

## Decadal changes of cyclone tracks in the Bay of Bengal

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**सार** – उष्णकटिबंधीय समुद्री सतह के गर्म तापमान से पर्यावरणीय पवन क्षेत्र में भी परिवर्तन हो सकता है जिससे उष्णकटिबंधीय चक्रवात (TC) की उत्पत्ति, तीव्रता और मार्ग प्रभावित हो सकता है। पिछले कुछ वर्षों में लगातार बढ़ते वैश्विक तापमान को ध्यान में रखते हुए वैज्ञानिकों ने मार्ग में विचलन पर अधिक ध्यान दिया है। हिंद महासागर में मॉनसून पूर्व (अप्रैल और मई) तथा मॉनसूनोत्तर (अक्टूबर से दिसंबर) ऋतुओं के दौरान अधिकांश प्रचंड चक्रवात भारत के पूर्वी तट पर टकराए, जिससे जन-धन की अपार क्षति हुई। अरब सागर की तुलना में बंगाल की खाड़ी में चक्रवातों की आवृत्ति तीन से चार गुना अधिक है। अक्टूबर-दिसंबर ऋतु के दौरान बंगाल की खाड़ी में चक्रवात, उत्तर हिंद महासागर में ऊपरी क्षोभमंडलीय पवन और भारतीय ग्रीष्मकालीन मॉनसून वर्षा बहुत अधिक अंतर-वार्षिक परिवर्तनशीलता प्रदर्शन करती है। इस अध्ययन में दशकीय समय-सीमा पर बंगाल की खाड़ी में अक्टूबर-दिसंबर के दौरान उष्णकटिबंधीय चक्रवात के मार्गों में हुए परिवर्तनों की जांच करने का प्रयास किया गया है। पिछले तीन दशकों से परिवर्तनशीलता की जांच करने के लिए वायुमंडलीय प्राचलों के अतिरिक्त, SST, TCHP (उष्णकटिबंधीय चक्रवात ऊष्मा क्षमता), UOHC (ऊपरी महासागर ऊष्मा तत्व), ताप प्रवणता गहराई जैसे महासागरीय प्राचल सर्वोत्तम प्राचल पाए गए हैं।

**ABSTRACT.** Warming tropical sea surface temperatures may also change the environmental wind field, which could affect genesis, intensity and track of Tropical Cyclone (TC). In recent years under ever-increasing global warming, scientists have directed more attention to the variation in the track. In the Indian Ocean, most of the severe cyclones during pre-monsoon (April and May) and post-monsoon (October to December) seasons hit the east coast of India, causing loss of life and damage to property. The frequency of cyclones is 3 - 4 times higher over the Bay of Bengal (BoB) when compared with the Arabian Sea (AS). The cyclone tracks over BoB in October-December season, the upper tropospheric winds over the north Indian Ocean and Indian Summer Monsoon Rainfall exhibit large inter-annual variability. In this study an attempt has been made to examine the changes in TC tracks during October-December over BoB on decadal time scale. In addition to atmospheric parameters, oceanic parameters like SST, TCHP (tropical cyclone heat potential), UOHC (upper ocean heat content), thermocline depth, appear to be the best parameters to examine the variability for last three decades.

**Key words** – Tropical cyclones, decadal variability, SST, TCHP, Bay of Bengal.

### 1. Introduction

Both the Bay of Bengal and Arabian Sea experience cyclone events which affect Indian subcontinent severely. The genesis of tropical cyclones over these basins is highly seasonal, with primary maximum in the post-monsoon season (October to December) and secondary maximum during the pre-monsoon season (April and May). Generally, the post-monsoon storms are more devastating in nature and the Bay of Bengal is a potentially active region for the formation of such tropical cyclones. These devastating cyclones cause heavy floods, wind damages and storm surge; thus affecting socio-economic development of nation. Obviously the storm track is a significant factor, the places along which are under the effects of violent winds and rain-storms. Lin *et al.* (2015) has reported from the objective analysis of cyclone tracks in the Bay of Bengal, that total tracks can be separated into three types west, north, and north-

westward which are 16%, 56.5% and 27.5% and have origin in the south-western, central and southern Bay of Bengal respectively. In recent years under ever increasing global warming scientists have directed considerable attention to the variation in the track. Huang and Chen (2007) studied the relationship between tracks of north western Pacific and thermal regime of the “warm pool” therein and noted that in the presence of a warm (cold) state of warm pool the TC track is westward (eastward) of normal. Variation in the NW Pacific storm tracks in relation to El Nino or La Nina episode is reported by Wang and Chan (2002), Chia and Ropelewski (2002). Tu *et al.* (2009) indicated that after year 2000, the tracks in North West Pacific are more northward of normal resulting in increased number of typhoons striking the island of Taiwan. Chen and Chao (1997) studied the climate change influence on TC behavior and noted that global changes involve mainly the impacts of atmospheric circulations, air-sea interactions, SST, temperature-

salinity circulations upon TC genesis, frequency, intensity, track tendency and landing places, globally.

Many studies have emphasized the importance of large scale atmospheric environmental factors in the genesis and intensification process of a tropical cyclone. The regions of low vertical wind shear (VWS), weak upper-level forcing from troughs, and high relative humidity of the middle-to-low troposphere are favorable for TC generation and intensification (Kaplan and DeMaria, 2003). Venham and Wang (2007) showed lower-level monsoon confluence environmental flow plays critical roles in determining rapid intensification. In addition to atmospheric parameters, oceanic parameters also play an important role. One of the decisive factors influencing the TC intensity and its intensification is ocean thermal energy in the upper ocean. The relationship between TC potential intensity and sea surface temperature (SST) has been discussed for the past decade (DeMaria and Kaplan, 1994a). The intensity-SST relationship also plays an important role in statistical intensity prediction schemes such as the National Hurricane Center Statistical Hurricane Intensity Prediction Scheme (SHIPS) (De Maria and Kaplan, 1994b, 1999; DeMaria *et al.*, 2005).

However, recent studies focus on the relationship between the intensity and the upper ocean heat content (UOHC). In their study Maneesha *et al.* (2015) demonstrated the importance of UOHC and stratification in the intensification and movement of TCs in Bay of Bengal. Sharma and Ali (2014) found an improvement in the track prediction indicating the importance of SSHA (Sea Surface Height Anomaly), representing OHC. Satoru Yokoi and Takayabu Y. N. (2013) studied the variability in TC passage frequency over the Western North Pacific and found that on decadal time scales, passage frequency variability in mid-latitudes is primarily due to preferable track variability. This motivated us to investigate the track variability in BoB cyclones in relation to oceanic parameters like SST, UOHC, thermocline depth etc. Also atmospheric parameters like, 200 hPa wind anomaly and 300 hPa temperature anomaly are examined, following Joseph *et al.* (2016). In their recent study they found large percentage of northward moving cyclones in the dry epoch of 30 years producing frequent droughts in the Indian summer monsoon rainfall. In wet epoch cyclone movement is predominantly westwards. The equatorward intrusion of upper tropospheric westerlies in the October-December season is the main cause for the large percentage of northward moving BoB cyclones of that season in a dry epoch producing frequent disastrous droughts in Indian summer monsoon region. They also showed that the equatorward intrusion of westerlies over Asia is consistent with the cold temperature anomaly at

300 hPa over the Asian continent according to thermal wind considerations.

## 2. Data and methodology

In this study the best track data for north Indian Ocean comprising of two Indian seas, AS and BoB, is obtained from India Meteorological Department e-Atlas (<http://www.rmchennaieatlas.tn.nic.in>) for 30 years from 1986-2015. Monthly atmospheric field (winds and air temperature) at  $2.5^\circ \times 2.5^\circ$  grid, for different levels, are retrieved from the NCEP/NCAR reanalysis dataset for the same period as above. Oceanmixed layer depth and subsurface temperatures are used from GODAS (Global Ocean Data Assimilation System) monthly data at  $1^\circ \times 0.33^\circ$  at 29 levels for the same period. Depth of  $20^\circ\text{C}$  isotherm, D20 (used as thermocline depth here) and TCHP (tropical cyclone heat potential) are computed from GODAS fields. OISST data at  $0.25^\circ \times 0.25^\circ$  is also utilised for said 30 years. Tropical Cyclone Heat Potential, defined as a measure of the integrated vertical temperature from the sea surface to the depth of the  $26^\circ\text{C}$  isotherm, D26 (Leipper and Volgenau, 1972, Goni and Trinanes 2003, Shay *et al.* 2000) is estimated from equation (1) below.

$$\text{TCHP} = \rho C_p \int_{D26}^0 (T - 26) dz \text{ with } \rho C_p = 4.09 \times 10^6 \text{ JK}^{-1} \text{m}^{-3} \quad (1)$$

where,  $\rho$  is the density of the sea water at each layer,  $C_p$  is the specific heat at constant pressure,  $T$  is the sea temperature, and  $dz$  is the thickness of the layer.

## 3. Result and discussion

*In situ* and satellite observations, ocean-atmosphere reanalysis products, and reconstructed datasets show multi-decadal trends in upper Indian Ocean heat content, temperature, salinity and sea level since the 1950s. From an oceanographic perspective, the generation of decadal time scale variability in the Indian Ocean involves processes operating both at and below the air-sea interface. Subsurface oceanic processes in particular provide the memory of the system because of the vast thermal inertia of the interior ocean. Hence the study here presents the tropical cyclone track variability in north Indian Ocean over past 30 years from year 1986-2015 especially in relation to underlying ocean thermal structure, or ocean physics and dynamics in addition to atmospheric parameters.

Fig. 1 shows storm tracks in BoB for three decades (i) 1986-1995, (ii) 1996-2005 and (iii) 2006-2015 in the

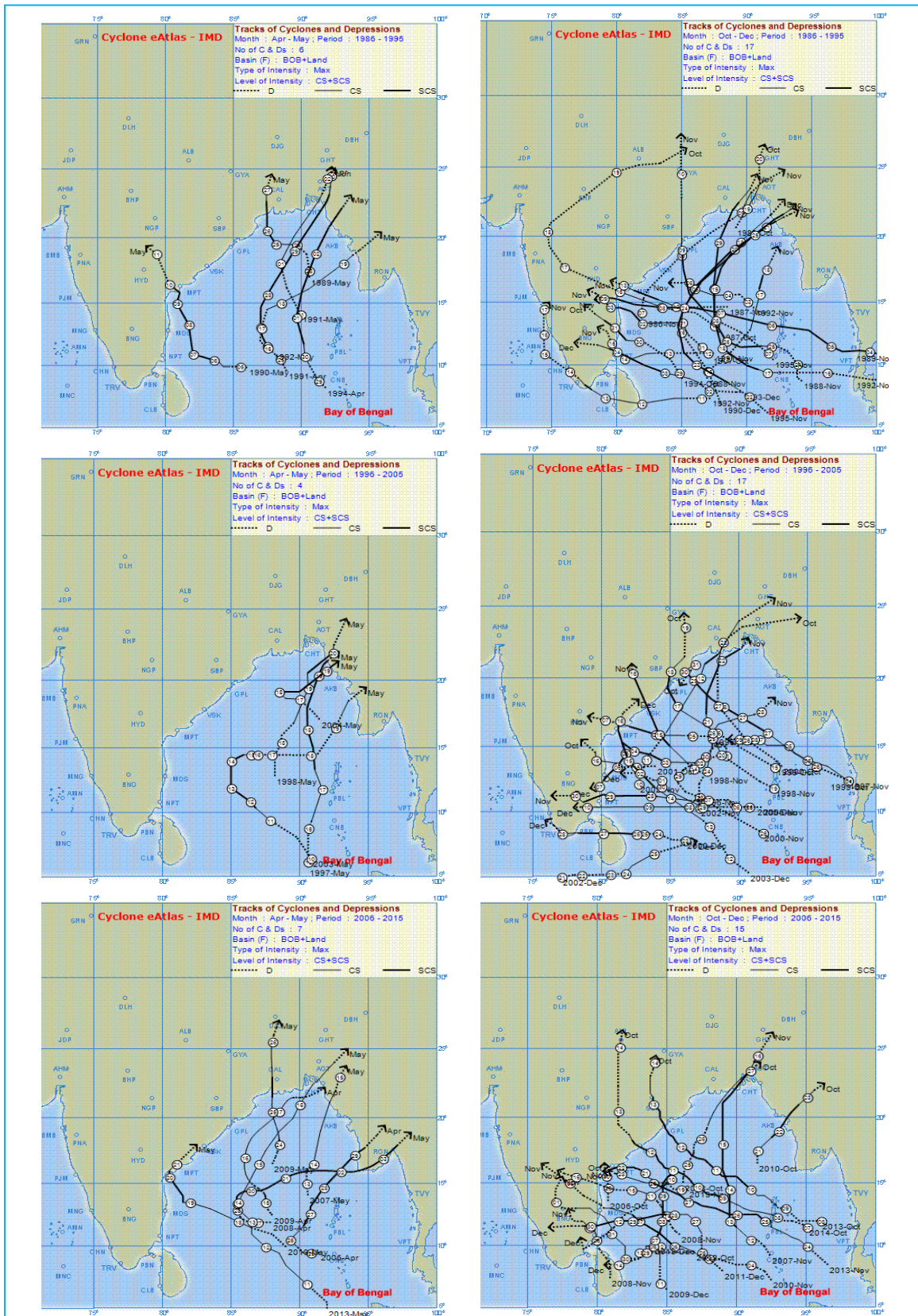


Fig. 1. Cyclone tracks in Bay of Bengal for April and May (left panel) and for October to December (Right panel) for three decades

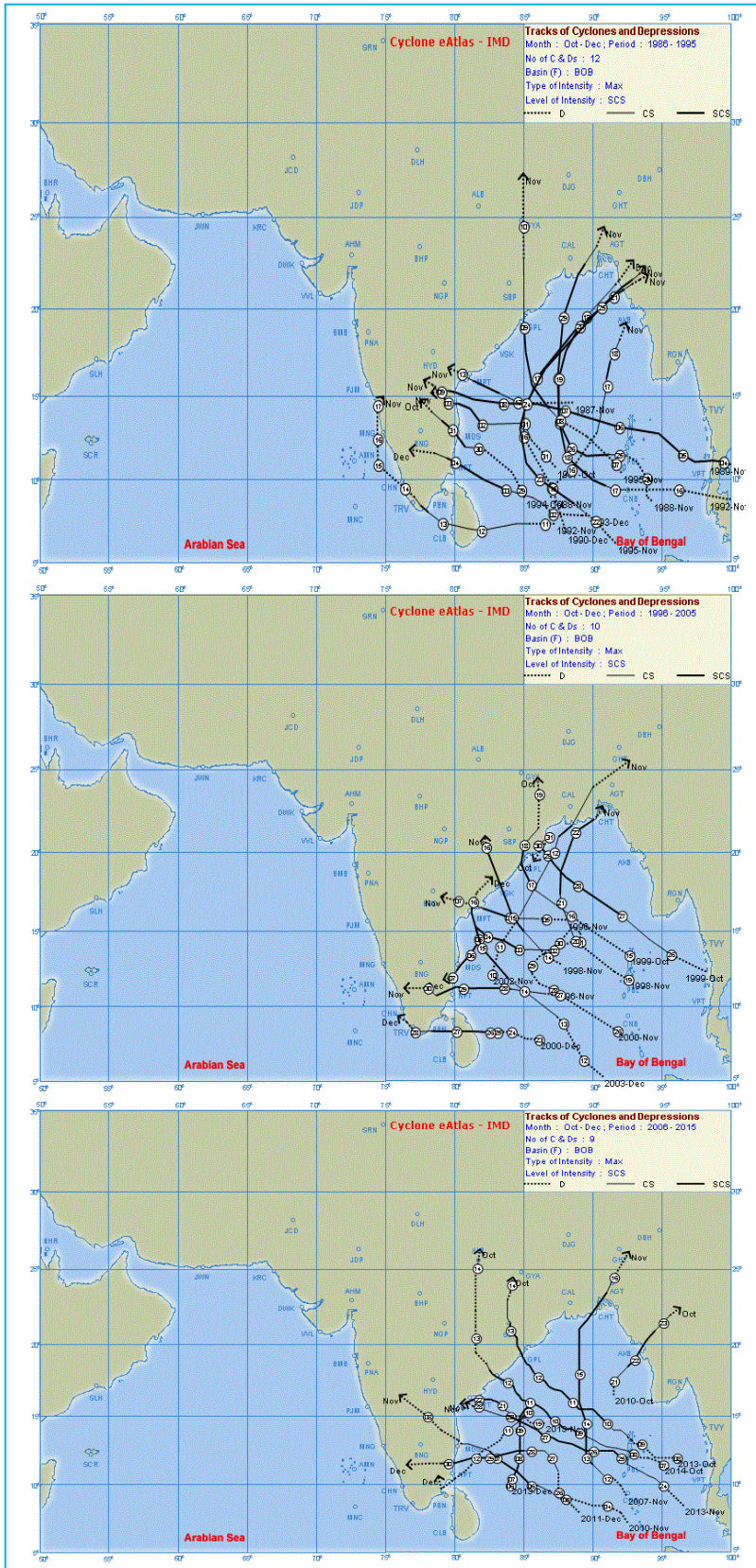


Fig. 2. Severe cyclone tracks in Bay of Bengal for October to December for three decades

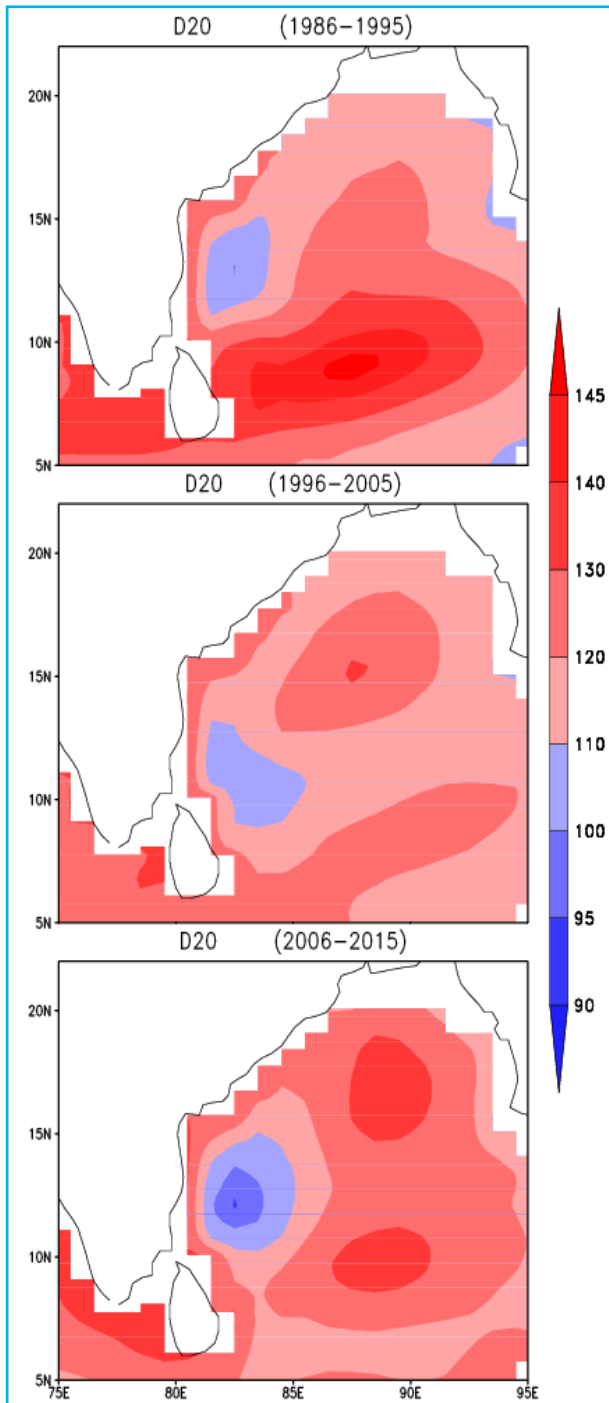


Fig. 3. Thermocline depth (m) in Bay of Bengal (Oct-Dec) for different decades

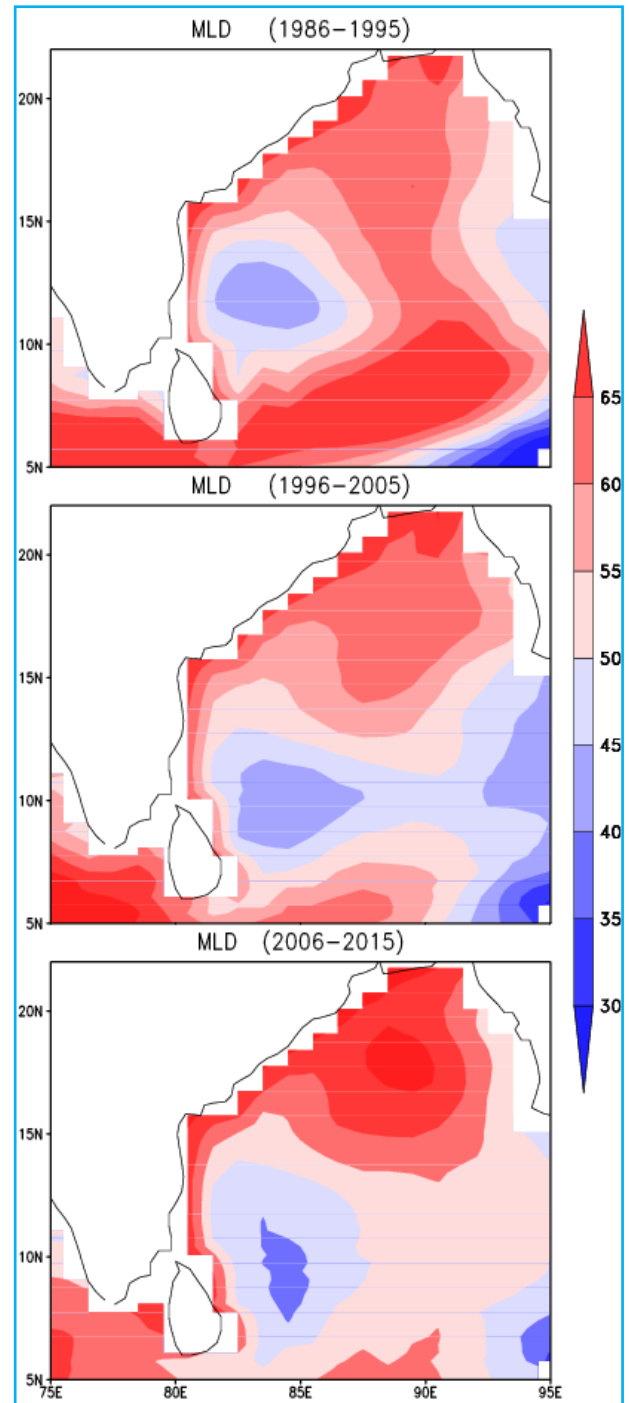
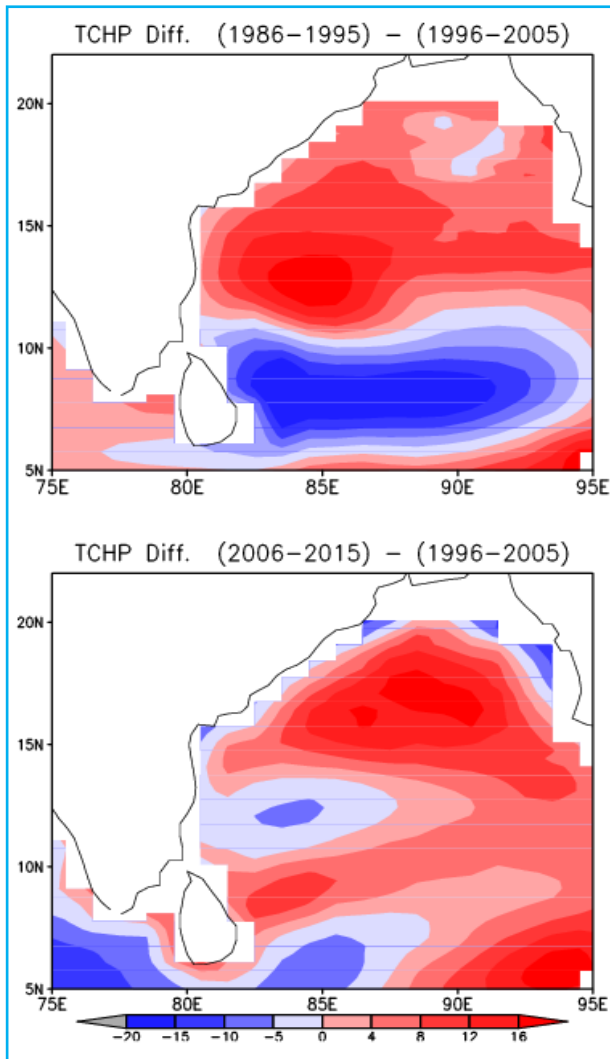


Fig. 4. Mixed layer depth (m) in Bay of Bengal (Oct-Dec) for different decades

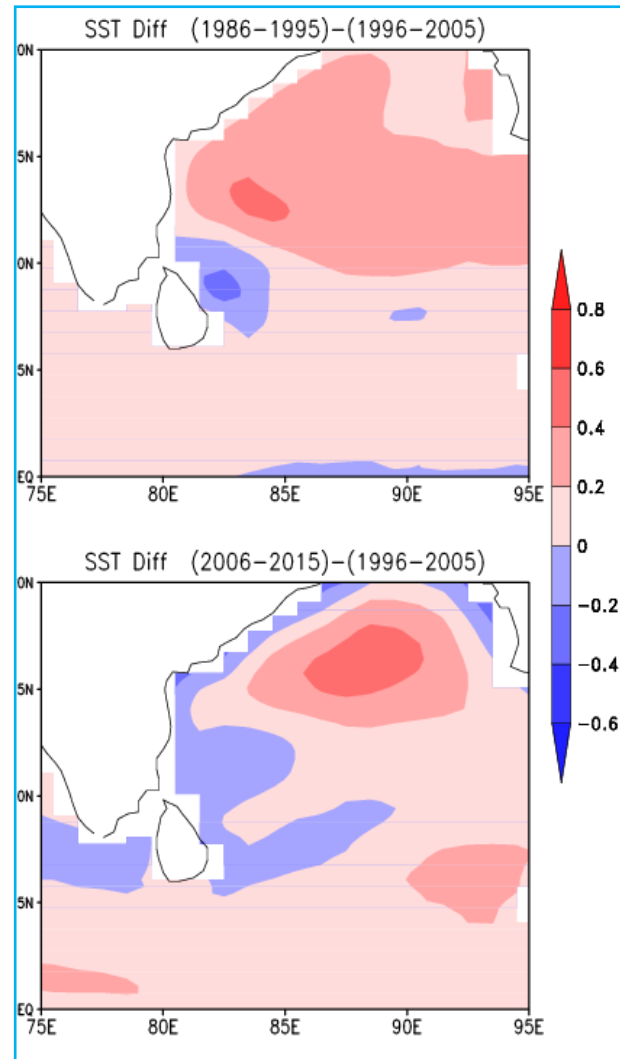
pre- and post monsoon season. It is seen that during April to May, the cyclone movement during all the three decades is mostly northwards. There is no decadal variability of TC tracks over BoB in pre-monsoon months. However during October to December, the TC tracks exhibit decadal variability. Fig. 2 displays the tracks of

category severe cyclonic storms (SCS) and above for three decades in this season. During the decade 1986-1995 cyclones move mainly in northward and westward direction. The recurving tracks (initially NW ward and then northeastward) are also considered as northward tracks since the total movement is towards north. Cyclones are



**Fig. 5.** Tropical cyclone Heat Potential difference ( $\text{kJ}/\text{cm}^2$ ) for different decades

hitting east coast of India northward of  $20^\circ \text{N}$  and southward of  $16^\circ \text{N}$ , the movement of which is northward and westward respectively. If cyclones of category severe cyclonic storms (SCS) and above are considered then this is clearly seen (Fig. 2). In the decade 1996-2005, cyclones move towards westnorthwest (WNW) and west making landfall on the east coast. Also intense cyclones are not hitting the east coast between  $12^\circ \text{N}$  to  $16^\circ \text{N}$ . In the last considered decade (2006-2015) it can be seen that generally, the storms travelling northward hit the coast above  $15^\circ \text{N}$  and those towards northwest below  $15^\circ \text{N}$ . The dominant track direction is northwest to north maintaining high intensity whereas only one westward moving SCS is present hitting east coast at around  $12^\circ \text{N}$  (Fig. 2). The main objective of the paper is to examine the possible oceanic and atmospheric factors supporting the decadal changes in cyclone tracks.



**Fig. 6.** SST difference ( $^\circ\text{C}$ ) for different decades

Mean thermocline depth (D20) for the decades 1986-1995, 1996-2005 and 2006-2015 during October to December is plotted in Fig. 3. Thermocline is deeper ( $>100 \text{ m}$ ) in northeast BoB during the decade 1986-1995. Tracks of SCS passing through the area ( $80-85^\circ \text{E}$ ;  $10-15^\circ \text{N}$ ) are sparse, whereas high density of tracks is seen in the region ( $85-90^\circ \text{E}$ ;  $10-15^\circ \text{N}$ ) which is supported by shallower ( $<110 \text{ m}$ ) and deeper ( $>120 \text{ m}$ ) thermocline depth respectively. In decade 1996-2005, thermocline is deeper ( $>120 \text{ m}$ ) in northward direction also the shallow thermocline ( $<110 \text{ m}$ ) off the east coast of India near  $10^\circ \text{N}$  restricts the movement of storms towards the coast. The last decade 2006-2015 shows deeper (about  $>120 \text{ m}$ ) thermocline in northward direction. The shallow thermocline ( $<100 \text{ m}$ ) at about  $12^\circ \text{N}$  supports for very few intense TC tracks towards west. Mixed Layer Depth (MLD) also exhibits similar variability for different

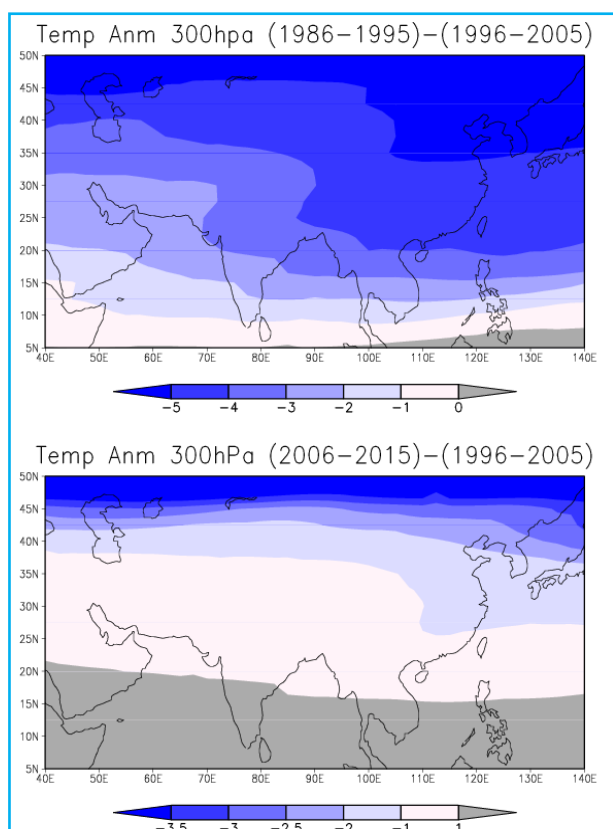


Fig. 7. Decadal difference in temperature anomaly ( $^{\circ}\text{C}$ ) at 300 hPa

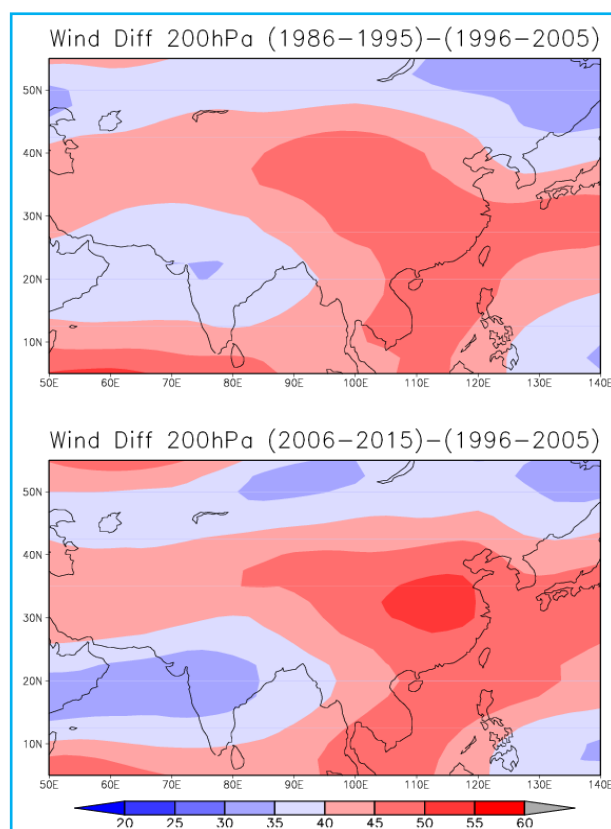


Fig. 8. Decadal difference of wind magnitude at 200 hPa (m/s)

decades (Fig. 4). Deeper MLD ( $>60$  m) in northward direction in the first and last decade and comparatively less deeper MLD ( $>50$  m) in the middle decade point towards warmer mixed layer in the northward direction favoring northward moving cyclones. Low MLD values ( $\sim 40$  m) in the northeast of Sri Lanka seems to restrict/weaken the cyclones in different decades. The changes in MLD along with those in thermocline depth, thus are found to support for the observed changes in the track directions in different decades. Fig. 5 depicts difference in TCHP of different decades. Upper plot shows TCHP and SST for the decades 1986-1995 minus 1996-2005 (first decade minus second decade) and lower panel shows those of decades 2006-2015 minus 1996-2005 (third minus second decade). Positive values of TCHP differences are seen in northern region in BoB favoring the intensification in the northward direction of the cyclone tracks in the first and last decade as compared to middle decade. SST difference similar to TCHP is plotted in Fig. 6. This also shows warm SST in northern part of BoB supporting northward track of SCS in the first and last decade, similar to TCHP. The deeper thermocline with deep mixed layer depth in turn keeps the SST warmer in northward direction for the first and last decade supporting the tracks of intense storms (Fig. 2). This suggests that surface and subsurface thermal structure of

the ocean may also contribute towards the movement of the cyclones, as is known to affect the intensification.

Next the atmospheric parameters like 300 hPa temperature and 200 hPa winds are utilised to examine the decadal changes. Fig. 7 shows the change in temperature at 300 hPa for Oct-Dec season in the different decades. Upper plot is mean seasonal temperature for decade 1986-1995 minus 1996-2005 (first minus second decade) and lower plot is for the decadal difference 2006-2015 minus 1996-2005 (third minus second decade). Similarly Fig. 8 shows the wind difference at 200 hPa for the decades same as for Fig. 7. Upper tropospheric cooling in the first and third decade as compared to the middle one is seen in Fig. 7 and also the positive wind anomalies over east Asia in first and third decade as compared to middle decade is seen from Fig. 8. This is equatorward intrusion of westerlies over Asia with the cold temperature anomaly at 300 hPa over the Asian continent and is consistent according to thermal wind consideration. Abish *et al.* (2015) also had found the large climate change in the upper tropospheric temperature (at 300 hPa) during the recent six decades in the mid-latitude belt between  $30^{\circ}$  and  $60^{\circ}$  in both the northern and southern hemispheres. Thus the cooler temperature trend, strengthening and shifting towards equator of the upper level westerlies over

East Asia, in the first and third decades might be the major atmospheric forcing for the BoB SCS of the season driving northward in these decades which is in agreement with Joseph *et al.* (2016). These qualitative results indicate that the changes in both atmospheric and oceanic parameters are responsible for changes in movement of cyclone.

#### 4. Summary

Examination of the cyclone tracks in Bay of Bengal during October-December season in the last 30 years, shows changes in their movement on decadal time scale. During the decade 1986-1995, it is mostly northward and westward. During the last decade 2006-2015 SCS mostly travel northwards with 1 or 2 moving westward. The middle decade has less northward moving tracks as compared to the other 2 decades. The changes in oceanic subsurface thermal structure like thermocline depth, tropical cyclone heat potential, MLD and SST seem to contribute towards the changes in the movement of BoB storms in post-monsoon season on decadal time scale indicating the importance of the subsurface and upper ocean parameters. Atmospheric parameter like upper tropospheric westerlies at 200 hPa during October-December season is also the cause for the northward movement of BoB cyclones in the season in association with change in the upper tropospheric temperature (at 300 hPa) in the mid-latitude belt, during the considered first and last decade. The role of track changes can be explored further while modeling the future TC intensity change.

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