

Frequency of genesis and landfall of different categories of tropical cyclones over the North Indian Ocean

MRUTYUNJAY MOHAPATRA, MONICA SHARMA, SUNITHA S. DEVI,

S. V. J. KUMAR and BHARATI S. SABADE

India Meteorological Department, Ministry of Earth Sciences, New Delhi – 110 003, India

e mail : m.mohapatra@imd.gov.in

सार – भारत मौसम विज्ञान विभाग (IMD) उष्णकटिबंधीय चक्रवातों (TCs) को चक्रवाती तूफान (CS), प्रचंड चक्रवाती तूफान (SCS), अति प्रचंड चक्रवाती तूफान (VSCS), अत्यंत प्रचंड चक्रवाती तूफान (ESCS) और महाचक्रवाती तूफान (SuCS) की श्रेणियों में वर्गीकृत करता है। इन श्रेणियों में उष्णकटिबंधीय चक्रवातों का दीर्घकालिक जलवायु विज्ञान और उत्तर हिंद महासागर (NIO) के ऊपर विकसित होने और विभिन्न तटीय क्षेत्रों को पार करने वाली इन श्रेणियों में उष्णकटिबंधीय चक्रवातों की आवृत्ति तथा तीव्रता की प्रवृत्तियाँ सीमित हैं। अतः उपग्रह युग (1965-2020) के आंकड़ों के आधार पर उत्तर हिंद महासागर (NIO) में उपर्युक्त श्रेणियों में चक्रवाती विशोभों की उत्पत्ति और तीव्रता तथा विभिन्न तटीय क्षेत्रों को पार करने की विशेषताओं का विश्लेषण करने के लिए एक अध्ययन किया गया है।

पूरे वर्ष के दौरान सबसे तीव्र उष्णकटिबंधीय चक्रवात (ESCS तथा इससे अधिक तीव्र) अधिकतम ओडिशा (ODS) तथा उसके बाद आंध्र प्रदेश (AP)/म्यांमार (MMR) तथा बांग्लादेश (BDS) तट पार करते हैं, और कम तीव्रता वाले उष्णकटिबंधीय चक्रवात (CS/SCS) अधिकतम BDS तथा उसके बाद AP, ODS और तमिलनाडु (TN) तट पार करते हैं, तथा मध्यम तीव्रता वाले उष्णकटिबंधीय चक्रवात (VSCS) अधिकतम TN / AP/ BDS तथा इसके बाद ODS / WB / MMR पार करते हैं। हालांकि मॉनसून-पूर्व ऋतु के दौरान अधिकतम CS/SCS श्रेणी के चक्रवात BDS को पार करते हैं, अधिकतम VSCS श्रेणी के चक्रवात BDS / MMR को पार करते हैं तथा अधिकतम ESCS श्रेणी के चक्रवात MMR तट पार करते हैं। जबकि मॉनसूनोत्तर ऋतु के दौरान अधिकतम CS/SCS/VSCS श्रेणी के चक्रवात AP तट को पार करते हैं तथा अधिकतम ESCS श्रेणी के चक्रवात ODS तट को पार करते हैं। AS में VSCS के स्थल प्रवेश की आवृत्ति सर्वाधिक अरब तथा अफ्रीका (AA) तट पर तथा उसके बाद सौराष्ट्र और कच्छ तट पर होती है।

ESCS के कारण बंगाल की खाड़ी (BoB) क्षेत्र पर तटीय भेद्यता बनी रहती है, क्योंकि ESCS तथा उससे अधिक तीव्रता के तूफानों की उत्पत्ति की आवृत्ति में कोई महत्वपूर्ण प्रवृत्ति नहीं है, हालांकि बंगाल की खाड़ी में D/ DD, CS, SCS, VSCS की उत्पत्ति की आवृत्ति में कमी की प्रवृत्ति है। अरब सागर में VSCS तथा अधिक तीव्रता के तूफानों की उत्पत्ति की आवृत्ति में वृद्धि के कारण AA तट पर तटीय भेद्यता की आवृत्ति में वृद्धि हुई है।

ABSTRACT. India Meteorological Department (IMD) categorises the tropical cyclones (TCs) as cyclonic storm (CS), severe cyclonic storm (SCS), very severe cyclonic storm (VSCS), extremely severe cyclonic storm (ESCS) and super cyclonic storm (SuCS). The long term climatology of TCs in these categories and the trends in frequency and intensity of TCs in these categories developing over the NIO and crossing different coastal regions are limited. Hence a study has been undertaken to analyse the characteristics of genesis and intensification of CDs in the above categories developing over the NIO and crossing different coastal regions based on the data of satellite era (1965-2020).

The most intense TCs (ESCS & above) cross the coast maximum over Odisha (ODS) followed by Andhra Pradesh (AP)/Myanmar (MMR) & Bangladesh (BDS) and low intensity TCs (CS/SCS) cross maximum over BDS followed by AP, ODS & Tamilnadu (TN) and medium intensity TCs (VSCS) cross maximum over TN/AP/BDS followed by ODS/West Bengal (WB)/MMR during a year as a whole. While maximum CS/SCS cross BDS, maximum VSCS cross BDS/MMR and maximum ESCS cross MMR coast during pre-monsoon season. While maximum CS/SCS/VSCS cross AP coast, maximum ESCS cross ODS coast during post monsoon season. Over the AS, the landfall frequency of VSCS is maximum over Arabia - Africa (AA) coast followed by Saurashtra and Kutch coast.

The coastal vulnerability due to ESCS continues over the Bay of Bengal (BoB) region, as there is no significant trend in the frequency of genesis of ESCS and above intensity storms, though there is decreasing trend in the genesis frequency of D/DD, CS, SCS, VSCS over the BoB. It has increased over the AA coast due to increasing trend in frequency of genesis of VSCS and above intensity storms over Arabian Sea.

Keywords – Tropical cyclone, Landfall, Bay of Bengal, Arabian Sea, Pre-monsoon, Post-monsoon.

1. Introduction

About 11 cyclonic disturbances (CDs) with maximum sustained wind speed (MSW) of 17 knots (kt) or more including depression(D)/deep depression (DD) with MSW of 17-33 kt and tropical cyclones (TCs) with MSW of 34 kt or more develop over the North Indian Ocean (NIO) during a year based on data of 1961-2010 (Mohapatra *et al.*, 2014). It includes 9 and 2 CDs over the Bay of Bengal (BOB) and Arabian Sea (AS) respectively. Out of these, about five intensify into TC including about 4 over BOB and 1 over the AS. About 3 severe TCs (MSW of 48 kt or more) are formed over the NIO during a year (Mohapatra and Sharma, 2019; Mohapatra *et al.*, 2014). The frequency of TCs is maximum during post-monsoon season (October-December) followed by pre-monsoon (March-May) and monsoon (June-September) season [India Meteorological Department (IMD), 2008].

Out of 5 TCs developing over the NIO, about 3 to 4 TCs make landfall (Tyagi *et al.*, 2010) causing loss of life and property. Though the number of such TCs is less as compared to other Ocean basins like north Pacific and north Atlantic Ocean, the impact is felt more in the region due to poor socio-economic condition. The tropical warm NIO, like the tropical north Atlantic, the south Pacific and the northwest Pacific, is a breeding ground for the disastrous TC phenomenon. Low lying coastal belts of West Bengal, Odisha and Andhra Pradesh have borne the brunt of the fury of these very severe TCs (IMD, 2003 & 2008; Mohapatra *et al.*, 2012a; Mohapatra, 2015). Though the number of deaths due to TCs have decreased significantly (Mohapatra and Sharma, 2019), still there is huge loss to property.

The risk management of the TCs depends on several factors including (i) hazard & vulnerability analysis, (ii) preparedness & planning, (iii) early warning, (iv) prevention and mitigation. The early warning component is a major component which is targeted for improvement through the improvement in skill of monitoring and prediction and effective warning products generation by IMD. The IMD has the responsibility of monitoring and prediction of CDs including TCs and D/DD, collection, processing and archival of all data pertaining to CDs and preparation of best track data over the NIO. IMD has taken a number of steps in recent years to continuously enhance the TC database to enable the research and development for the improvement in monitoring, numerical modelling and forecasting. Specially, in the satellite era since 1961, there has been significant improvement in TC monitoring which has further advanced with augmentation of upper air observations with pilot balloons in 1960s, radiosonde and radio wind (RS/RW) observations in 1970s, cyclone

detection radars in 1970s, introduction of Indian satellites in 1980s, meteorological buoys in late 1990s and augmentation of surface observational network including automatic weather stations and automatic rain gauges in 2000s (Mohapatra *et al.*, 2012b and 2014). Though, the TC data base is maintained by IMD since 1877, it is reasonably accurate for any kind of research and development in terms of climatological analysis, hazard analysis, landfall characteristics and impact studies for the period 1961 onwards (Mohapatra *et al.*, 2012b). As optimum observational network including satellite leading to better estimation of location and intensity without missing of CDs was available since 1961, the climatology of genesis, location, intensity, movement (track) and landfall can be best represented based on the data set of 1961 onwards. While real-time reception of satellite imagery by IMD commenced in December 1963 through an automatic picture transmission (APT) station at Mumbai, the imageries of past TCs during 1960-1963 collected from USA were investigated by several researchers. Koteswaram (1961) analysed first satellite pictures of a TC over the AS in 1960. However, as the satellite data were new in initial years there could be error in estimation of location and intensity based on satellite image in initial years. Hence in this study the climatological characteristics of landfalling TCs over the NIO during 1965-2020 have been analysed.

The categorisation of low pressure systems by IMD has undergone several changes in the past based on the availability of observational network and analysis tools and technique. The detailed review of this classification has been discussed by Mohapatra *et al.* (2012b). Till 1974, there were broadly three categories of CDs, *viz.*, D/DD, cyclonic storm (CS) with MSW of 34-47 kt and severe cyclonic storm (SCS) with MSW of 48 kt or more (IMD, 2008). A new classification was introduced in 1974 giving the classification of SCS into (i) SCS (MSW: 48-63 kt) and SCS with core of hurricane winds (≥ 64 kts) (IMD, 1974).

The introduction of above classification may be attributed to (i) introduction of geostationary satellites in 1974, (ii) adoption of Dvorak's technique in 1974 (Dvorak, 1975), (iii) installation of cyclone detection radars (CDR) during 1970-1973, (iv) commencement of pilot balloon & radio wind observations during 1960s and 1970s respectively and (v) augmentation of coastal surface observations during 1940s and 1950s (Mohapatra *et al.*, 2012b). There is similar classification based on 64 knots (33 mps) wind over other basins with different terminology. It is called as TC over southwest Indian Ocean, severe TC over southwest Pacific and southeast Indian Ocean, Typhoon over northwest Pacific and Hurricane over north Atlantic and northeast Pacific Oceans.

TABLE 1

Classification of low pressure systems over the NIO since 2015 and corresponding Dvorak's T Number and maximum sustained wind speed

Low pressure system	T Number	Maximum sustained surface wind speed (MSW)		
		kt	mps	kmph
Low pressure area (L)	T 1.0	< 17	< 9	< 31
Depression (D)	T 1.5	17-27	9-14	31-49
Deep Depression (DD)	T 2.0	28-33	15-17	50-61
Cyclonic Storm (CS)	T 2.5-3.0	34-47	18-24	62-88
Severe Cyclonic Storm (SCS)	T 3.5	48-63	25-32	89-117
Very Severe Cyclonic Storm (VSCS)	T 4.0-4.5	64-89	33-46	118-166
Extremely Severe Cyclonic Storm (ESCS)	T 5.0-6.0	90-119	47-61	167-221
Super Cyclonic Storm (SuCS)	T 6.5 -8.0	≥ 120	≥ 62	≥ 222

With the introduction of high wind speed recorder, meteorological buoys, scatterometer based sea surface wind observation, utilization of microwave based products from satellites and also due to increase in confidence in estimation of intensity based on Dvorak's technique (Dvorak, 1984) and Radars (Raghavan, 1997 & 2013), the criteria of classification further changed in 1999 (IMD, 1999). The terminology 'SCS with a core of hurricane winds' was changed to 'very severe cyclonic storm (VSCS)' for the wind speeds from 64 to 119 kt and a new terminology, *viz.*, super CS (SuCS) for the wind speeds 120 kt & above was introduced. The term SuCS was in line with the 'super typhoon' terminology introduced over the northwest Pacific Ocean by the Regional Specialised Meteorological Centre (RSMC), Tokyo with the same threshold wind speed. The other terminologies remained unchanged.

However, even after the introduction of SuCS, it was felt that the VSCS category was too broad. It is seen that in all the basins except for NW Pacific for the wind speed ≥ 64 kt (33 mps) there are three or more categories describing the intensities of TCs. Moreover, the bifurcation of VSCS had already been implemented with respect to its damage potential in India since 1999 (IMD, 2002). Hence with effect from 2015, VSCS category was bifurcated and a new terminology of Extremely Severe Cyclonic Storm (ESCS) was introduced for the MSW of 90-119 kt and the VSCS was defined with MSW of 64-89 kt, keeping the category of SuCS (120 kt or more), unchanged. The threshold wind speed of 90 knot of ESCS correspond to intense TC over the southwest Indian Ocean, severe TC (category 4) over southwest Pacific and southeast Indian Ocean (wind speed threshold of 87 knot and hurricane (category 2) over north Atlantic and northeast Pacific Ocean (wind speed threshold of 83 knot.

Most of the studies in the past are based on the three categories of the TCs, *viz.*, D/DD, CS and SCS & above,

as the data and tracks of the TCs are available in these three categories in the cyclone e-Atlas of IMD (2008). In recent years, the TC data has been classified into all the categories as used by RSMC, New Delhi like CS, SCS, VSCS, ESCS and SuCS as given in Table 1. The data of 1965-2020 (56 years) have been considered to find out different categories of CDs and TCs developing over the NIO and different categories of TCs making landfall over different coasts in the NIO region. This study will be helpful in assessment of climate change impact on TCs over the NIO region, hazard and vulnerability of coastal regions due to TCs as well as help in preparedness and planning measures for TCs management. It would also provide climatological guidance to the forecasters.

2. Data and methodology

Based on the present criteria/classification of CDs (Table 1), the digital dataset of TCs over the NIO has been prepared by RSMC, New Delhi for the period of 1965-2020 (www.rsmcnewdelhi.imd.gov.in). The CD and TC data of 1965-2020 (56 years) have been collected and analysed to find out different categories of TCs, *viz.*, D/DD, CS, SCS, VSCS, ESCS and SuCS developing over the BoB, AS and NIO as a whole. In the analysis, the D and DD have been considered as one category (now onwards, it will be referred as D only). Similarly, different categories of TCs as mentioned above making landfall over different coasts in the NIO region are collected and analysed during the same period to analyse the landfall characteristics. The frequency of D/DD, CS, SCS and above intensity storms have been collected from the TC e-Atlas of IMD (IMD, 2008). Similarly, the frequency of TCs in the above categories landfalling over different coastal states of India and the countries bordering BOB and AS has been collected from the TC e-Atlas of IMD (2008). The data on VSCS, ESCS and SuCS have been collected from various publications of IMD, *viz.*, Quarterly Journal Mausam, Weekly Weather Report and

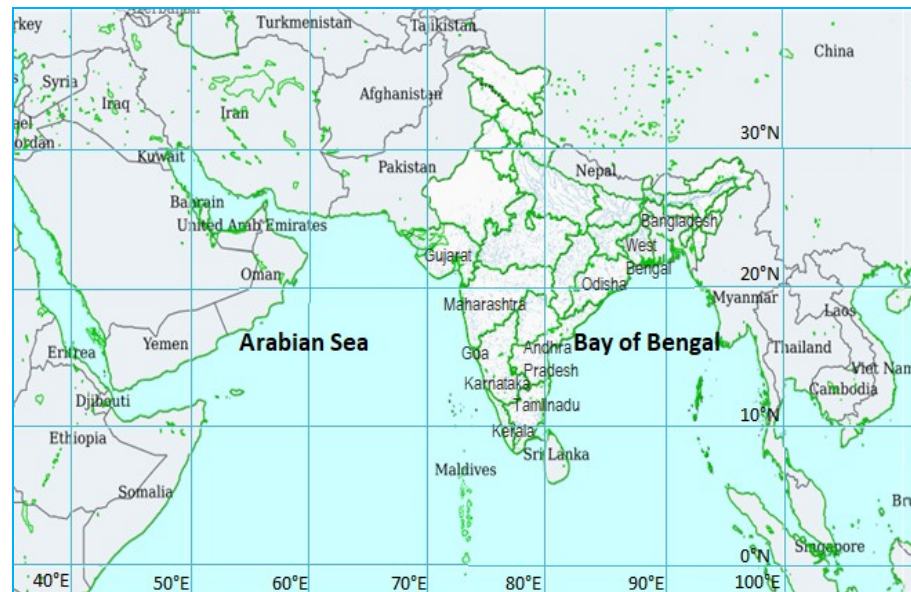


Fig. 1. Area of study

India Daily Weather Report published by IMD as the data on above categories are not available in TC e-Atlas of IMD (2008). Based on the analysis of these data, the VSCS, ESCS and SuCS have been identified and analysed based on the Standard Operation Procedure (SOP) of IMD. The details of the SOP are available in Sharma and Mohapatra (2017) and IMD (2003 & 2013).

In this study, the TC is said to have made landfall, when the centre of the TC lies over the land, though destructive effects may occur several hours before and after the landfall time and extend several hundred kilometres from the landfall point in the coast line. Observed landfall positions are accurate to within ± 30 km as estimated by Mohapatra *et al.* (2012b). Accuracy of observed landfall times is estimated to be ± 0.5 hr since 1974 with introduction of coastal observations and Radar along the coast to monitor the location of TCs (Mohapatra *et al.*, 2012b). The month of genesis and landfall of a CD/TC has been considered as the month in which the genesis (formation of D) occurred, though the landfall can occur in a subsequent month. Accordingly, the frequency of genesis and landfall are calculated for the month and the season. This is one of the limitations for the calculation and analysis of landfall frequency. However, since the study deals with seasonal and annual frequency, this discrepancy will not have any impact on the results and conclusions of the study.

The TCs show bi-modal behaviour in their genesis with primary maxima in post-monsoon season and secondary maxima in pre-monsoon season. The TCs

during these two seasons show different track, genesis and intensification characteristics. The number of CS, SCS, VSCS, ESCS and SuCS that crossed different coastal regions in the BOB and AS during pre-monsoon season (March-June), post monsoon season (September-December) and the year as a whole over the BoB, AS & NIO are calculated and analysed. There have been 17 (19) TCs formed during June (September) including 12 (7) over AS and 5 (12) over the BOB. Out of these there have been 11 (14) landfalling TCs during June (September) including 6 (2) over AS and 5 (12) over the BOB. Since the systems in the month of June during onset phase of monsoon have pre-monsoon characteristics, they have been considered as the TCs in pre-monsoon season for analysis purpose. Similarly, the TC in September has been considered in the category of the post-monsoon season, as it occurred during withdrawal phase of monsoon. There are 4 (all over BOB) and 6 (all over BOB) TCs during July and August respectively during 1965-2020. Out of these 3 and 5 TCs (3 CS and 2 SCS) crossed coasts during July and August respectively. While one each as CS crossed north Andhra Pradesh (AP), Odisha (ODS) and Bangladesh (BDS) coasts in July all the five TCs in August crossed Odisha coast.

The area of study and coastal regions considered in the study are shown in Fig. 1. It includes Myanmar (MMR), BDS, West Bengal (WB), ODS, AP, Tamil Nadu & Puducherry (TNP), Sri Lanka east (SLE), Sri Lanka west (SLW), Kerala (KRL), Karnataka (KTK), Maharashtra and Goa (MNG), Gujarat (GJT), Pakistan (PAK), Iran, Arabia and Africa (IAA). The IAA includes Somalia, Yemen, Oman and Iran coasts.

TABLE 2
Frequency of genesis and landfalling CDs over the BoB, AS and NIO

Category	Basin	Frequency of Genesis						Frequency of landfall					
		Pre-monsoon		Post-monsoon		Annual		Pre-monsoon		Post-monsoon		Annual	
		Total	Mean	Total	Mean	Total	Mean	Total	Mean	Total	Mean	Total	Mean
SuCS	BoB	3	0.05	3	0.05	6	0.11	1	0.02	2	0.04	3	0.05
	AS	1	0.02	1	0.02	2	0.04	0	0.00	0	0.00	0	0.00
	NIO	4	0.07	4	0.07	8	0.14	1	0.02	2	0.04	3	0.05
ESCS	BoB	10	0.18	23	0.41	33	0.59	10	0.18	16	0.29	26	0.46
	AS	5	0.09	7	0.13	12	0.21	3	0.05	2	0.04	5	0.09
	NIO	15	0.27	30	0.52	45	0.79	13	0.23	18	0.32	31	0.55
VSCS	BoB	9	0.16	38	0.68	47	0.84	8	0.14	26	0.46	35	0.63
	AS	4	0.07	9	0.16	13	0.21	4	0.07	4	0.07	8	0.14
	NIO	13	0.23	47	0.89	60	1.13	12	0.21	30	0.54	43	0.77
SCS	BoB	10	0.18	25	0.45	35	0.59	8	0.14	28	0.50	37	0.66
	AS	5	0.09	11	0.20	16	0.29	2	0.04	2	0.04	4	0.07
	NIO	15	0.29	36	0.64	51	0.89	10	0.18	30	0.54	41	0.73
CS	BoB	16	0.29	53	0.95	78	1.39	14	0.25	35	0.63	55	0.98
	AS	12	0.21	12	0.21	24	0.43	5	0.09	6	0.11	11	0.20
	NIO	28	0.50	65	1.16	102	1.82	19	0.34	41	0.73	66	1.18
D	BoB	45	0.80	105	1.91	241	4.30	46	0.82	93	1.66	222	3.96
	AS	22	0.39	38	0.68	64	1.14	10	0.18	11	0.20	22	0.39
	NIO	67	1.19	143	2.57	305	5.44	56	1.00	104	1.86	244	4.36

CD: Cyclonic disturbance, D: Depression/Deep Depression, CS: Cyclonic storm, SCS: Severe cyclonic storm, VSCS: Very severe cyclonic storm, ESCS: Extremely severe cyclonic storm and SuCS: Super Cyclonic Storm, BoB: Bay of Bengal, AS: Arabian Sea, NIO: North Indian Ocean

The mean frequencies of different categories of TC developing over the NIO during 1965-2020 and the mean values of different categories of TCs landfalling over different coastal regions during 1965-2020 have been calculated and analysed for different Ocean basins and different seasons. The probability of intensification of D into different categories of TCs and probability of intensification of TC into different categories of higher intensity are calculated and analysed for different seasons and over different basins. The ratios of frequency of occurrence of CDs and TCs during different seasons over BoB & AS are also calculated and analysed. The probability of landfall of TCs over different coasts are also calculated and analysed. Further the trends in frequencies of genesis and landfalling TCs over different coastal regions during different seasons and year as a whole are calculated and analysed.

The significance in the linear trends has been analysed through student's *t* test at 90% and 95% level of confidence and the results are presented and discussed.

The results are analysed and presented in section 3. The broad conclusions and future scope are presented in section 4.

3. Results and discussion

The frequency of genesis of various categories of CDs are presented and analysed in section 3.1. The trends in genesis frequency are analysed and discussed in section 3.2. The frequency of landfalling TCs and their trends are presented and analysed in section 3.3 and 3.4 respectively.

3.1. Mean frequency of genesis of CDs and their probability of intensification over the NIO

3.1.1. Annual frequency

Considering different categories of CDs, the mean frequency is about 6.5 for D, 1.8 for CS, 0.9 for SCS, 1.1 for VSCS, 0.8 for ESCS and 0.1 for SuCS develop over the NIO in a year (Table 2) and hence about 10 CDs and 5 TCs develop over the NIO during a year (Table 3). Comparing with Mohapatra *et al.*, 2014, based on the data of 1961-2010, the frequency of CD has decreased by 1 in recent decade and there is no change in the frequency of TCs. Out of these CDs, about 47%, 29%, 20% and 9% intensify into CS, SCS, VSC and ESCS respectively. Out of about 5 TCs 3 (62%) become SCS or above, 2 (42%) become VSCS or above and 1 (20%) become ESCS or

TABLE 3
Cumulative frequency of genesis and landfalling CDs over the BoB, AS and NIO during 1965-2020

Category	Basin	Frequency of Genesis						Frequency of landfall					
		Pre-monsoon		Post-monsoon		Annual		Pre-monsoon		Post-monsoon		Annual	
		Total	Mean	Total	Mean	Total	Mean	Total	Mean	Total	Mean	Total	Mean
SuCS	BoB	3	0.05	3	0.05	6	0.11	1	0.02	2	0.04	3	0.05
	AS	1	0.02	1	0.02	2	0.04	0	0.00	0	0.00	0	0.00
	NIO	4	0.07	4	0.07	8	0.14	1	0.02	2	0.04	3	0.00
ESCS & above	BoB	13	0.23	26	0.46	39	0.70	11	0.20	18	0.32	29	0.52
	AS	6	0.11	8	0.14	14	0.25	3	0.05	2	0.04	5	0.09
	NIO	19	0.34	34	0.61	53	0.95	14	0.25	20	0.36	34	0.61
VSCS & above	BoB	22	0.39	64	1.14	86	1.54	19	0.34	44	0.79	64	1.14
	AS	10	0.18	17	0.30	27	0.48	7	0.13	6	0.11	13	0.23
	NIO	32	0.57	81	1.45	113	2.02	26	0.46	50	0.89	77	1.38
SCS & above	BoB	32	0.57	89	1.59	121	2.16	27	0.48	72	1.29	101	1.80
	AS	15	0.27	28	0.50	43	0.77	9	0.16	8	0.14	17	0.30
	NIO	47	0.84	117	2.09	164	2.93	36	0.64	80	1.43	118	2.11
CS & above	BoB	48	0.86	142	2.54	199	3.55	41	0.73	107	1.91	156	2.79
	AS	27	0.48	40	0.71	67	1.20	14	0.25	14	0.25	28	0.50
	NIO	75	1.34	182	3.25	266	4.75	55	0.98	121	2.16	184	3.29
D & above	BoB	93	1.66	249	4.45	438	7.82	87	1.55	200	3.57	378	6.75
	AS	48	0.86	77	1.38	129	2.30	24	0.43	25	0.45	50	0.89
	NIO	141	2.52	326	5.82	567	10.13	111	1.98	225	4.02	428	7.64

Legends same as given with Table 2

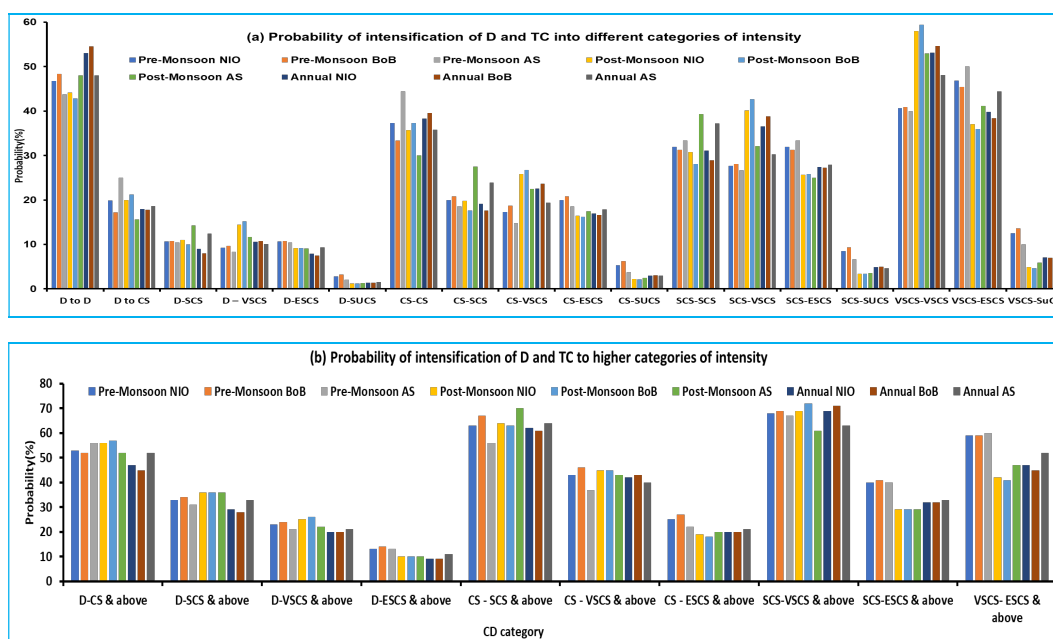
above intensity storms (Fig. 2). There is 69% and 32% probability for an SCS to intensify into a VSCS and ESCS respectively. Similarly, there is 47% probability for a VSCS to intensify into an ESCS.

Considering the BOB, the average frequency of D, CS, SCS, VSCS and ESCS are 4.3, 1.4, 0.6, 0.8 and 0.6 respectively (Table 2). The average frequency of CD, CS & above, SCS & above, VSCS & above and ESCS & above over the BOB is 7.8, 3.5, 2.2, 1.5 and 0.7 respectively (Table 3). Thus about 8 CDs develop over the BOB in a year, out of which 3-4 (45%) become the TCs [Fig. 2(b)]. About 61% of TCs become severe, 43% become very severe and 20% become extremely severe or above intensity storms [Fig. 2(b)]. Similarly, there is 71% and 32% probability for an SCS to intensify into a VSCS and ESCS respectively and 45% probability for a VSCS to intensify into an ESCS over the BOB [Fig. 2(b)].

Over the AS, the average frequency of D, CS, SCS, VSCS and ESCS is 2.2, 0.4, 0.3, 0.2, 0.2 respectively (Table 2). The average frequency is 2.3, 1.2, 0.8, 0.5 and 0.3 respectively for CD, CS & above, SCS & above, VSCS & above and ESCS & above intensity storms per year (Table 2). Thus, about 52% of CDs intensify into TC over the AS during a year [Fig. 2(b)]. The probability of a TC becoming severe is 64%, becoming very severe is

40% and becoming extremely severe is 21%. There is 63% and 33% probability for an SCS to intensify into a VSCS and ESCS respectively and 52% probability for a VSCS to intensify into an ESCS over the AS. The above results endorse the earlier findings of Mohapatra *et al.*, 2015. Thus, comparing the probability of intensification over the BoB and AS, the probability of a CS to intensify into SCS, VSCS and ESCS is almost same for both BOB and AS and the probability of a CD becoming a TC is less over the BOB as compared to AS by about 7%. It could be attributed to the fact that a large number of D/DD develop over the monsoon season (June-September) mainly over the head BoB which rarely intensify into TC due to unfavourable environmental conditions like vertical wind shear of horizontal wind in association with Tibetan High and Tropical Easterly Jet Stream (Mohapatra *et al.*, 2015 & 2017 and Rao, 1976).

Considering the SuCS, its frequency has increased during the recent years since 1990 both over the BoB and AS and hence over the NIO (Table 4). During the period 1990-2020, there have been 4 & 2 SuCS over the BOB and AS respectively against 2 and 0 over the BOB and AS during 1965-1989. There have been 7 ESCS over AS during 1990-2020 against 3 during 1965-1989. There is a rising trend in frequency of ESCS and above intensity storms over the AS since 1990. It will be further discussed in section 3.2.



Figs. 2(a&b). Probability of intensification of D and TC into different (a) individual categories of intensity of storm and (b) cumulative categories of intensity of storm during pre-monsoon season, post-monsoon season and year as a whole over BOB, AS and NIO during 1965-2020

TABLE 4

Super Cyclonic Storms over the north Indian Ocean during 1965-2019

S. No.	Period	Basin	T. No.	Peak Intensity (knot)	Landfall Point	Landfall Intensity (knot) & category
1.	14-20 Nov, 1977	BOB	T6.5	125	AP, Chirala	125 (SuCS)
2.	01-09 Nov, 1989	BOB	T6.5	130	AP, Kavali	115 (ESCS)
3.	4-10 May, 1990	BOB	T6.5	130	AP, Machilipatnam	102 (ESCS)
4.	24-30 Apr, 1991	BOB	T6.5	130	Bangladesh, Chittagong	127 (SuCS)
5.	25-31 Oct, 1999	BOB	T7.0	140	Odisha, Paradeep	140 (SuCS)
6.	1-7 Jun 2007, Gonu	AS	T6.5	130	Oman, Muscat	77 (VSCS)
7.	24 Oct-2 Nov 2019, Kyarr	AS	T 6.5	130	Weakened over sea	Weakened over Sea
8.	16-21 May, 2020, Amphan	BoB	T 6.5	130	West Bengal, Sunderbans	85 (VSCS)

3.1.2. Post monsoon season

About 6 CDs develop over the NIO during post monsoon season including about 4.5 over the BOB and 1.5 over the AS (Tables 2 & 3). Out of these about 3.2 (55%), 2.5 (57%) and 0.7 (51%) intensify into TCs over the NIO, BOB & AS respectively [Figs. 2(a&b)]. Out of these TCs about 2 (64%), 1.5 (45%) & 0.6 (19%) TCs over the NIO, 1.6 (63%), 1.1 (45%) & 0.5 (18%) TCs over the BoB and 0.5 (70%), 0.3 (43%) & 0.1 (20%) TCs over the AS intensify into severe, very severe & extremely severe TCs respectively [Figs. 2(a&b)]. Thus the probability of intensification of a CD into TC is higher over the BOB than over the AS by about 6% and the probability of

intensification of TCs into severe TCs is higher over the AS than over the BOB by about 7% [Figs. 2(a&b)]. The probability of SCS intensifying into a VSCS is higher over the BOB by about 11% [Figs. 2(a&b)].

While climate variability such as the El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) have known influences to NIO TC activity, results reveal that no single climate mode can well explain the TC development concentrating on AS or BoB only. Ng and Chan (2012); Yuan and Cao (2013); Girish Kumar & Ravichandran (2012); Mohapatra and Kumar (2017); Mohapatra *et al.* (2017 and 2015) and Wahiduzzaman *et al.* (2017) highlighted the impacts of the ENSO, IOD

and their combined impact on TC activity over the NIO. According to Mohapatra & Kumar (2017) and Girish Kumar & Ravichandran (2012), the negative IOD and La Nina conditions favour the TC activity over the BOB during post-monsoon season and they have no significant impact over the BOB during pre-monsoon season and over the AS during both the seasons.

Though the frequency of TCs is less over the AS, according to Sattar *et al.* (2019), AS is very active in a few years (but with quiet BoB season) and the opposite occurs in some others. This contrast occurs mostly during the post-monsoon season of October- December. Sattar *et al.* (2019) found that variability of the northeast monsoon is an important factor responsible for the difference between the two basins. Excess moisture is available over the AS due to anomalous low-level flow from the equatorial Indian Ocean in the years in which there are more TCs in that basin and drier condition is over the BoB. Nevertheless, the anomalous flow during active AS TC seasons is similar to that occurring during positive IOD and thus this climate variability may be responsible for redistributing the moisture content in the NIO.

3.1.3. Pre monsoon season

During pre-monsoon season about 2.5 CDs develop over the NIO including about 1.6 over the BOB and 0.9 over the AS (Table 2). Out of these CDs about 1.3 (53%), 0.8 (52%) and 0.5 (56%) intensify into TCs over the NIO, BOB & AS respectively [Table 3, Figs. 2(a&b)]. Out of these TCs, about 67% (56%), 46% (37%) & 27% (22%) intensify into severe, very severe and extremely severe TCs over the BOB (AS). Thus the probability of intensification of a TC into severe and very severe TCs is higher over the BoB than over the AS by about 10% each and into ESCS is higher by about 5% [Figs. 2(a&b)]. There is no difference in probability of intensification of an SCS over the BoB and AS into VSCS or ESCS and VSCS into an ESCS [Figs. 2(a&b)]. While about 65-70% of SCS intensify into VSCS, about 60% of VSCS intensify into ESCS over both the basins.

3.1.4. Ratio of frequency of TCs between BoB & AS

The ratio of TCs over the BoB to that over the AS varies from 1.6 to 2.3 for different categories of TCs during pre-monsoon season, 2.5 to 4.3 during post monsoon season and 2.0 to 3.8 during the year as a whole [Figs. 3(a-d)]. Considering the cumulative frequencies, it varies from 1.7 to 2.3, 3.1 to 3.8, 2.3 to 2.9 during pre-monsoon, post monsoon and year as a whole. In general, the ratio is higher in case of VSCS during pre-monsoon (2.3:1), post-monsoon (3.8:1) and years a whole (3.2:1). It can thus be inferred that the frequency of more intense

TCs is higher over the BoB as compared to AS during both pre-monsoon and post monsoon season. Further the ratio is lower during pre-monsoon season as compared to post-monsoon season for all categories of TCs. It can be attributed to the fact that most of the CDs/TCs (about 70%) over the BoB originate from the remnants of the TCs from the Northwest Pacific Ocean and the frequency of CDs & TCs are maximum during August to November over Northwest Pacific Ocean. It is not the case with AS.

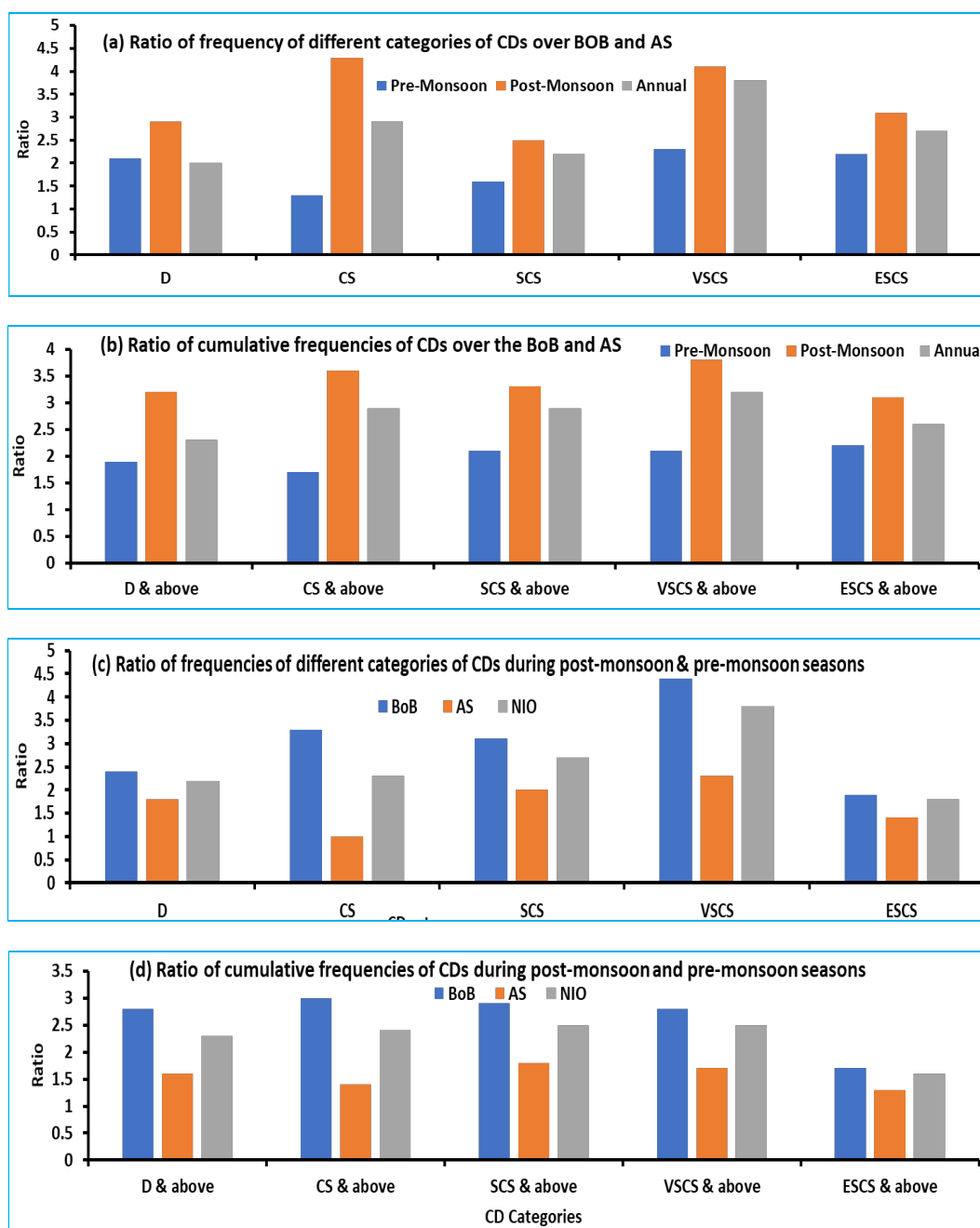
3.1.5. Ratio of frequency of TCs between pre-monsoon and post monsoon season

The ratio of Frequency of TCs during post-monsoon & pre-monsoon seasons over various basins is presented in Figs. 3(a-d). This ratio varies from 1.0 to 2.3 over AS, 1.9 to 4.4 over BoB and 1.8 to 3.8 over the NIO for various categories of storms. The ratio is maximum in VSCS category being 4.4:1 over BOB and 2.3:1 over the AS. Considering the cumulative frequency, it varies from 1.7 to 3.0, 1.3 to 1.8, 1.6 to 2.5 over BoB, AS & NIO respectively. Thus the variation from pre-monsoon to post-monsoon season is more over the BOB as compared to AS. The difference in cumulative frequency of TCs during post-monsoon & pre-monsoon seasons is higher over BoB & hence NIO due to the reason mentioned in previous section. The trends in seasonal variability in formation of CDs/TCs/severe TCs are analysed by Mohapatra *et al.* (2015 & 2017). According to them, considering the recent five decades (1961-2010), the ratio shows a significant decreasing trend for CDs and severe TCs over the BOB and increasing trend for TCs over the AS. The decreasing trend in the ratio of CDs and severe TCs over the BoB could be attributed to relatively higher decreasing trend in CDs and TCs frequency during post monsoon season over the BoB.

3.2. Trend in frequency of genesis

3.2.1. Trend in annual frequency of genesis

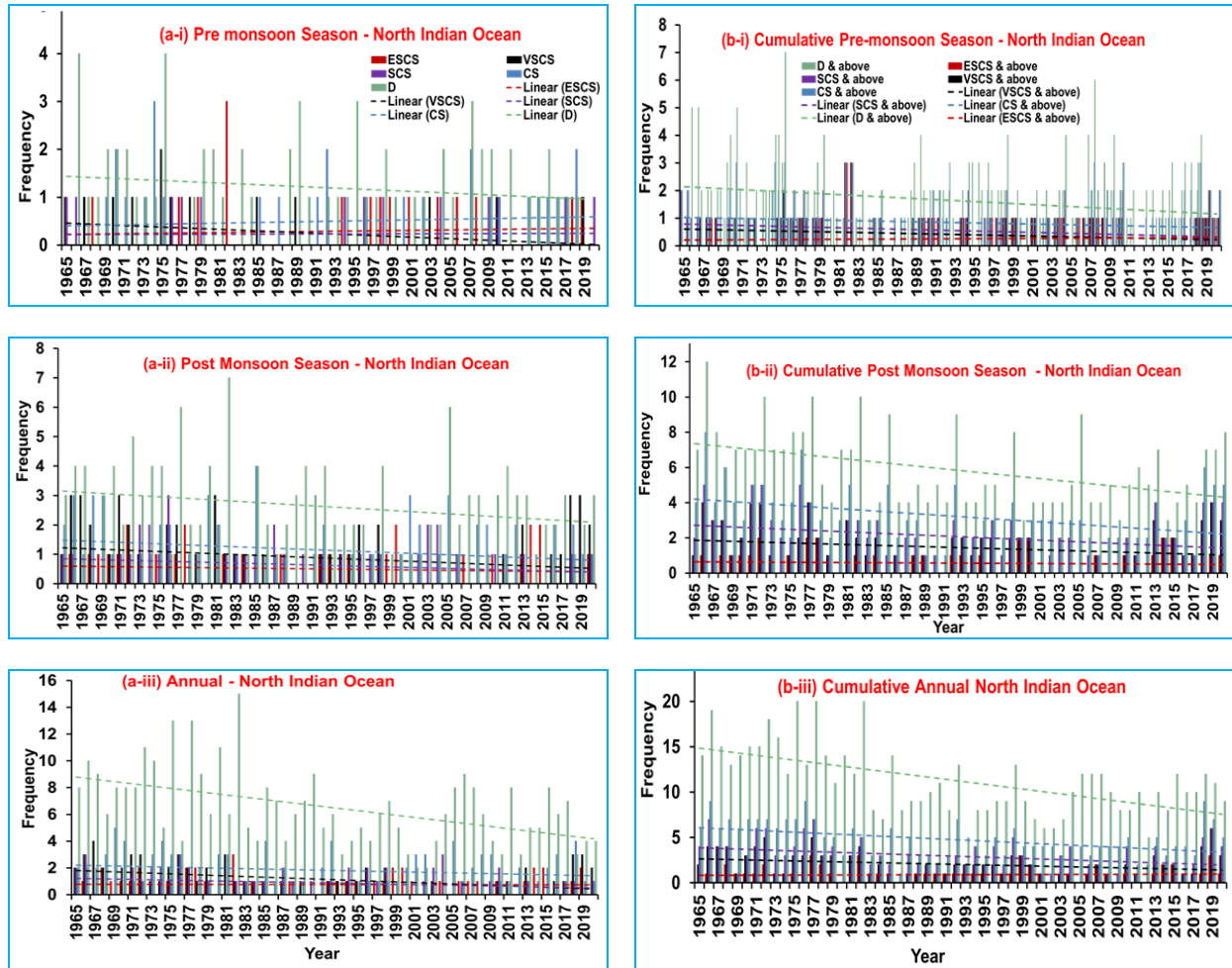
There is significantly decreasing trend in frequency of all categories of CDs including D/DD, CS, SCS, VSCS, ESCS over the BOB; and all except ESCS over the NIO during the year as a whole (Table 5, Figs. 4&5). There is also decreasing trend in frequency of D & above, CS & above, SCS & above, VSCS & above and ESCS & above over the BOB and all the above except ESCS & above over the NIO during the year as a whole [Table 5, Figs. 4&5]. However, there is no significant trend in frequency of any such category of storms over the AS during the period [Figs. 6{a&b(i-iii)}, Table 5] except that there is increasing trend in the frequency of ESCS. There is an increasing trend in the frequency of CS & above, SCS & above, VSCS & above and ESCS & above over



Figs. 3(a-d). Ratio of (a) frequency of different categories of CDs and (b) cumulative frequency of different categories of CDs over the BOB and AS during pre-monsoon, post-monsoon and year as a whole and ratio of (c) frequency of different categories of CDs and (d) cumulative frequency of different categories of CDs during post-monsoon and pre-monsoon seasons over the BOB, AS and NIO

the AS during the year as a whole [Table 5, Figs. 6{a&b(i-iii)}]. Thus, while the increasing trend in cumulative frequencies of different categories of storm over the AS can be attributed to similar trend in the frequency of ESCS & above, the decreasing trend in cumulative frequencies over the BOB can be attributed to similar trend in all the categories. According to Mohapatra

et al. (2014) based on data of (1961-2010), this trend in frequency of annual CDs is mainly due to the decreasing trend in frequency of CDs during monsoon season. Decreasing trend in the frequency of (i) CS and above, (ii) SCS and above and (iii) VSCS and above intensity storms over the BOB and NIO as a whole endorses earlier findings of Mohapatra *et al.* (2014). Mandal & Prem Krishna



Figs. 4[a&b(i-iii)]. (a) Individual and (b) cumulative frequency of various categories of TCs during (i) pre-monsoon, (ii) post-monsoon and (iii) year as a whole over the North Indian Ocean during the period 1965-2020

[D: Depression & deep depression, CS: Cyclonic storm, SCS: Severe cyclonic storm, VSCS: Very severe cyclonic storm, ESCS: Extremely severe cyclonic storm, Linear: Linear trend line]

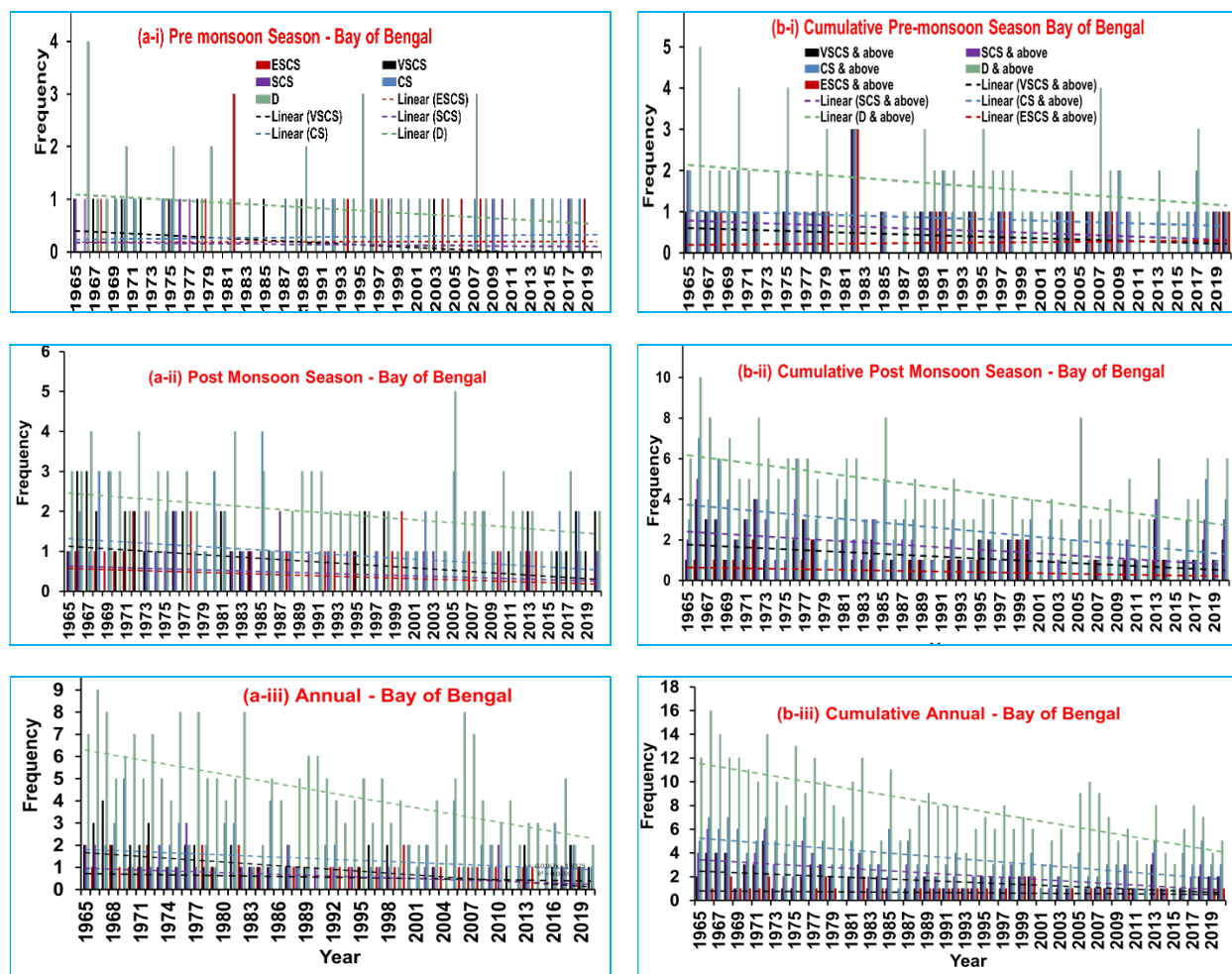
(2009) have also shown decreasing trend of frequency of very severe TC over the NIO during 1965-2008 and no trend in the MSW associated with VSCS during the same period. Comparing with the present study, the trend over the NIO is mainly due to similar trend over the BoB.

The past studies show that there has been significant increasing trend in sea surface temperature (SST) over the BOB, AS and NIO during the satellite era (Pattanaik, 2005; Roxy *et al.*, 2015 and Elsner & Kocher, 2000). Pattanaik (2005) based on the NOAA SST data during 1891-2004 has shown that the SST over BOB (Lat. 10-25° N and Long. 80-100° E) shows significant increasing trend during pre-monsoon, monsoon and post monsoon seasons. Similar increasing trend is also observed over equatorial Indian Ocean (0° N-10° N, 55° E-95° E). Thus, there is decrease in frequency of CDs, TCs and severe

TCs since 1970s, though there is increase in SST over the BOB and NIO.

According to Singh *et al.* (2018), an increasing SST, surface wind, mid-tropospheric relative humidity and potential evaporation factor (PEF) are helpful in the formation of intensified storms over the AS. A large temperature anomaly difference between atmosphere and Ocean also perceived to play a key role in modulating the enhanced intensity of TCs. The SST range of 27.5 °C to 29.5 °C and supportive flow field is helping to enhance the middle and upper tropospheric moisture content; eventually, resulting in increased SST, PEF and relative humidity through a possible feedback mechanism.

Knutson *et al.* (2019, 2020) conclude that there is only low confidence in detection and attribution of any



Figs. 5[a&b(i-iii)]. Same AS Fig. 4, but over the Bay of Bengal (BoB)

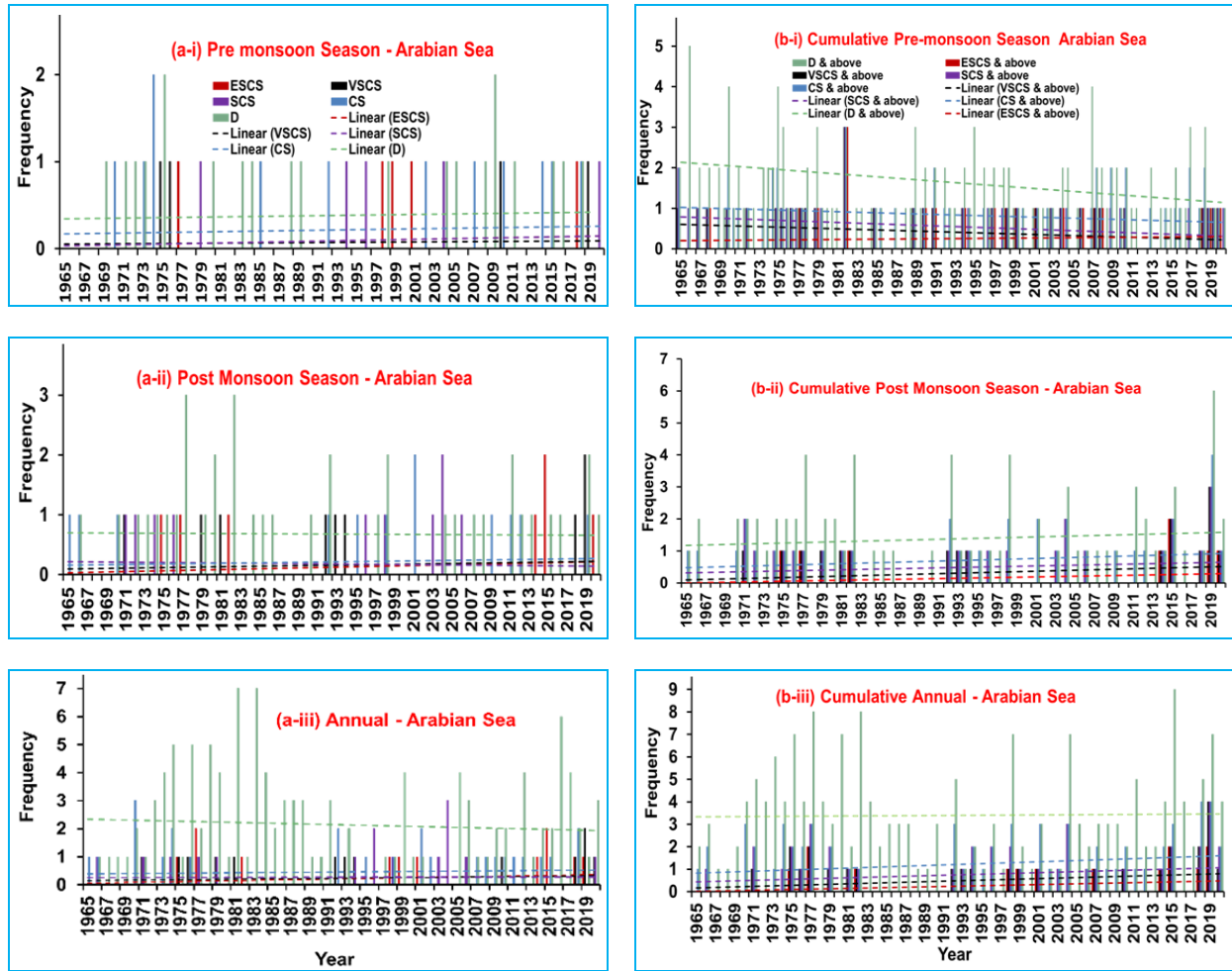
anthropogenic influence on historical TC intensity in any basin or globally. However, the balance of evidence suggests that there is a detectable increase in the global average intensity of the strongest (hurricane strength) TCs since the early 1980s. They have given similar conclusion on detection and attribution to the trend in frequency of TCs over the AS.

3.2.2. Trend in frequency of genesis during post-monsoon season

Considering post-monsoon season, there is significant decreasing trend in the frequency of D/DD, CS, SCS, VSCS & ESCS over the BOB and D/DD, CS & VSCS over the NIO (Table 5, Figs. 4&5). There is no significant trend over the AS during the post-monsoon season [Table 5, Figs. 6{a&b(i-iii)}]. There is also decreasing trend in frequency of D & above, CS & above, SCS & above, VSCS & above, ESCS & above over the BoB and all except ESCS & above over the NIO (Table 5,

Figs. 4&5). According to Mohapatra *et al.* (2015), considering the rate of intensification from TC to severe TC, significant decreasing trends are noted in the monsoon and post-monsoon seasons as well as year as a whole over the BOB. According to Mohapatra *et al.* (2017) based on the data of 1961-2010, significant decreasing trend in mid-tropospheric humidity is associated with the decreasing trends in frequency of CDs and their intensification to severe TCs over BOB during post-monsoon season. Interestingly, low level cyclonic vorticity has also decreased over the southern parts of BOB south of 15° N which is the climatological region of cyclogenesis during October to December, but, it has increased over the northern BOB during the recent years.

There is increasing trend in the frequency of VSCS & above and ESCS & above over the AS [Table 5, Figs. 6{a&b(i-iii)}]. Thus, during post monsoon season, the decreasing trend in cumulative frequency over the BoB is due to similar trend in individual categories of



Figs. 6[a&b(i-iii)]. Same as Fig.4, but over the Arabian Sea (AS)

storms. The increasing trend in frequency of VSCS/ESCS & above over the AS is due to similar insignificant trend in the categories of VSCS and ESCS. According to Mohapatra *et al.* (2017), over the AS, there are increasing trends in intensification of CDs to TCs and TCs to severe TCs which could be in association with decreased vertical wind shear aside from other synoptic scale forcing). According to Knutson *et al.*, 2019, the balance of evidence suggests there has been some detectable increase in the frequency of post-monsoon ESCS and above intensity storms over the AS and there is low confidence that anthropogenic forcing has contributed to the increase.

3.2.3. Trend in frequency of genesis during pre-monsoon season

During pre-monsoon season, there is a decreasing trend in frequency of D & above, SCS & above and VSCS & above over the BoB which could be attributed to similar decreasing trend in the frequency of D/DD and VSCS

(Table 5, Figs. 4&5). The cumulative frequencies over the NIO do not show significant trends. According to Mohapatra *et al.* (2017), during the pre-monsoon season, the decreasing trend in intensification of CD to TC over BOB is associated with unfavourable decrease in mid-tropospheric humidity. According to Mohapatra *et al.* (2015), there is significant decreasing trend in rate of intensification of CDs to TCs over NIO and BOB during pre-monsoon season during 1961-2010.

There is insignificant rising trend over the AS for different categories of storms [Table 5, Figs. 6{a&b(i-iii)}]. But the frequency of CS & above and SCS & above over the AS show significant increasing trend at 90% level of confidence and insignificant rising trend in the frequency of VSCS & above and ESCS & above [Table 5, Figs. 6{a&b(i-iii)}]. According to Mohapatra *et al.* (2015 and 2017), intensification of CDs to TCs and TCs to severe TCs during the pre-monsoon season over the AS shows significantly increasing trend during 1961-2010

TABLE 5

Linear Trend Coefficient (per 100 years) of individual and cumulative categories of CDs during pre-monsoon, post monsoon and year as a whole over the period of 1965-2020

Category	Basin	Pre-monsoon	Post-monsoon	Annual	Category	Basin	Pre-monsoon	Post-monsoon	Annual
ESCS	BoB	0.02	-0.71	-0.61	ESCS & above	BoB	0.18	-0.79	-0.54
	AS	0.21	0.35	0.55		AS	0.31	0.53	0.83
	NIO	0.23	-0.36	-0.06		NIO	0.49	-0.27	0.29
VSCS	BoB	-0.88	-1.50	-2.78	VSCS & above	BoB	-0.69	-2.3	-3.32
	AS	0.07	0.23	0.30		AS	0.38	0.76	1.13
	NIO	-0.81	-1.27	-2.48		NIO	-0.32	-1.54	-2.19
SCS	BoB	-0.15	-0.68	-1.31	SCS & above	BoB	-0.84	-2.98	-4.62
	AS	0.21	-0.14	0.03		AS	0.58	0.61	1.16
	NIO	0.06	-0.82	-1.27		NIO	-0.26	-2.37	-3.46
CS	BoB	0.17	-1.42	-1.67	CS & above	BoB	-0.67	-4.4	-6.29
	AS	0.16	0.20	0.25		AS	0.75	0.81	1.41
	NIO	0.33	-1.22	-1.42		NIO	0.08	-3.59	-4.88
D	BoB	-1.02	-1.86	-7.20	D & above	BoB	-1.79	-6.25	-13.49
	AS	0.14	-0.08	-0.73		AS	0.81	0.73	0.23
	NIO	-0.87	-1.93	-8.38		NIO	-0.98	-5.52	-13.27

CD: Cyclonic disturbance, D: Depression/Deep Depression, CS: Cyclonic storm, SCS: Severe cyclonic storm, VSCS: Very severe cyclonic storm, ESCS: Extremely severe cyclonic storm, BoB: Bay of Bengal, AS : Arabian Sea, NIO: North Indian Ocean

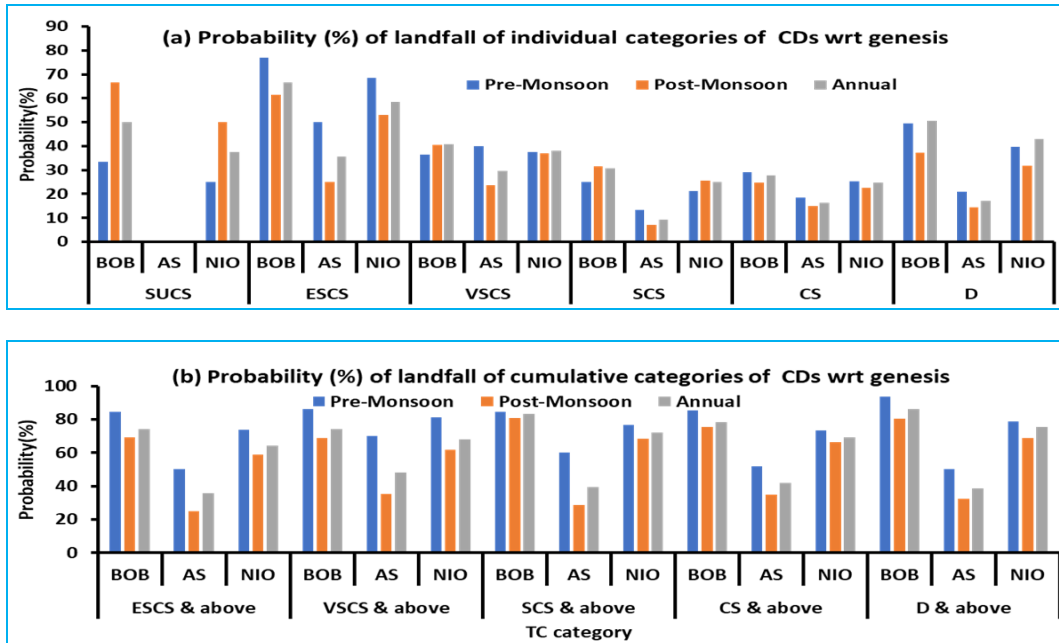
Bold: Statistically significant at 95% level of confidence, Bold & Italics: Statistically significant at 90% level of confidence

which could be in association with decreased vertical wind shear aside from other synoptic scale forcing. According to Evan *et al.* (2011 a&b), the increase in the intensity of pre-monsoon AS TCs during May and June over the period of 1979-2010 was found to be associated with a decrease in vertical wind shear which was caused by an upward trend in anthropogenic black carbon and sulphate emissions. They argued that anthropogenic aerosols cause anomalous atmospheric circulation over south Asia, which then reduce the basin-wide vertical wind shear. Reduced wind shear thus creates an environment more favorable for intensification of TCs. According to Rajeevan *et al.* (2013), during recent years, an increase in the intensity of pre-monsoon TCs over the AS could be attributed to epochal variability in the storm ambient vertical wind shear and TC heat potential (TCHP). There is a significant increase ($0.53 \text{ kJ cm}^{-2} \text{ year}^{-1}$) of TCHP during recent years. The warmer upper ocean helps TCs to sustain or increase their intensity by an uninterrupted supply of sensible and latent heat fluxes from the ocean surface to the atmosphere (Goni & Trinanes, 2003; Emanuel *et al.*, 2004; DeMaria *et al.*, 2005).

Zhang *et al.* (2019) examined the impacts of tropical South Atlantic SST anomalies on the frequency of the AS TCs during the pre-monsoon season (May-June) using observations and climate model experiments. There is a statistically significant association between the Atlantic

SST anomalies and the frequency of AS TCs during May-June of 1979-2016 based on the observations. These results can be explained from a physical perspective through the classic Matsuno-Gill responses to the Atlantic SST forcing, leading to changes in vertical wind shear in the AS. The reduced vertical wind shear related to the Atlantic SST warming is associated with anomalous upper-level westerlies and lower-level easterlies. The reduced vertical wind shear is associated with increase in frequency of TCs in pre-monsoon season over the AS. The physical mechanisms identified in the observations are strongly supported by a suite of experiments with an atmospheric general circulation model.

More recently, the ESCS over the AS have been projected to increase under anthropogenic forcing using high-resolution fully-coupled climate models (Murakami *et al.*, 2017). Wang *et al.* (2013), based upon ensembles of global reanalyses and precipitation datasets, demonstrated a robust intensification of the May monsoon trough over the BOB since 1979, with a corresponding modulation of pre-monsoon TCs. It has resulted in more intense TCs (VSCS and above) in general and an increase in the number of TCs that impacted Myanmar. Such circulation changes in the pre-monsoon season have deepened the BOB monsoon trough and led to a tendency that TCs are occurring earlier each year. The deepened monsoon trough also affected the frequency and track of TCs in



Figs. 7(a&b). Probability (%) of landfall of (a) different categories of CDs and (b) cumulative categories of CDs with respect to genesis frequency

the BOB. Such a change in pre-monsoon circulation has been attributed to atmospheric warming caused by increased anthropogenic aerosols in the Indo-Gangetic Plain. Analyses of the Coupled Earth System Model (CESM) single-forcing experiments provide further evidence for the effect of aerosols on the deepening of the BOB monsoon trough and the resulting increases in TC frequency, intensity and trajectory. However, there is a significant decreasing trend in the frequency of SCS & above and VSCS & above over the BOB [Table 5, Figs. 5{a&b(i-iii)}].

Considering all the above studies, Knutson *et al.* (2019, 2020) have concluded that, there is significant increase in intense TCs over the AS during pre-monsoon season with a low confidence in detection and attribution to anthropogenic influences as the frequency of intense TCs are less and the studies in this regard are limited and based on recent years only.

3.3. Mean frequency of landfalling TCs

3.3.1. Mean frequency and probability of landfalling TCs over the BoB and AS

Considering the data during 1965-2020, about 7.6 CDs and 3.3 TCs (CS & above) make landfall over the NIO (Tables 2&3). Basin-wise, the average frequency of landfall is about 6.7 for CDs and 2.8 for TCs over the BoB and 0.9 and 0.5 respectively over the AS. Similarly, out of

about 2.1 SCS and above landfalling over the NIO, 1.8 make landfall over BoB and 0.3 over the AS. Out of 1.38 landfalling VSCS & above over the NIO, about 1.14 are from BoB and 0.23 from the AS. About 0.6 landfalling ESCS over the NIO includes 0.5 over the BoB and 0.1 over the AS. According to Alam *et al.* (2003), the annual average number of CDs over the BoB that crossed the coasts is 6.7 in a year, which is 86% of the total annual number of CDs that formed based on the data of 1975-1999 over the BoB. The annual average number of TCs over the BoB that crossed the coasts is 3.1. Thus comparison of the results with that of Alam *et al.* (2003) indicates that the frequency of landfalling TCs over the BoB has decreased in recent years.

About 69%, 72%, 68% and 64% of CS & above, SCS & above, VSCS & above and ESCS & above developing over the NIO cross the coast with at least the intensity of CS, SCS, VSCS & ESCS respectively [Figs. 7(a&b)]. The remaining ones either dissipate over the sea or cross coast as a relatively weaker system. Considering BoB (AS), about 78% (42%), 84% (40%), 74% (48%) and 74% (36%) of CS & above, SCS & above, VSCS & above and ESCS & above cross the coast with at least the intensity of CS, SCS, VSCS & ESCS respectively. Thus, the rate of dissipation/weakening is significantly higher over the AS. It may be due to (a) large sea area as compared to BoB, (b) colder sea over west AS and (c) larger role of mid latitude westerlies leading to increase in vertical wind shear, (d) dry air entrainment

from the desert region of Arabia-Africa. On the other hand, BoB is warmer, less influenced by the mid-latitude westerlies & dry/cold air entrainment and has smaller area which favour it to have more probability of landfall of TCs with higher intensity. Considering the individual categories of TCs, over the AS(BOB) about 16% (28%), 9% (31%), 30% (41%), 36% (67%) in case of CS, SCS, VSCS and ESCS respectively cross coast with same intensity [Figs. 7(a&b)]. Thus, considering individual category also the probability of landfall is higher over the BoB than over the AS by about 10-30% and it is significantly higher in case of ESCS category.

The frequency of landfalling TCs is higher during post-monsoon (2.2) than in pre-monsoon (1.0) season over the NIO (Tables 2&3). It is about 1.9 (0.3) and 0.7 (0.3) over the BoB (AS) during post-monsoon and pre-monsoon seasons respectively. According to Alam *et al.* (2003), of all the TCs that crossed the BoB coasts, 20.99% crossed in the pre-monsoon season (March-May) and 54.32% crossed in the post-monsoon season (October-December). On an average, the maximum frequency of CDs crossing the coasts is 1.4 and occurs in the month of October; that of TCs is 1.0 and occurs in November. During post-monsoon season, about 67%, 68%, 62% and 59% of CS & above, SCS & above, VSCS & above and ESCS & above developing over the NIO cross the coast with at least the intensity of CS, SCS, VSCS & ESCS respectively [Figs. 7(a&b)]. Considering BoB (AS), about 75% (35%), 81% (29%), 69% (35%) and 69% (25%) of CS & above, SCS & above, VSCS & above and ESCS & above cross the coast with intensity of at least CS, SCS, VSCS and ESCS respectively. Considering the individual categories of TCs, over the BOB(AS) about 25% (15%), 32% (07%), 41% (24%), 62% (25%) in case of CS, SCS, VSCS and ESCS respectively cross coast with same intensity. Thus, the probability of landfall is higher over the BoB than the AS by about 10-35% for different categories of TCs.

During pre-monsoon season, about 73%, 77%, 81% and 74% of CS & above, SCS & above, VSCS and above and ESCS & above developing over the NIO cross the coast with at least the intensity of CS, SCS, VSCS and ESCS respectively [Figs. 7(a&b)]. Considering BoB (AS), about 85% (52%), 84% (60%), 86% (70%) and 85% (50%) of CS & above, SCS & above, VSCS & above and ESCS & above cross the coast with at least the intensity of CS, SCS, VSCS & ESCS respectively. Considering the individual categories of TCs, over the BOB/AS about 29%/19%, 25/13%, 36%/40%, 77%/50% in case of CS, SCS, VSCS and ESCS respectively cross coast with same intensity. Thus, the probability of landfall is higher over the BoB than the AS by about 10-22% in case of CS, SCS, ESCS and almost same in case of VSCS.

Comparing post and pre-monsoon season, the probability of landfall is higher during pre-monsoon season by about 6, 9, 19 and 15% in case of CS & above, SCS & above, VSCS & above and ESCS & above over the NIO. Similarly, it is higher by about 10% (17%), 3% (31%), 17% (35%) and 16% (25%) over the BoB (AS) during pre-monsoon than in post-monsoon season for CS & above, SCS & above, VSCS & above and ESCS & above respectively.

Considering individual categories, the probability of landfall is higher during pre-monsoon than in post-monsoon season by about 4, 16, 15 and 25% for CS, SCS, VSCS & ESCS respectively over the AS. It is higher during pre monsoon season than in post monsoon season in case of CS (4%) and ESCS (15%) and lower in case of SCS (7%) and VSCS (5%) over the BoB.

3.3.2. Annual frequency of landfalling TCs over different coastal regions

About 1.71(1.13) and 0.18(0.16) CS and above (SCS & above) make landfall over east and west coasts of India respectively. About 0.68 and 0.17 VSCS & above 0.30 & 0.04 ESCSs & above make landfall over the east & west coasts of India respectively. Thus, while 3-4 TCs over the NIO make landfall, about 2 TCs make landfall over east coast of India (Tables 6-8). Similarly, while 2 of the SCS & above over the NIO make landfall, 1 out of these make landfall over the east coast of India. While about 4 VSCS & above developing over the NIO in 3 years may make landfall, 2 out of these make landfall over east coast of India. While about 1 ESCS & above over the NIO in 2 years make landfall, east coast of India experiences landfall of TC with intensity of ESCS & above once in 3 years (Table 8).

Considering different coastal regions of BoB, the annual frequency of landfall is maximum over BDS coast followed by AP, ODS and TNP coasts in case of CS and above [Figs. 8(a&b)], over BDS followed by AP, TNP, ODS and WB coasts in case of SCS and above, over AP followed by ODS/BDS, MMR, TNP and WB in case of VSCS and above, over ODS followed by AP/MMR and BDS in case of ESCS and above. There have been one SuCS each crossing ODS, AP and BDS during the period (Table 4). According to Tyagi *et al.*, 2010, Over 48 percent of the TCs in the BoB strike different parts of the east coast of India, 26 percent strike coasts of BDS & MMR, 6 percent cross SLE and about 20 percent dissipate over the sea itself. Percentage of TCs dissipating over the AS is higher (63%) as the western AS is cooler.

Considering the individual categories of TCs, frequency of landfall is maximum over BDS followed by

TABLE 6

Linear trend coefficients in individual and cumulative frequency of TCs landfalling over various regions during 1965-2020

Landfalling region	Category	Total	Mean	Trend per 100 years	Category	Total	Mean	Trend per 100 years
NIO countries	ESCS & above	34	0.61	-0.44	ESCS	31	0.55	-0.37
BoB countries		29	0.52	-0.39		26	0.46	-0.32
AS countries		5	0.09	0.04		5	0.09	-0.04
NIO countries	VSCS & above	77	1.37	-2.37	VSCS	43	0.77	-1.93
BoB countries		64	1.14	-2.77		35	0.63	-2.38
AS countries		13	0.23	0.40		8	0.14	0.44
NIO countries	SCS & above	117	2.09	-3.7	SCS	41	0.73	-1.33
BoB countries		101	1.8	-4.24		37	0.66	-1.47
AS countries		16	0.29	0.54		4	0.07	0.14
NIO countries	CS & above	183	3.26	-4.65	CS	66	1.18	-0.95
BoB countries		156	2.79	-5.95		55	0.98	-1.71
AS countries		27	0.48	1.3		11	0.20	0.76

TC: Tropical cyclones, D: Depression/Deep Depression, CS: Cyclonic storm, SCS: Severe cyclonic storm, VSCS: Very severe cyclonic storm, ESCS: Extremely severe cyclonic storm, NIO: North Indian Ocean, BoB: Bay of Bengal and AS: Arabian Sea
 Bold: Statistically significant at 95% level of confidence, Bold & Italics: Statistically significant at 90% level of confidence

TABLE 7

Annual mean & linear trend coefficients (per 100 years) in actual frequencies of TCs landfalling over various regions during 1965-2020

Countries/ States of India	ESCS			VSCS			SCS			CS		
	Total	Mean	Trend per 100 years	Total	Mean	Trend per 100 years	Total	Mean	Trend per 100 years	Total	Mean	Trend per 100 years
SLE	1	0.02	-	2	0.04	-	0	0.00	-	5	0.09	-0.26
TNP	2	0.04	-	7	0.13	-0.06	7	0.13	-0.55	4	0.07	-0.51
AP	5	0.09	-0.15	7	0.13	-0.25	10	0.18	-0.34	14	0.25	-0.16
Odisha	7	0.13	-0.16	4	0.07	-0.35	2	0.04	-	13	0.23	-1.17
WB	1	0.02	-	4	0.07	-0.23	6	0.11	0.13	2	0.04	-
BDS	4	0.07	-0.01	7	0.13	-0.91	12	0.21	-0.59	16	0.29	-0.23
MMR	6	0.11	0.16	4	0.07	-0.47	0	0.00	-	1	0.02	-
Gujarat	2	0.04	-	2	0.04	-	2	0.04	-	2	0.04	-
MNG	-	-	-	-	-	-	1	0.02	-	1	0.02	-
KTK	-	-	-	-	-	-	1	0.02	-	-	-	-
IAA	2	0.04	-	6	0.11	0.64	0	0.00	-	7	0.13	0.58
ECI	15	0.27	-0.52	22	0.39	-0.7	25	0.45	-0.89	33	0.59	-1.39
WCI	2	0.04	-	2	0.04	-	4	0.07	0.17	3	0.05	-

TC: Tropical cyclone, CS: Cyclonic storm, SCS: Severe cyclonic storm, VSCS: Very severe cyclonic storm, ESCS: Extremely severe cyclonic storm, BoB: Bay of Bengal, AS: Arabian Sea, SLE: Sri Lanka East, TNP: Tamilnadu & Puducherry, AP: Andhra Pradesh, WB: West Bengal, BDS: Bangladesh, MMR: Myanmar, MNG: Maharashtra & Goa, KTK: Karnataka, IAA: Iran, Arabia & Africa, ECI: East Coast of India, WCI: West Coast of India,

Bold: Statistically significant at 95% level of confidence, Bold & Italics: Statistically significant at 90% level of confidence

AP and ODS in case of CS, over BDS followed by AP, TNP and WB in case of SCS, over BDS/AP followed by TNP/ODS/WB in case of VSCS, over ODS followed by MMR, AP and BDS in case of ESCS. Thus, to summarise, most intense TCs (ESCS & above with MSW \geq 90 kt) cross the coast maximum over ODS

followed by AP/MMR & BDS and low intensity TCs (CS/SCS with MSW 34-63 kt) cross maximum over BDS followed by AP, ODS & TNP and medium intensity storms (VSCS with MSW 64-89 kt) cross over TN/AP/BDS followed by ODS/WB/MMR.

TABLE 8

Annual mean & linear trend coefficients (per 100 years) in cumulative frequencies of TCs landfalling over various regions during 1965-2020

Countries/ States of India	ESCS & above			VSCS & above			SCS & above			CS & above		
	Total	Mean	Trend per 100 years	Total	Mean	Trend per 100 years	Total	Mean	Trend per 100 years	Total	Mean	Trend per 100 years
SL East	1	0.02	-	3	0.05	-	3	0.05	-	8	0.14	-0.49
TN	2	0.04	-	9	0.16	-0.06	16	0.29	-0.55	20	0.36	-0.50
AP	6	0.11	-0.25	13	0.23	-0.50	23	0.41	-0.84	37	0.66	-1.00
Odisha	8	0.14	-0.12	12	0.21	-0.46	14	0.25	-0.65	26	0.46	-1.87
WB	1	0.02	-	5	0.09	0.04	11	0.19	-0.13	13	0.23	-0.22
BDS	5	0.09	-0.02	12	0.21	-0.94	24	0.43	-1.53	40	0.71	-1.76
MMR	6	0.11	0.16	10	0.18	-0.31	10	0.18	-0.31	11	0.2	-0.15
Gujarat	2	0.04	-	4	0.07	-0.27	6	0.11	-0.32	8	0.13	-0.36
MNG	0	-	-	0	-	-	2	0.04	-	1	0.02	-
KTK	0	-	-	0	-	-	1	0.02	-	1	0.02	-
IAA	2	0.04	-	8	0.14	0.63	8	0.14	0.63	15	0.27	1.21
ECI	17	0.30	-0.59	38	0.68	-1.29	63	1.13	-2.18	96	1.71	-3.57
WCI	2	0.04	-	4	0.07	-0.27	9	0.16	-0.1	10	0.18	-0.03

TC: Tropical cyclone, CS: Cyclonic storm, SCS: Severe cyclonic storm, VSCS: Very severe cyclonic storm, ESCS: Extremely severe cyclonic storm, BoB: Bay of Bengal, AS: Arabian Sea, SLE: Sri Lanka East, TNP: Tamilnadu & Puducherry, AP: Andhra Pradesh, WB: West Bengal, BDS: Bangladesh, MMR: Myanmar, MNG: Maharashtra & Goa, KTK: Karnataka, IAA: Iran, Arabia & Africa, ECI: East Coast of India, WCI: West Coast of India.

Bold: Statistically significant at 95% level of confidence, Bold & Italics: Statistically significant at 90% level of confidence

Considering the landfalling TCs over the AS, the landfall frequencies of CS & above and SCS & above and VSCS & above are the maximum over IAA followed by GJT [Figs. 8(a&b)]. There is no VSCS or above intensity storm crossing M&G coast. Further, there has been no landfalling TC over GJT region, KRL and SLW coast during 1965-2020. All the TCs making landfall over GJT have crossed Saurashtra and Kutch coast during this period. Tyagi *et al.* (2010) based on data of 1891-2007 also have shown that maximum landfall of TCs over the AS occurs over GJT coast (18% of total TCs in AS) of India followed by Oman coast.

3.3.3. Landfalling TCs for different coastal regions during pre-monsoon season

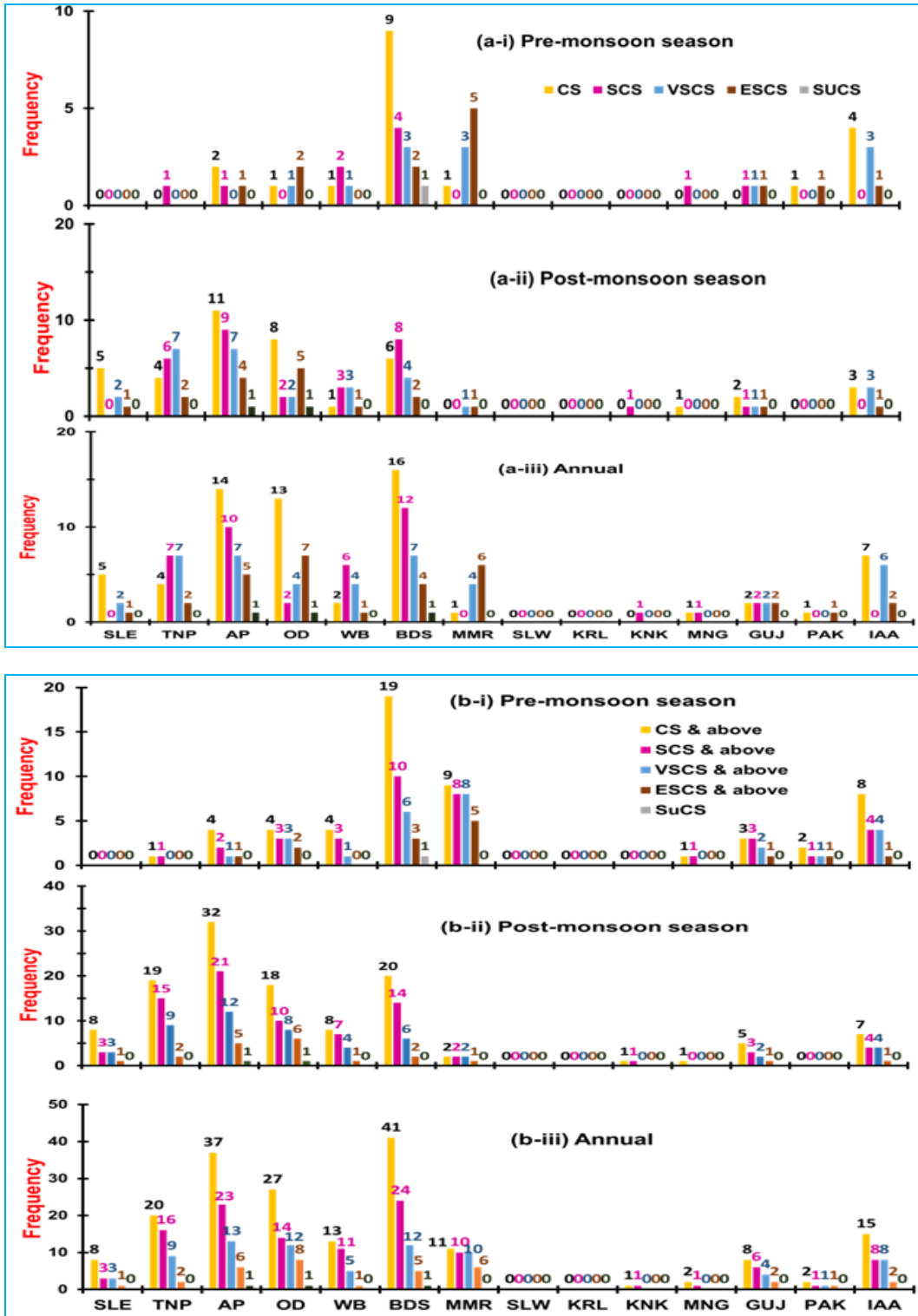
During pre-monsoon season, the frequency of landfalling TCs is maximum over BDS followed by MMR in case of CS & above and SCS & above, over MMR followed by BDS in case of VSCS & above and ESCS & above intensity storms [Figs. 8(a&b)]. Considering individual categories, the landfall frequency is maximum over BDS in case of CS and SCS, over BDS/MMR in case of VSCS and over MMR in case of ESCS. Thus, while maximum CS/SCS cross BDS, maximum VSCS cross BDS/MMR and maximum ESCS cross MMR coast during pre-monsoon season. According to Pal and Chatterjee (2020),

the pre-monsoon TCs dissipated further northward compared to the monsoon and post-monsoon TCs in BoB. The pre-monsoon TCs over the BoB also significantly moved eastward from average genesis location of 11.8° N / 88.7° E to 21.3° N / 91.1° E during pre-monsoon season against 11.3° N / 88.8° E to 19.2° N / 83.5° E during post-monsoon season. It could be therefore, the reason for TCs to cross BDS/MMR more frequently during pre-monsoon season. Wang *et al.* (2012 and 2013) have also discussed the role of mid latitude westerlies for increased frequency of intense storms landfalling over Myanmar.

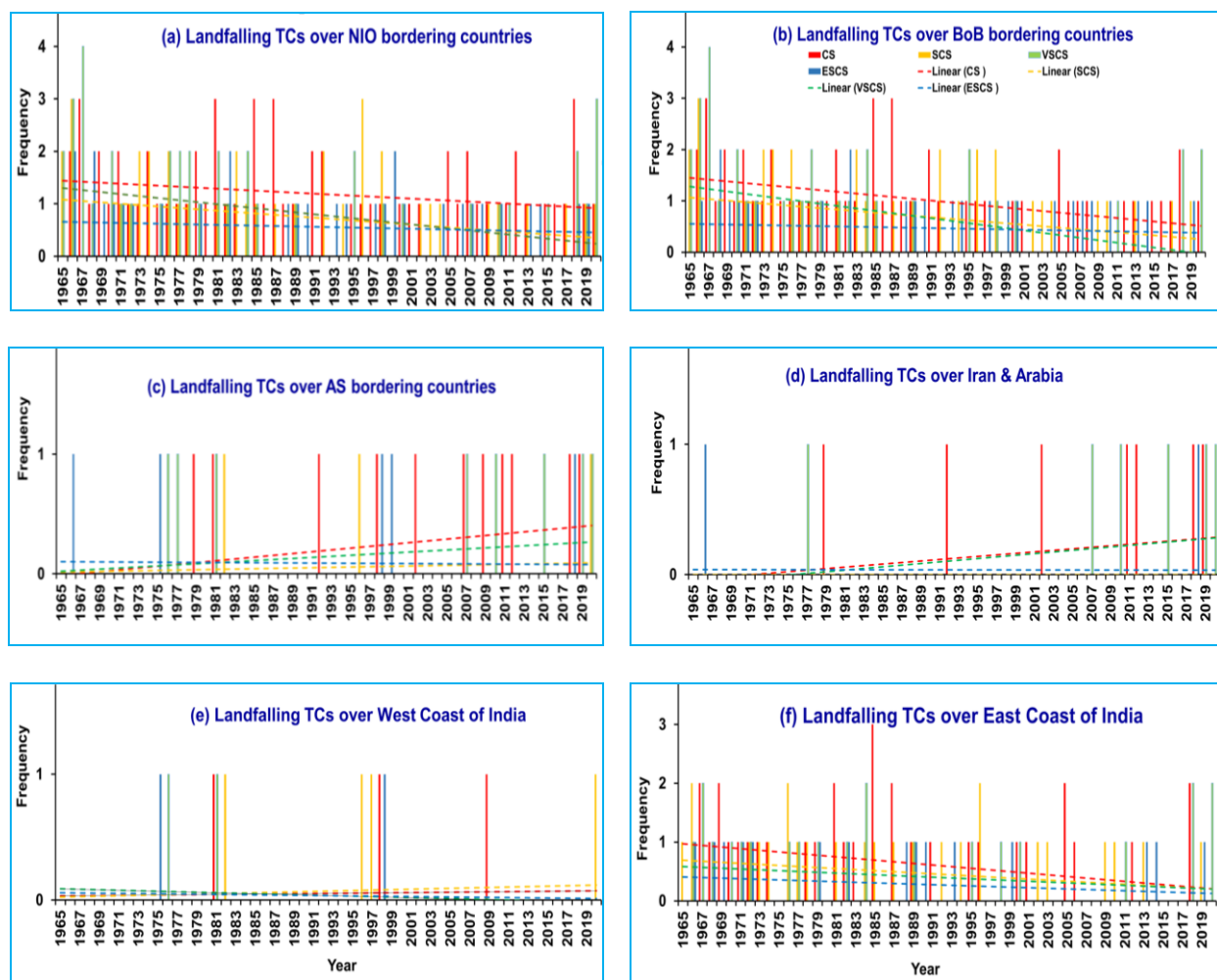
Considering the landfalling TCs over the AS, the landfall frequency of CS & above, SCS & above and VSCS & above are maximum over IAA followed by GJT. Over the AS, the mean genesis point is 12.3° N / 63.9° E and dissipation point is 19.4° N / 61.2° E during pre-monsoon season (Pal and Chatterjee, 2020). During pre-monsoon season usually genesis takes place over the AS in association with onset of monsoon and they move west-northwestwards towards IAA coasts.

3.3.4. Landfalling TCs for different coastal regions during post-monsoon season

During post-monsoon season, the frequency of landfall is maximum over AP followed by BDS, TNP,



Figs. 8[a&b(i-iii)]. (a) Individual frequency and (b) cumulative frequency of various categories of landfalling TCs during (i) pre-monsoon, (ii) post-monsoon and (iii) year as a whole over the period 1965-2020
 TC: Tropical cyclone, CS: Cyclonic storm, SCS: Severe cyclonic storm, VSCS: Very severe cyclonic storm, ESCS: Extremely severe cyclonic storm and SuCS: Super Cyclonic Storm
 SLE: Sri Lanka East, TNP: Tamilnadu and Puducherry, AP: Andhra Pradesh, OD: Odisha, WB: West Bengal, BDS: Bangladesh, MMR: Myanmar, SLW: Sri Lanka West, KRL: Kerala, KNK: Karnataka, MNG: Maharashtra and Goa, GUJ: Gujarat, PAK: Pakistan, IAA: Iran, Arabia and Africa



Figs. 9(i). Individual frequency of landfalling TCs over (a) NIO, (b) BoB & (c) AS and frequency of TCs landfalling over (d) Iran, Arabia & Africa (e) West coast of India & (f) East coast of India during 1965-2020

TC: Tropical cyclone, BoB: Bay of Bengal, AS: Arabian Sea, NIO: North Indian Ocean, CS: Cyclonic storm, SCS: Severe cyclonic storm, VSCS: Very severe cyclonic storm and ESCS: Extremely severe cyclonic storm, Linear: Linear Trend Line

ODS in case of CS & above, over AP followed by TNP, BDS, ODS in case of SCS & above, over AP followed by TNP, ODS, BDS in case of VSCS & above, over ODS followed by AP, TNP/BDS in case of ESCS & above intensity storms. Considering the individual categories, the frequency of landfalling TCs is maximum over AP followed by ODS, BDS, SLE, TNP in case of CS, over AP followed by BDS & TNP in case of SCS, over AP/TNP followed by BDS, WB & ODS in case of VSCS and over ODS followed by AP, TNP/BDS in case of ESCS. Thus, while maximum CS/SCS/VSCS cross AP coast, maximum ESCS cross ODS coast during post-monsoon season.

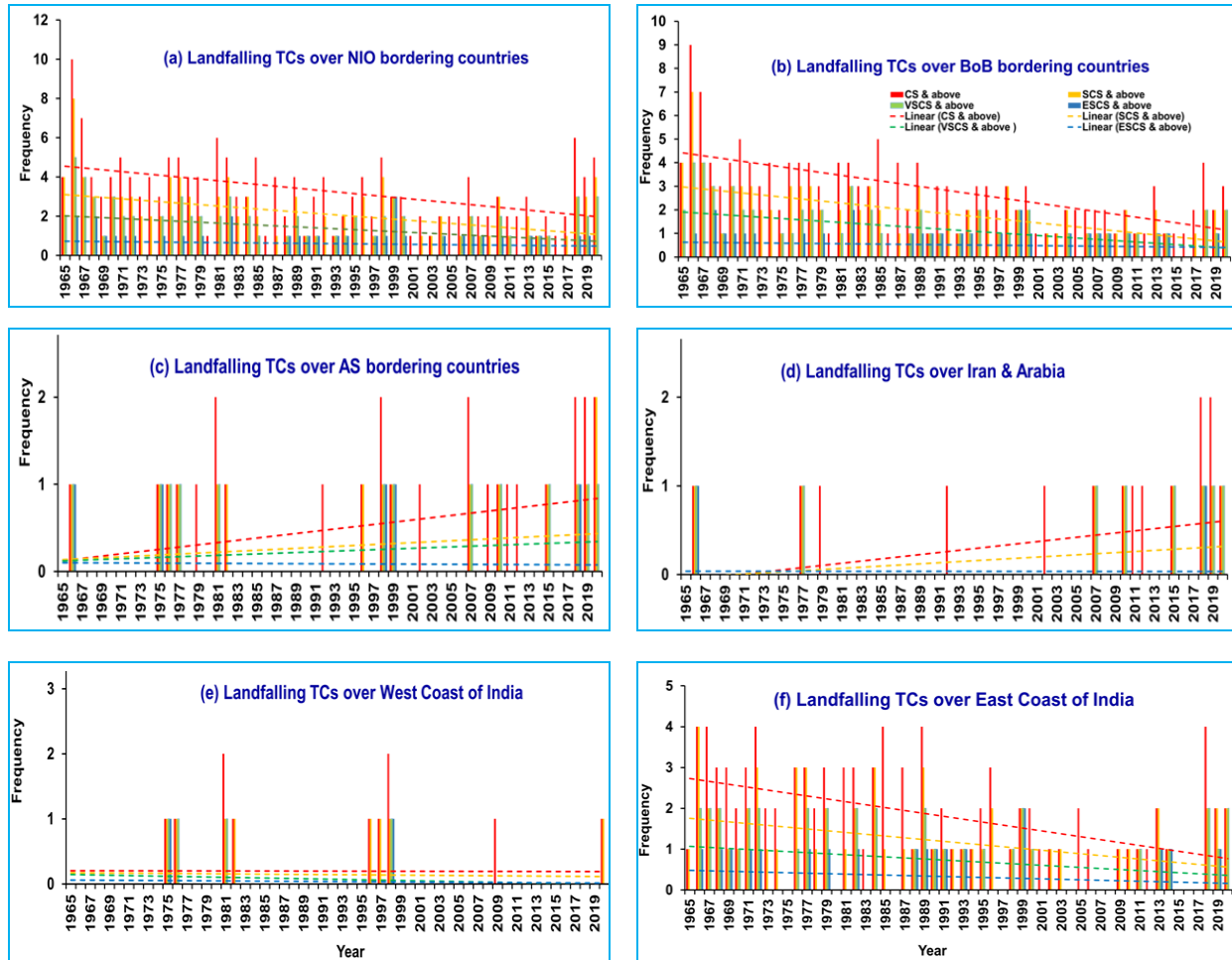
Considering the landfalling TCs over the AS, the landfall frequency of CS & above and SCS & above and VSCS & above are maximum over IAA followed by GJT.

It is also equal over IAA and GJT in the category of VSCS & above. The maximum number of landfall over IAA may be due to climatological track characteristics (west-northwestward or northwestward movement of TCs developing over the low latitude, *i.e.*, over south AS) of the TCs over the AS. According to Pal and Chatterjee (2020), over the AS, the mean genesis point is near 12.1° N/ 66.6° E and dissipation point is near 17.5° N/ 60.9° E during post-monsoon season.

3.4. Trends in landfalling TCs

3.4.1. Trends in landfalling TCs over the Bay of Bengal and Arabian Sea

There is a rising trend in frequency of VSCS and CS over the AS [Table 6, Fig. 9 (i)]. Accordingly, there is a



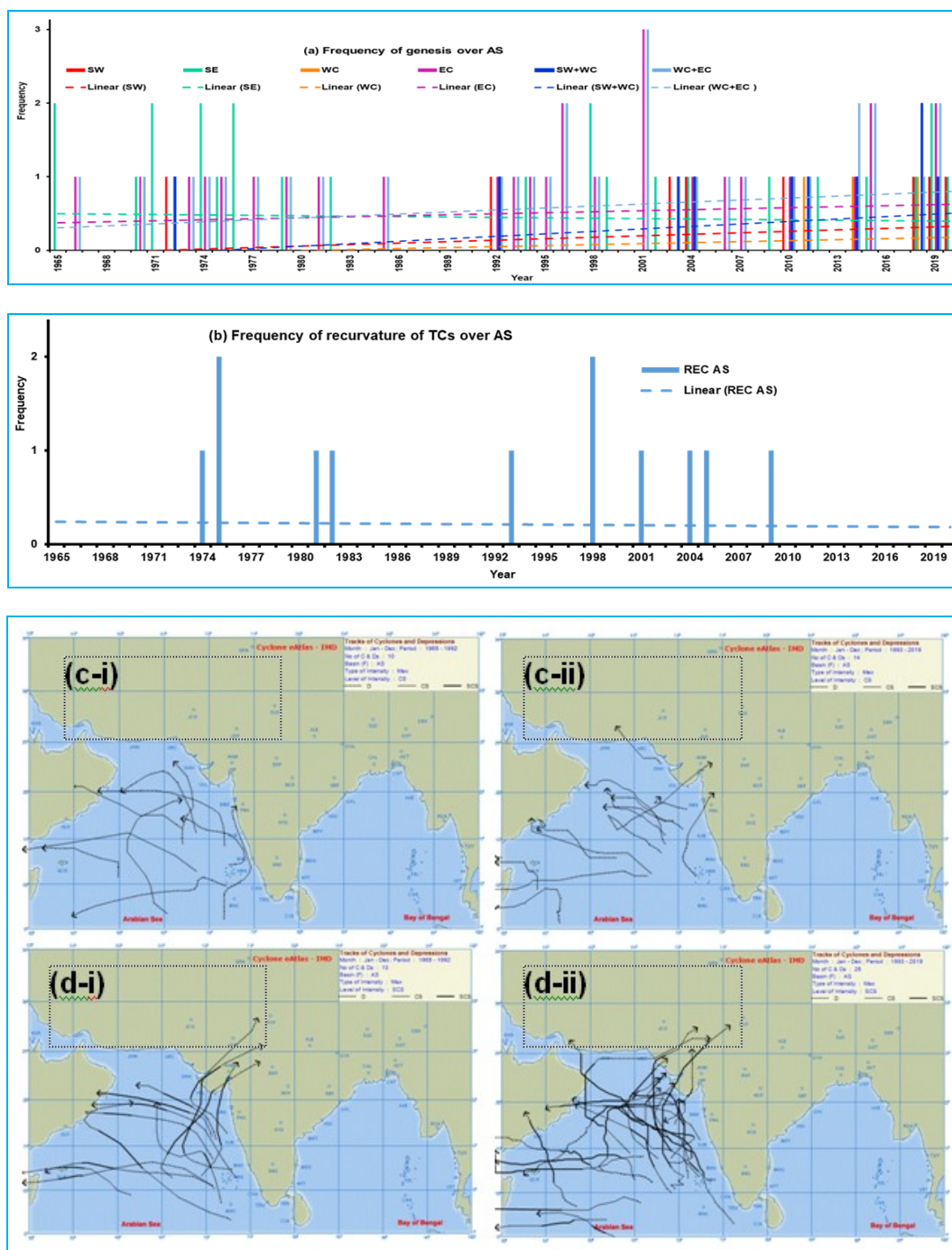
Figs. 9(ii). Cumulative frequency of landfalling TCs over (a) NIO, (b) BoB & (c) AS and frequency of TCs landfalling over (d) Iran, Arabia & Africa (e) West coast of India & (f) East coast of India during 1965-2020

TC: Tropical cyclone, BoB: Bay of Bengal, AS: Arabian Sea, NIO: North Indian Ocean, CS: Cyclonic storm, SCS: Severe cyclonic storm, VSCS: Very severe cyclonic storm and ESCS: Extremely severe cyclonic storm, Linear: Linear Trend Line

rising trend in the frequency of landfalling CS & above, SCS & above and VSCS & above over the AS [Fig. 9(ii)]. Comparing the similar trend analysis over individual states of west coast of India and other countries like IAA, PAK and SLW, it is found that there is rising trend in landfalling TCs over the IAA [Table 7, Fig. 9(i)]. Thus, to summarize, there is an increasing trend in the frequency of landfalling TCs over AS namely in the categories of VSCS and CS resulting in an increase in the frequency of landfalling TCs over the IAA in the same categories and accordingly in the frequency of CS & above, SCS & above and VSCS & above crossing IAA. It could be attributed to the fact that the (i) frequency of formation of TCs over the AS might have increased in lower latitudes and also in western longitude, (ii) westward movement of the TCs over the AS could have increased and (iii) these TCs are able to maintain their intensity over the relatively colder west AS resulting in increased landfall over

Arabia-Africa. On the other hand, the frequency of northeastward recurvature of the TCs over the AS could have decreased due to weaker mid-latitude westerlies.

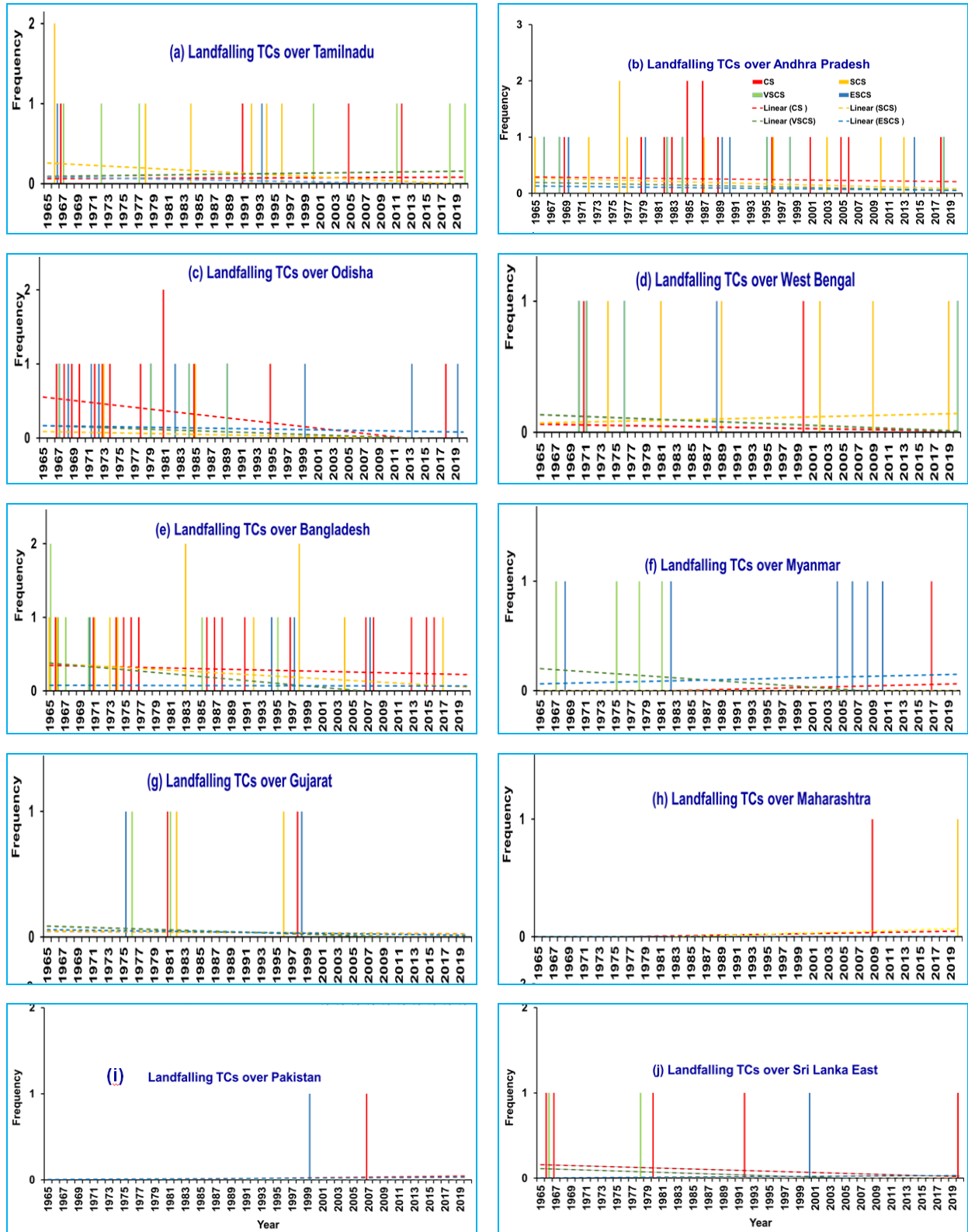
There is insignificant decreasing trend in the frequency of landfalling TCs over the west coast of India [Fig. 9, Tables 7&8]. To verify above hypothesis, we analysed the westward moving and recurving tracks as well as their genesis area over the AS. It is found that there is a significant increasing trend in the genesis of TCs over the southwest and westcentral AS (west of 64° E and south of 20° N) as shown in Table 9 (Fig. 10). Most of these TCs moved west-northwestward or northwestward towards IAA leading to increase in landfall frequency over the IAA. At the same time there is no trend in the frequency of TC genesis over the east AS (east of 64° E) and also there is no trend in the frequency of recurving TCs over the AS [Figs. 10(a-d)].



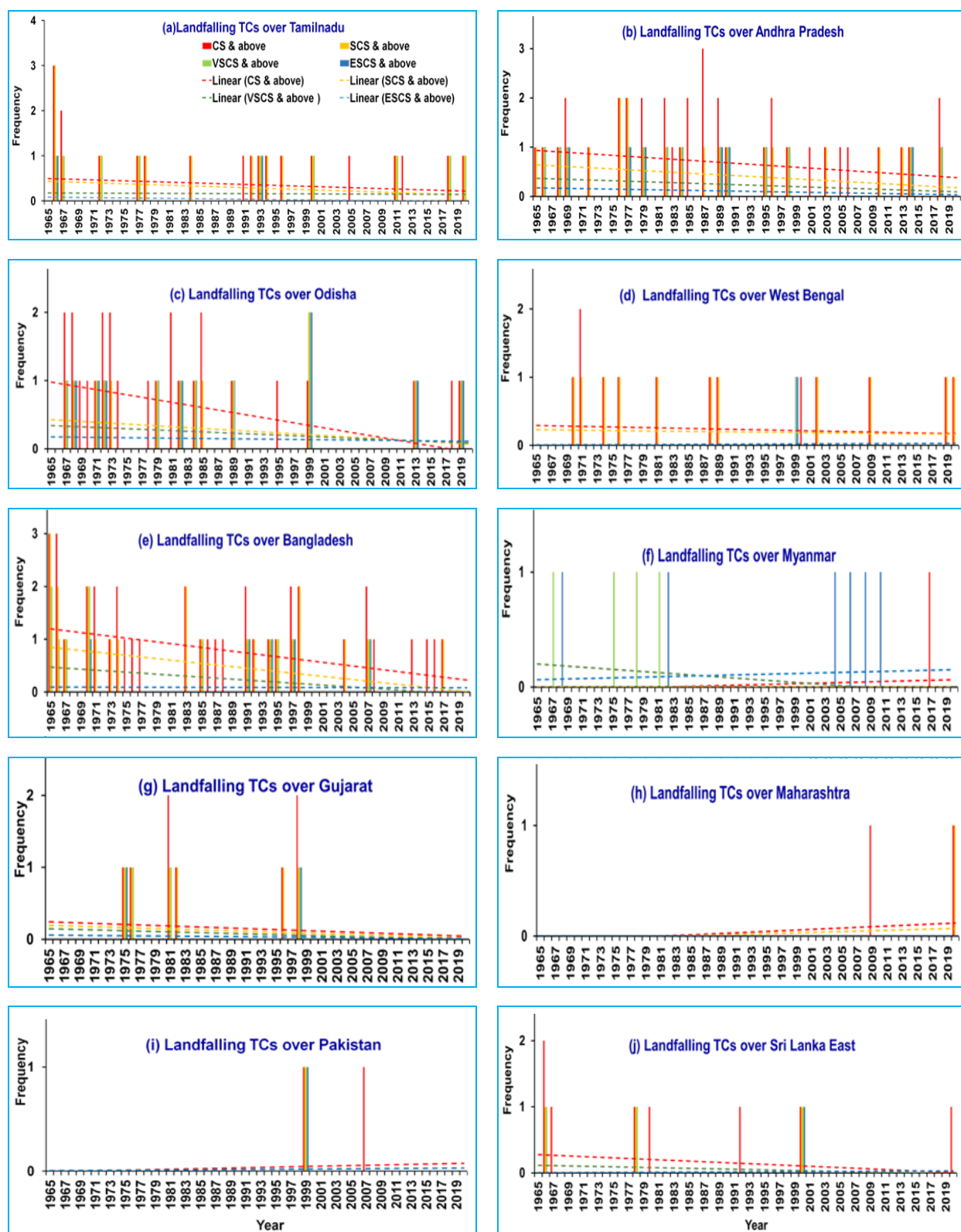
Figs. 10(a-d). (a) Frequency of genesis and (b) frequency of recurvature of TCs over the AS during 1965-2020 and tracks of (c) CS and (d) SCS over the AS during (i) 1965-1992 and (ii) 1993-2019
 SW: Southwest, SE: Southeast, WC: Westcentral, EC: Eastcentral, AS: Arabian Sea, TC: Tropical Cyclone, Linear: Linear Trend Line

Considering the landfalling TCs over the BoB, there is a decreasing trend in CS & above, SCS & above, VSCS & above and no trend in case of ESCS & above. Similar trends are noticed in the individual categories of CS, SCS & VSCS also (Table 6). The frequency of total landfalling

TC categories for east coast of India shows also decreasing trend in case of CS & above, SCS & above and VSCS & above and decreasing trend in the individual category of CS, SCS, VSCS and ESCS. Tyagi *et al.* (2010) have shown no significant trend in frequency of



Figs. 11(a-j). Actual Frequency of landfalling TCs over (a) Tamil Nadu, (b) Andhra Pradesh, (c) Odisha, (d) West Bengal, (e) Bangladesh (f) Myanmar, (g) Gujarat (h) Maharashtra, (i) Pakistan and (j) Sri Lanka East during 1965-2020
 TC: Tropical cyclone, BoB: Bay of Bengal, AS: Arabian Sea, NIO: North Indian Ocean, CS: Cyclonic storm, SCS: Severe cyclonic storm, VSCS: Very severe cyclonic storm and ESCS: Extremely severe cyclonic storm, Linear: Linear Trend Line



Figs. 12(a-j). Cumulative frequency of landfalling TCs over (a) Tamil Nadu, (b) Andhra Pradesh, (c) Odisha, (d) West Bengal, (e) Bangladesh (f) Myanmar, (g) Gujarat (h) Maharashtra, (i) Pakistan and (j) Sri Lanka East during 1965-2020
 TC: Tropical cyclone, BoB: Bay of Bengal, AS: Arabian Sea, NIO: North Indian Ocean, CS: Cyclonic storm, SCS: Severe cyclonic storm, VSCS: Very severe cyclonic storm and ESCS: Extremely severe cyclonic storm, Linear: Linear Trend Line

TABLE 9

Frequency of genesis and their linear trend coefficients over different regions of AS during 1965-2020

Place of Origin	Total	Mean	Trend per 100 years
SW AS	8	0.14	0.67
SE AS	25	0.45	-0.19
WC AS	3	0.05	0.45
EC AS	28	0.50	0.45
SW+WC AS	11	0.20	1.12
SE+EC AS	53	0.95	0.26
SW+SE AS	33	0.59	0.48
WC+EC AS	31	0.55	0.90

SW: South West, SE: South East, WC: West Central, EC: East Central, AS: Arabian Sea

landfalling CDs over east and west coasts of India during 1891-2007 excluding the short lived systems.

3.4.2. Trends in frequency of landfalling TCs over different coastal regions

There is decreasing trend in the total frequency of landfalling storms in the category CS & above and SCS & above over ODS, CS & above, SCS & above and VSCS & above over AP and BDS coasts during the year as a whole (Table 7, Figs. 11&12). According to Singh *et al.*, 2018, GJT and IAA are more vulnerable coastal areas of AS irrespective of seasons considered. According to Wang *et al.* (2013), the ratio of frequency of TCs during pre-monsoon season to the total annual frequency of TCs over the BoB which moved towards Myanmar and Bangladesh shows increasing trend during 1976-2011 which is opposite to the findings of the current study.

4. Conclusions

Following broad conclusions are drawn from the above results and discussion.

About 10 CDs and 5 TCs develop over the NIO during a year including about 6.5 D, 1.8 CS, 0.9 SCS, 1.1 VSCS, 0.8 ESCS and 0.1 SuCS. Thus about 47%, 29%, 20% and 9% of CDs intensify into CS, SCS, VSCS and ESCS respectively over the NIO. Similarly about 62%, 42% and 20% of total TCs intensify into SCS, VSCS and ESCS respectively over the NIO. There is 69% and 32% probability for an SCS to intensify into a VSCS and ESCS respectively and 47% probability for a VSCS to intensify into an ESCS.

The average frequency of D, CS, SCS, VSCS and ESCS over the BoB(AS) are 4.3 (2.2), 1.4 (0.4), 0.6 (0.3),

0.8 (0.2) and 0.6 (0.2) respectively. The average frequency of CD, CS & above, SCS & above, VSCS & above and ESCS & above over the BoB (AS) is 7.8 (2.3), 3.5 (1.2), 2.2 (0.8), 1.5 (0.5) and 0.7 (0.3) respectively. The probability of a CS to intensify into SCS, VSCS and ESCS is almost same for both BOB and AS and the probability of a CD becoming a TC is less over the BOB as compared to AS by about 7% during the year as a whole.

The frequencies of genesis and landfall of all categories of TCs are higher (by about 3 to 4 times) during post-monsoon than in pre-monsoon season over the BoB. While the genesis frequency is slightly higher in SCS, VSCS and ESCS category, the landfall frequency is almost same in both the seasons over the AS.

About 7.6 CDs (75% of genesis frequency) and 3.3 CS & above intensity storms (70% of CS and 33% of genesis frequency) make landfall over the NIO. It includes about 6.7 (0.9) and 2.8 (0.5) landfalling CDs and TCs respectively over the BoB (AS). About 75% (35%), 81% (29%), 69% (35%) and 69% (25%) of CS & above, SCS & above, VSCS & above and ESCS & above during post-monsoon season and 85% (52%), 84% (60%), 86% (70%) and 85% (50%) of CS & above, SCS & above, VSCS & above and ESCS & above during pre-monsoon season and 78% (42%), 84% (40%), 74% (48%) and 74% (36%) of CS & above, SCS & above, VSCS & above and ESCS & above over the BoB (AS) during year as a whole cross the coast with at least the intensity of CS, SCS, VSCS & ESCS respectively.

The most intense TCs (ESCS & above) cross the coast maximum over ODS followed by AP/MMR & BDS and low intensity TCs (CS/SCS) cross maximum over BDS followed by AP, ODS & TNP and medium intensity TCs(VSCS) cross maximum over TN/AP/BDS followed by ODS/WB/MMR during year as a whole. While maximum CS/SCS cross BDS, maximum VSCS cross BDS/MMR and maximum ESCS cross MMR coast during pre-monsoon season. While maximum CS/SCS/VSCS cross AP coast, maximum ESCS cross ODS coast during post-monsoon season. Over the AS, the landfall frequency of CS & above and SCS & above and VSCS & above are maximum over IAA followed by Saurashtra & Kutch during both the seasons and year as a whole.

There is decreasing trend in genesis frequency of all categories of CDs including D/DD, CS, SCS, VSCS, ESCS and accordingly in frequency of D & above, CS & above, SCS & above, VSCS & above and ESCS & above during the post-monsoon season and the year as a whole, in the frequency of D/DD, SCS, VSCS and hence D & above, SCS & above and VSCS & above during pre-monsoon season over the BoB. Accordingly, there is a

decreasing trend in landfalling CS, SCS, VSCS, CS & above, SCS & above, VSCS & above over the BoB. It has resulted in decreasing trend in the frequency of landfalling CS, VSCS, CS & above and SCS & above over ODS, CS & above, SCS & above and VSCS & above over AP, SCS, VSCS, CS & above, SCS & above and VSCS & above over BDS, VSCS over MMR coasts during the year.

There is increasing trend in the frequency of ESCS, CS & above, SCS & above, VSCS & above and ESCS & above during the year as a whole, VSCS, ESCS, VSCS & above and ESCS & above during post-monsoon season and CS & above and SCS & above during pre-monsoon season over the AS.

There is an increasing trend in the frequency of landfalling TCs over AS in the categories of VSCS and CS resulting in an increase in the frequency of landfalling TCs over the IAA in the same categories and accordingly in the frequency of CS & above, SCS & above and VSCS & above crossing IAA. It could be attributed to increase in genesis frequency of the TCs over the western AS and no significant trend in the frequency of eastward/northeastward recurving TCs over the AS apart from other synoptic and dynamical influences like increase in TCHP and decrease in vertical wind shear over the region. There is decreasing trend in frequency of landfalling SCS & above and VSCS & above over Saurashtra and Kutch, while there have been no landfall over Gujarat region during the period.

While with no significant trend in the frequency of ESCS and above intensity storms the coastal vulnerability due to ESCS continues with same magnitude over the BoB region, it has increased over the IAA coast due to increasing trend in frequency of VSCS and above intensity storms.

A further examination of TC occurrences is needed to establish a direct cause-and-effect relationship behind the significant trends in genesis and landfall frequencies of TCs over the BoB and AS including the role of local and large scale dynamical and thermodynamical, atmospheric and Oceanic factors as well as the role anthropogenic influence on TC activity over the region. The latter could be better understood through fine-resolution regional climate modelling and reanalyses of historical TC dataset to reduce the uncertainty in the estimation of intensity of TCs.

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