severe cyclonic storm (ESCS)	90	90–119	40.2
10	T5.5	Extremely severe cyclonic storm (ESCS)	102	90–119	51.6
11	T6.0	Extremely severe cyclonic storm (ESCS)	115	90–119	65.6
12	T6.5	Super cyclonic storm (SUCS)	127	≥120	80.0
13	T7.0	Super cyclonic storm (SUCS)	140	≥120	97.2
14	T7.5	Super cyclonic storm (SUCS)	155	≥120	119.1
15	T8.0	Super cyclonic storm (SUCS)	170	≥120	143.3

storm) is shown as *per* the convention of the Regional Specialized Meteorological Centre, New Delhi (RSMCND). The RSMCND is entrusted by the World Meteorological Organization for analysis of the track and intensity of TCs over the north Indian Ocean (NIO).

It should be noted that regional variations and modifications (Velden, 2006a) to the SDT are also needed in other basins as described by Dvorak (1984). Zehr *et al.* (2010) showed that the SDT is relatively stable with respect to satellite sensor resolution. The consistency analysis (Guard, 1988) of the SDT showed that 54% and 82% of 87 of the more difficult TCs over the western North Pacific in 1986 were within T number ±0.5 and ±1.0 respectively. The error in estimation of a T number of ±0.5 and ±1.0 corresponds to a wind speed error by about 10 kt and 20–25 kt respectively. Dispersion statistics of a controlled study (Mayfield *et al.*, 1988) of 14 analysts of eastern Pacific TCs showed that standard deviations from the consensus average were 4.3, 9.0, 10.7 and 12.0 kt for tropical depressions, tropical storms, hurricanes with intensities of 65–95 kt and hurricanes with intensities greater than 95 kt respectively.

For a TC, estimation of the current intensity is also based on the preceding intensity and certain restrictions are made that do not allow a current intensity to increase or decrease by a certain amount compared with the previously made intensity estimate. Therefore, when cyclones undergo rapid intensification and rapid decay the cloud patterns can be ambiguous and make it difficult to have an accurate intensity estimate.

With the advancement of numerical weather prediction models the uncertainty about weather forecasting has reduced to a reasonable extent. In this process satellite data play an extremely significant role in providing model initial conditions. In the simulation of TCs the satellite observations also play a major role for approximating the vortex where the satellite derived initial position and intensity of the TCs are synthetically forced into model initial conditions. As a result the performance of forecasts depends markedly upon accurate intensity analysis. Forecasts are also verified against analysed intensity for performance evaluation. Moreover, accurate analyses of TCs based on satellite observations help in assessing the extent of threat to life and property, thereby helping disaster management preparedness. Therefore, it is important to scrutinize satellite based analyses of TC initial conditions, the position and intensity available to the forecasters and the modellers. Any ambiguity in information available to the stakeholders may create confusion and many more multifaceted difficulties.

In view of the above, this study compares intensity estimates by two institutions, namely the Joint Typhoon Warning Center (JTWC) and the RSMCND, for TCs over the NIO. The purpose of this comparison is to document characteristic variations and possible systematic differences between intensity estimates made by the two different operational agencies. The results may be useful in operational calibration of SDT intensity estimates. Differences in identifying the location of the storms were also computed.

Sections 2 and 3 describe the dataset and methodology respectively used in this study. Detailed results of the comparison are presented in Section 4 and the concluding Section 5 summarizes the results of TC best-track data analysis.

2 | DATA SOURCES

A database for the track, intensity and other variables of 91 TCs formed over the NIO during the period 1990–2016 was used in this study. The 6 hr position and intensity of cyclones are available in the RSMCND report from the year 1990. Accordingly, this study compares intensity estimates by the JTWC and the RSMCND from 1990. The 91 TCs contributed a total of 1,437 cases. The JTWC estimates for the corresponding cyclones' intensity and location were obtained from the JTWC "best-track" database. Figure 1 shows the RSMCND best-track locations of the storms used in this study.

The data table includes date, time, position in latitude and longitude, central pressure, pressure drop at the centre and intensity (maximum sustained surface winds in knots). Six-hourly observations based on 0000 UTC, 0600 UTC, 1200 UTC and 1800 UTC were considered in this study. Primarily, the SDT is used to estimate TC track and intensity. The estimated TC intensity is rounded off to the nearest 5 kt. In this study, knots are used instead of standard unit metres *per* second as winds are expressed in knots (1 kt = 0.5144 m/s).

3 | METHODOLOGY

3.1 | Data Divisions

The complete dataset during the period 1990–2016 was split into a multi-stratification of intensity. For this purpose, the intensity determined by maximum sustained wind speed was divided into seven categories as shown in Table 1. Out of all the stratified samples of 1,437 cases, 16.7%, 18.6%, 34.1%, 11.5%, 10.8%, 7.5% and 0.8% were depressions (D), deep depressions (DD), cyclonic storms (CS), severe cyclonic storms (SCS), very severe cyclonic storms (VSCS), extremely severe cyclonic storms (ESCS) and super cyclonic storms (SUCS), respectively. The differences in intensity between RSMCND best-track data and JTWC best-track data associated with each of the observations were calculated. The comparison was also classified by intensity, storm motion speed and intensity trend.

3.2 | Statistical Measures Used

Four statistical measures were used to analyse the data.

1. The difference (D) = intensity estimates by the JTWC – intensity estimates by the RSMCND. The mean difference MD is the mean of all the D values.
2. The absolute difference (AD) for each datum is the absolute value of the difference given by AD = | intensity estimates by the JTWC – intensity estimates by the RSMCND |. The mean absolute difference (MAD) is the mean of all the individual ADs.
3. The third statistical measure used is the root mean square difference (RMSD). Here, the RMSD is used to compare differences between two observations (JTWC and RSMCND).
4. The final statistical measure is the standard deviation (SD).
5. The location difference (LD) of a TC is defined as the distance between two centres (φ_1, λ_1 and φ_2, λ_2) identified by the RSMCND and the JTWC for the same TC at the same time. From the spherical law of cosines, the distance (d) between two centres is given by $d = R$ acos [sin(0.0174533 φ_1) sin(0.0174533 φ_2) + cos (0.0174533 φ_1) cos(0.0174533 φ_2) cos(0.0174533 $\Delta\lambda$)], where R is the radius of the Earth (mean radius 6,371 km), φ is latitude and λ is longitude, and $\Delta\lambda = \lambda_2 - \lambda_1$.

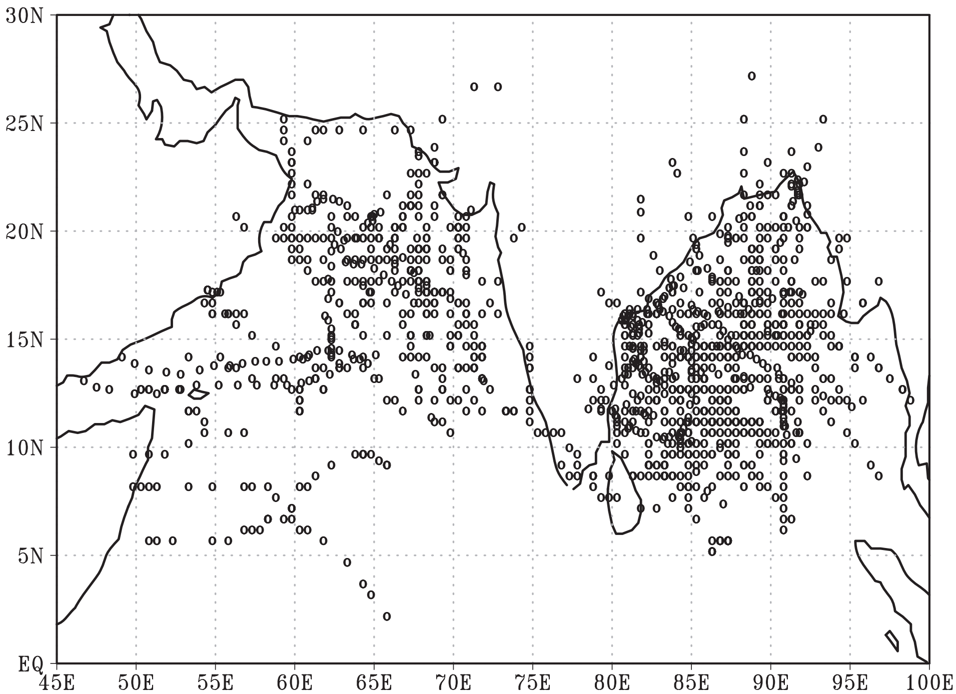

FIGURE 1 Locations of the Regional Specialized Meteorological Centre, New Delhi, best-track points of cyclonic disturbances during 1990–2016

4 | RESULTS

4.1 | Frequency distributions of the differences (*D*) of intensity estimation

The frequency distribution of the differences of intensity estimation by the two agencies of all 1,437 cases under study is shown in Figure 2. Only in 19.8% of cases are the estimations of intensity by the two agencies found to be the same. Furthermore, Figure 3 shows that only in 24.2%, 17.9%, 24.9%, 16.4%, 13.5%, 6.5% and 18.2% of the cases in each of the categories D, DD, CS, SCS, VSCS, ESCS and SUCS respectively was there agreement between the intensity estimations. This indicates that irrespective of the stages of the TC the consensus in intensity estimation has always been less than 25%. Figure 3 clearly reveals that the disagreement in intensity estimation by the JTWC and the RSMCND does not depend upon the category of the TC and hence the pattern of the systems. Moreover, for ESCS, a higher category system when the eye of the TC is most often visible, the percentage of agreement is poorest at only 6.5% of the 108 cases. A difference score analysis by *t* test shows that the disagreement in intensity estimation by the two agencies is significant at the 99.9% level and the co-efficient of determination (R^2) of regressions is 0.809. For the 236 cases where the magnitudes of the difference in intensity are 20 kt or more the value of R^2 is decreased to 0.71.

4.2 | Interannual variations

The interannual changes of the differences in intensity estimates were examined to see if changes in technology during 1990–2016 have affected the variation in intensity estimates by the two agencies. Figure 4 shows the interannual variations of MD, MAD and RMSD of the intensity estimation of TCs over the NIO by the two agencies (JTWC and RSMCND) during 1990–2016. No statistically significant trends are found in the MAD or RSMD. The differences are random rather than systematic depending on the performance of the two agencies.

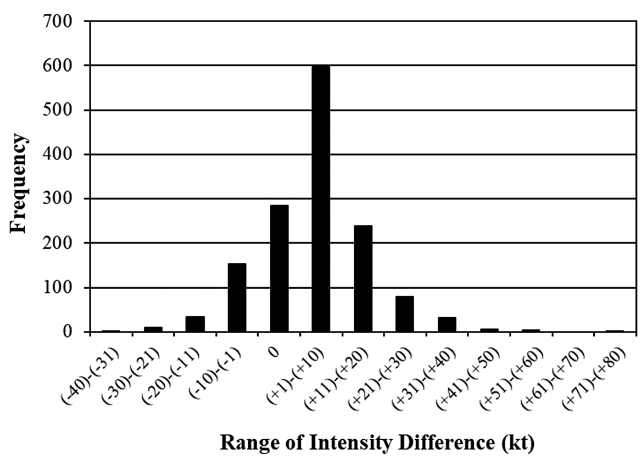

FIGURE 2 The frequency distribution of differences (*D*) in intensity estimation

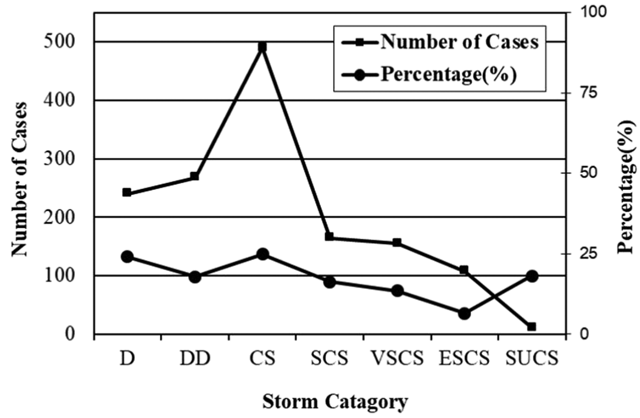

FIGURE 3 The same intensity estimation cases (zero difference) as a function of the storm category

4.3 | Differences as a function of intensity

Figure 5 shows that for a particular intensity estimated by the RSMCND there is significant variation in the estimation of intensity (overestimation as well as underestimation) by the JTWC. In some cases it was found that the intensity estimated by the JTWC was even more than two intensity categories (as *per* Table 1) higher or lower than the RSMCND estimation. The MD, MAD, RMSD and SD are 7.2 kt, 9.7 kt, 13.3 kt and 11.2 kt respectively for all sample data. Figure 6 shows the MD, MAD, RMSD and SD associated with the SDT based intensity estimates for all storm categories and also the number of cases in each category. There are limited numbers of cases (11) with intensities greater than 119 kt in the data sample. The MAD and RMSD shown in Figure 6 appear to be a function of intensity and the MD values show that the intensity estimates by the JTWC have a tendency to overestimate the RSMCND estimates in each category. The MAD, RMSD and SD range from 8.0 kt to 15.6 kt, from 11 kt to 19.0 kt and from 8.2 kt to 16.9 kt respectively from the D stage to the ESCS stage and the MAD, RMSD and SD are 5.9 kt, 7.6 kt and 7.9 kt respectively at the SUCS stage.

The computation of the intensity changes during 12 hr (weakening and strengthening) for different ranges of intensification (figure not shown) indicates that in general the 12 hr intensity changes for RSMCND intensity estimations are higher than the JTWC estimations at all stages of the TC. Figure 7 shows the frequency of 12 hr intensity changes of the JTWC *versus* 12 hr intensity changes of the RSMCND best-track data with the number of observations. The figure shows that for all the 263 weakening cases reported by the RSMCND, the JTWC reported about 80%, 14% and 6% weakening, no change and strengthening of cases, respectively. For 424 cases of no change in intensity in the RSMCND data, about 21%, 36% and 43% weakening,

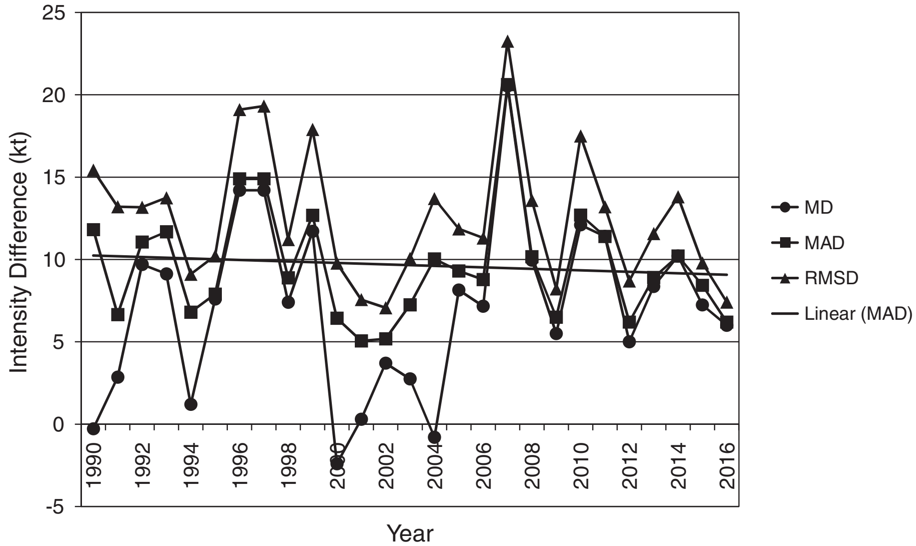

FIGURE 4 Time series of the interannual variability of differences

no change and strengthening of cases, respectively, were reported by the JTWC. There are a total of 586 strengthening cases in the RSMCND data. For these cases, the corresponding JTWC records about 7% of cases weakened, 17% of the cases have no change in intensity and 76% of the cases strengthened. Interestingly, these statistics show that for a weakening storm as assessed by one agency there are cases of no change of intensity and even strengthening cases recorded by the other agency and *vice versa*.

The maximum and minimum changes of intensity during a 12 hr interval as reported by the JTWC corresponding to the changes of intensity during the same interval as *per* the RSMCND database are shown in Figure 8. The figure shows that for the lowest weakening by −5 kt in 12 hr by the RSMCND, the corresponding changes in intensity by the JTWC varied from a minimum of −30 kt to a maximum of +10 kt. Similarly, for the highest −60 kt decrease in 12 hr reported by the RSMCND, the changes by the JTWC varied between −80 kt and −35 kt. In the strengthening cases it shows that, for the lowest 5 kt increase by the RSMCND, the minimum and maximum changes by the JTWC are −20 kt and +35 kt, respectively. Similarly, for the highest 50 kt changes by the RSMCND, the JTWC reported intensity changes varied from +25 kt to +35 kt. The statistics depicted in the figure show that there is wide variation in intensity estimation between the two agencies in terms of intensity changes in 12 hr.

4.4 | Change in intensity as a function of translation speed

The average translation speeds for the sample of this study were 16.9, 12.8, 13.9, 13.0, 13.3, 15.4 and 17.3 km/hr for D,

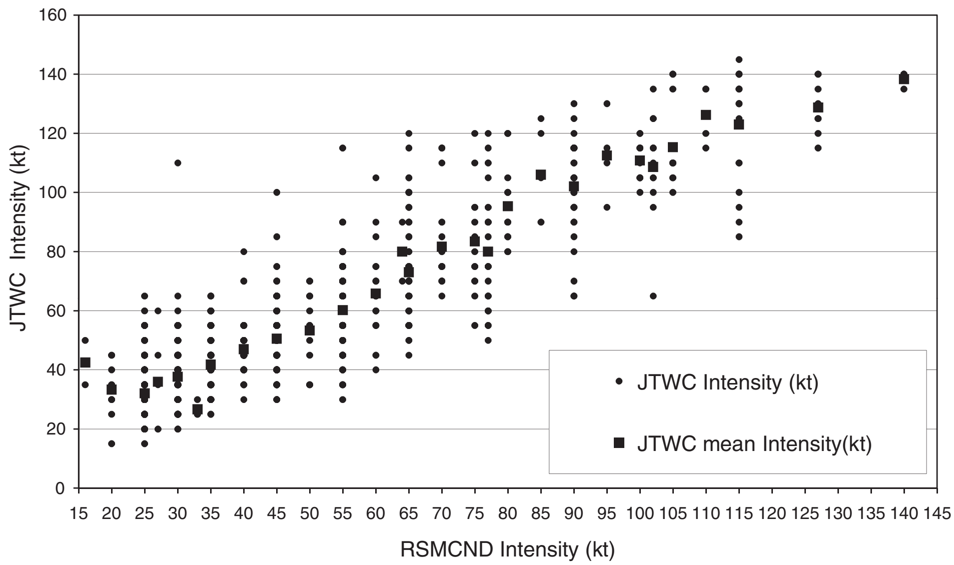

FIGURE 5 Plot of Regional Specialized Meteorological Centre, New Delhi (RSMCND), estimated intensity *versus* Joint Typhoon Warning Center (JTWC) estimated intensity for all data samples

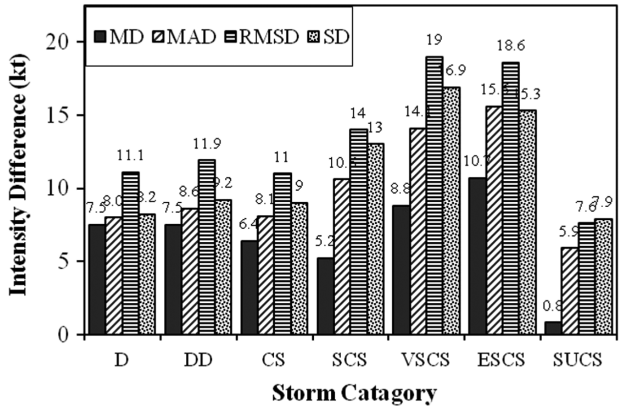

FIGURE 6 Differences of intensity estimation as a function of the storm category

DD, CS, SCS, VSCS, ESCS and SUCS respectively, with an average of 14.0 km/hr for all samples. This result highlights the fact that stronger storms generally move faster. Computation of the effects of the variation of translation speed suggests (not shown) that slow (fast) moving TCs have low (high) changes in intensity. These results support the findings of Brown and Franklin (2002, 2004), Velden (2006b), Holland (2008) and Courtney and Knaff (2009). The 12 hr intensity change is found to be almost the same for the RSMCND and the JTWC for all translational speed categories for strengthening cases. For weakening cases, the decrease of intensity during 12 hr is found to be higher for higher translational speed in the RSMCND dataset than the JTWC for all categories of TCs.

4.5 | Analysis of location estimation

Figure 9 shows the frequency distribution of the LD identified by the RSMCND and the JTWC. The figure reveals that the LD is up to 50 km in 49% of cases, 50–100 km in 31% of cases and greater than 100 km in 20% of cases. Figure 10 shows the mean LD along with the SD (vertical line on error

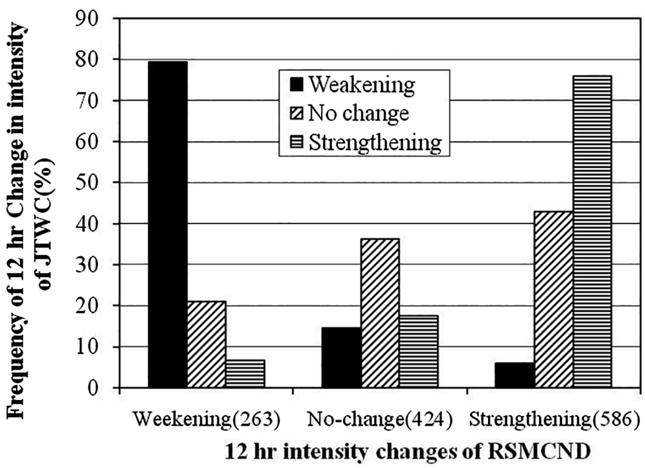

FIGURE 7 Frequency of 12 hr intensity changes of the Joint Typhoon Warning Center (JTWC) *versus* 12 hr intensity changes of the Regional Specialized Meteorological Centre, New Delhi (RSMCND)

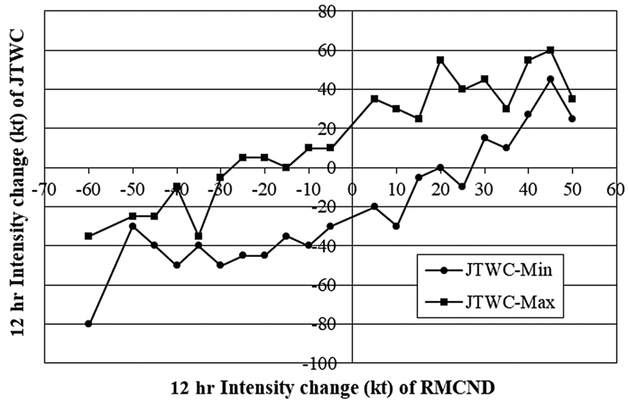

FIGURE 8 12 hr maximum (JTWC-max) and minimum (JTWC-min) intensity changes of the Joint Typhoon Warning Center (JTWC) *versus* 12 hr changes of the Regional Specialized Meteorological Centre, New Delhi (RSMCND)

bar) associated with the location identified by the two agencies at all storm categories and also the number of cases in each category. The figure shows an almost linear decreasing trend of LD from weaker (D stage) to stronger storms (SUCS stage). The mean LD values for the sample of this study are 98, 79, 65, 56, 44, 43 and 37 km with SD 69, 56, 44, 47, 35, 34 and 18 km for D, DD, CS, SCS, VSCS, ESCS and SUCS respectively. The MD and SD of the latitude analyses are 38 km and 37 km respectively, while the MD and SD of the longitude analyses are 47 km and 49 km respectively.

4.6 | Location difference as a function of translation speed

The average translation speed for the sample of this study is 14.0 km/hr. Climatologically, the average speed of TCs is 15–20 km/hr. The speed of movement of slow moving TCs is 10–14 km/hr and for fast moving TCs the speed of movement is more than 25 km/hr. Figure 11 shows the LD is least for the cases which moved with climatological speed and for the stationary or slower and faster moving TCs the LD is larger.

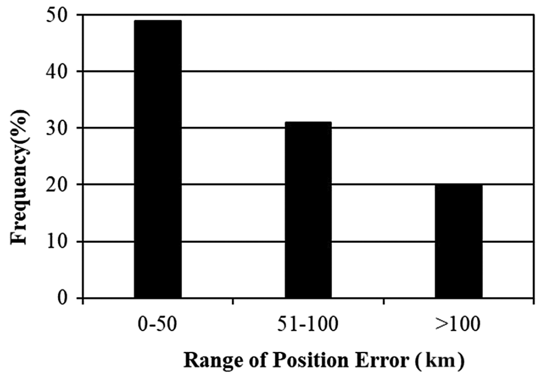

FIGURE 9 Frequency of the position error of storms

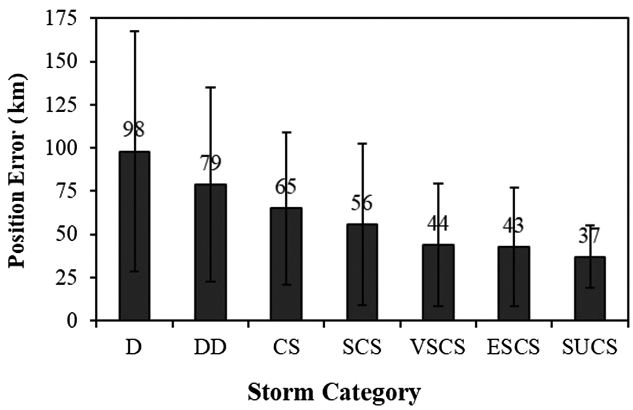

FIGURE 10 Position error as a function of storm category together with the standard deviation (SD) (vertical line on error bar)

5 | SUMMARY OF TC BEST-TRACK DATA ANALYSIS

The statistics documented in this study give operational forecasters and users the quantitative differences of the Dvorak technique based intensity and location estimates by two operational agencies (Joint Typhoon Warning Center [JTWC] and Regional Specialized Meteorological Centre, New Delhi [RSMCND]) based on a large data sample over the north Indian Ocean (NIO).

It is found that the JTWC has a tendency to overestimate intensities of tropical cyclones (TCs) over the NIO than the RSMCND for each category of storms. The mean difference (MD), mean absolute difference (MAD), root mean square difference (RMSD) and standard deviation (SD) are 7.2 kt, 9.7 kt, 13.3 kt and 11.2 kt respectively. Irrespective of the stages of the TC the consensus in intensity estimation is always less than 25%. The MAD, RMSD and SD range from 8.0 kt to 15.6 kt, from 11.0 kt to 19 kt and from 8.2 kt to 16.9 kt respectively for the depression to extremely severe cyclonic storm stages. The difference is a function of intensity, 12 hr intensity change and translational speed.

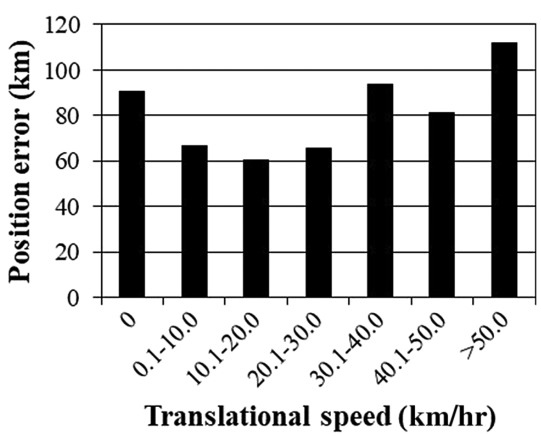

FIGURE 11 Range of translational speed (km/hr) versus position error (km)

It is found that for cases when one agency reported weakening the other agency reported intensification. Similarly, for strengthening cases of TCs as reported by one agency there are cases where no change of intensity and even weakening were reported by the other agency. For no change of intensity cases of one agency there are weakening as well as strengthening cases reported by the other agency.

The average location estimation differences are 98, 79, 65, 56, 44, 43 and 37 km for depressions, deep depressions, cyclonic storms, severe cyclonic storms, very severe cyclonic storms, extremely severe cyclonic storms and super cyclonic storms respectively showing an almost linear decreasing trend with increase in intensity.

These results provide a measure of the expected degree of disagreement in intensity estimation and location identification between the two independent agencies and also offer an estimate of the errors in historical best-track data over the NIO. In the numerical weather prediction method, vortex approximation is applied using satellite derived estimates and assimilated into a large-scale background field to improve the initial condition. Therefore, to make a more correct forecast it is crucial that the current intensity of a TC is estimated accurately. Verification of forecast performance depends on the analysed intensity of the TC. The differences of intensity and location estimations made by the RSMCND and the JTWC lead to the inference that neither of the observations can be considered as the "standard." This result also indicates that the errors in intensity and track forecasts of numerical models and official forecasts shown in earlier studies (e.g. Mohapatra *et al.*, 2013a, 2013b; Kotal *et al.*, 2014) may not have been reflected properly as possible uncertainties are involved in the best-track dataset itself which was considered as standard. The advanced Dvorak technique (Olander and Velden, 2007), aircraft reconnaissance data and microwave image information can reduce this ambiguity in intensity estimation and location determination. A consensus estimate combined with other techniques, namely the Advanced Microwave Sounding Unit (e.g. Herndon and Velden, 2004; Demuth *et al.*, 2006), would further improve operational intensity estimates. It is preferable to produce unique best-track data over a basin by using a consensus and objective technique and by co-ordination between different agencies, RSMCs and analysts. Despite various limitations associated with this study, the results will provide useful information to operational forecasters and researchers for better monitoring of TCs in real time and also in research studies. The factors which affect intensity estimates quantified in this paper will also be useful for better post-storm best-track data analysis. Having better best-track data will help in proper scrutiny of performance and further development of intensity prediction models and thus it will be easier to address the challenge of TC intensity prediction.

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