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RESEARCH ARTICLE

A mini-warm pool during spring in the Bay of Bengal

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Abstract: Characteristics of the mini-warm pool (MWP) that exists in the Bay of Bengal (BoB) during spring inter-monsoon have been examined. Analysed ocean and atmospheric data revealed warming of ocean water during April, which gradually occupies most of the bay in May, and collapses with the onset of summer monsoon in early June. To define spring MWP, sea surface temperature exceeding 29.5 °C was taken as the criteria. The estimated depth of MWP from model data ranges between 10 – 20 m during April and 15 – 25 m in May, while observations at two moorings suggest that it may increase up to 50 m during spring. It is worth noting that the observed depth of warm water layer (> 29.5 °C) at both moorings is located within the low salinity layer (~ 40 m) showing the importance of salinity for the maintenance of spring MWP. Further, a relationship between the spring MWP and El Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) events have been noted. However, more studies are required to quantify the effects of ENSO and IOD on spring MWP in the BoB.

Keywords: Bay of Bengal, mini-warm pool, spring inter-monsoon.

INTRODUCTION

'Warm pools' are a feature of tropical oceans and are coupled with ocean-atmospheric processes. The best known and the largest warm pool in the world is the Western Pacific Warm Pool (WPWP). The temperature in this area remains higher than 28 °C throughout the year, thus termed as a warm pool. The warm pacific water spread towards the Indian Ocean across the Indonesian Through Flow and favours the formation of the Indian Ocean warm pool (IOWP). Hence, the combined region is known as the Indo-Pacific warm pool (IPWP) (Deckker, 2016). Unlike the WPWP, the IOWP is influenced by seasonal fluctuations in the region, thus limiting the presence of warmer water (> 28 °C) only in a part of the year. Further, the IOWP is categorised into three regions as Equatorial waters, Eastern Arabian Sea (AS) and the Bay of Bengal (BoB) (Vinayachandran & Shetye, 1991).

The BoB (Figure 1) is known as a unique and highly complex region in the Indian Ocean due to the fact that the region is highly influenced by Asian Monsoons. With the monsoonal fluctuations, temperature and salinity in the BoB vary to a great extent throughout the year. The seasonal barrier layer (BL) is one of the striking features in the BoB and its variability has been attributed to the changes related to the shoaling thermocline, Ekman pumping (Thadathil *et al*., 2008), mixed-layer depth (MLD) (Vinayachandran *et al*., 2002), and wave propagation in the BoB (Girishkumar *et al*., 2011). During spring inter-monsoon, the BoB is characterised by higher solar radiation, weaker currents and weaker winds (Narvekar & Kumar, 2006) and relatively low freshwater influx (Kumar *et al*., 2007). In addition, a weakening of both mixed layer and BL (almost absent) in spring have been suggested by Montegut *et al*. (2007). Although the presence of warmer water (> 29) during spring has been reported (Venkateshan *et al*., 2014), the existence of a spring mini-warm pool (MWP) and its regulating factors have not been discussed. So far, the formation, maintenance, and collapse of the AS MWP

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has been well documented, however little is known about the spring MWP in the BoB.

Formation of a warm pool is a combination of atmospheric and oceanic processes (Wang & Mehta, 2008). Kurian and Vinayachandran (2007) have reported that trapping of solar radiation in a thin mixed layer is the leading fact, which force the formation of the AS MWP. In addition, stratification caused by low salinity water has been supportive for the formation of MWP in the AS (Shenoi *et al*., 1999). The importance of down-welling and BL formation on AS MWP has been examined by Kurian and Vinayachandran (2007). The study showed that during times with weaker winds which are incapable of mixing the surface water, BL triggers the stratification and it favours the warming of mixed layer by inhibiting the entrainment cooling, forming a warm pool in AS. Further, it is concluded that the components of air-sea heat fluxes are more crucial than BL mechanism for the sea surface temperature (SST) evolution. Importance of surface heat fluxes and entrainment in the formation of AS MWP has been studied by Rao and Sivakumar (1999). Venkateshan *et al*. (2014) have reported the importance of diurnal and intra-seasonal oscillation of SST to the warm pool in the AS and BoB. As described in their studies, the onset of southwest monsoon, then rainfall and upwelling as consequences, effect for the SST decrease while collapsing the warm pool.

Most of the previous studies have identified the influence of inter-annual variations of warm pools for the climate and weather changes in the region (Zhang *et al*., 2009; Saji *et al*., 2015; Deckker, 2016). Zhang *et al*. (2009) have discussed the role of the eastern Indian warm pool for the formation of Indian Ocean dipole (IOD). Rao and Lakshmi (2018) have pointed out the existence of higher SSTs during El Nino Southern Oscillation (ENSO) years and its influence on the formation of warm pool over the Indian Ocean. In addition, they have mentioned that the warm pool SST may affect the intensity and frequency of tropical cyclones that occur in the region. Also, the BoB region is more vulnerable to cyclones during spring and their intensity and frequency are much higher than the AS (Sahoo & Bhaskaran, 2015). Therefore, the spring MWP may have influences on the air-sea interaction processes in the BoB.

Thus, in this study an attempt was made to discuss in detail the spring MWP in the BoB and its characteristics (formation and collapse). Further, the changes of spring MWP during ENSO and IOD years have been examined.

METHODOLOGY

Data

The development of spring MWP and its characteristics were examined using SST data from Optimum Interpolation Sea Surface Temperature (OISST), net heat flux data from TropFlux, wind stress data from the Advanced Scatterometer (ASCAT), subsurface temperature and salinity data from RAMA, temperature data from Ocean General Circulation Model For the Earth Simulator (OFES), and surface salinity from Aquarius. Further, the annual variability in spring MWP is examined with respect to Oceanic Niño Index (ONI), and Dipole Mode Index (DMI). Summary of the datasets utilised in this study are given in Table 1. Tropical cyclone heat potential (TCHP) estimated using OFES data have been used as a measure of ocean heat content (OHC), following Nagamani *et al*. (2016).

Table 1: Summary of the datasets used in the study

Parameter	Source	Resolution	Time period
OISST daily SST (°C)	*https://www.ncdc.noaa.gov/oisst*	0.25° × 0.25°	1988 – 2017
TropFlux monthly net heat flux ($W.m^{-2}$)	*https://incois.gov.in/tropflux/*	1° × 1°	2005 – 2015
ASCAT daily wind stress (pa)	*http://apdrc.soest.hawaii.edu/*	0.25° × 0.25°	2007 – 2017
RAMA daily temperature (°C) and salinity (psu)	*https://www.pmel.noaa.gov/gtmba/*	-	2008 – 2017
Aquarius weekly salinity (psu)	*http://apdrc.soest.hawaii.edu/*	0.5° × 0.5°	2011 – 2015
OFES monthly temperature	*http://www.jamstec.go.jp/ofes/ofes.html*	0.25° × 0.25°	1988 – 2011
Oceanic Niño Index (ONI)	*https://origin.cpc.ncep.noaa.gov/*	-	1988 – 2017
Dipole Mode Index (DMI)	*http://www.jamstec.go.jp/aplinfo/sintexf/*	-	1988 – 2017

$$TCHP = \rho C_p \int_0^{D2} (T - 26)\, dz$$

Where ρ is the seawater density, C_p is the specific heat capacity, T is the ocean temperature, and $D26$ is the depth of 26 °C isotherm. TCHP is similar to other OHC proxies, except it considers the depth of $D26$ instead of a fixed depth used in other proxies.

Definition for spring MWP

Generally, any region of warm waters having a temperature in excess of 28 °C is known as a warm pool. Saji *et al*. (2015) have reported that a SST value of 28 °C can be used for larger-scale warm pools while the higher values can be used for smaller-scale warm pools. For example, SST exceeding 30.25 °C has been taken as the criteria to define the AS MWP (Neema *et al*., 2012) as a warm pool. To define the spring MWP, SST exceeding 29.5 °C was taken as the criteria, considering the following reasons: 1) As the BoB region is affected by both Indian Ocean warm pool and Indo-Pacific warm pool, SST criteria must be higher than 28 °C to isolate the region of spring MWP; 2) calculated mean SST from March to June for the period between 1988 to 2017 is 29.12 °C; 3) SST criteria exceeding 30 °C are not appropriate as they are limited to the month of May, which also fails to capture the evolution of MWP during April and its collapse in June. Therefore, the pool of water with temperatures exceeding 29.5 °C during spring inter-monsoon is considered as the spring MWP in this study.

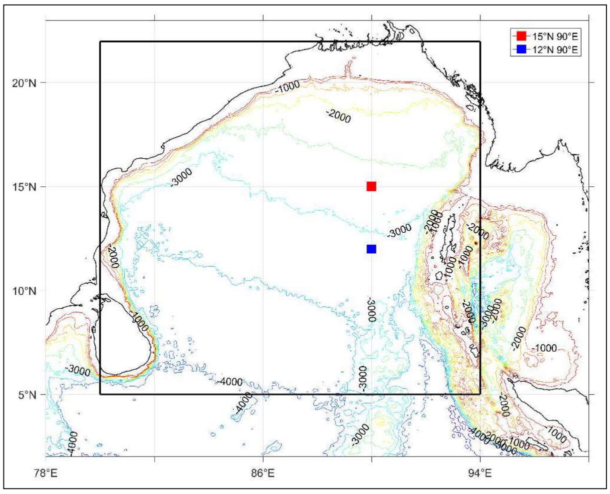

Figure 1: Study area. The SST data in the oceanic region marked with a box (5 – 22° N, 80 – 94° E) is being utilised to estimate the mean values. The squares in red and blue colour indicate the locations of the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) moorings. The bathymetry of the regions is illustrated with coloured contour lines.

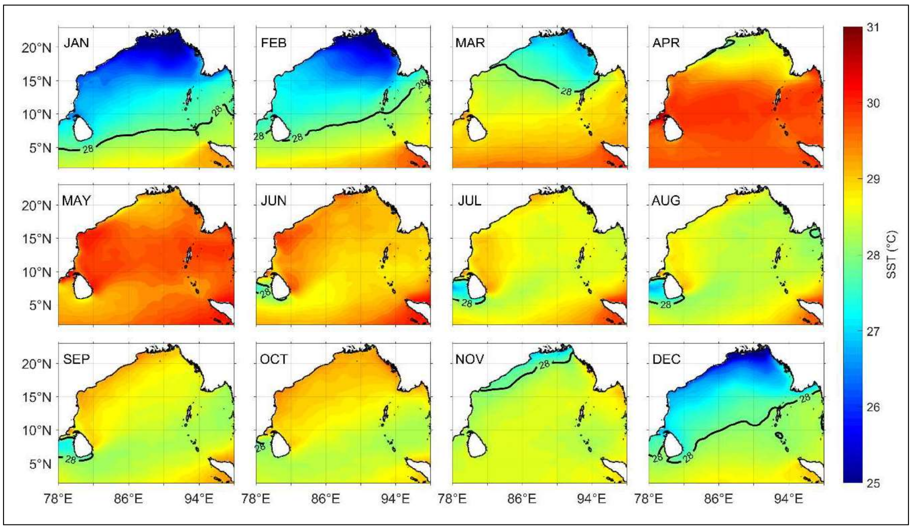

Figure 2: Monthly averaged SST in the BoB for the period of 1988 – 2017. 28 °C isotherm has been drawn to indicate the regions with temperature higher than 28°C

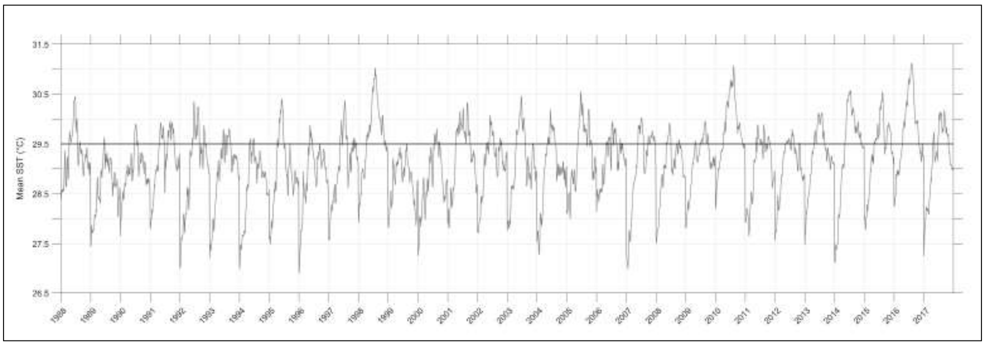

Figure 3: Mean SST calculated for the region marked with the black square in Figure 1. The SST values represent four months (March - June) for each year from 1988 to 2017. The black line denotes the SST criterion (29.5 °C) used to define the spring MWP.

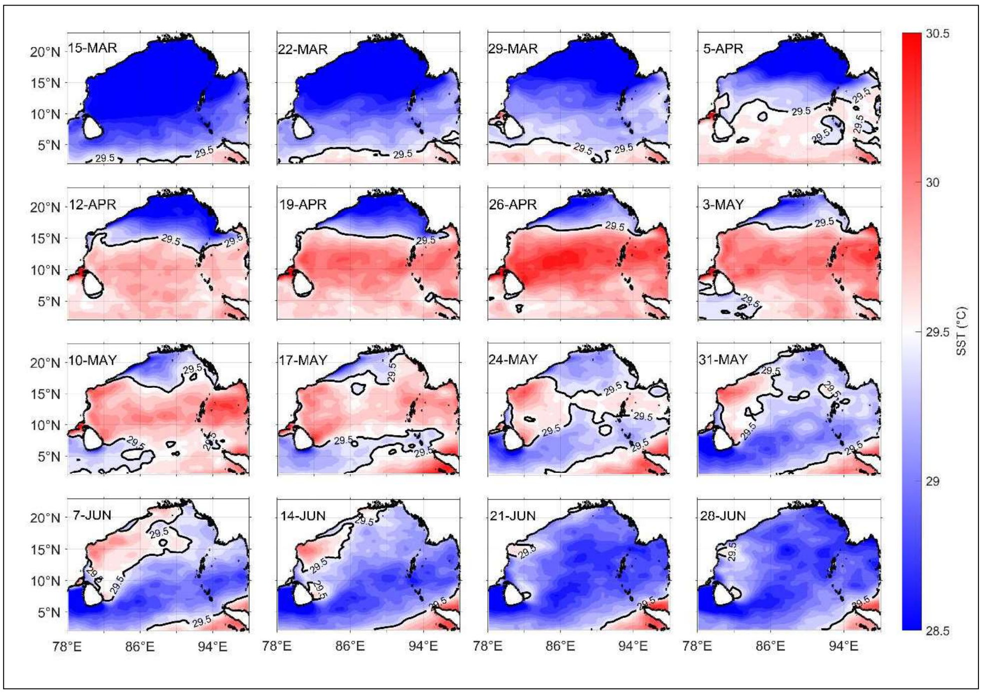

Figure 4: Appearance of the spring MWP in the BoB. Each figure represents the averaged SST for the period of 30 years for the specific date given. 29.5 °C isotherm indicates the boundary of the spring MWP.

RESULTS AND DISCUSSION

Formation of spring MWP

Monthly averaged SST for the period of 30 years clearly indicates that most of the BoB region remains warmer than 28 °C throughout the year and SST exceeds 29 °C from April to June (Figure 2). In order to examine the warming during spring, mean SST from March to June has been calculated for the region marked in Figure 1, and the results are given in Figure 3. The calculated mean SST (March-June) for the period of 30 years is 29.12 °C, and it exceeds 29.5 °C in the month of May every year during spring in the BoB. Thus, the warmer SSTs present during spring inter-monsoon strengthens the point of selecting the 29.5 °C isotherm as the boundary for the spring MWP in the BoB. Further, the mean SST in the BoB gradually increases since March and collapses during the month of June after gaining its maximum during the month of May.

Considering the mean SST variability during 1988 – 2017, a period of 15 weeks (15th of March to 28th June) has been selected for each year to examine the characteristics of the spring MWP and the results are presented in Figure 4. The warming (SST > 29.5 °C) appears from the southern BoB during late-March and spreads towards northern BoB gradually. Being a part of the IOWP, MWP is affected by the seasonal variation of IOWP (Vinayachandran & Shetye, 1991). In agreement with Vinayachandran and Shetye (1991), the warmer water occupies most of the

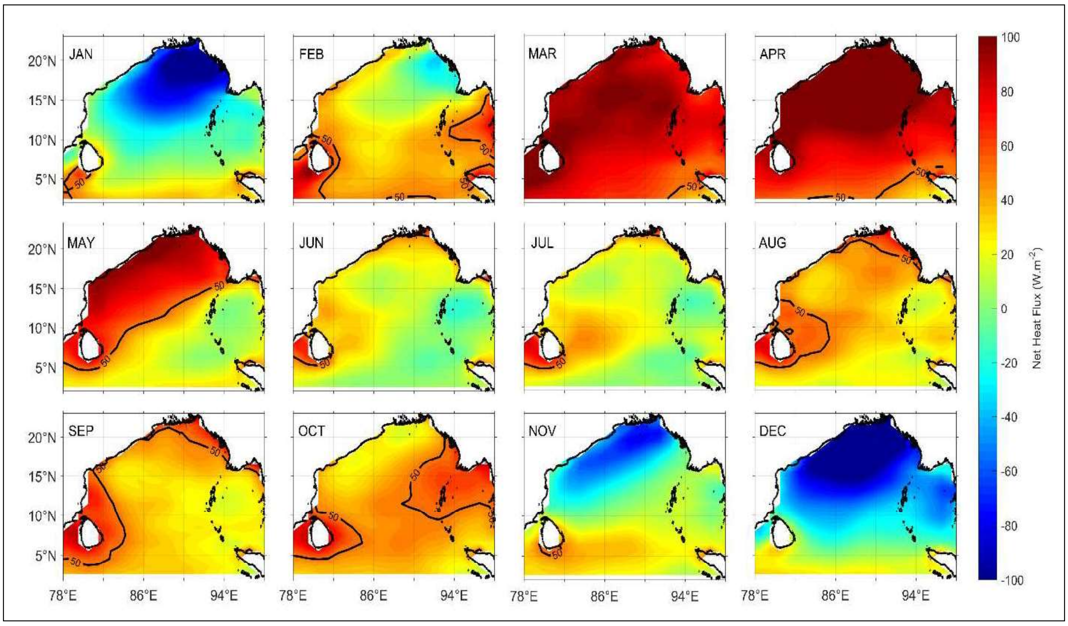

Figure 5a: Monthly average net heat flux in the BoB for the period 2005 to 2015

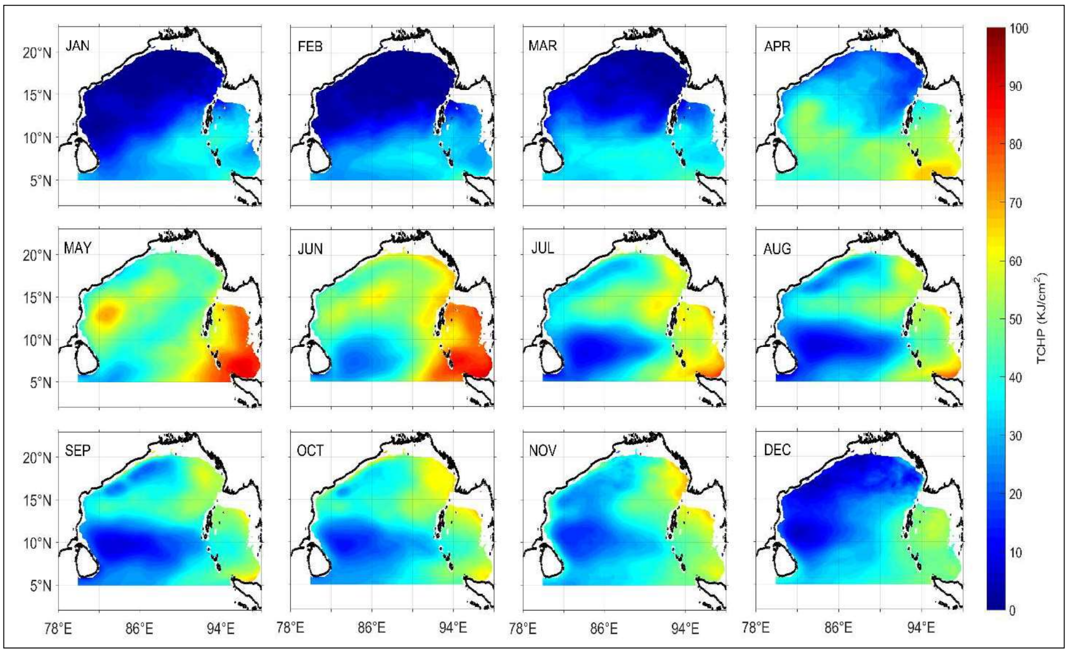

Figure 5b: Monthly average TCHP in the BoB region for the period 1988 to 2011

bay during April - May. Weakening of the BL evident during spring inter-monsoon is not supportive of warmer SSTs. Therefore, the enhanced warmer conditions in the bay is possibly a result of seasonal air-sea fluxes, which is strongest during spring inter-monsoon.

Inconsistent with previous studies (Deckker *et al*., 2002), the formation of warm pools in the tropics is a combination of the processes of atmosphere and ocean. Atmospheric forcing through solar heating in the form of incoming shortwave radiation is one of the major factors, which influence the SST warming in the BoB during spring inter-monsoon. The increment of net surface heat flux and its impact on the warming of the sea surface has been discussed by Rao & Sivakumar (1999). During spring, the BoB tends to increase the surface temperature due to the seasonal warming associated with the march of the sun. The relative weakening of outgoing longwave radiation, and sensible and latent heat fluxes further enhance this seasonal warming in the region (Pathirana *et al*., 2020). The distribution of monthly average net surface heat flux (summation of shortwave radiation, longwave radiation, sensible and latent heat fluxes) in the BoB region (2005 – 2015) is presented in Figure 5a. The figure clearly shows that the downward directed net heat flux is positive during inter-monsoons, while it peaks to its maximum during the spring inter-monsoon. Further, TCHP, which has been used as a measure of ocean heat content (Nagamani *et al*., 2016) also points out the seasonal warming from April to June in the BoB region (Figure 5b).

Vertical mixing between warmer waters in the surface layer and cooler waters in the thermocline and below play a key role in maintaining the water temperature, specifically in the upper-ocean. However, the amount of mixing depends on the strength of the winds and currents in the region. In general, the winds and the currents in the BoB are weaker during inter-monsoon periods (spring and autumn) compared to winter and summer monsoons (Narvekar & Kumar, 2006). The monthly average wind-stress over the BoB is presented in Figure 6. The lowest wind-stress is observed during the months of March and April, leading to the weakening of the wind-induced vertical mixing. Therefore, the weakening of winds during April and the resultant weaker mixing may have favoured the formation of the spring MWP in the BoB. Thus, weakening of the barrier layer, weakening of the winds and associated mixing may have indirectly supported to maintain warmer SSTs dominated by strong positive heat flux, and form a MWP during spring inter-monsoon in the BoB.

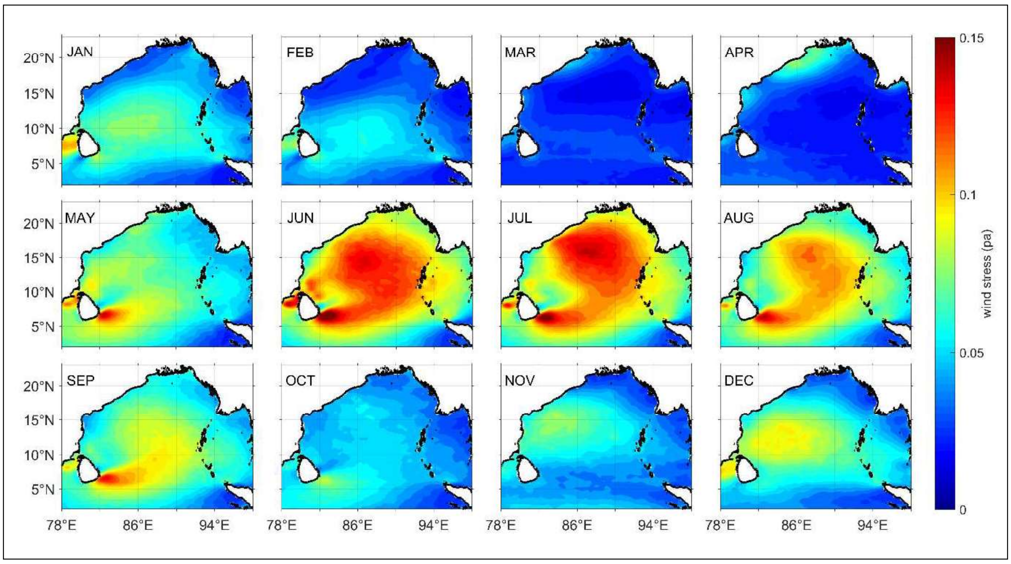

Figure 6: Monthly average wind-stress over the BoB for the period of 2007 – 2017.

Aside from water mixing, the winds act as a supportive factor for surface cooling through enhancing sensible and latent heat loss. Since the month of May, wind-stress tends to increase gradually and become stronger during June (Figure 6). Further, seasonal features such as summer monsoon current and Sri Lankan Dome in

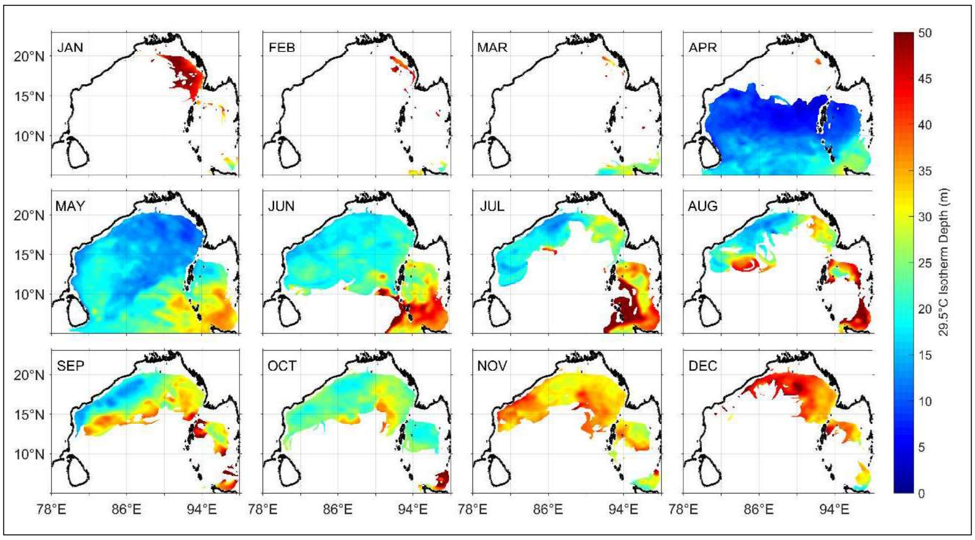

Figure 7: Monthly averaged depth of the 29.5 °C isothermal layer in the BoB

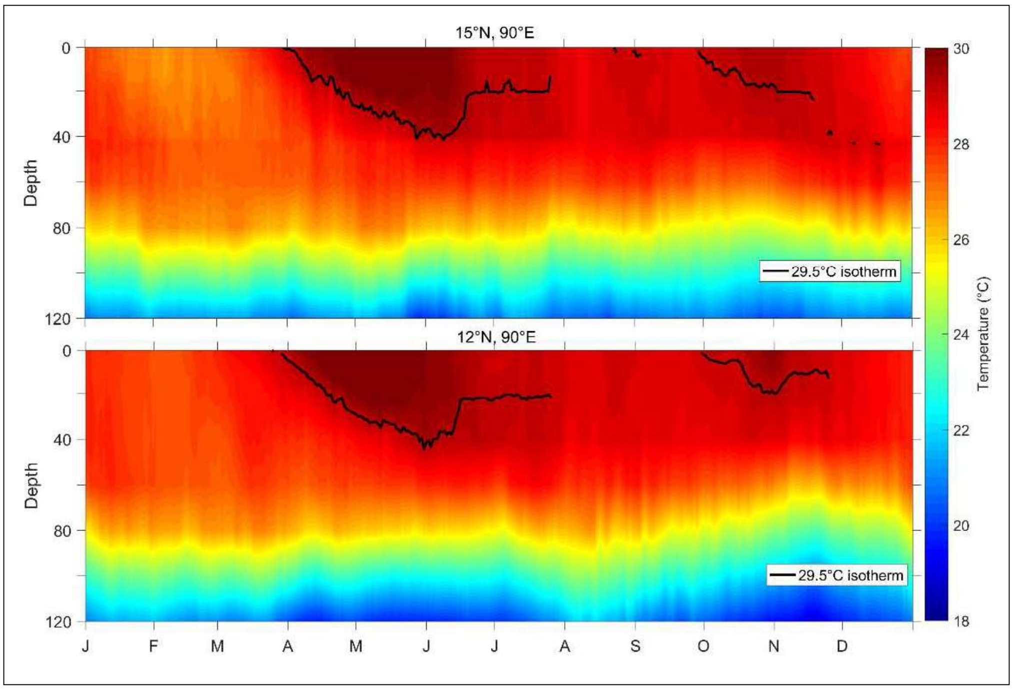

Figure 8: Temporal variation of 29.5 °C isothermal layer depth (black line) at the RAMA moorings

southern BoB enhance the upwelling of cooler waters with the onset of the summer monsoon (Vinayachandran & Yamagata, 1997). Therefore, cold water upwelling which negatively impacts on surface warming may have facilitated the collapse of spring MWP during late-May/early-June. Apart from that, the vertical extent of the warm water patch is an important fact in terms of air-sea interaction process. Utilising model and remote sensing data, the vertical structure of the spring MWP in the BoB is examined next.

Spring MWP characteristics

Water temperature

The depth of the 29.5 °C isothermal layer has been estimated using OFES data to identify the depth of spring MWP. Results indicate the existence of warm water layers (temperature = 29.5 °C) in the BoB from April to December. However, the warm water patch almost completely occupies the BoB region in spring and the vertical extent of the MWP remains 10 – 20 m during April and 15 – 25 m during May. Upper-waters in the region experience strong stratification in inter-monsoon periods due to temperature and salinity (Narvekar & Kumar, 2013), in which thermal stratification is stronger in the spring inter-monsoon. Further, associated shallow mixed layer makes the upper waters of the bay nutrient-depleted and oligotrophic (Narvekar & Kumar, 2013), and highlights the absence of vertical mixing. Thus, upper-waters with a thin mixed layer could trap more heat (Kurian & Vinayachandran, 2007) leading to warmer SSTs exceeding 29.5 °C during spring inter-monsoon. From November to December, a relatively deep patch of subsurface warm water is evident in the northern boundary of the BoB. Such observations could be due to the temperature inversions that exist in the BoB during the winter monsoon, which is facilitated by a strong barrier layer (Girishkumar *et al*., 2013).

Further, observational data from two RAMA moorings located at 15 °N 90 °E and 12 °N 90 °E were utilised to examine the vertical extent of the MWP. In agreement with model data, MWP is evident at the RAMA moorings from April to June in the BoB (Figure 8). However, the observations at the RAMA moorings indicate the presence of two warm water patches during spring and autumn inter-monsoons, in which the warm water patch during spring is well established compared to that during autumn. The depth of the 29.5 °C isothermal layer varies greatly with time at the RAMA moorings and attains its maximum depth (40 – 50 m) during late-May to early-June (Figure 8). In agreement with the SST observations, with the onset of southwest monsoon the 29.5 °C isothermal layer shoals indicating the collapse of spring MWP.

Water salinity

The BoB receives a large quantity of fresh water via precipitation and through rivers around the Indian sub-continent during summer. Several studies have indicated the importance of salinity for the formation of warm pools in the tropical oceans (Shenoi *et al*., 1999; Sanilkumar *et al*., 2004). Shenoi *et al*. (2002) have reported the strong relation between haline stratification and warmer SST in the BoB. Figure 9 illustrates the seasonal cycle of sea surface salinity (SSS) in the BoB. From April to June, most of the bay experience salinity around 32 – 34 psu, where it enhances from May to June (33 – 34 psu), and with the onset of the summer monsoon, SSS in the northern region tends to decrease gradually (< 32 psu). The SSS gradient is oriented southwest to northeast as a result of the freshwater influx, mainly from river runoff in the BoB.

Vertical distribution of the salinity at RAMA moorings are presented in Figure 10. Most of the year, upper 30 – 40 m demarcates a salinity level which varies between 32 – 33 psu, and the salinity increases towards the southern BoB. However, observations indicate a low salinity layer (~32 psu) during the spring inter-monsoon. It is interesting to note that at the moorings, during the times when there is warmer water (> 29.5 °C), the region is occupied by a layer of low saline waters. Thus, both thermal stratification and salinity stratification are evident during spring inter-monsoon and facilitate the existence of spring MWP in the BoB.

Response during ENSO and IOD events

Previous studies (Ramanathan *et al*., 1995; Deckker *et al*., 2002; Neale & Slingo, 2003; Wang & Mehta, 2008; Neema *et al*., 2012; Deckker, 2016) have discussed the influence of warm pools on the climate variability. Zhang *et al*. (2009) have reported that the interannual variations of eastern Indian warm pool is associated with the ENSO cycle. Further, they have concluded that those variations influence the onset and development of dipole over the Indian Ocean. In order to understand the response of spring MWP during ENSO and IOD years in the BoB, the changes in spring MWP with respect to Oceanic Nino Index (ONI) and Dipole Mode Index (DMI) were examined. Figure 11 illustrates the time series of ONI and DMI for the period of 30 years (1988 – 2017).

The increment of SST over the BoB during ENSO and IOD years is well evident in Figures 3 and 11. Anomalous warmer SSTs exceeding 30.5 °C are evident during 1998, 2010, and 2016 in the BoB which are associated with El Nino and positive IOD events. The appearance of strong El Nino events have been discussed in Zhang *et al*. (2009) while the occurrence of the strong positive IOD during 1997 – 1998 has been pointed out by Saji *et al*. (1999). Thus, it seems that during times of El Nino events and positive IOD events. The temperature in spring MWP in the BoB remains warmer than the normal years. As the major intention in this study was to discuss the formation of spring MWP and its characteristics, the changes in spring MWP with respect to other forcings (ex: ENSO) were not quantified. Therefore, further studies are required to examine the interannual variability of the spring MWP. As the strength of the spring MWP could influence the air-sea interaction processes (ex: tropical cyclones) in the region, such studies will have a positive impact on regional science.

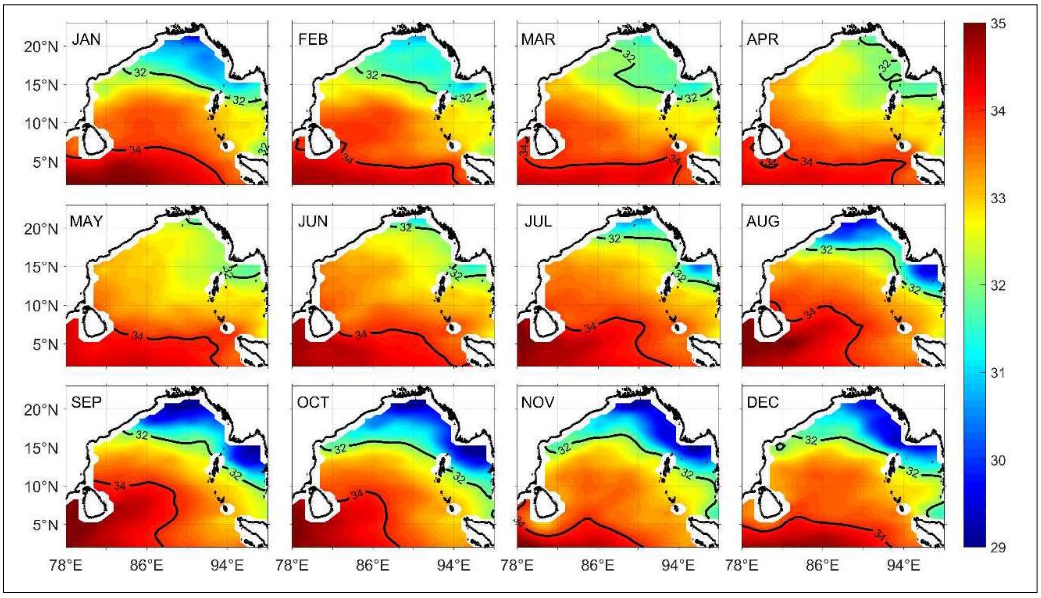

Figure 9: Annual cycle of SSS in the BoB. Black lines represent the 32 and 34 salinity contours. The colour bar represents the average sea surface salinity (psu).

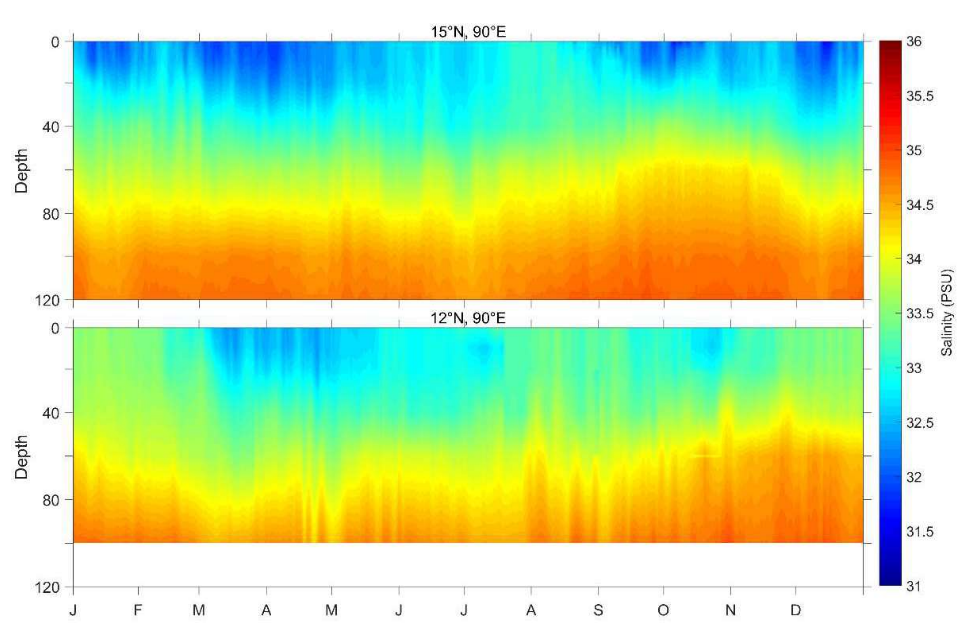

Figure 10: Temporal variation of the subsurface salinity at the RAMA moorings.

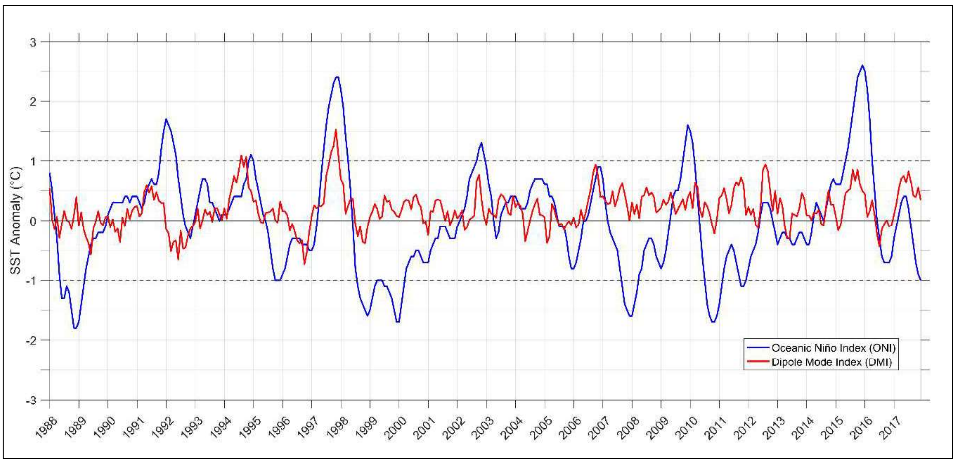

Figure 11: Time series of ONI and DMI indices from 1988 – 2017

CONCLUSION

Formation of the spring MWP and its characteristics have been examined using observations and model data. The 29.5 °C isotherm has been selected to define the region of spring MWP in the BoB, considering the estimated mean SST (29.12 °C) for the region over 30 years (from March to June) and defined threshold SST (28 °C) for tropical warm pools (ex: IPWP). Results clearly present the development of MWP in the bay during the month of April, which occupies most of the bay in May while decaying in early June with the onset of the summer monsoon. The formation of the spring MWP is supported by positive net heat flux and associated weaker mixing due to the weakening of winds over the bay during spring inter-monsoon. Coldwater upwelling, which enhances SST cooling, with the onset of summer monsoon may have facilitated the collapse of the MWP. The depth of the spring MWP estimated using model data deviates around 10 – 20 m during April and 15 – 25 m in May, while a maximum depth around 40 – 50 m is evident at the RAMA moorings. Further, the existence of thermal and haline stratification during spring in the BoB and its positive response for the formation of the spring MWP is observed. A relation between the spring MWP and ENSO, and IOD events has been noted. However, any conclusions with respect to ENSO and IOD events were not drawn but this highlight the importance of further studies. More studies are required to quantify the impacts of spring MWP on air-sea interaction processes (ex: tropical cyclones) in the BoB.

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