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Robustness of best track data and associated cyclone activity over the North Indian Ocean region during and prior to satellite era

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There are few studies focusing on analysing climatological variation in cyclone activity by utilising the best track data provided by the India Meteorological Department (IMD) over the North Indian Ocean (NIO). The result of such studies has been beneficial in decision-making by government and meteorological agencies. It is essential to assess the quality and reliability of the currently available version of the dataset so that its robustness can be established and the current study focuses on this aspect. The analysis indicates that there is an improvement over the years in the quality and availability of the data related to cyclones over NIO, especially in terms of frequency of genesis, intensity, landfall etc. The available data from 1961 onwards has been found robust enough with the advent of satellite technology. However, there can be still missing information and inaccuracy in determining the location and intensity of cyclones during the polar satellite era (1961–1973). The study also indicates undercount of severe cyclones during the pre-satellite era. Considering the relatively smaller size of NIO basin, these errors can be neglected and thus, the IMD best track data can be considered as reliable enough for analysing cyclone activity in this region.

Keywords. Tropical cyclones; best track; satellite; North Indian Ocean.

1. Introduction

Studies on tropical cyclone (TC) climatology and associated changes in environmental parameters have been emphasised by several researchers during last two decades (Mann and Emanuel 2006; Holland and Webster 2007; Mohanty *et al.* 2012; Deo and Ganer 2014; Sugi *et al.* 2014). Few of these studies indicated that the changes in TC activity could be due to the increased anthropogenic activities, including the rise in greenhouse gases throughout the globe (Holland and Webster 2007). Most of these studies used historical best track data from different sources, viz., JTWC (Joint Typhoon Warning Center), IBTrACS (International Best Track Archive for Climate Stewardship), JMA (Japan Meteorological Agency) and IMD (India Meteorological Department). Best tracking is the process of post-season analysis for determining the 'best estimate' of a TC's position

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and intensity during its lifetime (Mohapatra *et al.* 2012). However, these best track data sets have their limitations. The annual TC frequency counts over the global basins might have potential undercount bias (Landsea 2007; Chang and Guo 2007; Mann *et al.* 2007a, b), although the exact magnitude of this bias is controversial. The undercount in the magnitude of TC frequency is mainly because of the absence of efficient measurement techniques, better observations, aircraft reconnaissance and satellite technology during past centuries (Kozar *et al.* 2013).

There are several studies, which analyse the changes in TC activity over North Indian Ocean (NIO) region by considering the best track IMD data since 19th century (Singh *et al.* 2000; Srivastava *et al.* 2000; Mandke and Bhide 2003; Sikka 2006; Niyas *et al.* 2009; Tyagi *et al.* 2010; Mohanty *et al.* 2012; Mohapatra *et al.* 2012, 2015; Rajeevan *et al.* 2013; Vissa *et al.* 2013). Most of these studies found that there has been a decrease in the number of TCs over the basin (Mohaptra *et al.* 2012, 2015) although a few mentioned about the increase in severity (Mohanty *et al.* 2012). All of these studies used IMD data for their studies. It is realised that there is a continuous modification in it by incorporating information collected from various sources, especially satellite-derived ones. Very few studies (Mohapatra *et al.* 2012, 2015) examined the reliability of the data set by considering an earlier version (e-Atlas 2008a version). Since the data set has been improving continuously, and the current version of it is 2.0 or version 2011, and none of the studies examined its robustness, it is intended to do so in the present work. The current study analyses the quality and reliability of the data used by earlier studies so that robustness can be established and the trend provided by these studies can be verified to carry out further climatological analysis under the impact of changing climate scenario. An attempt is made here to address the following questions:

(i) Whether prior to satellite era there was any data-sparse region over NIO.
(ii) How much difference in the percentage of cyclonic disturbances (or CDs) striking/coming across the land is there during and prior to satellite era?
(iii) Is the possibility of missing a cyclonic depression formed over the basin higher or uncertainties in the count is overestimated over NIO?
(iv) Is there any error in the intensity determination process in the absence of satellite technique?
(v) Is the annual frequency for depressions, cyclonic storms (CS), severe cyclonic storms (SCS) provided by the best track data over NIO reliable?
(vi) Was the determination of proper track of CDs erroneous?

Most of the points mentioned are not yet taken up by any of the studies over NIO region. Further, the questions mentioned above are also answered by separately analysing the IMD data for CDs formed over Arabian Sea (AS) and Bay of Bengal (BOB) sub-basins by considering the seasonal behaviour during pre-monsoon, monsoon and post-monsoon months distinctly. Therefore, the present study is quite important and is expected to help in enhancing the understanding regarding the IMD best track data and its reliability.

2. Data and methodology

The present study mainly attempts to assess the quality and hence reliability of IMD best track data for cyclonic systems (version 2.0/2011 version) over NIO region. Most of the previous studies considered an earlier version (i.e., version 2008a) for the study of cyclonic activities over NIO basin (Mohapatra *et al.* 2012, 2015; Mohanty *et al.* 2012) by considering the data sets until 2010, unlike the present study where the consideration is until 2016. The data is obtained from the cyclone e-Atlas archive provided by IMD (http://rmcchennaieatlas.tn.nic.in). The frequency of CDs is also obtained from the JTWC archive (http://www.metoc.navy.mil/jtwc/jtwc.html?north-indian-ocean) to make a comparative study of both the data sets. The NIO region lies in the range 45°–100°E longitude, and the latitudinal extent is from 0° to 30°N. The east side of the basin is the BOB, and on the west, lies AS.

Following the IMD classification, over NIO basin, different types of cyclonic systems are (Singh *et al.* 2016):

(i) Depressions (D) having maximum sustained surface wind speed (MSW) of 17–27 knots
(ii) Deep depression (DD) with MSW of 28–33 knots,
(iii) Cyclonic storm (CS) with MSW of 34–47 knots,

(iv) Severe cyclonic storm (SCS) with MSW of 48–63 knots,
(v) Very severe cyclonic storm (VSCS) with MSW of 64–89 knots
(vi) Extremely Severe Cyclonic Storm (ESCS) with MSW of 90–119 knots
(vii) Super cyclonic storm (SuCS) with MSW of 120 knots or more.

On the other hand, IMD cyclone e-Atlas provides data, in three major categories, i.e., for depressions (cyclonic depressions that includes D and DD types), CS and SCS (which also includes VSCS, ESCS and SuCS types). For the current study, the term 'CD' (hereafter) refers to the consideration of all categories of cyclonic systems, i.e., depressions, CS, and SCS formed over NIO. This study considers 'TCs' (hereafter) as the CDs with intensity higher than 34 knots (i.e., CS and above). The analysis in this work is performed for whole NIO basin by considering all the coastlines, i.e., including those of the RIM countries (Bangladesh, Myanmar, Sri Lanka, Pakistan, Oman, Yemen, and Somalia) as well as India.

Initially, the study focusses on the historical background of data capturing capability in the absence of satellite technology over NIO and enhancement of coastal observatory network over India. Thereafter, assessment of the reliability of IMD best track data is done by following Landsea (2007). The best track data from IMD is statistically analysed considering non-parametric Kendal tau test at 95% significance level by computing correlations, bias and other relevant parameters. Further, trend analysis is also performed to evaluate the robustness of the data. Following Landsea (2007), differentiating between the frequency of CDs that struck land vs. those remained over the open ocean analysed considering the long-term percentage of CDs. A similar approach is adopted for NIO TCs to estimate the error in annual frequency. The percentages are also computed separately for BOB, and AS systems those struck the land out of the total number of systems formed for pre-monsoon, monsoon and post-monsoon seasons respectively.

Additional relevant analyses are carried out to identify the inherent limitations if any. More detailed analysis of the data is performed by considering 'decadal change in frequency and genesis location', 'changes in mean life period', 'annual frequency of depressions, CS and SCS', 'annual frequency of unusual tracks (viz., looping tracks, recurving tracks and southward moving)' and 'mean tracks'. Analysing these factors would help in assessing major differences between two periods and hence the drawbacks in detection and life cycle determination during the pre-satellite era. In addition, Student's *t*-test at 95% significance level is also performed to validate the difference in results between two periods.

3. Discussing the robustness of IMD best track data

Studies assessing the reliability of best track data over NIO is limited. The present work would be helpful in assessing the trustworthiness of long-term variations in the behaviour of CDs and their frequency trend over the basin. It is well known that NIO region is relatively smaller than Pacific or Atlantic basin. Landsea (2007) observed that, as one goes back in time (e.g., before 1960), the number of people living in coastal regions was less; the number of shipping lanes and ships was not much, and these factors increase the probability of missing some hurricanes over Atlantic regions. If we look into NIO region case, it is a comparatively smaller basin with marginal population across the coast even back in time (to 19th century). In 1865, first storm warning centre was established in Kolkata when two severe systems caused massive destruction among the coastal regions in 1864 (www.rsmcnewdelhi.imd.gov.in). It is worth mentioning that the world's highest storm tide (Bakherganj cyclone near Meghna Estuary, Bangladesh) of 45 feet was recorded in 1876 that occurred in BOB region. To reduce the loss caused by such destructive systems, tracking over NIO started during the 19th century.

The detection and estimation of cyclone intensity is a critical process. It is not necessary that satellites are always capable of detecting a CD or provide a better estimate of its intensity. For example, mesocyclone Ogni (28–30 October 2006) was detected by radar and coastal observations, but was missed by satellite (IMD 2011). Therefore, the determination of life cycle of CDs and understanding of associated meteorological features need inputs from different sources including satellites (e.g., Deb *et al.* 2011; Panda and Giri 2012; Kishtawal *et al.* 2012; Panda *et al.* 2015) and radars (Osuri *et al.* 2015). Over NIO, the surface observations got an ideal status by 1960 due to expansion in the 1940s and 1950s; radar observations got enhanced by 1973, pilot balloon and radio wind observations by 1980 (Mohapatra *et al.* 2012). The polar satellite input was used since 1961, Dvorak's technique since 1974, Indian geostationary satellite since 1983, AWS and buoys observations since 1997 and enhanced AWS network along with microwave imageries since 2008. All of the available observations including those from satellite, radar, ships, buoys, and coastal and island platforms are taken into consideration for developing the best track data by IMD (IMD 2003).

Further, with the advent of satellite technology after 1960, the determination of track and intensity of TCs became more accurate. The use of weather satellite by IMD has begun since the launching of TIROS-I in 1960 (Koteswaram 1961, 1971). Again, the use of data provided by geostationary satellites such as series of Indian National Satellites (INSAT) and Kalpana, delivered more accurate location and intensity of CDs over NIO. In addition to satellite technology, because of the enhanced coastal observatory network over NIO, the intensity of CDs was better estimated from the year 1940s and 1950s (Mohapatra *et al.* 2014). The best track data provided in the e-Atlas (IMD) contains genesis location, temporal variability in position, dissipation location and the position at which the systems change the direction of motion etc. The first position of a CD recorded during the period 1890–1990 was provided at 8.30 hrs local time and not the exact time/date of formation (cyclone eAtlas-IMD 2011). This may be the probable reason behind fewer genesis locations over a certain region of BOB and AS.

The IMD technical note on cyclone e-Atlas version 2.0 (IMD 2011), discusses the advent, improvements in the process identifying depressions, monitoring and warnings and about some of the published annual reports about CDs. The historical data over AS is available from 1648 onwards and for BOB since 1737. It is noteworthy that e-Atlas published by IMD has gone through several modifications to make the best track data homogeneous and reliable. From 1886, the annual report of IMD entitled 'Reports on the Meteorology of India' started taking into account depressions, TCs and their track over NIO (Mohapatra *et al.* 2012). The annual report of IMD (1964) provided a revised and more comprehensive publication of tracks of all tropical depressions those occurred over the area bounded by latitudes 5°–35°N and longitudes 50°–100°E for the period 1877–1890 and 1891–1960. In the 1979 edition of IMD best track data related report, there were several short-lived depressions, which do not have tracks, as NIO is prone to monsoonal depressions. Therefore, in the current e-Atlas version, these short-lived depressions without a track have been removed, to reduce the monsoonal depression counts and for better determination of the frequency of CDs. During the period of the pre-satellite era, a possibility of missing depressions cannot be denied in addition to the error in intensity and location estimation, especially for CDs formed to the south of 7.5°N over BOB. The area west of 65°N over AS has no depression during the pre-satellite era; therefore, chances of some missing depressions over the region is also expected.

For determining the extent to which the currently available IMD e-Atlas data is reliable to predict the annual frequency of CDs and associated cyclone activities over NIO, an attempt is made to assess the differences owing to the presence and absence of satellite technology and limitations during pre-satellite and satellite era. An effort is made to find the trend in location and frequency of their genesis, frequency of unusual tracks such as looping, recurving and southward moving tracks, and mean life of CDs during both the periods. Furthermore, mean tracks of CDs and mean track length are also analysed.

3.1 *Variation in genesis location*

A detailed investigation is carried out in order to find the data sparse region and perform a comparative analysis based on genesis location of CDs over NIO basin by considering the cyclone e-Atlas provided by IMD for the period 1891–2016. Figure 1 gives an idea about the variation in genesis locations of CDs, for the years 1891–2016 (primarily at an interval of 25 yrs except figure 1e). Here, the data considered and available is of 2.5° resolution. It is realised that monitoring is done throughout the basin and recorded for warnings. Even the e-Atlas of 19th century also covers the entire basin for providing CD tracks. The detection of the genesis of CDs near the southern part and central bay also found to be good (figure 1a–d). The genesis of cyclonic systems near the west coast of AS (50°–55°E) is absent for each interval considered. The frequency is higher ($\sim$70 cyclonic systems) during 1891–1965 over BOB and has a decreased frequency for 1966–1990 ($\sim$55 systems for the period) and severely decreased during

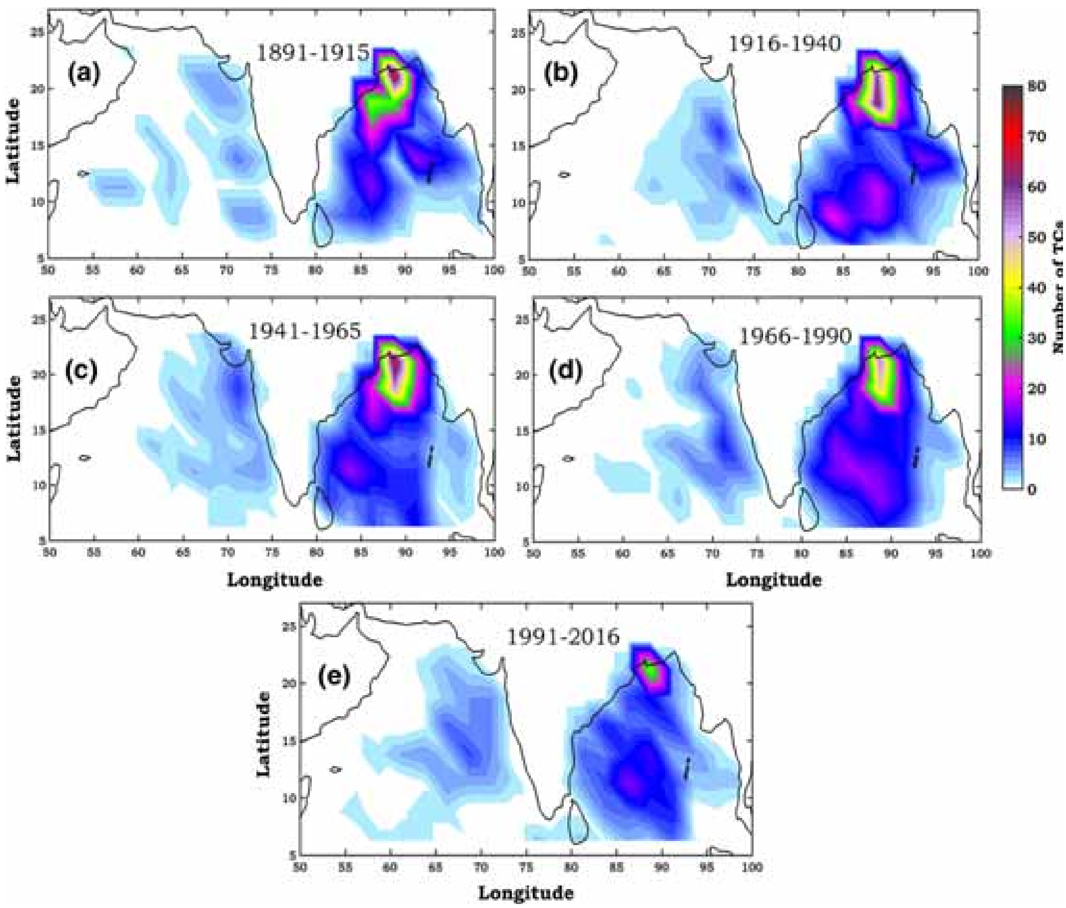

Figure 1. Spatial distribution of genesis location of cyclonic disturbances or CDs (includes deep depressions, depressions, cyclonic storms, severe cyclonic storms and higher intensity cyclones) over NIO as provided by IMD cyclone e-Atlas (www.rmcchennaieatlas.tn.nic.in) for five different periods i.e., **(a)** 1891–1915, **(b)** 1916–1940, **(c)** 1941–1965, **(d)** 1966–1990, and **(e)** 1991–2016. Here, 25-yr composite is considered for (a–d) but for **(e)**, 26 years is taken by including the year 2016.

1991–2016 ($\sim$35 cyclonic systems). It indicates a decrease in CD genesis over BOB in recent years. The seasonal analysis also showed similar kind of results. During pre-monsoon season (figure S1a–e), the genesis frequency of CDs over both BOB ($\sim$9) and AS ($\sim$5) was higher, which observed to have decreased ($\sim$5 and $\sim$3 respectively) during 1991–2016. However, an enhanced genesis is observed near the coast of Somalia after 1990, which was absent earlier. During monsoon season, the frequency over BOB is observed to be drastically decreasing (from 70 to $\sim$30; figure S2a–e). During post-monsoon season, the genesis was higher (up to $\sim$18) over a wider area during 1966–1990, but found to be decreasing drastically ($\sim$8) after 1991 (figure S3). The seasonal variation indicates that the detection of cyclogenesis was quite good irrespective of seasons in the past too.

The variation in decadal frequency in genesis location over BOB and AS during the considered periods is illustrated in figure 2 by considering different grids (5-degree lat./lon. difference) indicated along the x-axis. During both the periods, the maximum genesis location lies within 85°–90°E and 15°–20°N over BOB. However, the inter-quartile range of decadal variation in CD genesis over the grid is ranging from nearly 37–46 during the pre-satellite era and approximately 14–34 during satellite era over BOB (figure 2a, c). The 75th percentile of decadal genesis frequency decreases from 46 to 36 over that particular location, showing a reduction during satellite era. The data over the grid shows skewness during satellite era and indicates absence of normal distribution. A considerable number of genesis is also observed over the region 85°–90°E and 10°–15°N in BOB during satellite era. The inter-quartile ranges over other grids also show a significant increase in values during satellite era and spatial modification in genesis frequency indicates that during the absence of satellite technology, the detection of genesis location of a CD was not correct. Similarly, over

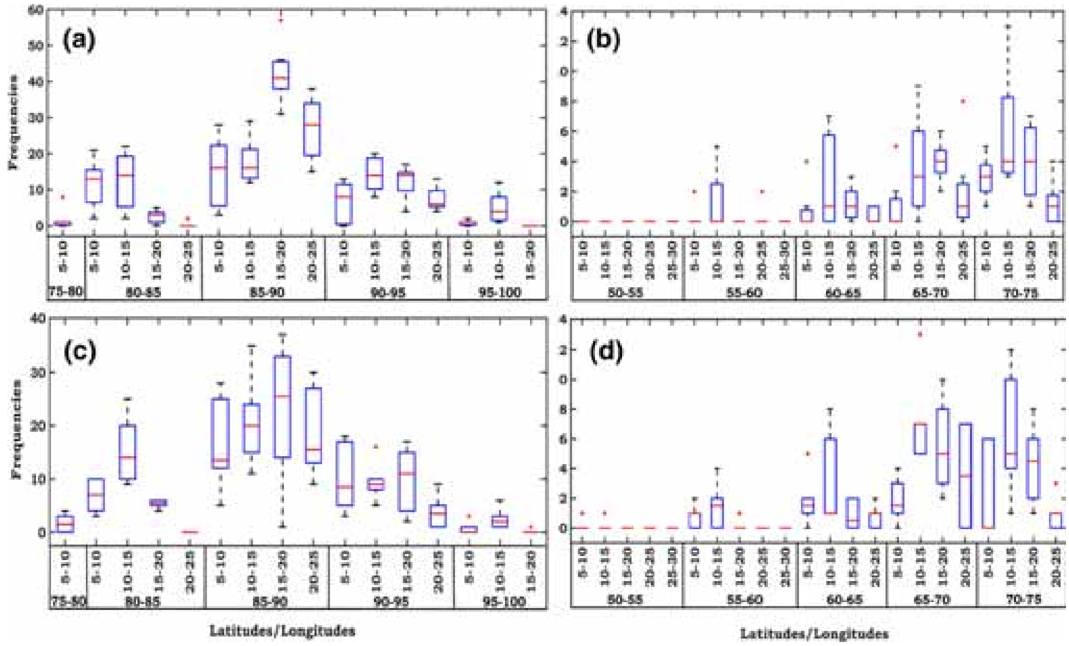

Figure 2. Decadal variation in genesis location of CDs during pre-satellite era **(a, b)** and satellite era **(c, d)** for BOB and AS, respectively. The left panel is for BOB and the right one is for AS.

AS, there is a relative increase in maximum value of genesis over the region lying between 65° and 75°E during satellite era (figure 2d). The interquartile range and 75th percentile also show an increase over the AS basin; thereby representing better detection of genesis. No difference is observed in maximum genesis locations during both periods. However, the frequency statistics change for other grid locations except the ones mentioned earlier, over both BOB and AS sub-basins.

Both figures 1 and 2 indicate that there is an increase in genesis near 80°–85°E/10°–15°N and 80°–85°E/15°–20°N regions, i.e., Tamil Nadu (TN) to Andhra Pradesh (AP) coast during the satellite era. Near Gujarat coast, CD genesis is absent during 1916–1940. There is also the absence of genesis near BOB coast during 1891–1915. The maximum genesis location over AS is varying during one period to another, whereas, over BOB, it is nearer to Bangladesh coast (figure 1). Over BOB, the second maximum genesis location is shifting randomly during each period of consideration. However, the absence of genesis near to the coasts pointed out here could not be subjected to the lack of observatory techniques. The coastal observatory over Indian coast was considerably good even back in time (Mohapatra *et al.* 2012). It is observed that during 1891–1915, the landfall of cyclonic systems over Odisha coast was 88, AP is 34 and TN coast was seven. During 1916–1940, the systems making landfall over AP was 39. If the landfalling systems could be detected, then the capability to detect the genesis of a system near the coast is not questionable. Moreover, Indian coast had marginal population even during 19th century. Thus, the chance of missing cyclonic systems near to coast is very less though cannot be zero.

3.2 *Annual frequency of cyclonic systems formed*

The decadal variation of CD frequency over NIO as a whole during pre-satellite and satellite era is analysed to find the chances of inclusion or exclusion of depressions during the pre-satellite era (figure 3). The trend for 75th percentile shows an increase during the pre-satellite era, whereas, during satellite era, decreasing trend is quite evident. The decades in between 1921 and 1950 show the highest value during pre-satellite era whereas decades in between 1960 and 1990 realise maximum frequency during satellite era and after 1990, started decreasing very sharply (figure 3b). The annual average frequencies are 12.9 and 11.39 during pre-satellite and satellite era. The t-test (t-crit = 1.981, t-stat = 2.481, p-value = 0.014) indicated that difference between the average frequencies during pre-satellite and satellite era is

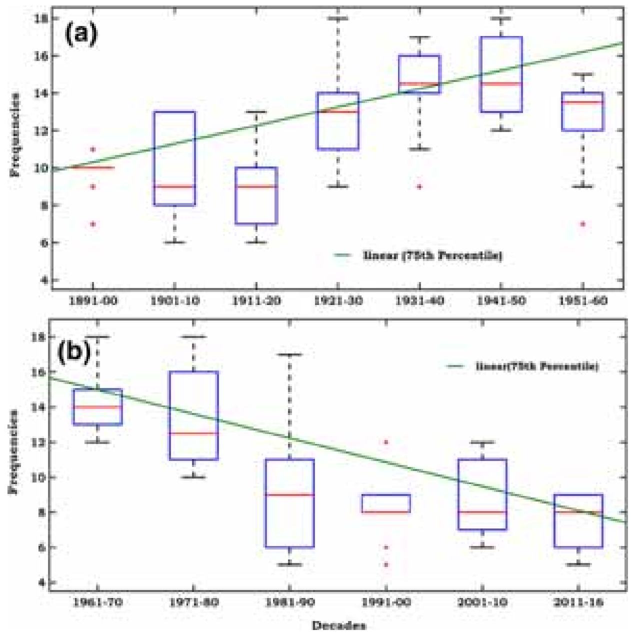

Figure 3. Variation of decadal frequency of occurrence of CDs over NIO for the period of 1891–2016 and trend of 75th percentile during **(a)** pre-satellite and **(b)** satellite era.

significant at 95% significance level. The annual frequency of cyclonic systems over NIO is continuing to decrease (Mohapatra *et al.* 2015) during recent years. The Kendall coefficients for pre-satellite era and satellite era are 0.390 and –0.425 at 95% significance level.

Further, the annual frequency of systems formed over NIO as detected by IMD is compared with that of JTWC best track data for NIO region. It is observed that till 1976, the difference between frequencies of CDs by both the agencies is zero for most of the years. From 1977 onwards, a huge difference in frequencies is observed (JTWC is providing an undercount frequency for NIO). Several depressions are also found to be missing in JTWC data set during recent years. The RMSE (root mean square error) is 0.258 during the pre-satellite era, whereas the corresponding error is 4.856 during satellite era. The RMSE is found to be 4.315 when calculated for the entire period of 1891–2016, which is not so large. There are primarily three differences between the data sets for several reasons. The first reason could be because of difference in the measurement of maximum sustained surface winds. JTWC measures the maximum sustained surface winds in tropical disturbances and cyclones in terms of '1-minute mean wind speed' (https://www.usno.navy.mil/JTWC/frequently-asked-questions-1/), whereas IMD provides '3 min averaging for the sustained wind' (http://imd.gov.in/section/nhac/wxfaq.pdf). JTWC reports higher maximum sustained surface wind speeds compared to that of IMD for the same cyclone. The second difference is that JTWC issues forecast out to 120 hrs as required by U.S. Department of Defence. The third difference is in adopting the numbering scheme, i.e., JTWC does not apply the same tropical cyclone numbering scheme used by the regional centres.

The decadal variation in CD frequency over BOB shows a decrease in 75th percentile trend for pre-monsoon, monsoon and post-monsoon season during satellite era (figure 4b, d and f). However, the decrease is very much significant for the monsoon season, where a sharp fall in frequencies is observed. The corresponding trend is increasing during pre-satellite era for all the three seasons (figure 4a, c and e). The annual average frequencies are 1.071, 5.871 and 3.4 in pre-monsoon, monsoon and post-monsoon season respectively during the pre-satellite era. The corresponding numbers are 0.982, 3.41 and 3.589 respectively during satellite era. The result for t-test (t-crit $=$ 1.659, t-stat $=$ 6.583, p $=$ 1.72001E-09) for monsoon season shows a significant decrease in annual average number of systems formed over BOB. The Kendall coefficients are 0.189, 0.193, 0.306 and –0.163, –0.545, –0.330 for the three seasons (pre-monsoon, monsoon and post-monsoon) during pre-satellite and satellite era respectively at 95% significance level. The result of Kendall test represents an increase during pre-satellite era and a decreasing trend during satellite era.

Similarly, for AS, the trend for 75th percentile is observed to be slightly increasing during pre-monsoon, monsoon season and is stable for the post-monsoon season during pre-satellite era (figure S4). The annual average number for systems formed during pre-satellite era is 0.342, 0.428 and 0.542 for pre-monsoon, monsoon and post-monsoon seasons respectively. During satellite era, the corresponding trend for pre-monsoon is found to be decreasing sharply, stable for monsoon season and increasing for the post-monsoon season (figure S4). The annual average frequencies are 0.321, 0.803 and 1.107 for all the three seasons respectively in satellite era. The student t-test results are significant during satellite era for monsoon and post-monsoon season. The Kendall coefficients are 0.077, 0.118 and 0.15 for pre-monsoon, monsoon and post-monsoon seasons during pre-satellite era. The respective coefficients are –0.163,

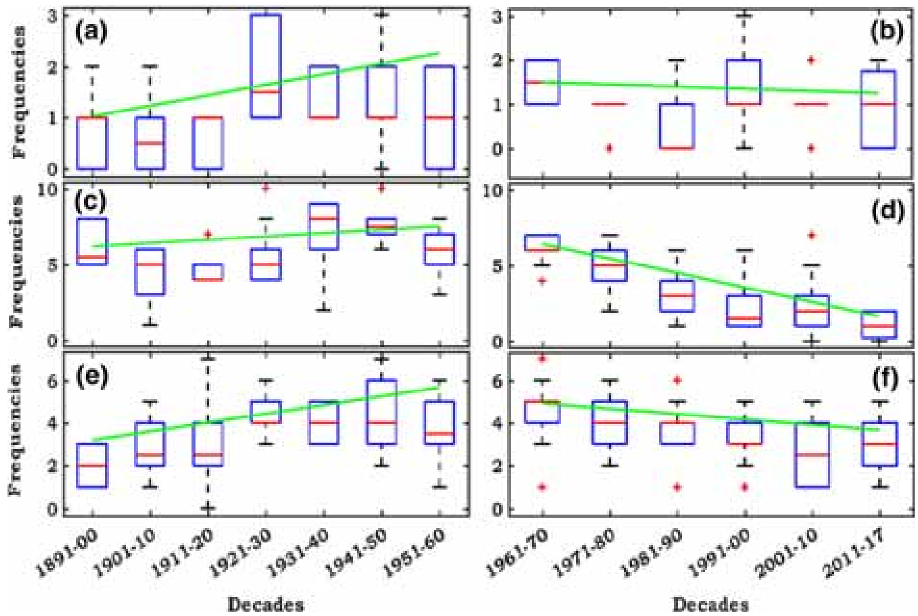

Figure 4. Variation of decadal frequency of occurrence of CDs over BOB for the period of 1891–2016 and trend of 75th percentile during **(a, b)** Pre-monsoon, **(c, d)** Monsoon **(e, f)** Post-monsoon season during pre-satellite era and satellite era, respectively. The green straight line represents the linear trend for 75th percentile of data. The left side panel is for pre-satellite and right side panel is for satellite era.

–0.545 and –0.33 during satellite era for all the three seasons.

It is evident from Singh *et al.* (2019b) that the surface level relative humidity has decreased, whereas an increase in surface wind hinders the genesis of CDs for pre-monsoon, monsoon and post-monsoon seasons over both BOB and AS in recent years. It is worth noting that during the warming climate, the surface level RH is an important factor for cyclogenesis to avoid dry intrusion into the systems that hinder the growth of cyclones. Therefore, the decrease in frequency CDs is in synchronisation with the environmental parameters. On that account, the role of implementation of satellite technology is very less on the increasing trend of CDs frequency during pre-satellite and decreasing trend of CDs frequency during satellite era.

The trend for annual frequency variation of CS over NIO shows a decrease during both satellite and pre-satellite era, but it is not so significant in the earlier case (figure 5a, b). The decreasing trend for CS during the satellite era is found to be significant (at 95% significance level) when examined with Kendall's tau test. The Kendall coefficient is found to be –0.182 (p-value = 0.036). The trend for SCS is found to be nearly stable during the pre-satellite era and significantly decreasing during satellite era (figure 5c–d) over NIO. The decreasing trend of SCS during satellite era is significant with Kendall coefficient value = –0.384 and p-value = 0. 0001.

Comparison of annual frequencies of CS during both the periods indicates that there may be a wrong estimation of intensity during the pre-satellite era. Therefore, a sudden fall in number of CS is observed with the implementation of satellite technology. Since NIO consists of two sub-basins BOB and AS, the frequency of TCs over them need to be analysed separately to make an affirmative statement in this regard during the considered seasons concerning pre-satellite and satellite era.

Over BOB, it is observed that during the pre-monsoon season, the trends are nearly stable both for CS and SCS for the pre-satellite era (figure S5a). However, during satellite era, the trend for CS is decreasing rapidly, but a stable trend is seen for SCS (figure S5b). During monsoon season, the number of CS is observed to be quite high with a decreasing trend for pre-satellite era (figure S5c). However, the number has decreased during satellite era with a further decreasing trend, and the trend is significant (at 95% significance level). The trend for SCS during monsoon season is found to be decreasing for both pre-satellite and satellite era over BOB (figure S5c and d). During post-monsoon season, the number of CS is higher than SCS with stable trend for pre-

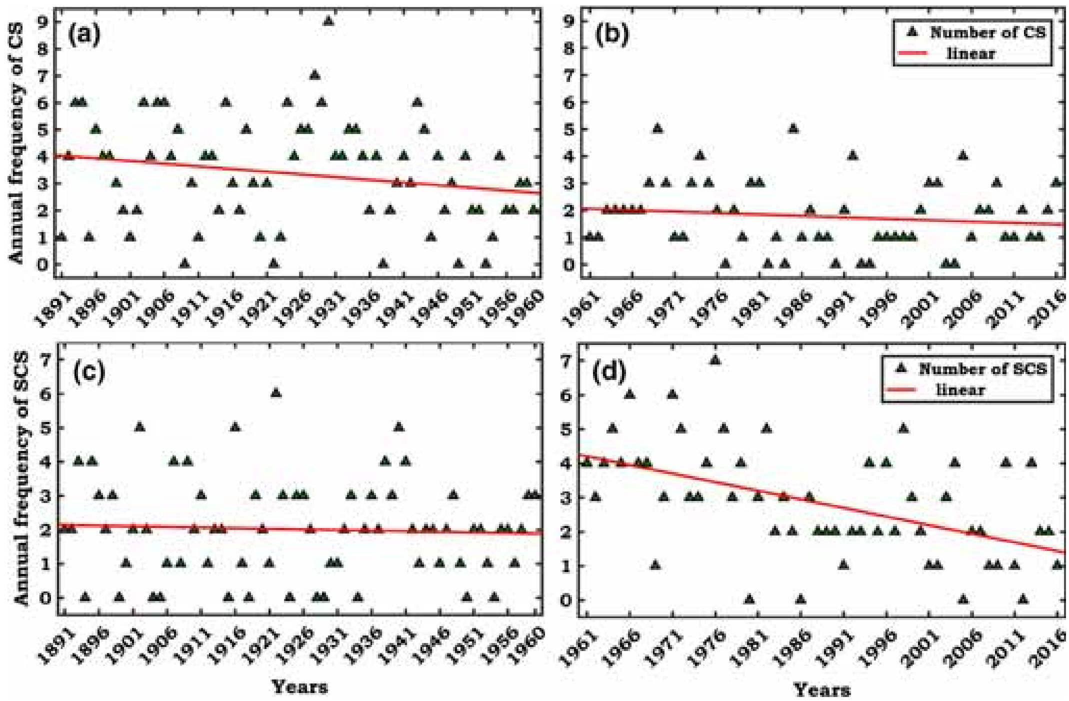

Figure 5. Annual frequency variation and linear trend of CS **(a, b)** and SCS **(c, d)** during pre-satellite and satellite era over NIO for the period of 1891–2016. The left side panel is for pre-satellite and right side panel is for satellite era.

satellite era (figure S5e). However, the number of SCS has increased during satellite era with a sharp decreasing trend (figure S5f). Significant Kendall coefficients for SCS are –0.227, –0.274 and –0.359 during pre-monsoon, monsoon and post-monsoon seasons for satellite era, which indicate a decreasing trend. The number of CS has decreased (shows a stable trend) in the satellite era in post-monsoon season. This analysis indicates possible error in intensity determination process during pre-satellite era. Several deep depressions and SCS were possibly termed as CS, and thus, their number is quite high in pre-satellite era, which decreased during satellite era.

Over AS, the frequency of CS and SCS are very few in comparison to BOB for all the three considered seasons during both pre-satellite and satellite era. However, the frequency of SCS has increased during monsoon and the post-monsoon season for satellite era although exhibit nearly stable trend (figure S6d and f). The Kendall coefficients for CS are –0.007, –0.066 and –0.109 respectively for pre-monsoon, monsoon and post-monsoon season during the pre-satellite era. The corresponding coefficients are –0.007, 0.062 and 0.062 for all three considered seasons during satellite era. The Kendall coefficients for SCS are –0.065, –0.049 and 0.068 for pre-monsoon, monsoon and post-monsoon seasons during pre-satellite era. The corresponding values are –0.056, –0.032 and 0.023 for all three seasons during satellite era. The values found through Kendall tau test for CS and SCS are observed to be of insignificant over AS for all seasons in both pre-satellite and satellite era.

3.3 *Formation vs. crossed/grazed cyclonic systems*

The temporal variability of frequency of CDs formed over the basin, and those crossed or grazed the coastal areas of NIO is analysed for the period 1891–2016 during peak cyclone seasons, i.e., pre-monsoon and post-monsoon seasons (figures S7, 6, 7). The number of CDs crossed or grazed is determined by their center either crossing or passing within 5° of a coastal region. The correlation coefficient between the number of CDs formed and those struck land is very high ($\sim$0.97). The reason behind such a significant correlation could be due to the smaller coastline compared to other basins like that of the Atlantic Ocean. It indicates that most of the cyclonic systems struck (the coasts) out of total CDs formed through the entire period of data considered. However, few CDs dissipating over sea might have been missed while preparing the best track data during pre-satellite era for some areas where coastal observatories were not functional, or sea-based observations were not taken. On the other hand, if such an argument does not hold good, then there could be no direct relationship between the total number of CDs formed and those crossing the coast. This is not 100% correct if the considerations of Landsea (2007) and size of NIO basin is taken into account.

For better understanding, the impact of introduction of satellite technology for monitoring the activities of NIO CDs, pre-satellite (1891–1960) and satellite (1961–2016) era are separately considered. It is observed that the number of CDs, those struck land and total number formed (including short-lived systems) are nearly equal for most of the years, irrespective of whether it is pre-satellite or satellite era for the whole NIO region. It is realised that very less number of systems stayed over ocean in both the periods considered here. When similar study is carried out for BOB basin, the number of systems formed and those crossed or grazed the coast are equal for most of the years for pre-monsoon, monsoon and post-monsoon seasons both during pre-satellite and satellite era (figure 6). The correlation coefficients for the number of systems crossed or grazed concerning the total number of systems formed is $\sim$0.9 for all three considered seasons during both epochs. Further, the number of systems those struck the coast out of the total number of systems formed over AS are also equal for most of the years during both the considered periods for all three seasons (figure 7). The correlation coefficients during pre-satellite era are 0.972, 1 and 0.882 for pre-monsoon, monsoon and post-monsoon season. The corresponding correlation coefficients for satellite era are 0.945, 0.824 and 0.864. The higher correlations indicate that most of the formed systems either crossed or grazed the coast of AS. As the size of the BOB basin is comparatively small, most of the systems developed over it do not get chance to dissipate over the ocean; whereas, few systems over AS are observed to dissipate over the sea although the numbers are not very high.

Further analysis of the data set is also carried out by considering the annual percentage of CDs those crossed or grazed the coastal areas out of the total number of the systems formed during pre-satellite and satellite era (figure 8) over NIO. It is observed that during both pre-satellite as well as the satellite era, the landfall percentage is 100% for most of the years (102 out of 126 years) as far as annual frequency is concerned. The slope values of the trend line during pre-satellite era is nearly –0.023 and that during satellite era is $\sim$0.027. The

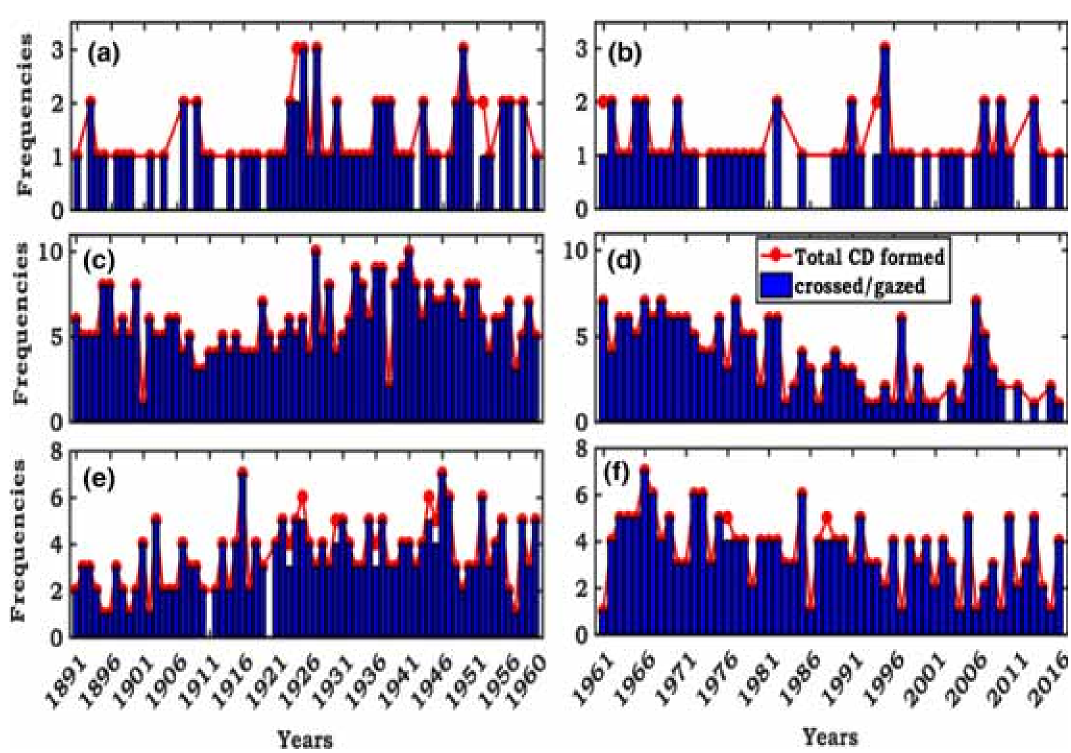

Figure 6. Total number of CDs formed over BOB vs. total number of systems crossed or grazed the coastal regions for pre-monsoon **(a, b),** monsoon **(c, d)** and post-monsoon season **(e, f)** during pre-satellite era and satellite era, respectively for the period 1891–2016.

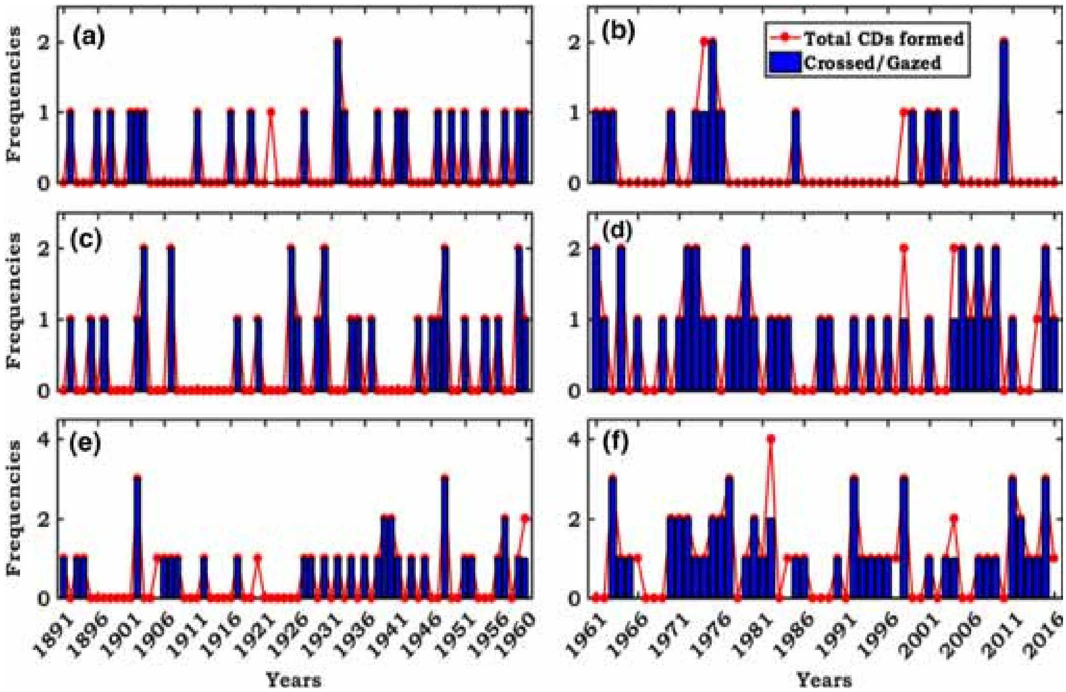

Figure 7. Total number of CDs formed over AS vs. total number of systems crossed or grazed the coastal regions for pre-monsoon **(a, b),** monsoon **(c, d)** and post-monsoon season **(e, f)** during pre-satellite era and satellite era, respectively for the period 1891–2016.

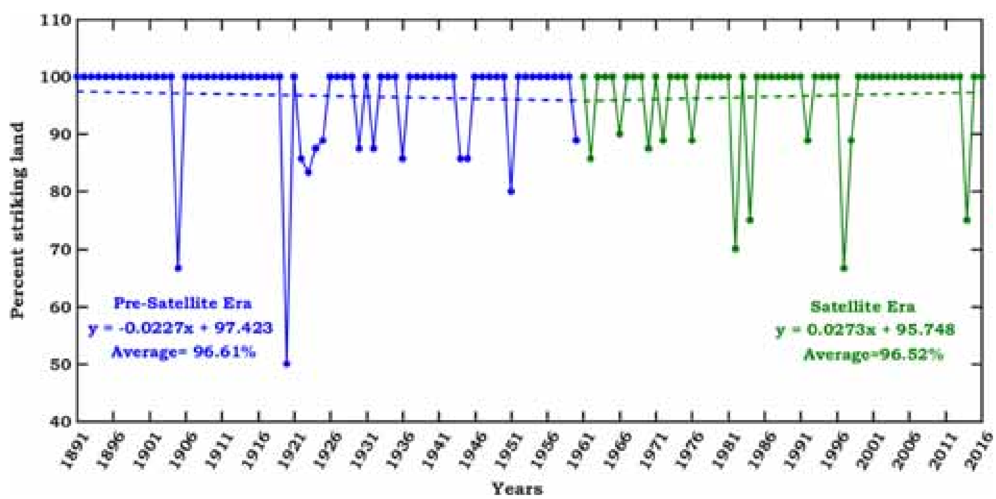

Figure 8. Annual percentage of CDs that crossed or grazed the coastal areas of NIO vs. the total number of systems formed over ocean for the period 1891–2016. Here, the cyclonic disturbances formed during monsoon seasons are excluded.

average percentage of the number of CDs struck the land during pre-satellite era is 96.61%, whereas during the satellite era it is 96.52%. This analysis indicates that there is hardly any issue with the detection of genesis and landfalling during pre-satellite and satellite era. However, one interesting aspect may be noticed in figure 8 that the frequency of dissipation over the sea is relatively higher during the period 1961–1998 in satellite era compared with the period 1920–1960 during the pre-satellite era. The absence of dissipated systems until 1920 probably indicates missing of some depressions those dissipated over the basin and were unable to gaze the coastal land. If it is presumed that some stayed over ocean and missed by IMD during pre-satellite era, 0.046 number of CDs per year could be added to the annual frequency for pre-satellite years, assuming an average number of 0.232 systems per year stayed over ocean during this period as compared to that of satellite era. In spite of the adjusted/corrected value, the trend for frequency of CDs for the period would remain unchanged due to insignificant variation (figure not shown). The trends also remain unaffected irrespective of inclusion or exclusion of short-lived depressions (life period of ∼24 hrs) during peak cyclone seasons.

The percentage of CDs those crossed or grazed the coast out of the total number of systems formed over BOB is also 100% for most of the years during all the three seasons pre-monsoon, monsoon and post-monsoon in both epochs (figure 9). The corresponding annual average percentages for pre-monsoon season are 98.39 and 97.6%, for monsoon season it is 100% each and for post-monsoon season are 98.18 and 99.28% respectively for both epochs. The trends are also nearly stable for all three seasons during both epochs over BOB. Over AS, the percentage of systems striking the land during the pre-satellite era is 100% for most of the years (figure S8) in all three seasons. However, the percentage is found to be low for some recent years during monsoon and post-monsoon seasons of the satellite era. The percentages during satellite era are 95.65, 100 and 91.66% for pre-monsoon, monsoon and post-monsoon seasons respectively. The corresponding percentages are 90, 94.11 and 87.17% during satellite era. The trend for percentages is observed to be slightly decreasing for pre-monsoon and monsoon seasons, but a nearly stable trend observed in post-monsoon season during satellite era.

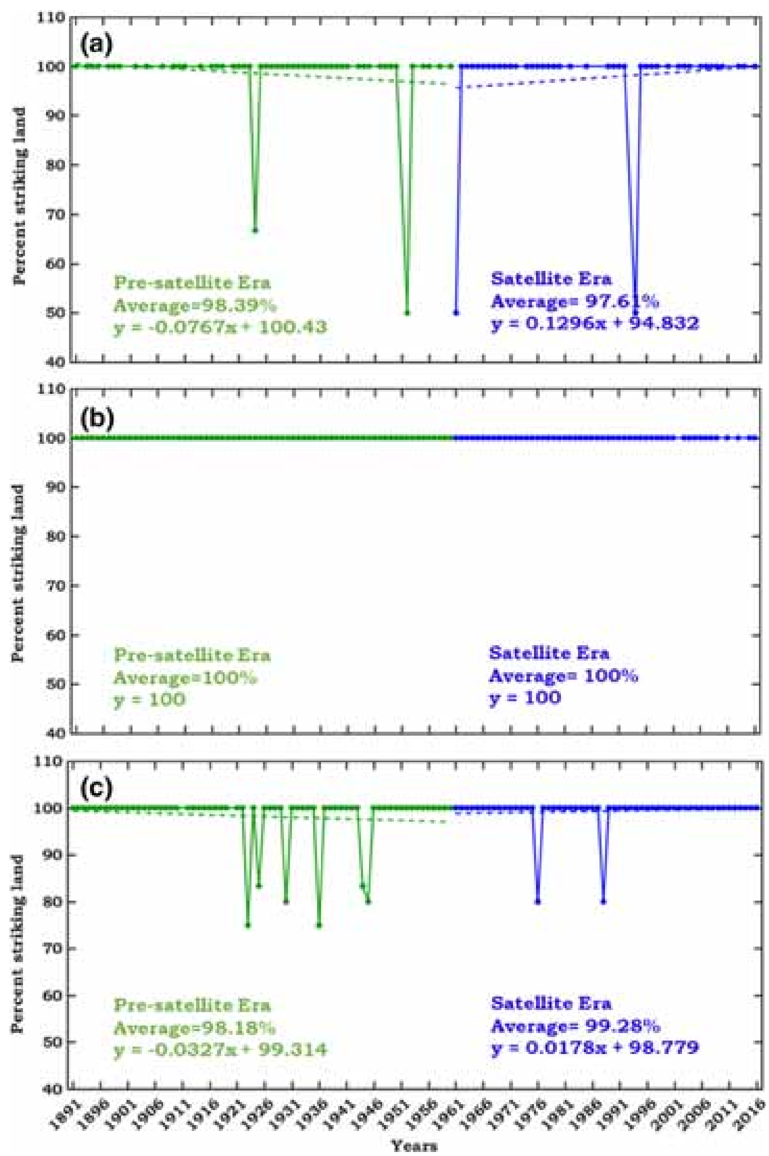

Figure 9. Annual percentage of CDs that crossed or grazed the coastal areas of BOB vs. the total number of systems formed over ocean during **(a)** pre-monsoon, **(b)** monsoon, and **(c)** post-monsoon for the period 1891–2016 for pre-satellite and satellite era. The dotted green and blue straight lines represent the linear trend for pre-satellite and satellite era respectively.

Under the impact of the warming climate, the rate of dissipation of CDs has increased over AS, since the climatological integrated wind circulation within 65°–70°E inhibits the landfalling (Singh *et al.* 2019a). Therefore, high annual percentage of system striking the coast during pre-satellite is due to the climatological factor rather than the chance of missing dissipated systems over ocean. When the percentages and its trends are analysed separately for BOB and AS, it can be observed that the chance of missing systems over both the basins is very less and the trend would not vary much with the addition of few missing systems, if there is any.

3.4 *Intensity variation*

Another attempt is made to analyse the difference in frequency of occurrence of different categories of tropical storms by considering the maximum CI (Cyclone Intensity) no. attained by CDs in both the pre-satellite and satellite era (figure 10). Prior to satellite era, the CDs were classified into three categories only, i.e., depressions having a CI no. in the range 1–2, CS with CI no. ranging between 2.5 and 3 and SCS with CI no. > 3. Number of CS during pre-satellite era is very high compared to the SCS, whereas the frequency of CS is lower than SCS for many years during satellite era. The frequency of CDs is quite high between the years 1923 and 1985. Until 1960, the SCS frequency is lower than CS, but after 1961, the SCS frequency shows a rise. The depressions formed during pre-satellite era is 57.36%, and during satellite era it is 58.62% out of the total number of systems formed. The percentage decrease for CS category from pre-satellite to satellite era is from 26.79% to 16.45% and for SCS, the percentage increases from 15.83% to 24.92%. The possible reason behind this variability could be the erroneous process of determination of T or CI nos. for higher intensity storms, though the annual frequency is less flawed during pre-satellite era.

3.5 *Mean life period*

The annual mean life period for most of the CDs during the pre-satellite era is observed to be

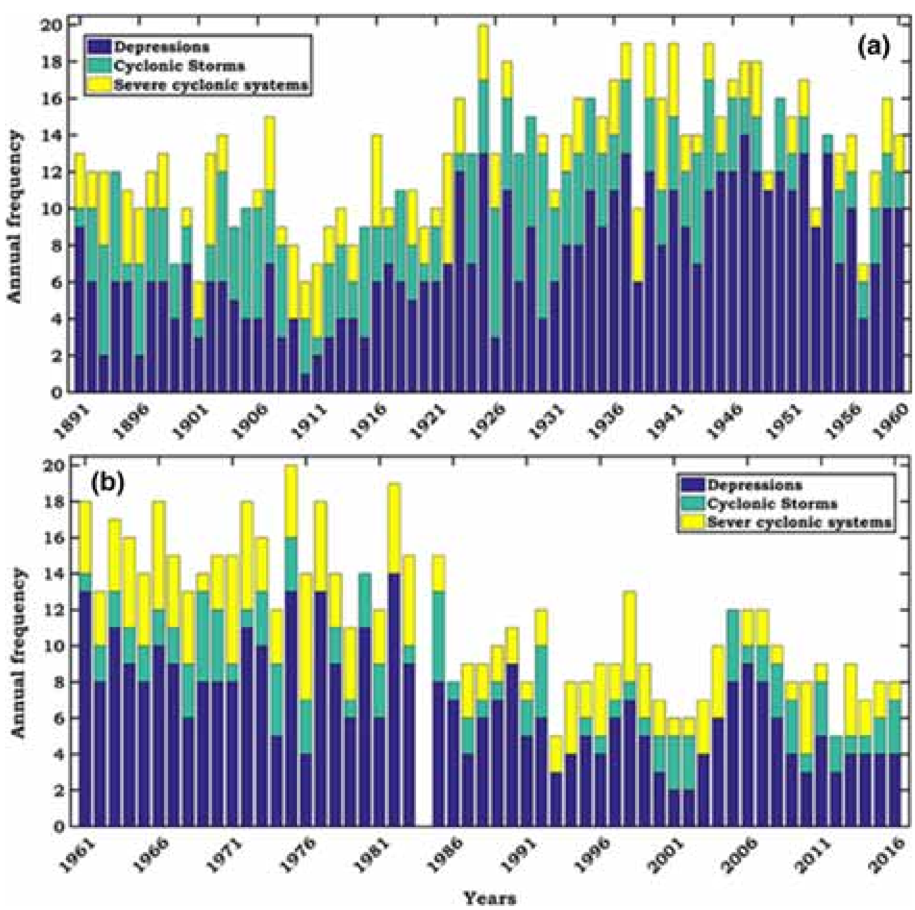

Figure 10. Annual frequency of CDs by considering their CI numbers of the systems formed during the period **(a)** pre-satellite and **(b)** satellite era over NIO.

between 3 and 6 days (an exception is found during 1953, where mean life is ∼2.5 days) and the trend is decreasing during that period (figure 11a). However, the annual mean life is observed to be ranging between 2.4 and 5.3 days during satellite era, and the trend is nearly stable (figure 11b). Thus, during pre-satellite era, the CDs had comparatively longer life span than the satellite period or post 1960. Similar inference can also be drawn from table 1, where life span of different categories of storms during both eras and results for student's *t*-test illustrated. The mean life for depressions during pre-satellite era is 3.964 days, whereas during satellite era it is 3.255 days. Similarly, for CS, the corresponding values are 4.667 and 3.668 days respectively and for SCS, the respective mean life periods are 4.842 and 4.092 days. Considering all the categories of cyclonic storms together, the corresponding mean life periods are found to be 4.431 and 4.147 days. A reduction in life period of CS and SCS is evident from table 1, indicating shorter life span during satellite compared to that of the pre-satellite era. The life span is gradually decreasing since 1891 (instead of a sudden decrease in life period during satellite era). The overestimation of life period during the pre-satellite era is not accountable as the exact time of genesis was not known, which indicates the exact life could be more than what is mentioned in best track data. Comparatively shorter life period during satellite era may be because of a greater number of rapidly intensifying and decaying CDs.

3.6 *Frequency of unusual tracks*

Figure 12 depicts the frequency of looping tracks, recurving tracks and southward moving CDs over NIO during the pre-satellite era and satellite era. Prior to the satellite era, the detection of looping cyclone is completely absent, whereas, during satellite era, the frequency is quite high. The southward moving CD frequency is relatively low during pre-satellite era. It is observed that prior to 1981, there are several years, where recurving CD frequency is 3–4 annually and post 1981, the years with such frequency is absent, though the

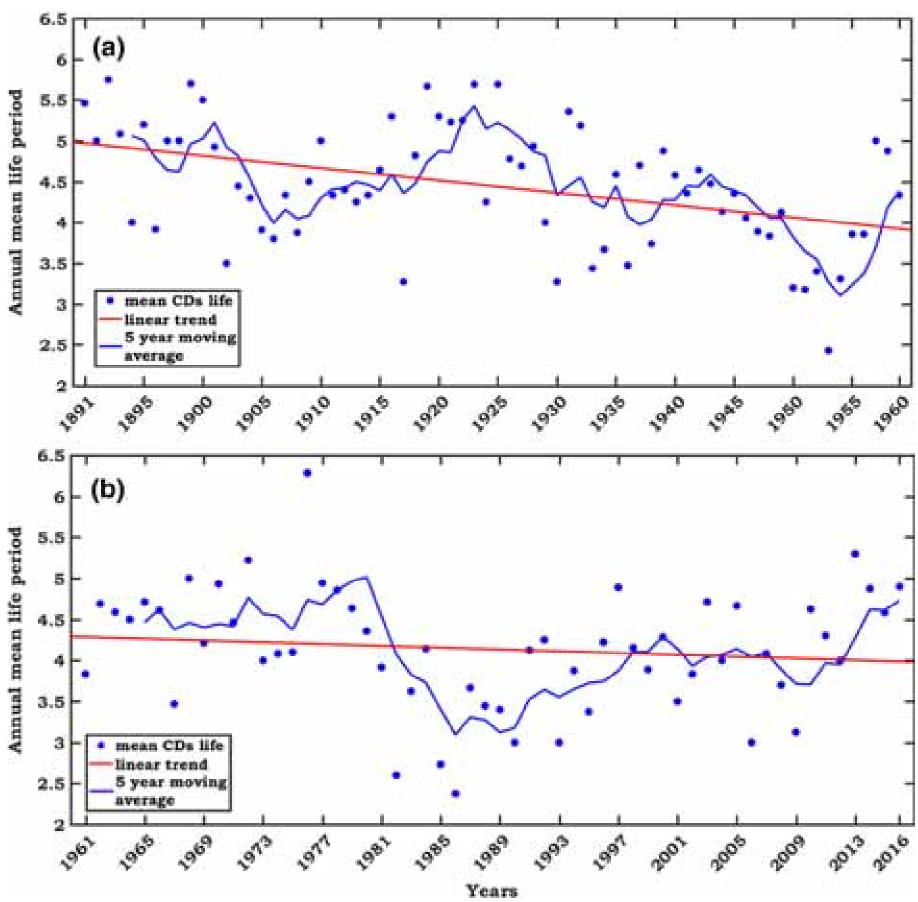

Figure 11. Variation of annual mean life period of CDs during **(a)** pre-satellite and **(b)** satellite era over NIO for the period of 1891–2016. Here, 5-yr moving average and linear trend is considered for both pre-satellite and satellite era.

Table 1. *The annual mean life period of cyclonic depressions, cyclonic storms (CS) and severe cyclonic storms (SCS) and all CDs as a whole (including depressions, CS and SCS) for pre-satellite era (PSE) and satellite era (SE).*

Category	Alpha	Mean life (PSE)	Mean life (SE)	*t*-stat	df	*p*-value
Depression	0.05	3.964	3.255	4.768	122.520	5.1757E−06
CS	0.05	4.667	3.668	4.795	108.003	5.2386E−06
SCS	0.05	4.842	4.092	3.075	82.807	0.003
CDs	0.05	4.431	4.147	2.102	113.063	0.038

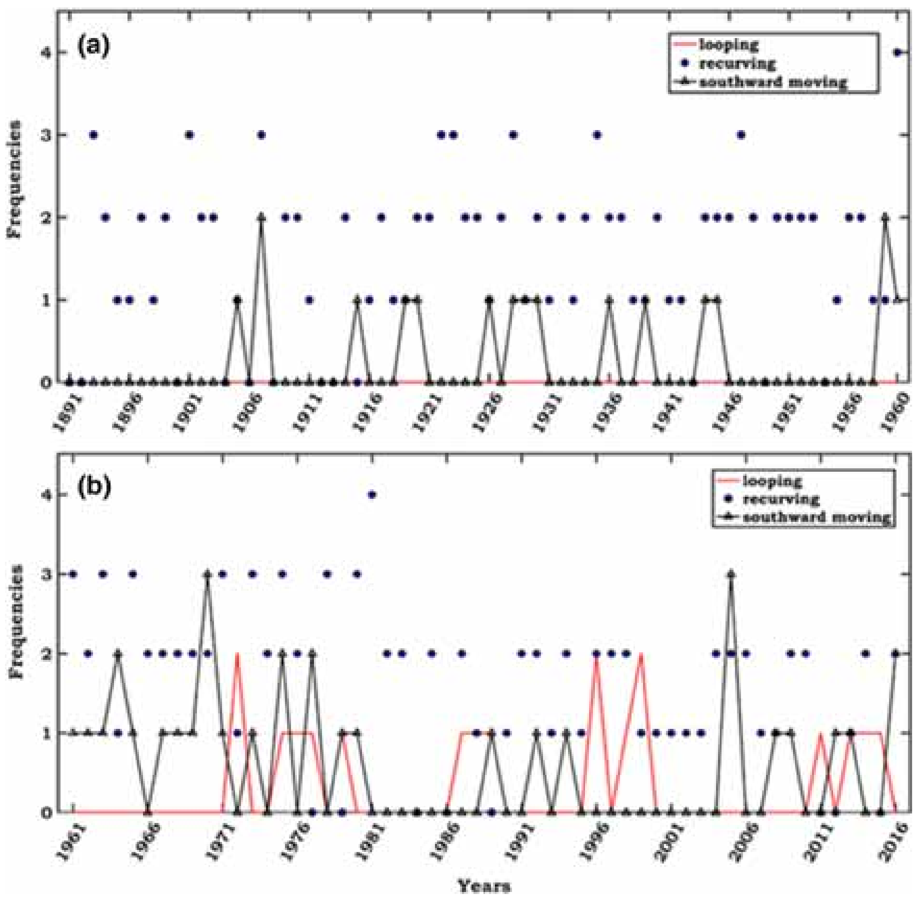

Figure 12. Annual frequency of unusual tracks including those of looping, recurving and southward moving CDs over NIO during the **(a)** pre-satellite and **(b)** satellite era.

maximum value is up to 2. Thus, it appears that the detection of recurving CDs is considerably good irrespective of periods considered. However, in between the genesis and landfall, the proper path of travel of CDs was not well detected during pre-satellite era as evident from this analysis.

3.7 *Mean tracks and mean-track length*

Another important aspect is the comparison between the mean tracks of CDs and mean track length during pre-satellite and satellite periods that can give an idea about the reliability of the best track data. The climatological mean tracks of CDs are shown in figure 13. During the pre-satellite era, most frequent CD genesis region was 85°–90°E/15°–20°N and the cyclonic systems travelled to make landfall near Odisha and West Bengal coast. The mean track length found to be 882.39 km in this period. Interestingly, during satellite era, two different mean prevailing tracks were observed (figure 13b). The first track (located in the northern part of BOB) originates from 85°–90°E/15°–20°N region and travels towards

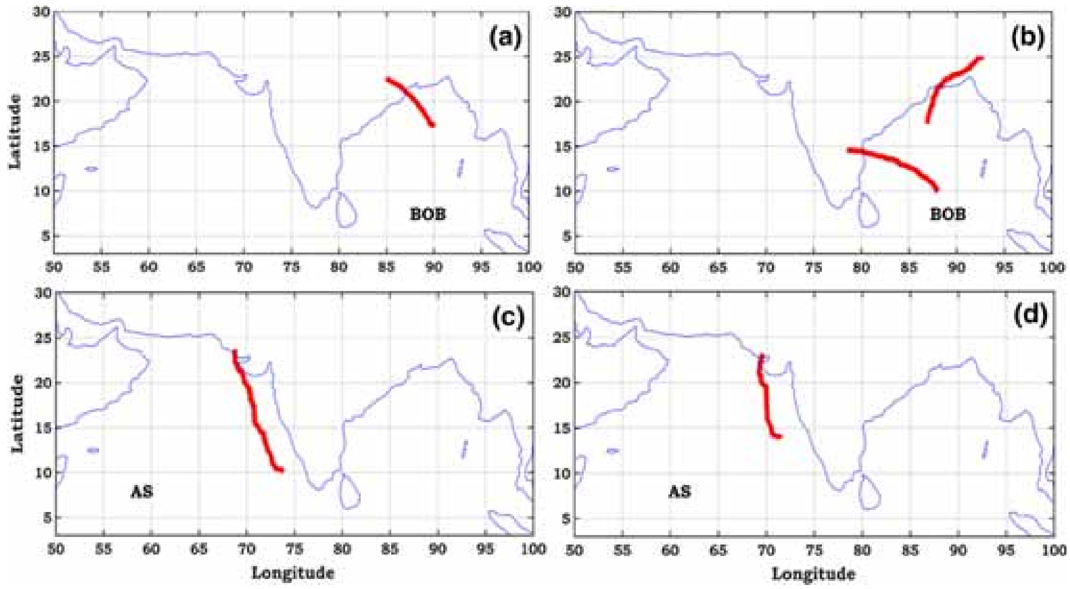

Figure 13. Mean track of CDs over BOB and AS during pre-satellite **(a, c)** and satellite **(b, d)** era.

West Bengal and Bangladesh coast to make landfall near Bangladesh with mean track length 1195 km. The second one (southern part of BOB) originates from 85°–90°E /10°–15°N region and travels towards Andhra Pradesh and Tamil Nadu coast with a mean track length of 1287 km. CDs can always originate from different regions and travel different paths. Nonetheless, having a sense of the climatological mean pattern can give a better idea of limitation of data acquisition over the region. The prevailing mean tracks indicate possible missing of few short-lived systems over central BOB during pre-satellite era.

The climatological track for AS does not show much variation except the length of the track (figure 13c and d). During the pre-satellite era, most of the cyclones over AS formed near 10°N latitude and 70°–75°E longitudes and travelled along the coast to make landfall near Gujrat and Pakistan region. The mean track length is observed to be nearly 1751 km in this period. Interestingly, the mean climatological track during satellite era starts from the location near to 14°N (though remains within the longitudinal extent 70°–75°E), travels along the coast and makes landfall near Gujrat. The mean track length during satellite era thus reduces to 1152 km, having a difference of nearly 599 km compared to that of the track during pre-satellite era. As the systems formed over AS are concentrated near to the coast, chances of missing systems are very less.

The tracks for BOB and AS basins are also analysed separately for pre-monsoon, monsoon and post-monsoon seasons to see the possible changes in accordance to the two epochs considered. For pre-monsoon season, the mean track over BOB (figure 14a) starts from 90°–95°E/10°–15°N region and travels towards Myanmar during the pre-satellite era. However, the route of mean track has changed to 85°–90°E /10°–15°N region and CDs are mostly travelling towards Myanmar with increased track length during satellite era (figure 14b). The track lengths are 1265.5 and 1829.5 km, respectively during pre-satellite and satellite era. During monsoon season, the tracks of CDs over BOB generate from 85°–90°E/15°–20°N and travel towards West Bengal, Odisha during pre-satellite era (figure 14c), and the track length is 1958.9 km. During satellite era, similar track is followed by CDs with an exception to the distance of travel (figure 14d), i.e., with track length 1313.8 km. For post-monsoon season, again similar types of tracks are observed to be followed by CDs for both the epochs except the region of genesis and landfalling. There are two most travelled routes of CDs in pre-satellite era over BOB, i.e., one is travelling towards Andhra Pradesh and Tamil Nadu border starting from 85°–90°E /5°–10°N with track length 959.87 km and the other one from same latitude/longitude region towards Myanmar with a recurved path (figure 14e) and mean track length 2171.1 km. During satellite era, one track starts from ~90°E/5°–10°N region travels towards

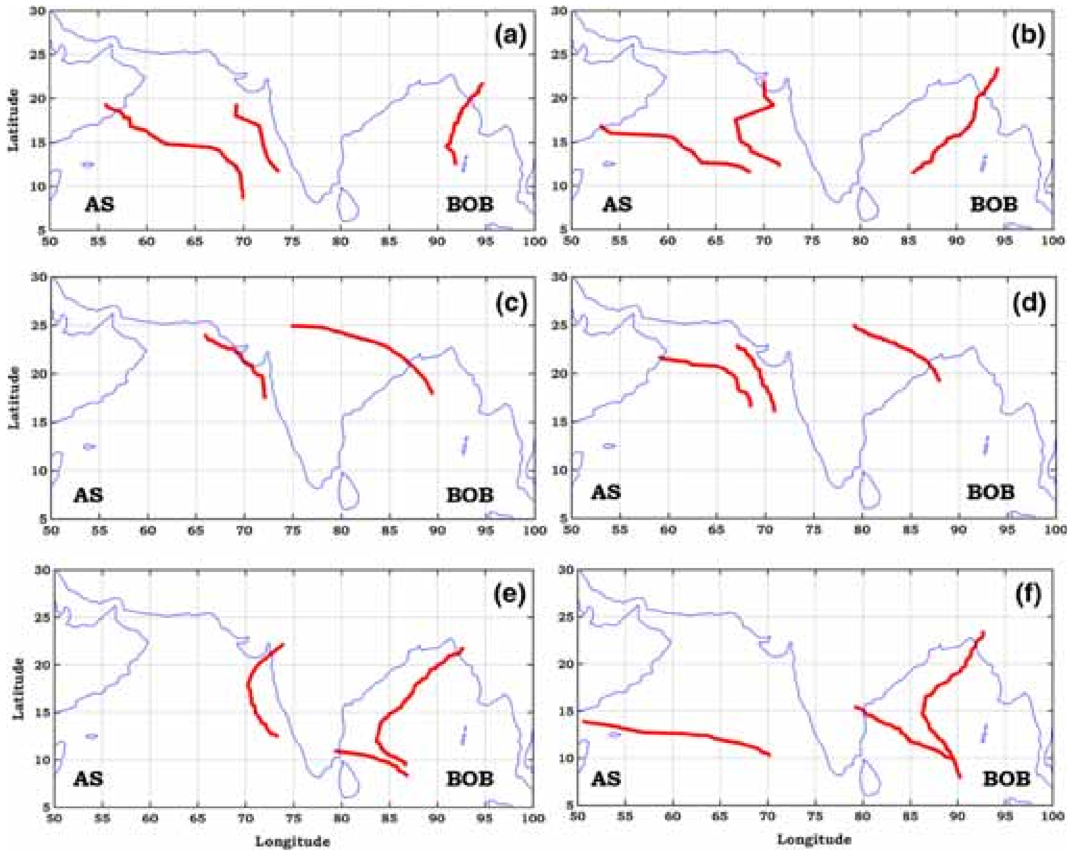

Figure 14. Mean track of CDs during pre-monsoon **(a, b)**, monsoon **(c, d)** and post-monsoon **(e, f)** during pre-satellite and satellite era, respectively over BOB and AS.

Andhra Pradesh with mean tack length 1477.3 km while another travels towards Myanmar by generating from the same area with mean track length 2251.9 km (figure 14f).

Over AS, different types of CD tracks are observed for different seasons of pre-satellite and satellite era. During pre-monsoon season, two mean tracks are observed during the pre-satellite era (figure 14a). One track with mean track length 1091km generates from 70°–75°E/10°–15°N travels along the western coast of India but do not make landfall, while another one with track length 2290.7 km, generates from ∼70°E/5°–10°N and travels westward to landfall at Yemen coasts. Similarly, during satellite era, two travelling tracks are observed for pre-monsoon season too but with different genesis and landfalling locations and track lengths (figure 14b). The track that was earlier travelling along the western Indian coast, observed to recurve towards Gujarat (increased track length to 1694.2 km) and the other one still travels towards Yemen (decreased track length to 1941.9 km) but it is now generated from 65°–70°E/10°–15°N region. For monsoon season, there is only one track, which starts from 70°–75°E/15°–20°N and travels along the Gujarat coast during pre-satellite era (figure 14c) with mean track length 1176.3 km. Unlike pre-satellite era of monsoon season, two tracks are observed over AS during satellite era (figure 14d). One of the tracks originates from 70°–75°E/15°–20°N travelling along the coast of Gujarat (track length 993.5 km) and the other track (track length 1364.6 km) originates over 65°–70°E/15°–20°N region and moves towards Oman during satellite era. During post-monsoon, two completely different tracks are observed in the two epochs. During pre-satellite era, the mean track starts from 70°–75°E /10°–15°N and then recurves to cross Gujarat coast by travelling ∼1413.4 km. During satellite era, the mean track (length 2269.3 km) starts from ∼70°E/10°–15°N region and travels towards Somalia.

The season-wise variability in mean track characteristic features for both BOB and AS (figure 14) is found to be quite distinct as when compared with the overall mean track (figure 13). The overall mean track over BOB in the pre-satellite era (figure 13a) is found to be similar to that of the monsoon season in terms of the direction of travel (figure 14c). For AS, the overall mean track (figure 13c) shows similar characteristics as those of monsoon and post-monsoon seasons (figure 14c, e). In satellite era, the overall track characteristics over BOB (figure 13b) appear to be similar to those of pre-monsoon (one track similar) and post-monsoon seasons (figure 14b, f). In case of AS, the overall mean track during satellite era (figure 13d) appears to have similar characteristics with one of the tracks (that travels along the Indian coast) of pre-monsoon and monsoon seasons (figure 14b, d).

4. Concluding remarks

The average difference in location estimated through satellite-based observations of IMD and the best track is nearly 55km in deep ocean (Goyal *et al.* 2013). The average error in intensity estimation during pre-satellite era was almost one stage in Beaufort scale. According to Mishra and Raj (1975), the maximum sustained wind is underestimated by 8–17 kts in depression phase, 26–28 kts in cyclonic storm phase and 37 kts in case of severe ones. Although the characteristics features of CDs is erroneous, the error in annual frequency is not appreciable over NIO. Considering the size of the AS and BOB basin, coastal populations, the CD detection procedure described in technical notes of IMD (IMD 2011), it could be concluded that the missed cyclones during the 20th century are not substantial.

The correlation between the number of CDs formed and those struck the land is notably high ($\sim$0.97) due to the smaller size of the basin as compared to other world basins and maximum number of landfalls over NIO region. Even the corresponding correlation values are very high ($\sim$0.9) when analysed separately for pre-monsoon, monsoon and post-monsoon seasons over BOB and AS during both epochs. The trend for percentage of landfall is also not showing much variation with lower slope values of –0.022 and 0.027 during pre-satellite and satellite era respectively over NIO. The trends over BOB and AS for pre-monsoon, monsoon and post-monsoon seasons are nearly stable during both epochs. The average percentages of CDs striking the coastal areas of NIO during the considered periods are 96.61% and 96.52% respectively. The average percentage of CDs hitting the coast of BOB ranges between 97 and 100% when analysed for all the three seasons considered separately during pre-satellite and satellite era. The percentages over AS ranges between 91 and 100% during pre-satellite era, whereas the percentages decreased during satellite era (ranging between 87 and 94%) for all the three considered seasons. The reason behind the decrease in percentage of systems striking the land is not related to the implementation of satellite technology. Instead, because of the well-organised wind circulation persisting over AS, the scenario encourages dissipation of systems in recent years (Singh *et al.* 2019a).

While analysing the decadal variation in genesis location, significant spatial variability is observed over several regions of BOB and AS. However, change in the annual frequency is found to be insignificant over NIO and the decrease in annual frequency in recent years may not be related to the availability of satellite inputs. It is mostly due to decrease in surface-level relative humidity along with increase in surface wind for pre-monsoon, monsoon and post-monsoon season (Singh *et al.* 2019b). The comparison of annual frequency from IMD and JTWC gives an RMSE value of 0.258 and 4.856 during pre-satellite and satellite era. The difference between both the data is associated with the intensity estimation process adopted by JTWC and therefore, several depressions are missing from its archive during recent years. The annual mean life period of CDs shows a decrease after 1940, which may be because of the better detection and determination of life span of CDs after the augmentation of enhanced coastal observatory systems. The current study also suggests chances of wrong interpretation of CD intensity for storms of higher category during pre-satellite era. With the implementation of satellite technology, a significant change is observed in frequency of different types of CDs.

With the implementation of satellite technology, the development in procedure for detection of proper path or track of CDs both over BOB and AS is also observed during satellite era. Analysis of the mean tracks of both the periods over BOB indicates few missing short-lived systems over central part during pre-satellite era. It may also be due to the lack of recognition of proper genesis location and track of CDs. The mean track over AS shows systems dissipating near Somalia during satellite era for post-monsoon season indicating chances of erroneous track determination during pre-satellite era. The frequency of looping track, recurving and southward moving CDs increased when the satellite data is incorporated for preparing best track data. Distinct differences among season-wise mean tracks over BOB and AS in both epochs also indicate erroneous track determination in pre-satellite era to some extent. However, incorporation of satellite data may not be the only reason for such behaviour. The changing climate may partly be responsible for this too.

The present analysis suggests that though the genesis location, tracks of CDs and their intensity are erroneous, indicative landfall point is considerably good. The error in CDs' annual frequency records is supposed to be insignificant in IMD best track data. Moreover, there have been several modifications (peer-reviewed adjustments) in different phases of NIO CDs best track publications by IMD (Mohapatra *et al.* 2012). Further, several studies (Mandke and Bhide 2003; Mohanty *et al.* 2012; Sugi *et al.* 2014; Deo and Ganer 2014; Mohapatra *et al.* 2015; Singh *et al.* 2016, 2019a, b) in recent past also used the dataset to analyse and review the cyclonic activities over NIO region. Thus, it could be inferred that the frequency provided by IMD e-Atlas gives a reasonable understanding of the trend of CDs over NIO even during the pre-satellite era and thus, establishes the robustness of it. It may be noted that there is a considerable data gap between satellite and pre-satellite era in other world ocean basins (Landsea 2007). Compared to the other ocean basins of the world, being relatively smaller and having less CD frequency gap between satellite and pre-satellite era also indicates the IMD best track data to be reasonable for use.

Based on the present study and available relevant literature, the IMD best track data can be considered reliable enough for understanding cyclonic activities over the NIO basin on a climatological scale. Nonetheless, CD monitoring capabilities and predictability over NIO basin in the present century has increased further because of accuracy in intensity measurement, size and number count due to the adopted advanced technologies. The technological platforms include high-resolution weather satellites, installed Doppler weather radar systems at coastal areas and large AWS installations.

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