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On the Tropical Cyclone Activity and Associated Environmental Features over North Indian Ocean in the Context of Climate Change

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Abstract: Global warming and its impact on severe weather events have been one of the most popular topics of scientific interest during the recent decades. Several studies have examined impact of global warming over the frequency and intensity of tropical cyclones (TCs) forming over different oceanic basins. While some studies have reported a decrease in TC frequency and an increase in severe TC frequency during the recent years, some others are uncertain on whether changes in TC activity have exceeded the variability expected from natural causes. The present study analyses variability in TC activity over the North Indian Ocean (NIO) basin [which comprises the Bay of Bengal (BOB) and the Arabian Sea (AS)] in the context of changing environmental conditions under global warming scenario based on data of 1951-2010. Significant trends in cyclonic disturbances (CD), TC and severe TC activity over NIO are noted and environmental features known to be associated with cyclonic activity, viz., sea surface temperature (SST), vertical wind shear (VWS), low level vorticity and mid-tropospheric humidity are examined in relation to the trends in the CD/TC/severe TC activity over the NIO. The trends are also analysed from the point of view of ENSO forcing.

Significant decreasing trends are observed in CD frequency and their further intensification into severe TCs over BOB during the post-monsoon chief cyclone season and the monsoon season despite increasing SST. Concomitant with this decrease, there is a significant decreasing trend in mid-tropospheric humidity over BOB during both the seasons. Over the AS, no significant trends in frequency of CD, TC and severe TC are observed during the post-monsoon and monsoon seasons. However, probability of intensification into TCs and severe TCs over AS has increased in association with decrease in VWS over AS during the two seasons. There are no significant trends in the frequency of CDs, TCs and severe TCs over BOB and AS during the pre-monsoon season. However, frequency of CDs intensifying into TCs and TCs intensifying into severe TCs have increased significantly over AS and BOB respectively in association with decreased VWS over AS and increased low level cyclonic vorticity over BOB. Concomitant with the decreasing CD frequency, in general, a decrease in frequency of cyclogenesis over the southern parts of BOB leading to a northward shift of mean latitude of formation is also observed. Examination of role of ENSO on the CD, TC and severe TC trends indicates that the impact of ENSO has decreased in recent years.

Keywords: Tropical cyclone; Trend; SST; Humidity; Vertical wind shear; Vorticity; ENSO.

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Introduction

Global warming and its impact on severe weather events have been one of the most popular topics of scientific interest during the recent decades. Concerns about possible effects of global warming on Tropical Cyclone (TC) activity have motivated TC researchers worldwide to study the response of TC activity in a global warming scenario. A review of multi decadal scale TC variations and possible “greenhouse warming” effects has been covered by Landsea (1998). It has been documented by Webster et al. (2005) that TC frequency has decreased over all oceanic basins of the world except the North Atlantic, but the number of severe TCs has increased over all the oceanic basins. Emanuel (2005) has raised concerns on increasing destructiveness of TCs in the recent decades. However, Knutson et al. (2010) examined impact of global warming over the frequency and intensity of TCs forming over different oceanic basins and concluded that it was uncertain whether changes in TC activity have exceeded the variability expected from natural causes. Such studies have further kindled the scientific interests of TC researchers in the context of climate change.

TCs are, in general, seasonal phenomena with most tropical ocean basins having maximum frequency of formation during the late summer to early autumn period, associated with the period of maximum sea surface temperature (SST), although other factors, such as the seasonal variation of the Inter-Tropical Convergence Zone (ITCZ)/monsoon trough location are also important (Gray, 1968). However, unlike other ocean basins, the TC frequency over the North Indian Ocean (NIO) comprising the Bay of Bengal (BOB) and the Arabian Sea (AS) shows bimodal character, with primary peak during October to December (OND, post-monsoon season) followed by the secondary peak during the pre-monsoon season (March-May, MAM).

About 11 Cyclonic Disturbances (CDs) with maximum sustained wind speed (MSW) of 17 knots or more including depressions (MSW of 17-33 knots) and TCs (MSW of 34 knots or more) develop over the NIO during a year including nine and two over the BOB and AS respectively based on data of 1961-2010 (Mohapatra et al., 2014). Out of these, about five intensify into TC (maximum sustained surface wind (MSW) speed of 34 knots or more) including about four over BOB and one over the AS. About three severe TCs (MSW of 48 knots or more) are formed over the NIO during a year which includes two over the BOB and one over the AS. Considering the frequency of very severe TCs (MSW of 64 knots or more), there have been about two VSCS per year. During the southwest monsoon season (SWM) of June to September (JJAS), intense systems usually do not develop due to northward shift of the convergence zone over the land and high vertical wind shear (VWS) (Rao, 1976). About 5-6 CDs including about one TC form over the NIO during the monsoon season. TC activity in monsoon season usually occurs during the onset phase (month of June) and withdrawal phase (month of September) of SWM.

The east and west coasts of India bear the brunt of the destructive features of TC activity over the NIO (Mohapatra et al., 2012a). The India Meteorological Department (IMD) has meticulously archived records of CDs over the NIO for more than a century (IMD, 2008, 2011) so as to facilitate studies on TCs of NIO. An extensive climatology of TCs of NIO covering statistical aspects of CD formation, intensification, movement, landfall, dissipation etc. has been documented using these archives by Raj (2011). Regarding trends in CD/TC activity over NIO, significant decrease in the number of total CDs, TCs and severe TCs have been noticed during the recent years [Sikka (2006); Mohapatra et al. (2012b); Tyagi et al. (2010); Niyas et al. (2009); Mohapatra et al. (2014)].

Patnaik (2005) examined variability of storm activity over the NIO during various seasons and found that large-scale atmospheric circulation is the main cause of the observed inter-decadal variability of the storm activity over the Indian region rather than the variability of SSTs over the region. It has been noted by Landsea (2000) that the most dramatic effect of one of the greatest climate forcings, viz., the El Nino and Southern Oscillation (ENSO), upon the climate system is in changing TC characteristics around the world. TCs over various oceanic basins do not respond identically to ENSO. Based on coupled interaction of local parameters and large scale interaction of oceanic and atmospheric circulation features embedded in large scale oscillations such as ENSO, some show changes in frequency of genesis, while others show shifts in the genesis locations or in intensity. Detailed review is available in Girish Kumar and Ravichandran (2012) and Girish Kumar et al. (2014).

Ng and Chan (2011) have examined the inter-annual variations of TC activity over the NIO during 1983–2008 and have shown that such variations over the BOB during OND, can be attributed to similar variations in the atmospheric flow patterns and moist static energy that are apparently forced largely by the ENSO instead of local SSTs. In an El Nino year, conditions for TC genesis and development, including 850-hPa relative vorticity, 200–850-hPa vertical shear of zonal wind, moist static energy, 500-hPa zonal wind, 500-hPa and 850-hPa geopotential height and 200-hPa divergence, are generally less favourable in BOB and fewer intense TCs are observed during OND. The reverse occurs during a La Nina event.

The present study is to analyse variability in TC activity over NIO in the context of changing environmental conditions under global warming scenario. Significant trends in CD, TC and severe TC (STC) activity over NIO during 1951-2010 are noted and environmental features known to be associated with TC activity, viz., SST, VWS, low level vorticity (vorticity at 850 hPa (VOR850)) and mid-tropospheric humidity (Relative humidity at 500 hPa (RH500)) (Gray, 1979) are examined in relation to the trends in the CD/TC activity over the NIO. The trends are also analysed from the point of view of ENSO forcing.

Data and Methodology

The primary data used for the analysis is IMD's *Cyclone eAtlas* (IMD, 2008, 2011). Time series analysis of frequency of tropical disturbances is carried out based on intensity stratification into (a) CDs, (b) TCs and (c) severe TCs for the pre-monsoon, monsoon and post-monsoon seasons for the NIO as well as for the BOB and the AS separately. Linear trend for each of these categories is determined based on data of 1951-2010 in the inter-annual scale and tested for significance using least squares method. Trends significant at 5% level are discussed.

To study the trends in intensification, ratio of TCs to CDs and severe TCs to TCs are examined for pre-monsoon, monsoon and post-monsoon seasons as well as the year as a whole for NIO, BOB and AS for the same period. The analysis is carried out on 30-year running mean rather than with the yearly values owing to small and varying sample size. Trends in sub-seasonal and sub-basin variability are also presented and analysed from 30-year running means.

To understand the environmental features associated with significant CD/TC trends, (i) concomitant trends in the TC parameters, namely, the SST, VWS, VOR850 and RH500 during the period 1951-2010 and (ii) significant difference in mean values of the parameters between the periods 1951 to 1980 and 1981 to 2010 are also examined on seasonal scale over the region, Equator to 30°N and 50°E to 100°E using NCEP reanalysis I dataset (Kaplan SST V2 is used for SST analysis) by grid-point analysis as well as on sub-basin scale (BOB and AS separately) by area averaging over Equator to 25°N and 80°E to 100°E for BOB region and Equator to 25°N and 50°E to 75°E for the AS region.

The ENSO influence is studied by computing the CCs of SST anomaly over the four regions of equatorial Pacific, viz., Nino (1+2) (Equator-10°S, 90°W-80°W), Nino 3 (5°N-5°S, 150°W-90°W), Nino 3.4 (5°N-5°S, 170°W-120°W) and Nino 4 (5°N-5°S, 160°E-150°W) (https://climatedataguide.ucar.edu/climate-data/nino-sst-indices) with frequency of (a) CDs, (b) TCs and (c) severe TCs over the NIO in both antecedent and concurrent modes for pre-monsoon, monsoon and the post-monsoon seasons. The ENSO indices are taken from the climate datasets of Climate Prediction Centre, NOAA (www.esrl.noaa.gov/psd/data/climateindices/).

Linear Trends in CD, TC and Severe TC Frequencies

Table 1 presents the seasonal and annual linear trends in the frequencies of CDs, TCs and severe TCs over the NIO, BOB and AS during the period 1951-2010. Time series of significant trends (95% confidence level) over the BOB and the AS are presented in Figure 1. Considering the entire NIO basin, on a seasonal scale, significant decreasing trend (–0.90 and –0.16 per 10 years) in the frequencies of CDs and TCs is observed in the monsoon season and a significant decreasing trend of –0.269 per 10 years is also observed in CD frequency in the post-monsoon season. In the annual scenario, there is a significant decreasing trend in the frequency of CDs (–1.26 per 10 years) over the NIO. Considering the BOB alone, similar significant decreasing trends are observed for monsoon and annual CDs and TCs. Trend values of –0.82 (–1.13) and –0.18 (–0.16) per 10 years are obtained for frequencies of CDs and TCs during the monsoon season (year as a whole). A significant decreasing trend of –0.25 per 10 years is observed for CDs over BOB during the post-monsoon season. For the AS alone, there are no significant trends in CD, TC and severe TC frequencies during 1951-2010. These results endorse the earlier findings of Mohapatra et al. (2014).

Trends in Intensification of CDs and TCs

Table 2 and Figure 2 present the trends in ratio of frequency (30-year running total) of TCs to total CDs and that of severe TCs to total TCs over NIO, BOB and AS for different seasons and year as a whole for the period 1951-2010. There are significant decreasing trends in intensification of CDs into TCs during all the

Table 1: Linear trend in frequency of CDs, TCs and severe TCs over North Indian Ocean based on data of 1951-2010

Basin	*Annual/Season*	*CDs*			*TCs*			*Severe TCs*		
		Mean	*SD*	*Trend/ 10 years*	*Mean*	*SD*	*Trend/ 10 years*	*Mean*	*SD*	*Trend/ 10 years*
NIO	Annual	12.10	3.80	**-1.257**	4.68	1.81	-0.256	2.78	1.61	-0.137
	Pre-monsoon	1.42	0.87	-0.062	1.07	0.80	-0.032	0.72	0.74	-0.001
	Monsoon	5.73	2.75	**-0.901**	0.97	0.97	**-0.160**	0.38	0.67	-0.004
	Post-monsoon	4.75	1.78	**-0.269**	2.58	1.32	-0.084	1.67	1.19	-0.136
BOB	Annual	8.93	3.07	**-1.134**	3.55	1.57	**-0.284**	2.12	1.29	-0.162
	Pre-monsoon	1.02	0.75	-0.034	0.78	0.61	-0.034	0.55	0.59	-0.003
	Monsoon	4.03	2.19	**-0.820**	0.58	0.74	**-0.176**	0.17	0.42	-0.0393
	Post-monsoon	3.68	1.50	**-0.254**	2.12	1.26	-0.092	1.38	1.06	-0.124
AS	Annual	2.13	1.51	-0.021	1.05	1.05	0.036	0.65	0.82	0.0295
	Pre-monsoon	0.38	0.58	-0.033	0.28	0.52	0.003	0.17	0.38	0.0020
	Monsoon	0.77	0.74	-0.031	0.32	0.57	0.039	0.20	0.44	0.0403
	Post-monsoon	0.98	0.97	-0.019	0.45	0.59	-0.006	0.28	0.49	-0.0018

Significant trends are highlighted in bold.

three seasons over the NIO and during the monsoon and pre-monsoon seasons over the BOB. But, over the AS, significant positive trends are observed in the pre-monsoon and monsoon seasons. Considering the year as a whole, there are significant positive trends in the ratio of frequency of TCs to total CDs over NIO, BOB and AS. However, over the NIO, once formed, rate of intensification of TCs into severe TCs has increased significantly during pre-monsoon and monsoon seasons but decreased significantly during the post-monsoon season. Considering BOB alone, significant decreasing trends are observed in intensification of TCs to severe TCs during the monsoon and post-monsoon seasons, but significant increasing trend in intensification of pre-monsoon TCs into severe TCs. Over the AS, there is a significant increase in the intensification of TCs into severe TCs during the monsoon season which is also reflected in the year as a whole.

Trends in Spatial and Temporal Distribution of CDs, TCs and Severe TCs

Seasonal variations in the formation/intensification of CDs/TCs/severe TCs over NIO, BOB and AS are examined by analysing the trends in the ratio of post-monsoon to pre-monsoon CD, TC and severe TC frequency (30-year running total) during the period 1951-2010. These are presented in Table 3 and Figure 3. There are significant positive trends in the ratios of post-monsoon to pre-monsoon CDs over NIO and AS and significant positive trends in the ratio of post-monsoon to pre-monsoon TCs over all the three basins indicating relatively increased (decreased) activity during the post-monsoon (pre-monsoon) season. Considering ratio of post-monsoon to pre-monsoon severe TCs, there is a significant decreasing trend over the BOB due to decreased severe TC activity over the BOB during the post-monsoon season.

Table 4 and Figure 4 present the variability in sub-basin of formation/intensification by depicting the trends in BOB to AS ratio of CD/TC/severe TC frequency (30-year running total) over for pre-monsoon, monsoon and post-monsoon seasons as well as the year as a whole for the period 1951-2010. The ratio shows significant decreasing trends for monsoon and post-monsoon seasons and year as a whole in all the cases—CDs, TCs and severe TCs. However, CD frequency ratio for BOB to AS shows an increasing trend in the pre-monsoon season.

Trends in Associated Environmental Parameters

Trends in the environmental parameters namely SST, VWS, VOR850 and RH500 are analysed for BOB and AS from the time series of area averaged seasonal and annual mean values of the parameters during the period

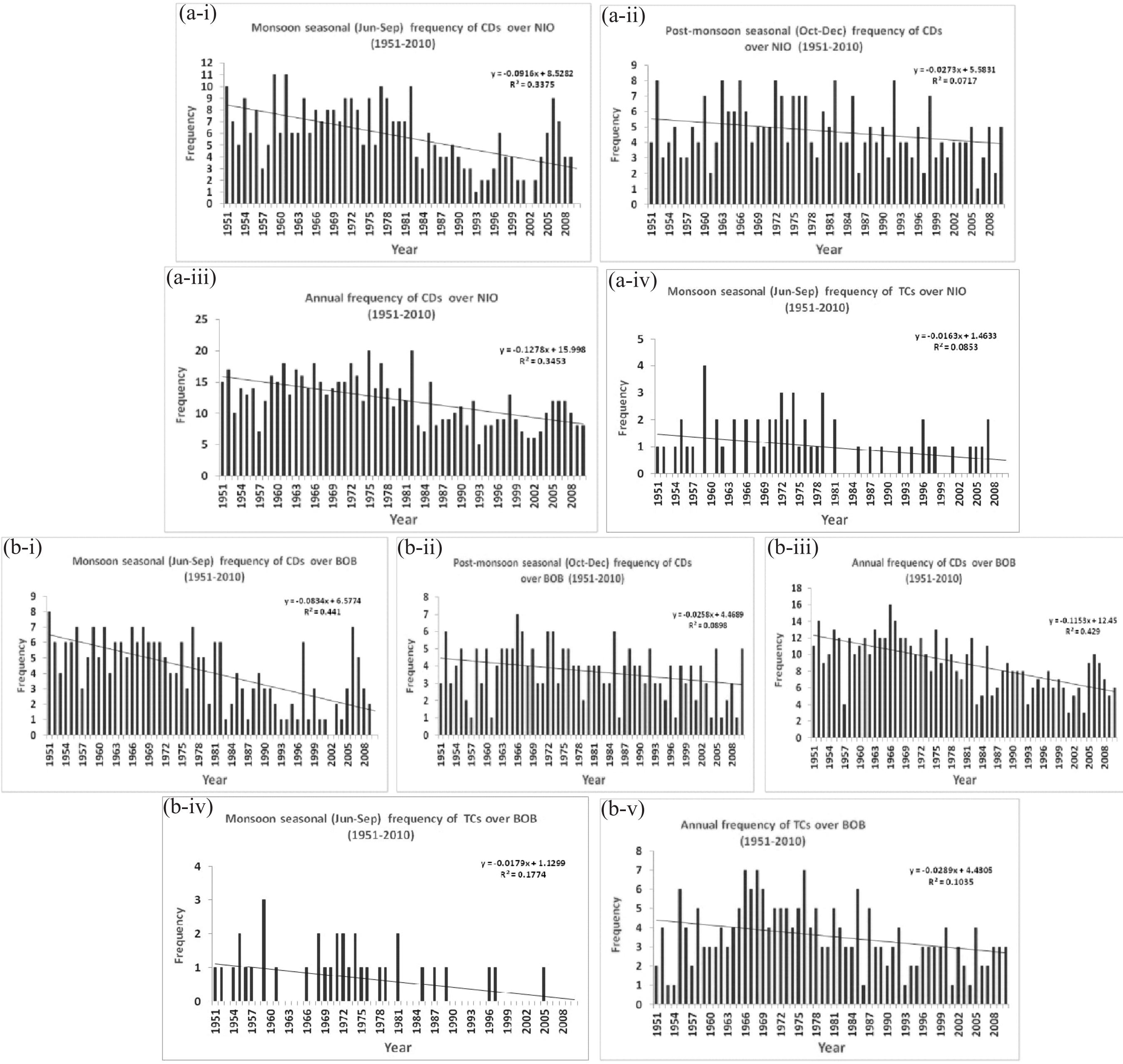

Figure 1: a(i-iv), b(i-v): Significant trends in frequency of (a) CDs in (i) monsoon season, (ii) post monsoon season, (iii) year as a whole and (iv) TCs in monsoon season over NIO and (b) CDs in (i) monsoon season (ii) post monsoon season, (iii) year as a whole and TCs in (iv) monsoon season and (v) year as a whole over BOB during 1951-2010.

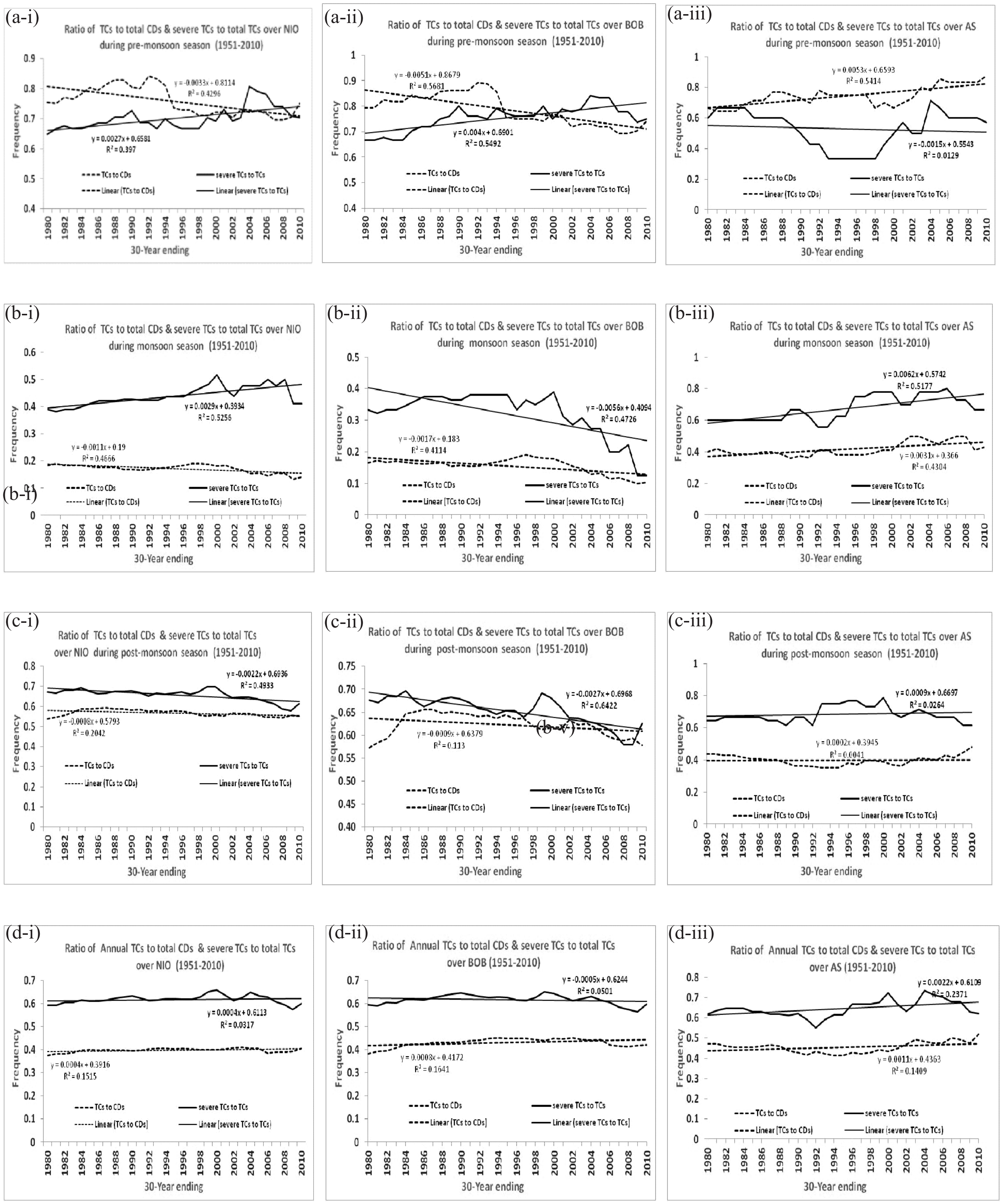

Figure 2: Linear trends in ratio of TC to CD and severe TC to TC frequencies (30-year moving total) during (a) pre-monsoon, (b) monsoon, (c) post-monsoon and (d) year as a whole over (i) NIO, (ii) BOB and (iii)AS for the period 1951-2010.

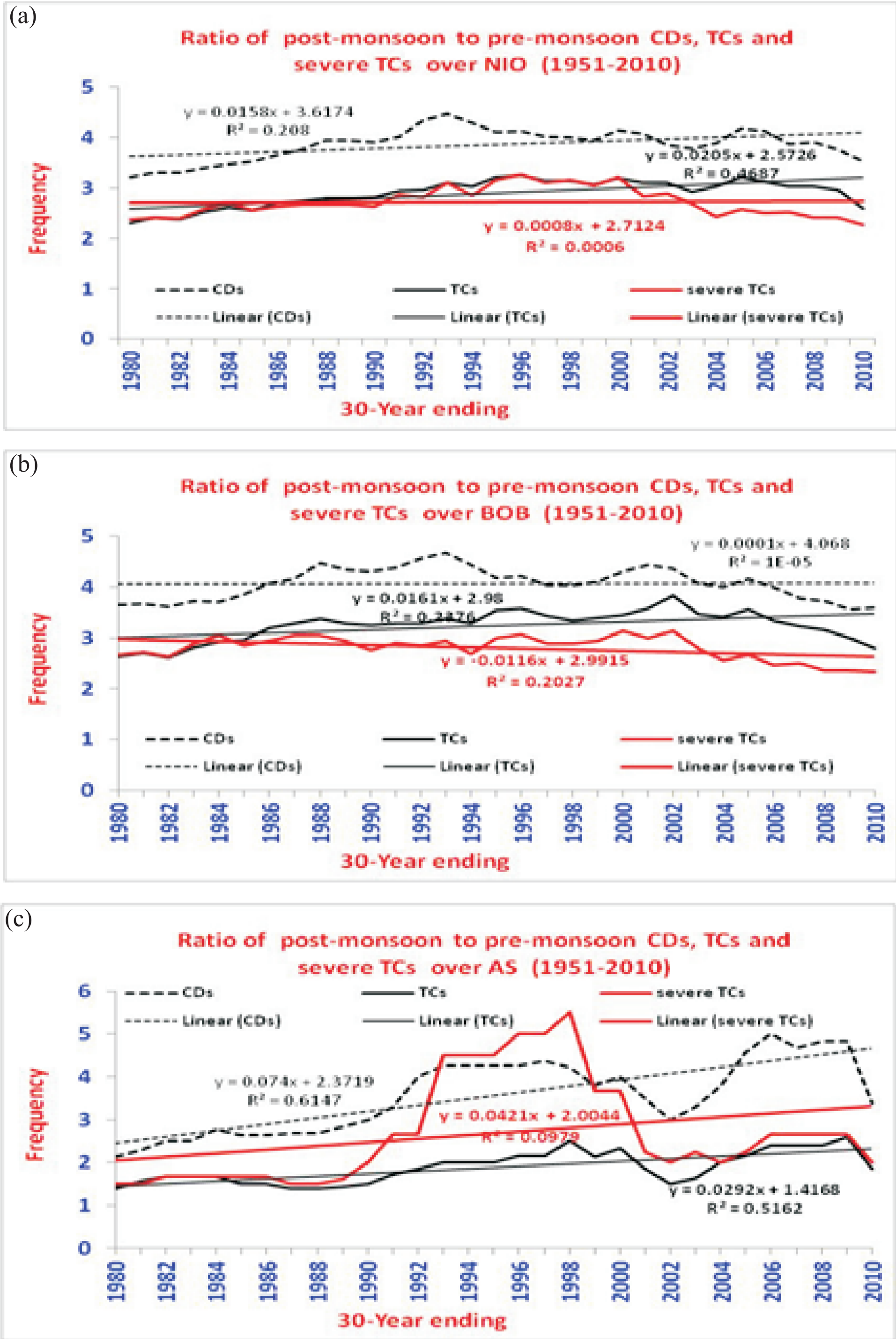

Figure 3: Linear trends in ratio of post-monsoon to pre-monsoon CD, TC and severe TC frequencies (30-year moving total) over (a) NIO, (b) BOB and (c) AS during 1951-2010.

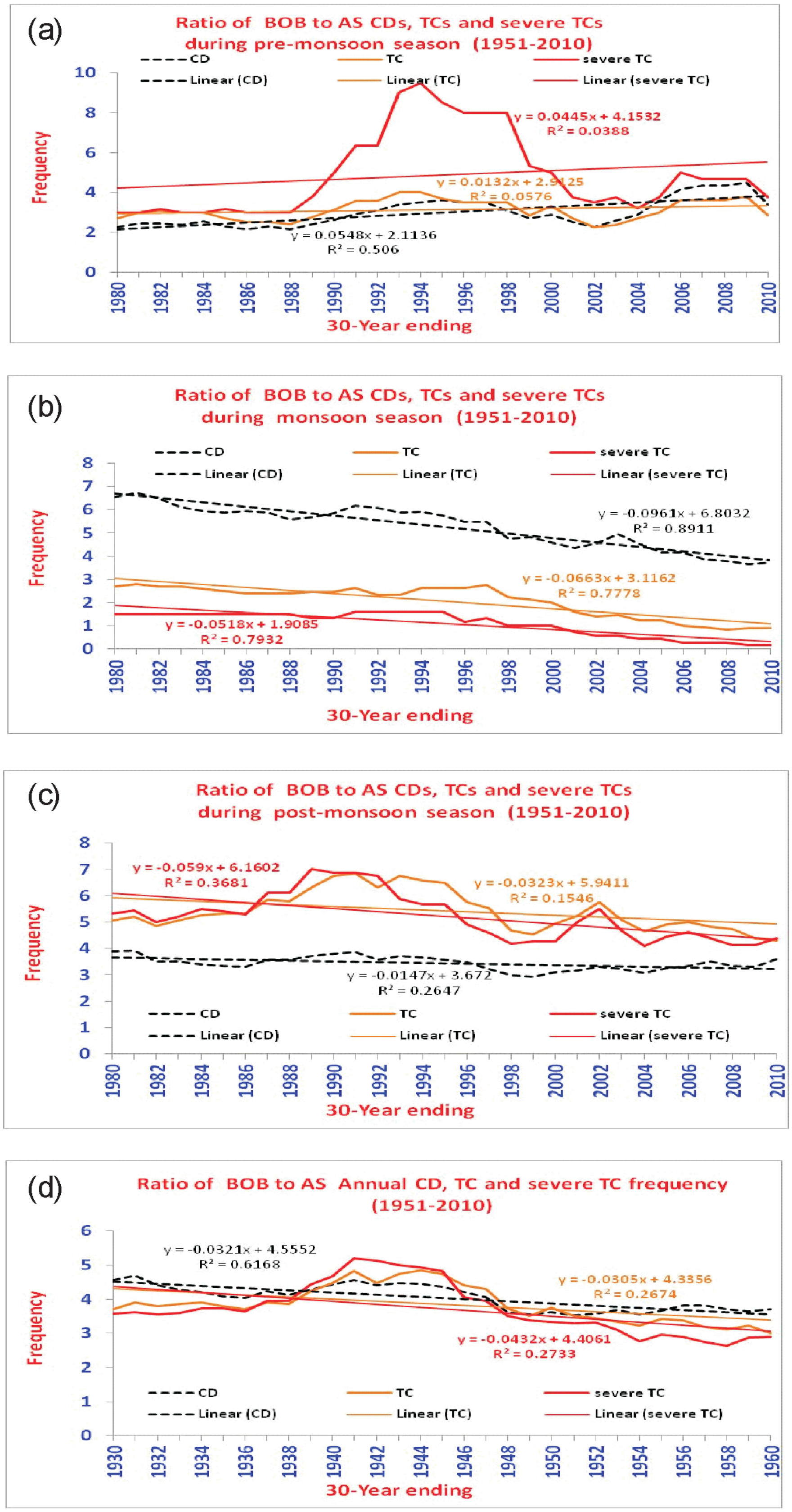

Figure 4: Linear trends in ratio of BOB to AS CD, TC and severe TC frequencies during (a) pre-monsoon, (b) monsoon, (c) post-monsoon and (d) year as a whole over the period 1951-2010.

Table 2: Linear trend in ratio of TC to CD and severe TC to TC frequencies over North Indian Ocean during 1951-2010

Basin	*Annual/Season*	*Ratio of 30-year running total TC to CD frequency*			*Ratio of 30-year running total severe TC to TC frequency*		
		Mean	*SD*	*Trend/ 10 years*	*Mean*	*SD*	*Trend/ 10 years*
NIO	Annual	0.40	0.01	**0.004**	0.62	0.02	0.004
	Pre-monsoon	0.76	0.05	**-0.032**	0.70	0.04	0.026
	Monsoon	0.17	0.02	**-0.011**	044	0.04	0.028
	Post-monsoon	0.57	0.02	**-0.008**	0.66	0.03	-0.021
BOB	Annual	0.43	0.02	**0.008**	0.62	0.02	-0.005
	Pre-monsoon	0.79	0.06	**-0.049**	0.76	0.05	**0.039**
	Monsoon	0.15	0.03	**-0.016**	0.32	0.08	**-0.054**
	Post-monsoon	0.62	0.02	-0.009	0.65	0.03	**-0.026**
AS	Annual	0.75	0.06	**0.011**	0.65	0.04	**0.021**
	Pre-monsoon	0.75	0.06	**0.051**	0.53	0.12	**-0.015**
	Monsoon	0.42	0.04	**0.030**	0.68	0.08	**0.060**
	Post-monsoon	0.45	0.03	**0.002**	0.69	0.05	**0.009**

Significant trends are highlighted in bold.

Table 3: Linear trend in ratio of post-monsoon to pre-monsoon CD/TC/severe TC frequencies (30-year running total) over North Indian Ocean during 1951-2010

Basin	*Ratio of post-monsoon to pre-monsoon CDs*			*Ratio of post-monsoon to pre-monsoon TCs*			*Ratio of post-monsoon to pre-monsoon severe TCs*		
	Mean	*SD*	*Trend/ 10 years*	*Mean*	*SD*	*Trend/ 10 years*	*Mean*	*SD*	*Trend/ 10 years*
NIO	3.89	0.30	**0.153**	2.92	0.25	**0.198**	2.74	0.28	0.008
BOB	4.08	0.31	0.001	3.26	0.28	**0.156**	2.81	0.24	**-0.112**
AS	3.60	0.83	**0.716**	1.90	0.36	**0.283**	2.72	1.22	0.407

Table 4: Linear trend in ratio of BOB to AS CD/TC/severe TC frequencies (30-year running total) over North Indian Ocean during 1951-2010

Annual/Season	*Ratio of BOB to AS CD frequency*			*Ratio of BOB to AS TC frequency*			*Ratio of BOB to AS severe TC frequency*		
	Mean	*SD*	*Trend/ 10 years*	*Mean*	*SD*	*Trend/ 10 years*	*Mean*	*SD*	*Trend/ 10 years*
Annual	4.0	0.4	**-0.311**	3.8	0.5	**-0.295**	3.7	0.8	**-0.418**
Pre-monsoon	3.0	0.7	**0.530**	3.1	0.5	0.128	4.9	2.1	0.431
Monsoon	5.3	0.9	**-0.930**	2.1	0.7	**-0.642**	1.1	0.5	**-0.501**
Post-monsoon	3.4	0.3	**-0.142**	5.4	0.7	**-0.313**	5.2	0.9	**-0.571**

1951-2010 and presented in Table 5 and significant trends are depicted in Figures 5-8a. As any change in atmospheric and oceanic circulation patterns due to climate change is expected to reflect in the difference in mean values of these parameters between the first and the second half of the period under consideration, differences in their means between the two 30-year periods 1951-1980 and 1981-2010 are presented in Table 6 and Figures 5-8b and significant differences in means are discussed.

Pre-monsoon Season

Environmental features in the pre-monsoon season show significant changes during the period 1951-2010 (Table 5). There is a significant increasing trend in the SST at the rate of 0.07°C per 10 years over BOB and AS. VWS is significantly decreasing over the AS at the rate of –0.32 ms^{-1} per 10 years (Table 5). It endorses the earlier findings of Rajeevan et al. (2013). On the spatial distribution, VWS has increased by 0-2 ms^{-1} over most parts of BOB, but, has decreased over most parts of AS (–2 to 0 ms^{-1}) during the recent 30-year period (1981-2010) compared to the previous 30-year period (1951-1980) [Figure 5b(ii)]. There is a significant enhancement of low level cyclonic vorticity (VOR850) over the BOB and significantly decreasing anti-cyclonic vorticity over the AS (Figure 5a). This enhancement of VOR850 over BOB is confined to the northern and eastern parts of BOB and there is a slight decrease of VOR850 in the southwestern parts of BOB in the recent period (1981-2010) [Figure 5b(iii)]. The mid-tropospheric humidity (RH500) is significantly decreasing over both BOB and AS at –1.3% and –2.2% per 10 years respectively (Table 5). The decrease is more pronounced in the southern parts of the AS, south of 10°N (8-12%), compared to rest of AS and BOB [Figure 5b(iv)].

The above significant trends in the environmental parameters are also supported by significant differences in their mean values between the periods 1951-1980 and 1981-2010 (Table 6). Thus, even though, SST and VOR850 over BOB and SST, VWS and VOR850 over AS are becoming more favourable for increasing the cyclogenesis and TC activity, the significant decreasing trend in RH500 over both BOB and AS could play a major role in offsetting the favourable situations for enhanced cyclonic activity over BOB and AS and hence no significant trend in CD/TC/severe TC activity is observed over the BOB and AS during the pre-monsoon season. However, the increased VWS and decreased VOR850 over southern part of BOB may be associated with the significant decreasing trend in the intensification of CDs to TCs over BOB during the pre-monsoon season. Once formed, significantly increasing

Table 5: Annual and seasonal trends in environmental parameters over BOB and AS during 1951-2010

Parameter	*Annual/Season*	*BOB*			*AS*		
		Mean	*SD*	*Trend/10 years*	*Mean*	*SD*	*Trend/10 years*
SST (anomaly)	Pre-monsoon	0.091	0.229	**0.067**	0.101	0.244	**0.066**
	Monsoon	0.169	0.283	**0.113**	0.144	0.265	**0.084**
	Post-monsoon	0.166	0.279	**0.112**	0.171	0.300	**0.094**
	Annual	0.132	0.235	**0.093**	0.124	0.205	**0.075**
VWS	Pre-monsoon	13.56	1.01	0.015	13.70	1.37	**-0.315**
	Monsoon	23.63	1.32	**-0.263**	25.17	1.90	**-0.437**
	Post-monsoon	14.40	1.18	-0.177	15.36	1.09	**-0.190**
	Annual	17.82	0.71	**-0.132**	18.81	0.92	**-0.288**
VOR850 ($\times 10^{-5}$ s^{-1})	Pre-monsoon	0.082	0.09	**0.022**	-0.207	0.06	**0.015**
	Monsoon	0.301	0.09	-0.005	-0.220	0.08	**-0.020**
	Post-monsoon	0.222	0.12	0.007	0.085	0.09	**0.015**
	Annual	0.179	0.06	0.009	-0.139	0.05	0.003
RH500	Pre-monsoon	33.06	4.23	**-1.275**	22.85	4.80	**-2.213**
	Monsoon	57.27	3.40	**-1.423**	43.87	4.91	**-2.139**
	Post-monsoon	45.48	4.19	**-0.661**	30.02	3.57	**-0.709**
	Annual	43.86	3.15	**-1.152**	31.51	3.41	**-1.600**

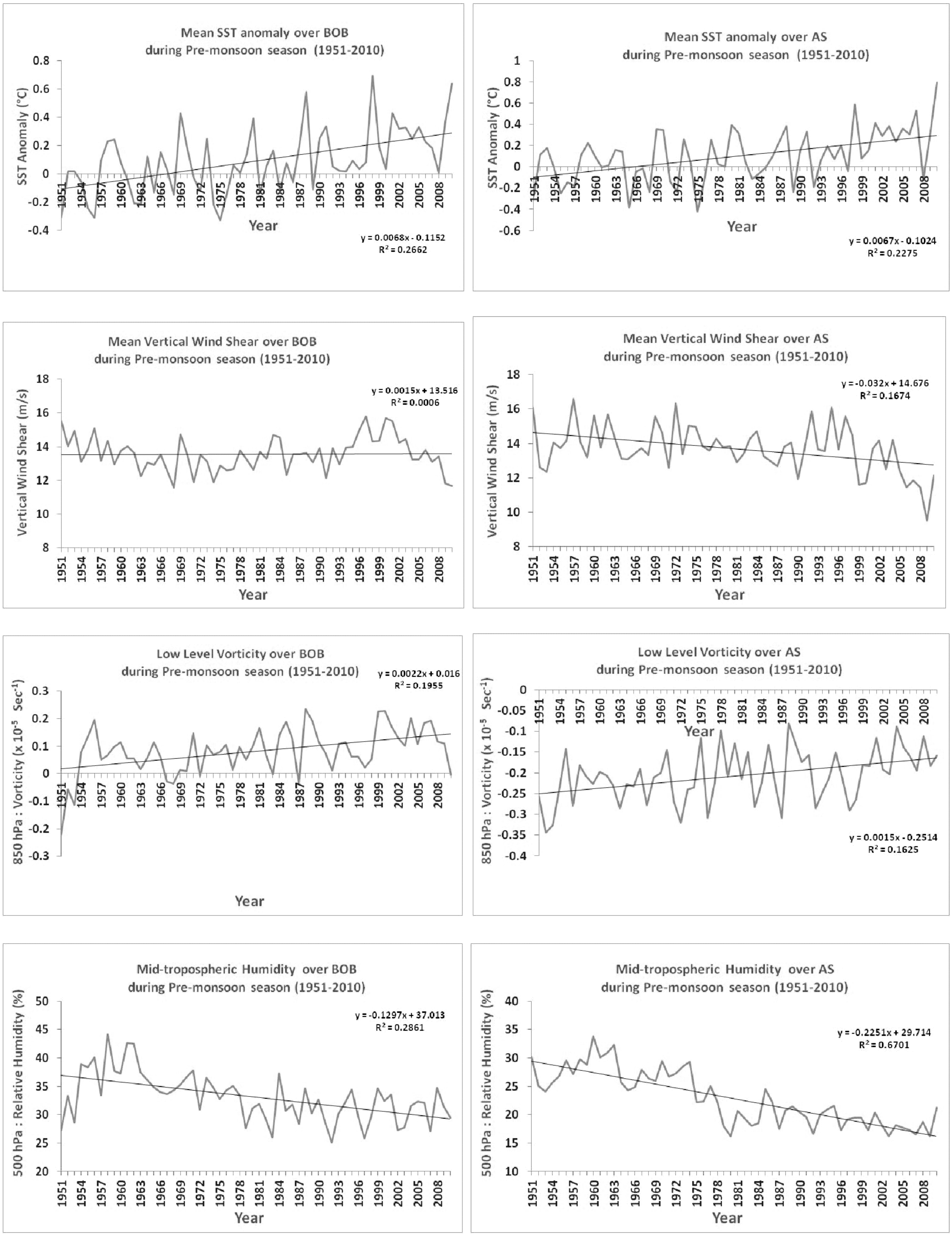

Figure 5a: Trends in pre-monsoon (i) SST, (ii) VWS, (iii) VOR850 and (iv) RH500 over BOB (averaged over Equator to 25°N and 80°E to 100°E) and AS (averaged over Equator to 25°N and 50°E to 75°E).

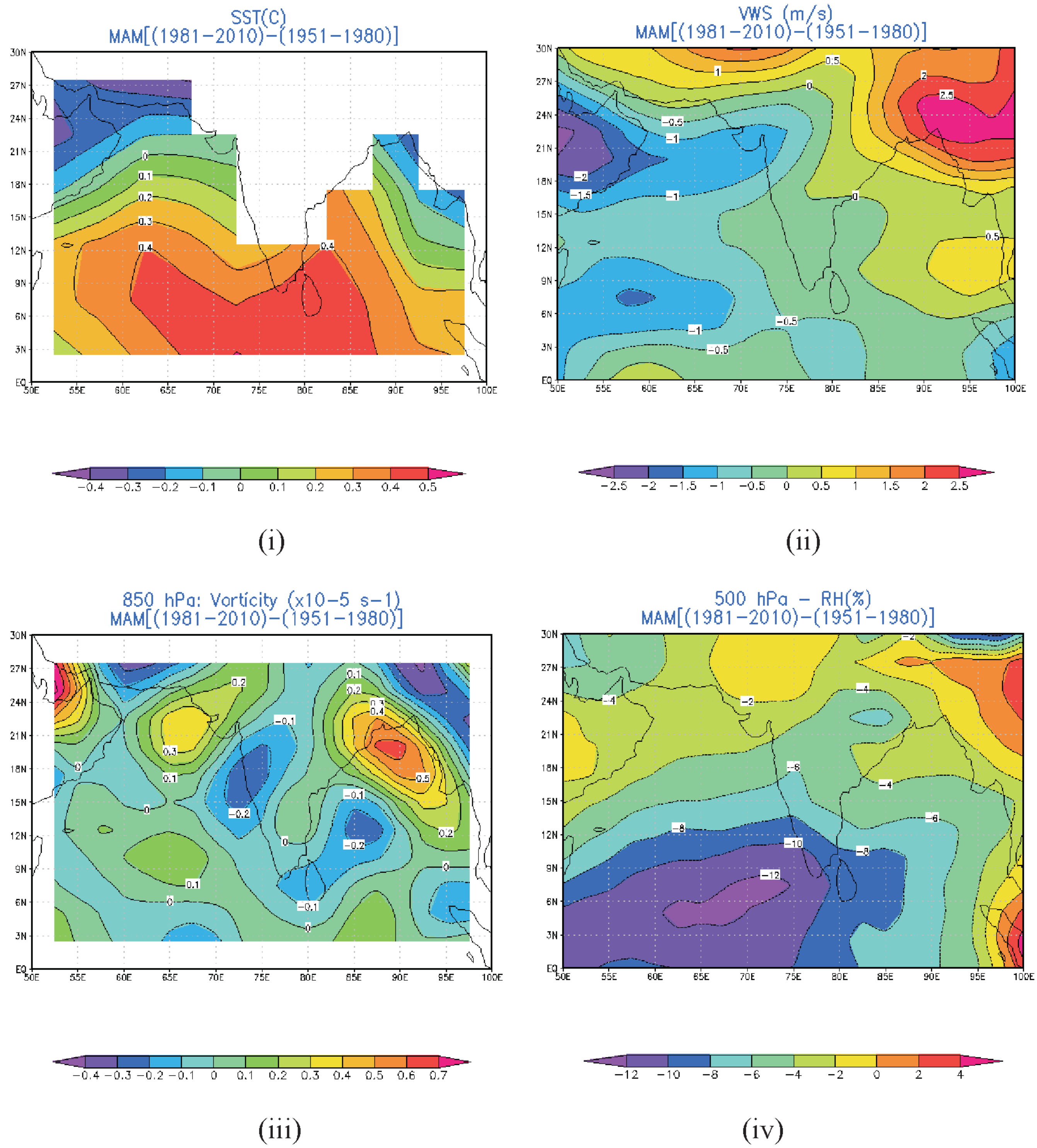

Figure 5b: Spatial distribution of differences in mean (i) SST, (ii) VWS, (iii) VOR850 and (iv) RH500 during the pre-monsoon season.

Table 6: Differences in means of environmental parameters between 1951-1980 and 1981-2010 over BOB and AS

Environmental parameter	*Basin*	*Parameter statistic*	*MAM*	*JJAS*	*OND*	*Annual*
SST (ano)	BOB	Mean (M1)	-0.003	-0.010	0.004	-0.007
		Mean (M2)	0.185	0.348	0.328	0.272
		Diff (M1 – M2)	**0.188**	**0.357**	**0.325**	**0.279**
		SD1	0.204	0.189	0.251	0.185
		SD2	0.216	0.247	0.202	0.196
	AS	Mean (M1)	0.009	0.012	0.022	0.010
		Mean (M2)	0.192	0.276	0.321	0.238
		Diff (M1 – M2)	**0.183**	**0.264**	**0.299**	**0.228**
		SD1	0.217	0.206	0.278	0.163
		SD2	0.237	0.254	0.244	0.180
VWS	BOB	Mean (M1)	13.357	23.865	14.501	17.883
		Mean (M2)	13.763	23.390	14.295	17.747
		Diff (M1 – M2)	0.407	-0.475	-0.206	-0.135
		SD1	0.957	1.264	1.216	0.751
		SD2	1.031	1.343	1.160	0.671
	AS	Mean (M1)	14.155	25.721	15.693	19.229
		Mean (M2)	13.244	24.611	15.019	18.397
		Diff (M1 – M2)	**-0.911**	**-1.110**	**-0.674**	**-0.833**
		SD1	1.125	1.897	1.030	0.624
		SD2	1.449	1.766	1.052	0.977
VOR850	BOB	Mean (M1)	0.047	0.303	0.211	0.163
		Mean (M2)	0.116	0.299	0.232	0.195
		Diff (M1 – M2)	**0.069**	-0.004	0.020	**0.033**
		SD1	0.082	0.095	0.109	0.060
		SD2	0.075	0.091	0.125	0.056
	AS	Mean (M1)	-0.225	-0.174	0.076	-0.132
		Mean (M2)	-0.189	-0.267	0.094	-0.146
		Diff (M1 – M2)	**0.037**	**-0.093**	0.018	-0.014
		SD1	0.061	0.075	0.073	0.047
		SD2	0.060	0.066	0.099	0.042
RH500	BOB	Mean (M1)	35.356	59.499	46.755	45.781
		Mean (M2)	30.760	55.037	44.204	41.935
		Diff (M1 – M2)	**-4.596**	**-4.462**	**-2.552**	**-3.846**
		SD1	4.085	2.648	4.043	2.700
		SD2	2.975	2.477	4.007	2.278
	AS	Mean (M1)	26.524	47.435	31.498	34.266
		Mean (M2)	19.174	40.303	28.536	28.748
		Diff (M1 – M2)	**-7.350**	**-7.132**	**-2.963**	**-5.518**
		SD1	3.876	3.955	3.850	2.526
		SD2	1.987	2.677	2.575	1.206

1 and 2 in statistical parameters indicate periods 1951-1980 and 1981-2010 respectively. Significant differences are indicated in bold.

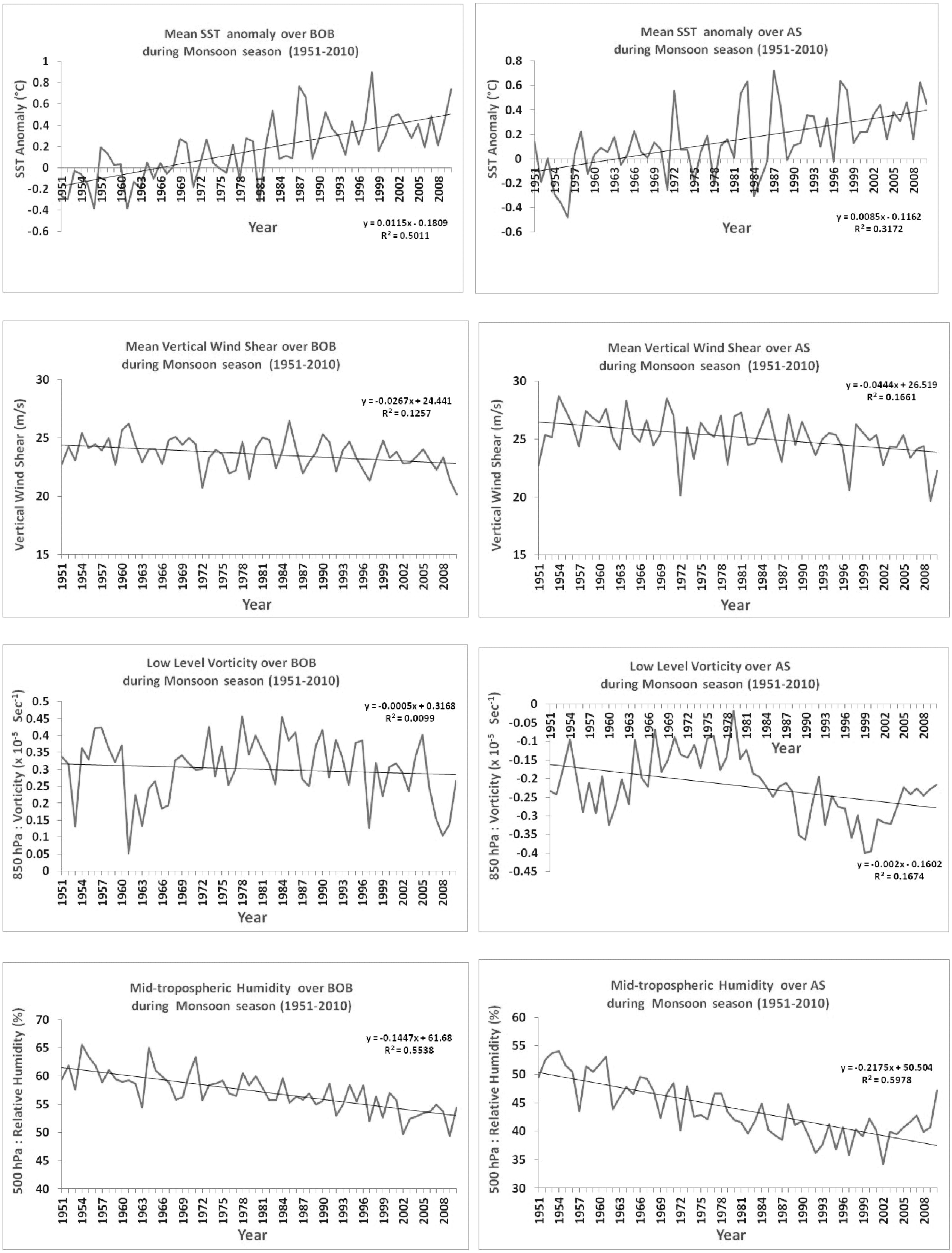

Figure 6a: Same as Figure 5a, but for the monsoon season.

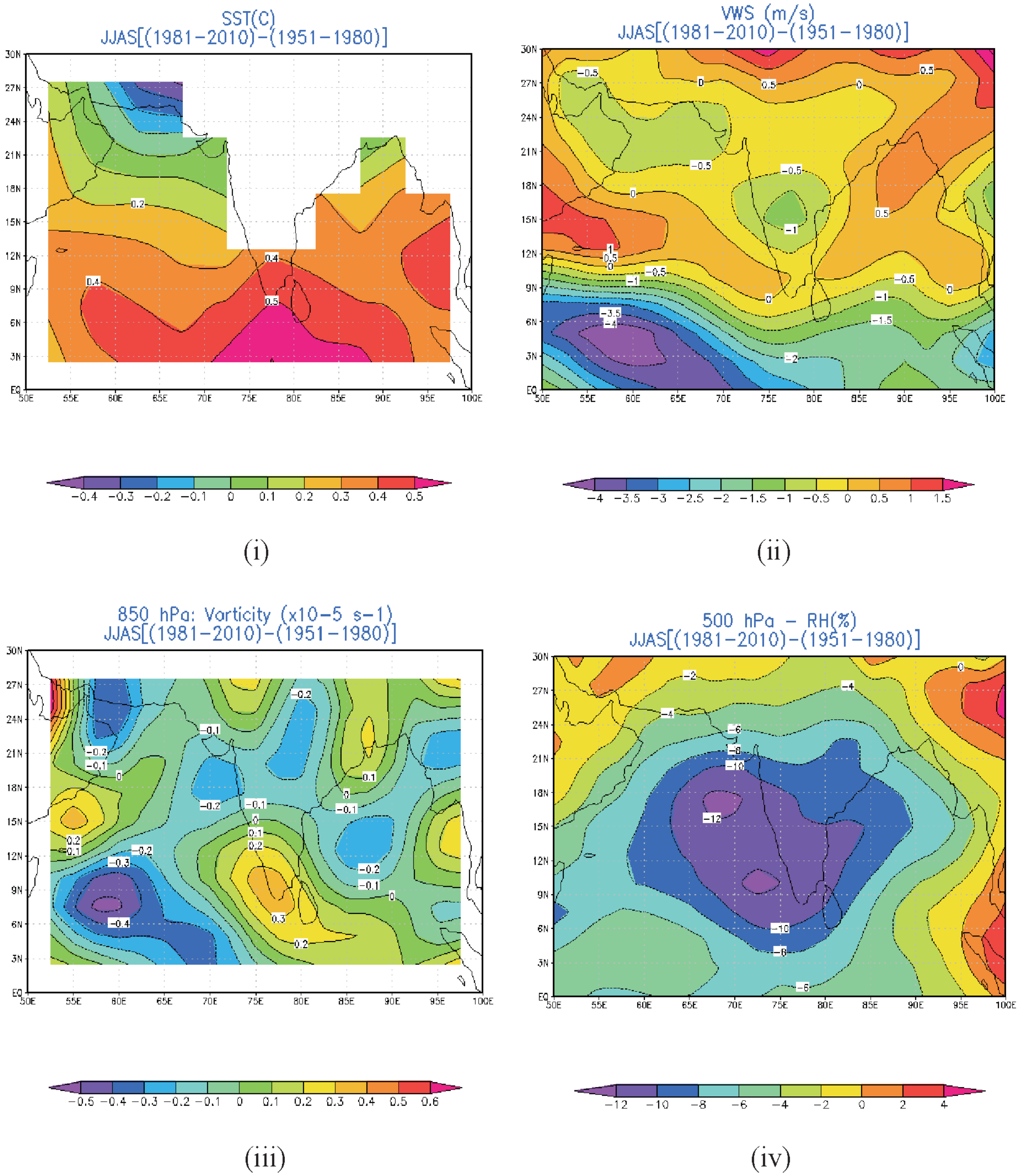

Figure 6b: Same as the Figure 5b, but for the monsoon season.

trend in intensification of TCs into severe TCs over the BOB could be associated with the favourable factors such as enhanced SST and increasing VOR850 in the northern and eastern parts of BOB aside from synoptic scale interactions known to be associated with intensification of TCs.

Monsoon Season

During the monsoon season, there is a significant increasing trend in the SST at the rate of 0.11°C over BOB and 0.08°C over AS per 10 years (Table 5). The VWS is significantly decreasing over both BOB and AS at the rate of –0.26 ms^{-1} and –0.32 ms^{-1} per 10 years respectively (Table 5). The decrease is confined to the southern parts of BOB and AS, south of 10°N and it is more pronounced over the southwest AS (a difference of –3 to –4 m s^{-1} during the period 1981-2010 compared to 1951-1980). However, there is a slight increase in the VWS over the central and northern parts of BOB by 0-1 ms^{-1}, the region is climatologically favourable for formation of synoptic scale systems [Figure 6b(ii)]. There is no significant trend in VOR850 over BOB. Over AS, there is a significantly increasing anti-cyclonic vorticity (Table 5 and Figure 6a). However, there is a decrease of anti-cyclonic vorticity at 850 hPa level over the southeastern parts of AS [Figure 6b(iii)]. The RH500 is significantly decreasing over both BOB and AS at –1.4% and –2.1% per 10 years respectively (Table 5). The decrease is well pronounced over the eastern parts of the AS (8-12%) during 1981-2010 compared to 1951-1980 [Figure 6b(iv)].

There is also significant difference in the mean values (between the periods 1951-1980 and 1981-2010) of the parameters having significant trends as discussed above (Table 6). Thus, in the monsoon season, despite enhanced SST and decrease of VWS over BOB and AS, significantly decreasing RH500, increasing VWS over northern parts of BOB and increasing anti-cyclonic vorticity over AS have contributed towards significant decreasing trends in CD and TC frequency over BOB and for the entire NIO as well. However, the enhanced SST, decrease in VWS and decrease of anti-cyclonic vorticity over the southeastern parts of AS could have contributed towards significantly increasing trends in intensification of CDs to TCs and TCs to severe TCs over the AS during the monsoon season.

Post-monsoon Season

During the post-monsoon season, there is a significant increasing trend in the SST at the rate of 0.09°C over BOB and 0.08°C over AS per 10 years (Table 5). The VWS is significantly decreasing over the AS at the rate of –0.19 ms^{-1} per 10 years (Table 5). Over BOB, VWS has decreased by 0-2 ms^{-1} over the southern parts, south of 12°N, but, has increased over the northern parts during the recent 30-year period [Figure 7b(ii)]. There is a significant enhancement of VOR850 over the AS (Figure 7a). Even though there is no significant trend in VOR850 over the BOB, the difference in the mean value between the two 30-year periods 1951-1980 and 1981-2010 indicate increased cyclonic vorticity over the northern parts of BOB (North of 15°N) and decreased cyclonic vorticity over the southern and western parts of BOB (South of 15°N) [Figure 7b(iii)]. The RH500 is significantly decreasing over both BOB and AS at –0.66% and –0.71% per 10 years respectively (Table 5). Thus, significantly decreasing trends in CD frequency over BOB and entire NIO and significantly decreasing trends in intensification of CDs to TCs over NIO during the post-monsoon season could be associated with the decreased cyclonic vorticity over the southern parts of BOB and significantly decreasing trends in RH500 over BOB.

On the Formation and Movement of CDs under Changing Environment

As significant changes in environmental features are likely to affect the area of formation and the direction of movement of TCs, tracks of CDs during the periods 1951-1980 and 1981-2010 and the mean latitude and longitude of formation are analysed for various seasons. There are no discernible differences in the direction of movement of CDs between the two periods during pre-monsoon, monsoon and post-monsoon CDs (not shown). Regarding the genesis location, Table 7 presents the seasonal mean latitude and longitude of formation of CDs over BOB and AS during the two 30-year periods. It is noted that there are significant differences in the mean latitude and longitude of formation of CDs over the AS during the pre-monsoon season. There is a significant northward shift of mean latitude of formation by 1.7° from 10.99°N during 1951-1980 to 12.68°N during 1981-2010 and westward shift of mean longitude of formation by 3.7° from 69.59°E to 65.86°E between the same periods over AS during the pre-monsoon season. However, such differences in mean latitude and longitude of formation over AS and BOB during other seasons are not significant even though, it may be mentioned that a northward shift of latitude of formation is observed during the post-monsoon season even in monthly scale though not statistically significant as yet. The mean latitude of formation during the post-monsoon

Table 7: Seasonal normal latitude and longitude of formation over BOB and AS during 1951-1980 and 1981-2010

Season/ Basin	*No. formed*		*Mean lon. of formation (E)*		*Mean lat. of formation*		*S.D of lon. of formation*		*S.D of lat. of formation*	
	1951-1980	1981-2010	1951-1980	1981-2010	1951-1980	1981-2010	1951-1980	1981-2010	1951-1980	1981-2010
	MAM									
AS	14	8	**69.59**	**65.86**	**10.99**	**12.68**	3.55	6.46	2.92	1.64
BOB	34	28	89.47	88.92	12.65	12.90	3.95	3.28	3.74	4.08
	JJAS									
AS	31	23	69.92	69.38	18.88	18.72	2.44	3.29	4.19	4.09
BOB	194	97	88.46	87.58	19.55	19.97	2.64	3.30	2.54	2.55
	OND									
AS	32	27	69.47	68.43	12.18	11.46	3.29	3.58	4.02	3.77
BOB	126	100	88.22	87.62	**10.82**	**11.91**	3.91	4.41	3.80	3.81

season shows a northward shift by about 1°N during 1981-2010 (11.9°N) compared to that during 1951-1980 (10.8°N) and in monthly scale, the mean latitude of formation during the two periods are 13.31°N and 14.67°N respectively in October, 9.78°N and 10.75°N in November and 7.5°N and 8.0°N in December.

On examining the difference in the frequency of formation over various 2.5° × 2.5° latitude/longitude boxes, it is noted that there is a sharp decrease in the frequency of formation of CDs over the box of 5°N to 10°N and 80°E to 92.5°E during the period of 1981-2010 compared to 1951-1980. It is interesting to note that there is a decrease of 27 CDs in frequency of CDs formed over this box during the recent 30-year period (26 in 1981-2010) compared to the earlier period (53 in 1951-1980), but the frequency of CD formation over rest of the BOB is the same for both the periods (70 CDs). The same is depicted pictorially in Figure 8. This suggests that the decreasing CD trends over BOB during the post-monsoon season could be in association with drastic decrease of cyclogenesis over the southern latitudes where there is a decrease of cyclonic vorticity during the recent years.

Role of ENSO on CD/TC/Severe TC Frequency Trends

Aside from the changing environment due to climate change, TC activity is also modulated by the two major climate settings, viz., El Nino and La Nina (Ng and Chan, 2011). To understand the role of El Nino and La Nina in the changing climate scenario, we next analyse the tele-connective influence of ENSO on cyclonic activity over NIO during the period 1951-2010 in the context of climate change. Table 8 presents the frequency of CDs, TCs and severe TCs over NIO during the two cyclone seasons (pre-monsoon and post-monsoon) for the periods 1951-1980 and 1981-2010 for two different climate settings, viz., El Nino and La Nina years (based on NCEP's concurrent Oceanic Nino Index, ±0.5°C). During the pre-monsoon season, greater CD/TC/severe TC activity is observed in the La Nina years compared to El Nino years of both the periods. During the post-monsoon season, there is a sharp decrease in CD/TC/severe TC activity over NIO during the El Nino years of the recent 30-year period (1981-2010) compared to 1951-1980. No such difference is observed for the La Nina years. Further, not much difference noted in CD/TC/severe TC frequencies over NIO between the El Nino and La Nina years of the same period, but, discernible differences are noted in the tracks, especially in the case of severe TCs (Figure 9). Whereas most of the severe TCs tracked westwards during El Nino years, they tracked northwards during La Nina years. Associated with the above changes, concomitant changes in the relation between ENSO and CD/TC/severe TC frequencies during the period 1951-2010 are presented and discussed season-wise based on 30-year sliding CCs.

Pre-monsoon Season

Figure 10 depicts the relationship of frequency of CDs, TCs and severe TCs over NIO with the four Nino indices in the antecedent mode (Jan-Feb: JF) and in the concurrent mode during the pre-monsoon season. Regarding the Nino relationship with the CD

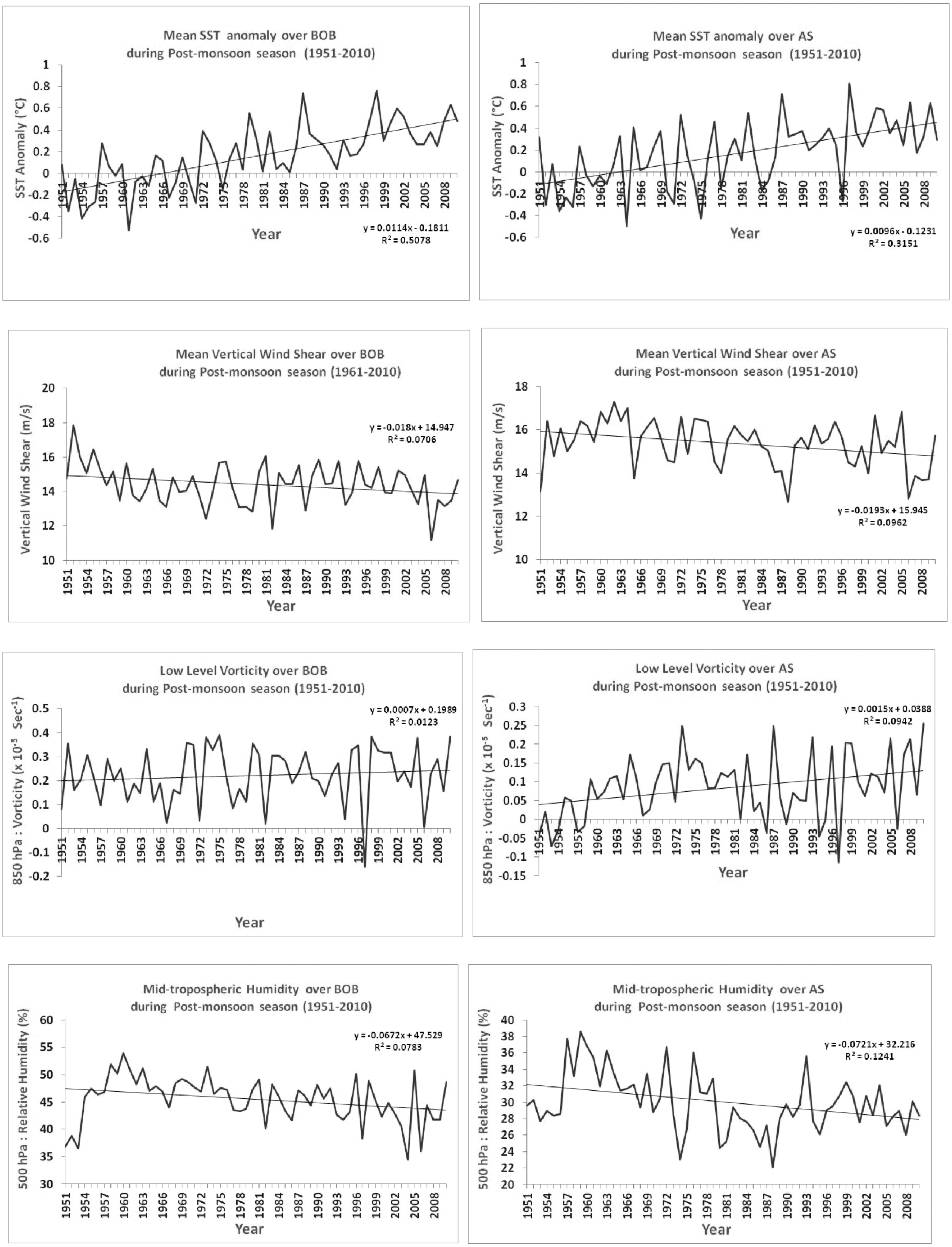

Figure 7a: Same as Figure 5a, but for post-monsoon season.

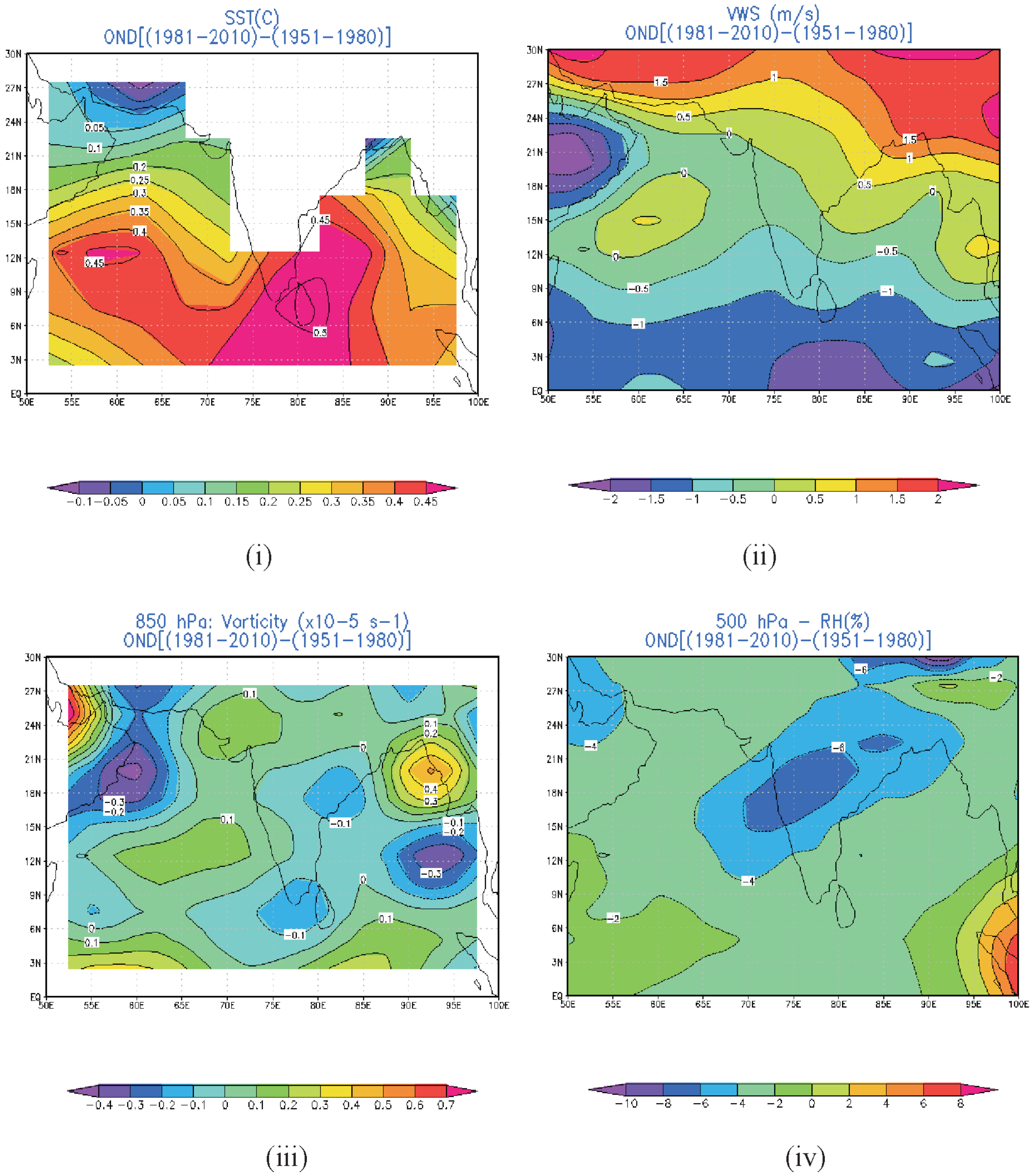

Figure 7b: Same as Figure 5b, but for post-monsoon season.

Table 8: Frequency of CDs, TCs and severe TCs over NIO during El Nino and La Nina years for the pre-monsoon and post-monsoon seasons of the periods 1951-1980 and 1981-2010

Season	*El Nino years*						*La Nina years*					
	1951-1980			*1981-2010*			*1951-1980*			*1981-2010*		
	CD	*TC*	*STC*	*CD*	*TC*	*STC*	*CD*	*TC*	*STC*	*CD*	*TC*	*STC*
Pre-monsoon	7	4	2	6	5	3	13	11	5	11	6	4
Post-monsoon	**60**	**36**	**22**	**34**	**18**	**9**	46	24	19	43	26	19

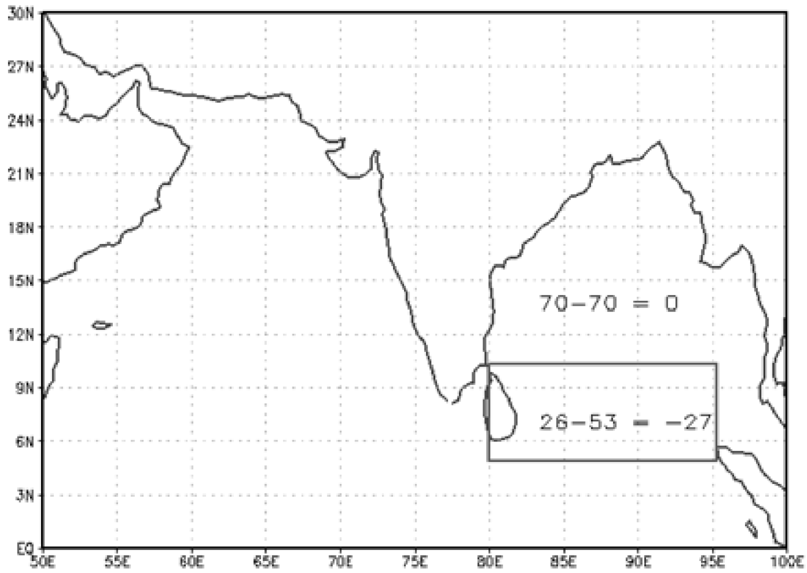

Figure 8: Comparison of number of CDs formed over the box 5-10°N and 80-92.5°E and rest of BOB during 1951-1980 and 1981-2010.

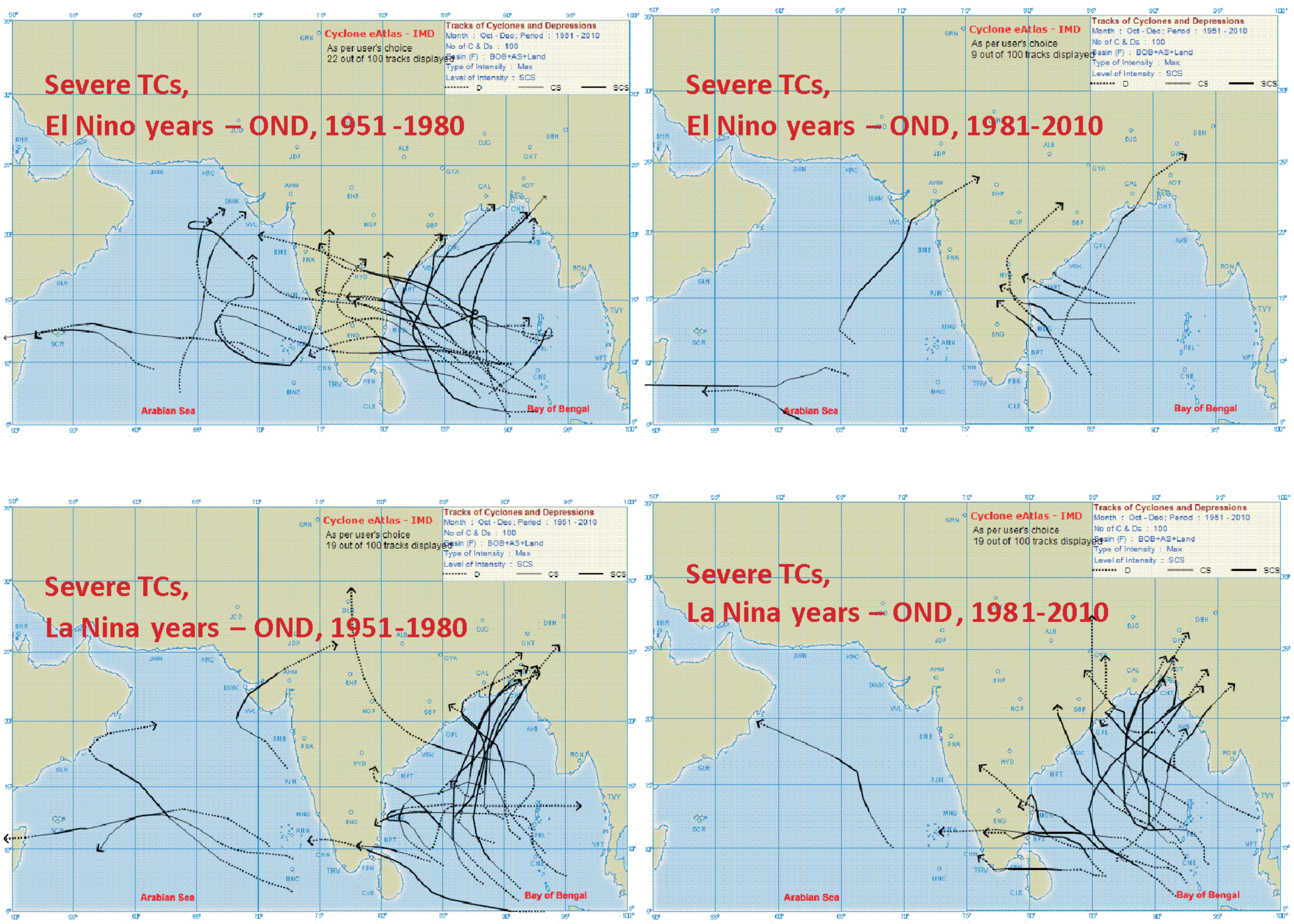

Figure 9: Tracks of severe TCs over NIO during El Nino and La Nina years of post-monsoon season over the periods 1951-1980 and 1981-2010.

Table 9: Summary of significant trends in TC parameters

TC parameter	*Significant trends during 1951-2010*			*Significant trends/difference between 1951-1980 and 1981-2010 in environmental parameters*
	NIO	*BOB*	*AS*	
Pre-monsoon season				
Frequency				SST (BOB and AS): Increased
Intensification of CD to TC	Decreasing	Decreasing	Increasing	RH500 (BOB and AS): Decreased
Intensification of TC to severe TC	Increasing	Increasing	No trend	VOR850: Cyclonic vorticity has increased over BOB VWS: Decreased over AS
Monsoon				
Frequency	Decreasing CDs Decreasing TCs	Decreasing CDs Decreasing TCs	No trend	SST (BOB and AS): Increased RH500 (BOB and AS): Decreased
Intensification of CD to TC	Decreasing	Decreasing	Increasing	VWS (BOB and AS): decreased
Intensification of TC to severe TC	Increasing	Decreasing	Increasing	VOR850: Anticyclonic vorticity has increased over AS
Post-monsoon				
Frequency	Decreasing CDs	Decreasing CDs		SST (BOB and AS): Increased
Intensification of CD to TC	Decreasing	No significant trend	No trend	RH500 (BOB and AS): Decreased VWS: Decreased over southern parts (S of 15°N) of BOB;
Intensification of TC to severe TC	Decreasing	Decreasing	No trend	increased over northern parts. Decreased over AS. VOR850: Increased over AS; Increased over northern BOB; decreased over southern BOB
Annual				
Frequency	Decreasing CDs	Decreasing CDs Decreasing TCs	No trend	No trend
CD to TC Intensification	Increasing	Increasing	Increasing	No trend
TC to severe TC	No trend	No trend	Increasing	No trend

frequency, the CCs are not persistently significant over the period 1951-2010 and the relation has been changing over the years. There is no significance in the relationship of the frequency of CDs over the NIO with any of the four Nino indices in recent years, at least after 1965. The gradual decrease in relationship in recent years may be due to climate shift over the Pacific Ocean (Girish Kumar et al., 2014). Also, there is no significant relation between the frequency of TCs over NIO and the Nino indices since the mid-seventies. The relationship was quite stable and significant prior to the seventies with the Nino 3, Nino 3.4 and Nino 4 indices. Regarding severe TCs, there is a persistent negative relation with antecedent Nino 3.4 (JF) but not significant throughout (Figure 10). The magnitude of the CC has also decreased gradually in recent years. Thus it is found that frequency of severe TCs over the NIO is least dependent on the SSTs over the Nino regions as compared to the frequency of CDs and TCs in the pre-monsoon season.

Monsoon Season

For the monsoon season, there has been a significant negative relation between frequency of CDs and Nino 1+2 and Nino 3 indices until the mid-seventies after which the relationship started weakening (Figure 11). There is no significant relationship with the other Nino indices throughout the period under consideration. Even the magnitude of CC has decreased in recent years for all the Nino indices. No significant relationship is present between frequency of TCs and all the four Nino indices in the concurrent and antecedent modes (Figure 11). Similar trends are observed in the case of severe TCs also (not shown).

Post-monsoon Season

There is a persistently increasing negative relation, after 1960, between frequency of CDs during post-monsoon season and concurrent Nino indices, especially Nino 3.4 and Nino 4, though not significant (Figure 12). The CCs have changed sign from positive to negative around 1960. Similar relation exists with antecedent

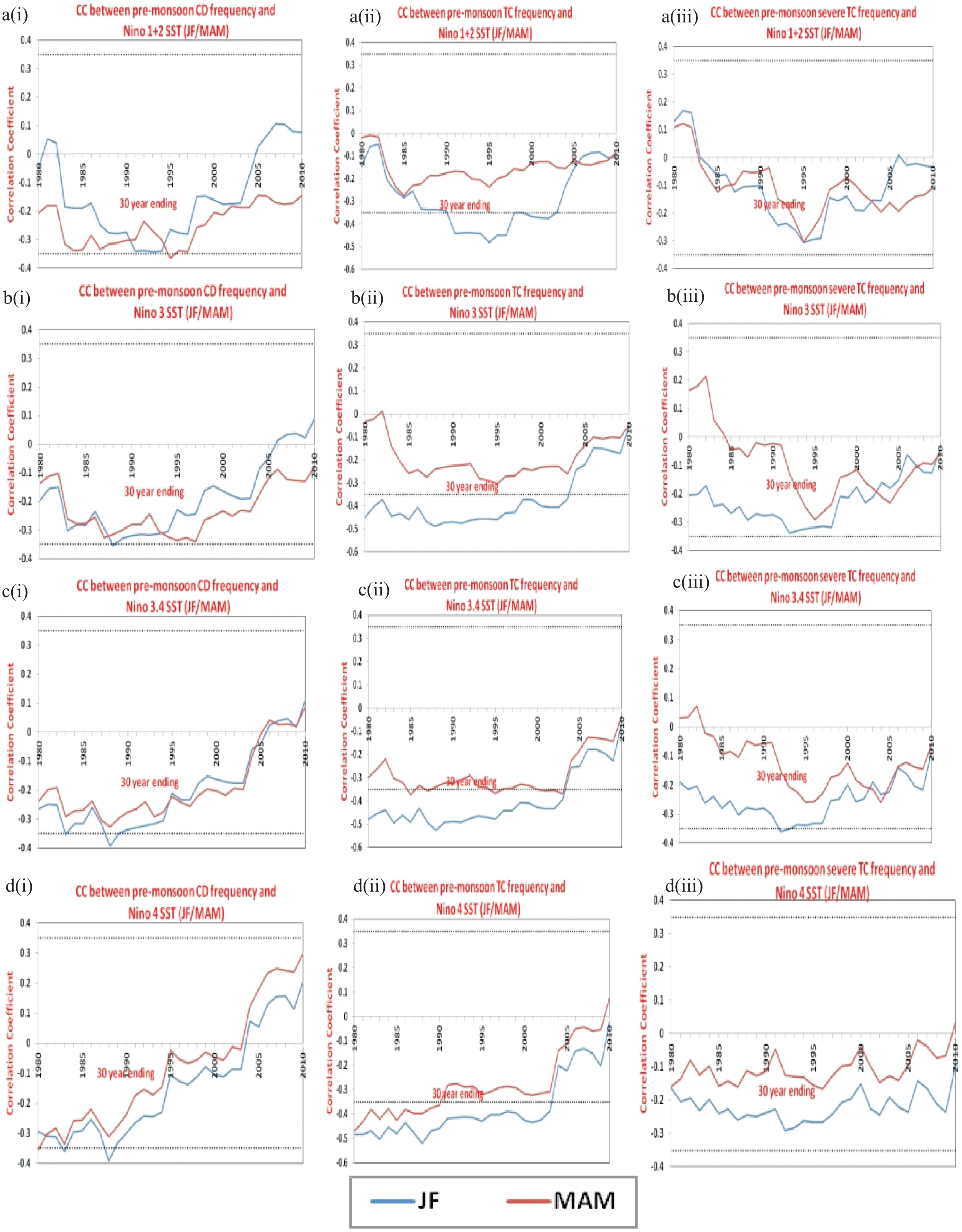

Figure 10: 30-year sliding correlation coefficient between frequency of (i) CDs, (ii) TCs and (iii) severe TCs over NIO during the pre-monsoon season and (a) Nino 1+2, (b) Nino 3, (c) Nino 3.4 and (d) Nino 4 SSTs during the antecedent winter (JF) and concurrent pre-monsoon (MAM) season based on data of 1951-2010. (95% level of significance are indicated by dotted lines)

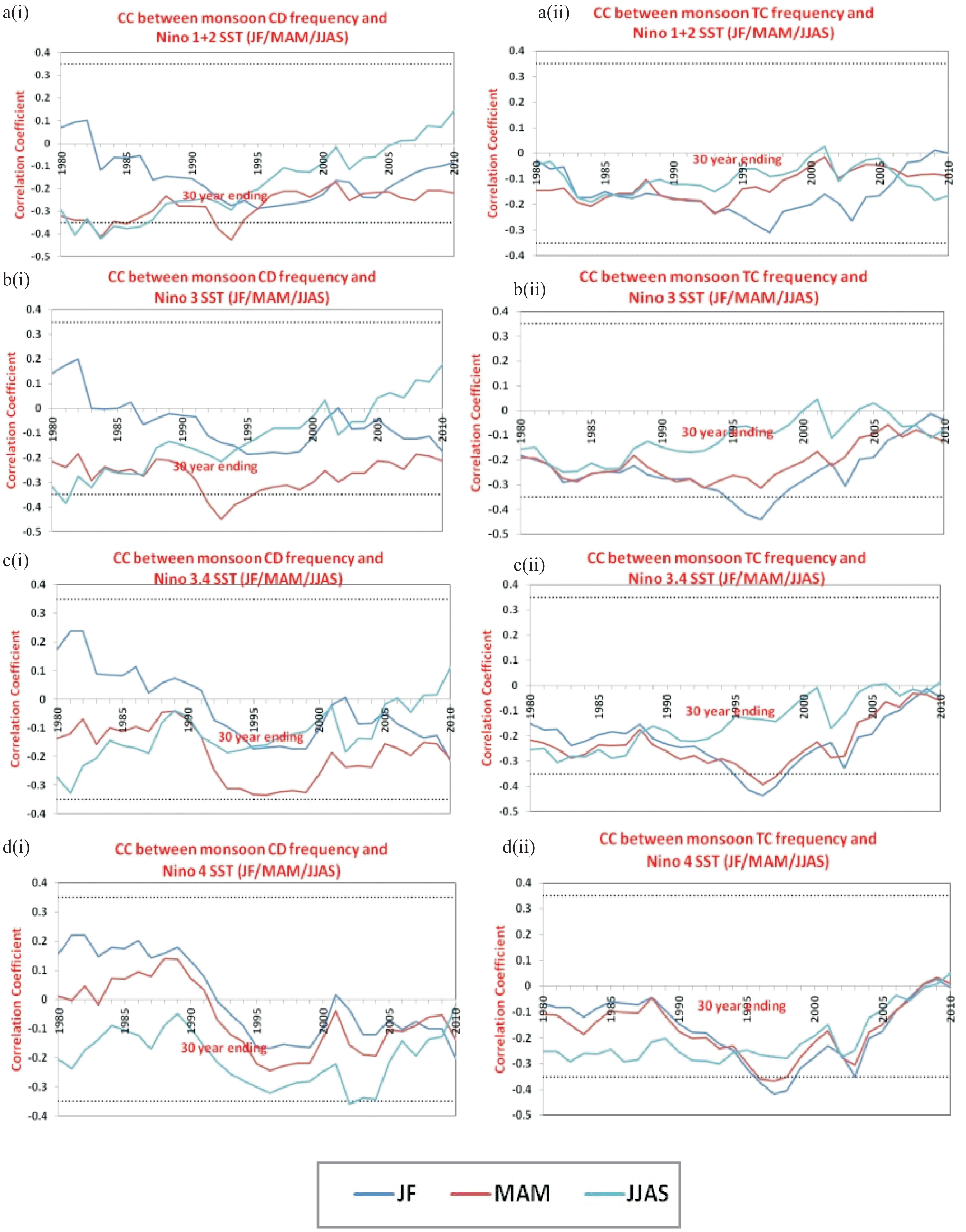

Figure 11: 30-year sliding correlation coefficient between frequency of (i) CDs and (ii) TCs over NIO during the monsoon season and Nino indices (a) Nino 1+2, (b) Nino 3, (c) Nino 3.4 and (d) Nino 4 SSTs during the antecedent winter (JF)/pre-monsoon (MAM) season and concurrent monsoon (JJAS) season based on data of 1951-2010. (95% level of significance are indicated by dotted lines)

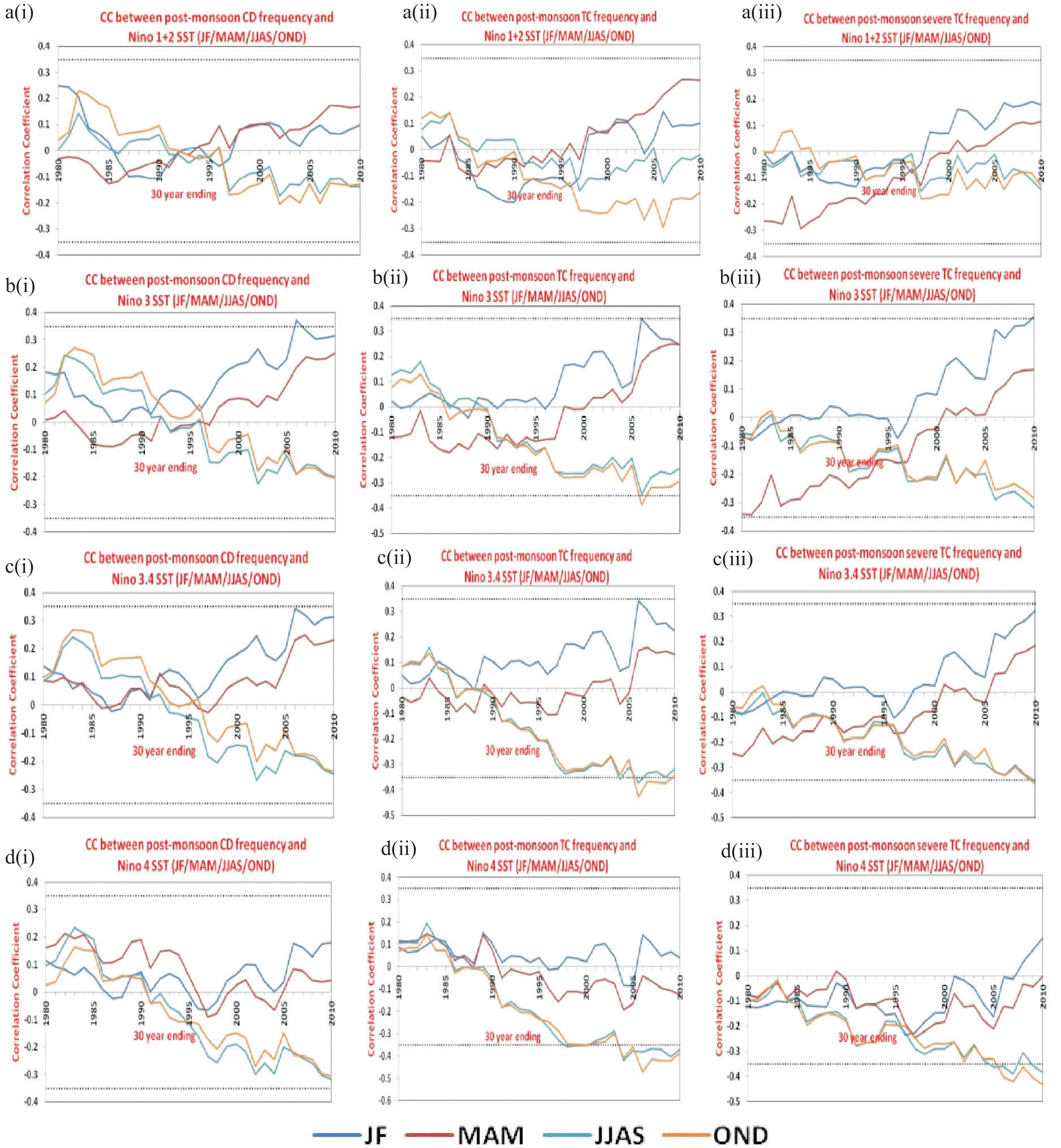

Figure 12: 30-year sliding correlation coefficient between frequency of (i) CDs, (ii) TCs and (iii) severe TCs over NIO during the post-monsoon season and Nino indices (a) Nino 1+2, (b) Nino 3, (c) Nino 3.4 and (d) Nino 4 SSTs during the antecedent winter (JF)/pre-monsoon (MAM)/monsoon (JJAS) season and concurrent post-monsoon (OND) season based on data of 1951-2010. (95% level of significance are indicated by dotted lines)

Nino indices of JJAS. However, a positive relation is building up since mid-seventies between frequency of CDs during post-monsoon season and Nino 3/Nino 3.4 of winter/pre-monsoon seasons. In the case of TCs, significant negative relation has emerged since mid-seventies with concurrent Nino 3.4 and Nino 4 and antecedent Nino 3.4 and Nino 4 of monsoon season (Figure 12). Similar relation has emerged for severe TCs also (Figure 12). There is no significance in the relationship of frequency of CDs/TCs/severe TCs with Nino 1+2 and Nino 3 indices throughout the period under consideration.

Summary and Conclusions

Trends in CD, TC and severe TC activity over BOB, AS and NIO as a whole are analysed in the context of climate change based on data of 1951-2010 and significant trends in frequency and intensification aspects are summarised season-wise in Table 9. Concomitant changes in the environmental parameters associated with cyclonic activity are also noted against each. The following are the salient features observed:

(i) During the post-monsoon chief cyclone season, there are significant decreasing trends in frequency of CDs over BOB and NIO as a whole. Also, there is a significant decreasing trend in intensification of TCs to severe TCs over BOB. There are no trends in frequency of CDs, TCs and severe TCs as well as in their intensification over AS. Considering NIO as a whole, there is a decreasing trend in intensification of CD to TC as well as TC to severe TC. On the environmental influences, it is observed that 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. 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.

(ii) During the pre-monsoon cyclone season, there is no significant trend in the frequency of CD, TC and severe TC over BOB, AS and NIO as a whole. But, there are significant decreasing trends in intensification of CDs to TCs and increasing trends in intensification of TCs to severe TCs over BOB and NIO as a whole and significant increasing trend in intensification of CDs to TCs over AS. Associated with these trends, there are contrasting trends in the environmental features. Whereas SST shows a significant increasing trend, mid-tropospheric humidity shows a significant decreasing trend over both BOB and AS. Decreasing trend in intensification of CD to TC over BOB is associated with unfavourable decrease in mid-tropospheric humidity. However, enhanced intensification from TC to severe TC could be associated with increased low level cyclonic vorticity over BOB as well as other synoptic scale forcings.

(iii) During the monsoon season, there are significant decreasing trends in the frequency of CDs and TCs over BOB and NIO as a whole. Also, there are significant decreasing trends in intensification of CDs to TCs and TCs to severe TCs over BOB. These decreasing trends are associated with significant decrease in mid-tropospheric humidity despite increased SST and decreased vertical wind shear. Over AS, whereas there is no significant trend in frequency of CDs, TCs and severe TCs, 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 forcings.

(iv) On the location of cyclogenesis, a northward shift in the mean latitude of formation by about 1° is observed over BOB during the post-monsoon cyclone season between the periods 1951-1980 and 1981-2010 (though not significant) and a significant northward shift in the mean latitude of formation over AS during the pre-monsoon cyclone season.

(v) Examination of role of ENSO on the CD/TC/severe TC trends indicates that the impact of ENSO has decreased in recent years. However, in the case of post-monsoon TCs and severe TCs, significant negative relation has emerged since mid seventies with concurrent Nino 3.4 and Nino 4 SST and antecedent Nino 3.4 and Nino 4 SST of JJAS, which could be in association with the climate shift over the Pacific in association with Pacific Decadal Oscillation. It needs further investigation.

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