Observed Buildup and Collapse of Warm pool in the Eastern Arabian Sea and Bay of Bengal from Moored Buoy SST Records during 1998 - 2008

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Abstract
The observed nature of buildup and collapse of warm pool in the eastern Arabian Sea and the Bay of Bengal is examined with help of sea surface temperature (SST) data collected by NIOT buoy network during the period 1998-2008. During the buildup phase, the SSTs showed a progressive increase in both the eastern Arabian Sea and the Bay of Bengal. During this phase, the amplitudes of the diurnal oscillations of SST are relatively larger in the Bay of Bengal compared to those in the Arabian Sea. During the collapse phase, the SST cooling was dramatic in the eastern Arabian Sea caused by the monsoon onset vortex. Relatively larger amplitude intraseasonal oscillations are seen only in the Bay of Bengal and off the southwest coast of India during the collapse phase.

Keywords: Warm pool, Collapse, SST, Diurnal variability, Intraseasonal variability

1.INTRODUCTION:
The observed variability of SST is widely studied due to its large impact on ocean-atmosphere interactions. The sea surface is the lower boundary of the atmosphere and SST influences the evolution of weather and climate. The SST exhibits warming of surface waters during the pre-monsoon period and the collapses with the onset and progress of summer monsoon. The Arabian Sea warm pool is a unique feature with anomalous warm surface waters in the southeastern Arabian Sea, which collapses by the onset of summer monsoon (Seetaramya and Master, 1984). Rao et al. (1994) studied the evolution of SST in the mini warm pool region (SST> 30°C) and evaluated the relative importance of surface heat fluxes and entrainment in the buildup of this mini warm pool. Sengupta et al. (2002) have reported the spring warming of SST between February and late May or early June is about 4°C in 1998 and 1999, and 2.5°C in 2000. The abrupt termination of spring warming in the eastern Arabian Sea in early June 1998 and late May 1999 is due to passage of tropical cyclones and the spring warming in the Bay of Bengal is terminated by a depression that subsequently developed into tropical cyclone in May 1998. Sengupta et al. (2002) and Weller et al. (2002) pointed out the significance of surface heat fluxes in the warming of the mixed layer. The net heat gain by the sea in a thin surface layer leads to an anomalous rise in SST. Sanilkumar et al. (2004) have reported highest SST is 31.2°C during May 2000. The SST cools quickly with the onset and progress of the summer monsoon, under the effect of latent heat loss (de Boyer Montegut et al., 2007a). Bhat and Narasimha (2007), have studied the time series of SST during the monsoon onset, and reported SST collapse to be sudden over the eastern Arabian Sea but gradual over the Bay of Bengal. The warming phase, SST rises mainly due to heat absorbed within the mixed layer i.e., net surface heat flux minus penetrative flux of solar radiation through the base of the mixed layer and during the cooling phase, SST cools rapidly because
penetrative flux of solar radiation through the base of the mixed layer is larger than net surface heat flux and advective cooling (Sengupta et al. 2008). Sengupta et al. (2008) have studied the observed SST variability of during 21-26 April, 2005 and the cooling phase of 29 April – 2 May, 2005 in the southeastern Arabian Sea. Lakshmi et al. (2009) have reported the DS1 and DS2 locations in the Arabian Sea, the DS2 location relatively warmer throughout the year (most of the time greater than 28°C). Using TMI satellite data, Chacko et al. (2012) have studied the characteristics of warm pool in the Arabian Sea during normal and early monsoon years.

The intraseasonal oscillation (ISO) is a significant component of the coupled ocean-atmosphere system and it affects the atmospheric circulation throughout the global tropics and subtropics. It has an important impact on cyclone activity and short term climate variability. The existence of ISO in atmospheric as well as oceanic properties is reported by many studies and it revealed the influence of atmospheric forcing in inducing these oscillations. The evolution of SST during July-September differs between the Arabian Sea and the head Bay. In the head Bay greater intraseasonal variability is seen. There are more studies about the intraseasonal oscillations in atmosphere than that in the oceans. A peak in zonal winds at 850 mb with periods between 30 and 50 days was observed during the summer of 1979 in the Arabian Sea (Krishnamurti & Subrahmanyam, 1982) and a 40-50 day oscillation in surface winds observed in western Indian Ocean during 1976 and 1979 (Mertz and Mysak, 1984). Krishnamurti et al. (1988) suggested that the resultant changes in air-sea fluxes influence intraseasonal variability of the monsoon atmosphere. The analysis of SST data at DS3 and DS4 buoys in the central Bay of Bengal by Sengupta and Ravichandran (2001), has shown large amplitude intraseasonal oscillations. Hareshkumar et al. (2001), reported intraseasonal oscillations in oceanographic and meteorological parameters and observed that remote forcing dominate the local forcing in oceanographic parameters in the Bay of Bengal.

Diurnal variability of the ocean surface layer, especially skin SST, is increasingly being looked at with greater importance. Resolving the diurnal change in skin SST has also been examined with increasing interest to view possible feedbacks it has on the atmosphere (Clayson and Chen, 2002). In the tropics, the diurnal warming in SSTs can have a significant amplitude of up to 3°C or more under calm and clear conditions (Fairallet al., 1996). Recent work suggests that diurnal characteristics of the ocean surface layer affect longer timescale variability of SSTs with relation to such events as the Madden-Julian Oscillation (MJO) (Shinoda, 2004) and ENSO (Solomon and Jin, 2005). Kawai and Wada (2007) described the importance of the diurnal variability of SST on air-sea interaction. Mujumdar et al. (2011) have reported that the diurnal and intraseasonal oscillations of the SST in the Bay of Bengal are very strong, particularly a during summer monsoon season.

The hydrographic and atmospheric variability in the Arabian Sea is characterized by the seasonally reversing winter (November–January) and summer (May–September) monsoons. The monsoon winds during summer and winter seasons trigger different processes that influence the SST and productivity in the oceanic region. With the onset of summer monsoon, associated rain and upwelling lowers the SST and thereby enhances biological productivity mainly off the central and west coast of India. The large scale upwelling off the southwest of coast of India associated with the summer monsoon, also significantly cools the surface waters (Swallow, 1984; McCreary and Kundu, 1989). The SST data collected from eight moored data buoys deployed in the eastern Arabian Sea and the Bay of Bengal during 1998-2008 are utilized to identify the characteristics of the observed buildup and collapse of the warm pool.

2. DATA AND METHODOLOGY:
In this study, the available first of its kind time series data collected by a network of eight moored buoys are utilized to describe the buildup and collapse of warmpool in the eastern Arabian Sea and the Bay of Bengal.

The area of study encompasses the eastern Arabian Sea and the Bay of Bengal where in the NIOT buoy locations are shown in Figure 1. All the buoys are equipped with sensors for the following parameters: sea surface temperature, wind speed, wind gust, wind direction, wave parameters, air humidity and air
temperature (Premkumar et al. 2000). The SSTs at DS1, DS2, DS3, D4, SW4, SW5 and SW6 are found to be of good quality and hence these data are used to characterize the buildup (February-May) and collapse (May-September) of the warm pool at these locations. The SST is measured using a platinum resistance detector element, which is attached to current meter and hence the measurement is at a depth of 2m below the sea surface. It has a measurement range of –2°C to +35°C, a resolution of 0.005°C, and an accuracy of 0.001°C. The SST is obtained from the average of 600 samples measured at a rate of 1Hz. The accuracies of the moored buoy data were discussed in detail by Premkumar et al (2000). The data buoys record and transmit data at synoptic hours (every three hour) through INMARSAT-C satellite to the shore station established at NIOT. The available data from these buoys during the years 1998-2008 are utilized to study the characteristics of warm pool is shown in table 1. These data sets enable us to describe the nature of the buildup and collapse of the warm pool in the eastern Arabian Sea and the Bay of Bengal. The details on the data utilized in this study are given in Table 1.

### Table 1. Buoy data utilized to study the characteristics of the warm pool

| Buoy ID | Buildup of Warmpool (February – May) | Collapse of Warmpool (May – September) |
|---------|-------------------------------------|----------------------------------------|
| DS1     | 1998, 1999, 2000, 2001, 2007         | 1998, 1999, 2000                       |
| DS2     | 1999, 2003, 2004, 2005               | 2002, 2006                             |
| DS3     | 1998, 2003                           | -                                      |
| DS4     | 2008                                | 1998, 2007                             |
| SW4     | -                                   | 2001, 2002, 2003                       |
| SW5     | -                                   | 1998, 1999, 2000, 2006                 |
| SW6     | -                                   | 1999, 2000, 2005                       |

3. RESULTS AND DISCUSSION

The analysis is focused for the periods beginning of February to May and from May to September during the period 1998 to 2008 at DS1, DS2, DS3, DS4, SW4, SW5 and SW6 locations for buildup and collapse phase of the warm pool in the eastern Arabian Sea and Bay of Bengal.
3a. Buildup of Warm Pool in the Deep Waters of eastern Arabian Sea

The warming of the southeastern Arabian Sea during pre-monsoon is important for the onset and advance of southwest monsoon along the western parts of India (Vinayachandran et al., 2007b). The buoy observations provided detailed information on the buildup of warm pool. The SST at DS1 in the eastern Arabian Sea progressively builds up during the pre-summer monsoon season (Fig. 2). The SST during the observational period shows an increasing trend till the monsoon onset. The progressive increase in SST also shows year to year differences. A small amplitude diurnal oscillations overriding the seasonal cycle is also seen. The SST observed at DS1 during February-May 1998 indicates that during the typical pre-monsoon warming phase it steadily increased from 28°C to 31°C. Towards the end of buildup phase, during 2001 the SST dropped to 26°C due to occurrence of monsoon onset vortex. In the south eastern Arabian Sea at DS2 location the SST increased by 3°C during February – May, 2004 and it is relatively larger compared to the corresponding values during 1999, 2003 and 2005 (Fig. 3).

Figure 2. Buildup of the warm pool at 16N/69E (DS1) location

Figure 3. Buildup of the warm pool at 11N/73E (DS2) location
The maximum SST observed was 33.84°C at DS2 location on 14th April 2004. The SST variation shows diurnal oscillations during April – May, 2004 of the order of greater than 0.5°C. Highest SST was recorded in May 2004 in the southeastern Arabian Sea associated with the mini warm pool.

3b. Buildup of Warm Pool in the Deep Waters of the Bay of Bengal

It is worth investigating the extent to which the variability of the warm pool determines the nature of the monsoon over the Bay of Bengal on interseasonal time scales. The warm pool in the Bay of Bengal shows peak values in excess of 31°C and 30°C occurring at DS3 (Fig. 4) and DS4 (Fig.5) locations respectively.

![Figure 4. Buildup of the warm pool at12N/91E (DS3) location](image)

![Figure 5. Buildup of the warm pool at18N/87E (DS4) location](image)

The amplitudes of the diurnal cycle is approximately 0.5°C (Mujumdar et al. 2011). Both buoy locations show pronounced diurnal cycle during the peak warming phase. At DS3 the amplitude of the diurnal cycle is larger towards latter part of the warming phase whereas no such pattern is seen at DS4.

3c. Collapse of Warm Pool - Deep Waters in the eastern Arabian Sea

The analysis period spans during May to September for the years 1998, 1999 and 2000 at DS1 and 2002 and 2006 at DS2 locations in the Arabian Sea. The collapse of the warm pool is dramatic during 1998 due to passage of monsoon onset vortex at DS1 location (Fig. 6). It is observed that SST decreases dramatically by >3°C following the occurrence of onset of monsoon vortex. The SST was around 31°C in the beginning of June, which decreased dramatically to around 28°C by the end of the cooling season. After the passage of onset vortex, the SST could not regain the pre-cyclonic conditions and it remained with an average value of 28°C during the rest of the period. The collapse of the warm pool at DS1 was less dramatic during the years 1999 and 2000 when no monsoon onset vortex formed. The intraseasonal variability during the collapse phase is relatively weak and the diurnal scale variability is also very small. Similar cooling patterns are seen at DS2 during both the years 2002 and 2006. During the collapse phase at DS2 in the Arabian Sea during 2002 and 2006 both intraseasonal and diurnal variability is small (Fig. 7).
3d. Collapse of Warm Pool in the Deep Waters of the Bay of Bengal

Unlike DS1 and DS2 in the eastern Arabian Sea the moored data buoy DS4 deployed in the northern Bay of Bengal showed large amplitude intraseasonal oscillations. These oscillations are forced by air-sea interaction processes (Sengupta and Ravichandran, 2001). The diurnal scale variability is also more pronounced during the peaks of the heating regimes of these intraseasonal oscillations. The intraseasonal oscillations as well as the diurnal oscillations are clearly seen at DS4 buoy location as shown in Figure 8. However the drop in SST is less compared to that in the Arabian Sea.

3e. Collapse of Warm Pool in the shallow water off southwest coast of India

The collapse of warm pool at SW4 location during the years 2001, 2002 and 2004 is shown in Figure 9. The time series observations of SST during the observational period show intriguing oscillations with amplitudes as larger of 5-6°C during 2002. Lowest SST values of 21.05°C and 20.94°C are observed at SW4 by the end of August in 2001 and 2002 respectively. Very low SST values during summer monsoon period off the southwest coast of India were reported by various authors. Darbyshire (1967) reported the lowest SST (~22°C) along the southwest coast of India between latitudes 8°N to 12°N due to upwelling phenomenon.
The data buoy SW4 was deployed close to coast off Mangalore and the data buoy DS2 is located at a distance of 325.35 nm southwest of SW4 buoy location. The SST along the west coast of India exhibits a wide range of variability both in time and space. A comparison of SST at DS2 (off Lakshadweep) and SW4 locations (off Mangalore) during the period of May to September 2002 is shown in Figure 10. The collapse of the warm pool in the year 2002 is dramatic and exhibited intriguing oscillations only at SW4 location. During the observation period, the minimum SSTs recorded at DS2 and SW4 locations are 28°C and 21°C respectively. Large amplitude intraseasonal oscillations are only seen in the shallow water (SW4) SST record.

3f. Collapse of warm pool in the Shallow Waters of southwestern Bay of Bengal

Two shallow water buoys (SW5 and SW6) are deployed off southeast coast of India. The analysis period spans from May to September during the years 1998, 1999, 2000 and 2006 at SW5 and during the years 1999, 2000 and 2005 at SW6 locations (Fig. 11 and Fig. 12). At SW5, among all the four years highest SST (32°C) occurred in the beginning of May 1998. The time series observations of both buoys clearly exhibited intraseasonal oscillations with variable amplitudes. The diurnal scale variability is relatively weak throughout the records. The intraseasonal variability of SST in the shallow waters off southeast coast of India is relatively week compared to the corresponding variability seen off the southwest coast of India during 2002.
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Figure 10. Comparison of SST record in the deep DS2 (11N, 72E) and shallow SW4 (13N, 75E) water region during May- September 2002

Figure 11. Collapse of the warm pool at 9N/78E (SW5) location

Figure 12. Collapse of the warm pool at 13N/81E (SW6) location
CONCLUSIONS
The warm pool in the Arabian Sea shows a progressive build up during February – May and collapse during the summer monsoon season. The collapse is dramatic during the years of monsoon onset vortex. The intraseasonal oscillations are seen relatively weaker amplitude during the summer monsoon season in the deep waters of the eastern Arabian Sea. Relatively large amplitude intraseasonal oscillations are seen in the coastal SST records in the Arabian Sea. In the Bay of Bengal the warm pool also shows similar build up and collapse patterns. But large amplitude intraseasonal oscillations are seen during the collapse phase of the summer monsoon in the bay. The diurnal oscillations are more pronounced during the heating regimes in the SST records. The governing mechanism for the observed features described in the study would be examined later.

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