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Warmest Sea Surface Temperature Event in the South Eastern Arabian Sea over the Decade using Satellite and *INS Sagardhwani* Observations

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ABSTRACT

South Eastern Arabian Sea is well known for its prolonged and warmer sea surface temperature (>30 °C) events generally known as Arabian Sea mini warm pool occurring during the pre-monsoon periods (March-May). To study the intensity and spatial extent of the warm pool, ten year (2007-2016) of satellite-derived weekly averaged SST and *in-situ* data measured from *INS Sagardhwani* are used. The analysis is done based on the precondition 'sea surface temperature > 30 °C' and lasts more than a week. These analysis demonstrate the existence of a strong inter-annual variability. It is also identified that the sea surface temperature in the year 2016 is the hottest over the decade with maximum spatial coverage and prolonged period of occurrence. These anomalous events are also explained in terms of variabilities of the atmospheric water vapour and wind at the sea surface.

Keywords: Arabian Sea mini warm pool; Sea surface temperature; Heat content

NOMENCLATURE

- μ Mean
- σ Standard deviation
- ρ Seawater density (kg/m^3)
- C_P Specific heat capacity at constant pressure
- T Ocean temperature (°C)

1. INTRODUCTION

The Arabian sea mini warm pool (ASMWP) is a region of relatively warmer waters with temperature above 30 °C at the surface. The core of this warm pool is about 0.5 °C to 1.0 °C warmer than the surrounding waters and is usually observed in the South Eastern Arabian Sea (SEAS) during pre-monsoon period[1,2]. Both oceanic and atmospheric mechanisms contribute to its formation, solar and evaporative flux control the warm pool temperatures while surface wind and near surface salinity stratification attribute to its spatial structure. Though the formation of ASMWP is almost a regular phenomenon, it exhibits inter-annual variability in its core temperature, location and spatial extent. Several studies have been carried out to characterise its formation, evolution and dynamics[3-8]. Temperature inversions occur in the SEAS during November to February due to the surface-advection of cold, less saline Bay of Bengal water over the relatively warm, high saline Arabian Sea water along the west coast of India[9]. This relatively low saline water propagate westward across the Lakshadweep with the annual Rossby waves[10] and the heat trapped within the inversion provide a significant contribution to the formation of ASMWP[11]. There were studies on the influence of low saline water from the Bay of Bengal by the East India coastal current and the winter monsoon current[6,7,12]. Studies were also conducted on the linkage between summer monsoon and warm pool[13,14].

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2. STUDY AREA

This study considers the ocean area earmarked by continuous black lines which is over a 12-degree square box with latitude ranging from 3 °N to 15 °N and longitude ranging from 65 °E to 77 °E as shown in Fig. 1. The dotted black lines represent the latitudinal transects 9.0 °N and 10.5 °N for which *in-situ* data measured from *INS Sagardhwani* are available.

3. MATERIALS AND METHODS

The sea surface temperature (SST) data measured from satellite sensors such as advanced microwave scanning radiometer (AMSR) and tropical rainfall measuring mission (TRMM) microwave imager (TMI) and the wind and atmospheric water vapour (AWV) measured from the sensor windsat are compiled. The aforementioned datasets were taken for pre-monsoon period i.e. from March-May of every year for the decade (2007-2016), so 13 dataset were available for each year and a total of 130 dataset for the decade. The details of the satellite datasets are as given in Table 1. In addition to this, the vertical profiles of Temperature measured during the month of May of the years 2008, 2009, and 2016 onboard *INS Sagardhwani* in the SEAS have also been considered for the study. The *in-situ* observational period was chosen during the pre-onset period of summer monsoon during which the ASMWP is most predominant.

The objective is to study the inter-annual variability of SST and to identify the warmest event in the decade i.e., during 2007-2016 and to estimate the heat content using *INS*

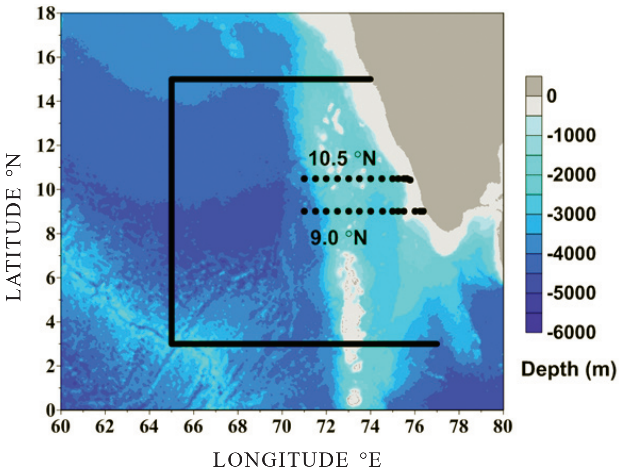

Figure 1. Location map showing the study area (65 °E - 77 °E and 3 °N - 15 °N).

Table 1. Details of satellite datasets utlised in the study

Parameter	Spatial resolution	Temporal resolution	Source
SST	0.25°×0.25°	Weekly	http://www.remss.com/missions/amsre http://www.remss.com/missions/tmi
Wind	0.25°×0.25°	Weekly	http://www.remss.com/missions/windsat
AWV	0.25°×0.25°	Weekly	http://www.remss.com/missions/windsat

Sagardhwani observations. In order to do that the impact of the warm pool was analysed at 3 level viz., a) sea surface, b) ocean depth, and c) atmosphere. This analysis was done in the following steps.

(a) Based on the precondition that SST exceeds 30 °C and lasts more than a week, the estimates of the warm events such as intensity, location and spatial extent were computed to analyse the superficial impact. A statistical analysis of this data was done to classify the years as 'weak', 'normal' and 'strong'.

(b) *INS Sagardhwani* missions' data were used to determine the heat content (HC) of the water column to understand the impact of the warm pool at ocean depth.

(c) To analyse the atmospheric impact, AWV and wind data were analysed. Wind data were also used to correlate the distribution and variability of AWV.

4. RESULTS AND DISCUSSION

4.1 Data Analysis

For each year of the decade, the average of the weekly averages of SST was done to study the inter-annual variability of SST in the earmarked location. Figure 2 shows the inter-annual variability of SST in the study region during the pre-monsoon period of 2007-2016. From the figure, it can be observed that SST did not exhibit any uniform spatial pattern and it was fluctuating. However this graph is not conclusive since it has been plotted using the averaged data. To quantify this fluctuations in SST over the decade, the number of occurrences per grid was calculated using 13 datasets available for the study period based on the precondition that if SST>30 °C then the number of occurrences is 1 for that particular grid. The same is repeated for every other grid for the decadal data available and the results are as shown in Fig. 3.

From the figure, it can be seen that at some grid points the SST is always >30 °C during the pre-monsoon period (i.e. the number of occurrences is 13). The year 2016 (2008) showed consistent warming with the maximum (minimum) number of occurrences.

4.2 Statistical Analysis

To study the spatial extent of the ASMWP and to classify each year as 'weak', 'normal' or 'strong', the surface area of the warm pool (km^2) was calculated and it is given in Table 2. The area was calculated by considering the number of occurrences of SST >30 °C, followed by normalisation and then multiplied with grid size. The area was converted into km^2 by multiplying it with 110^2.

The mean (μ) and standard deviation (σ) of the warm pool area were computed. Each year is classified under 'weak' ('strong') if its warm pool area is less (greater) than μ-0.5 σ (μ+0.5 σ) and under 'normal' if its warm pool area lied between μ-0.5 σ and μ+0.5 σ[8]. The statistical estimates of the warm pool area for the decade are as given in Fig. 4 and it shows that the years 2008 and 2012 fall under the category 'weak', the year

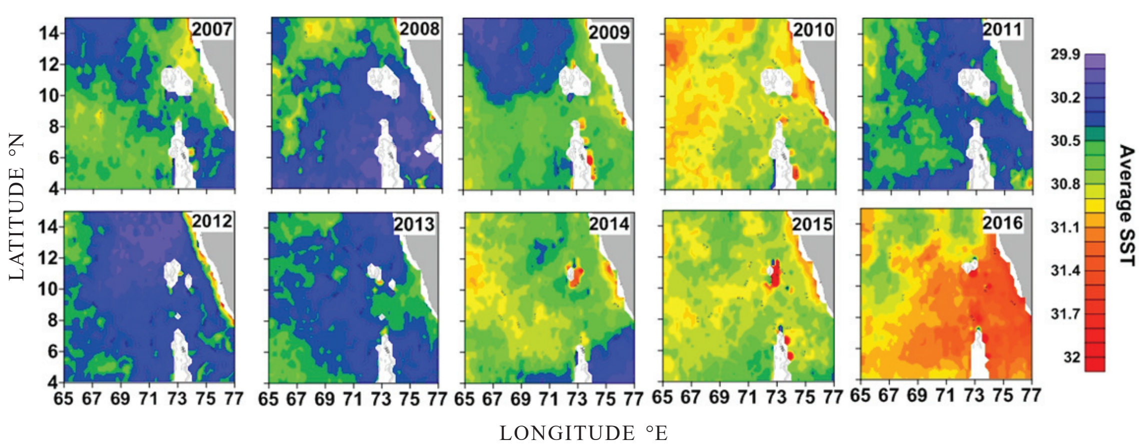

Figure 2. Inter-annual variability of SST during the pre-monsoon period of 2007-2016.

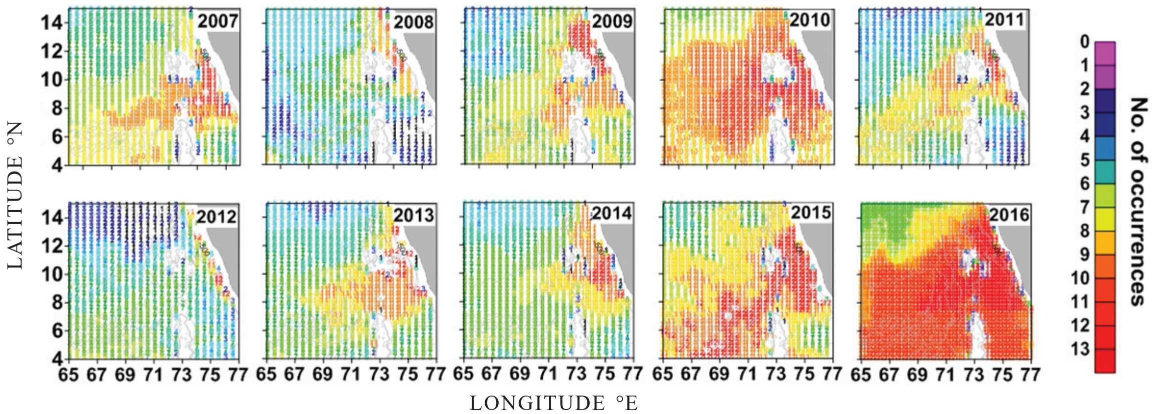

Figure 3. Number of occurrences of SST>30 °C during the pre-monsoon period of 2007-2016.

Table 2. Satellite data

Year	Pixels count (>30 °C)	Warm pool area (km^2)
2007	13695	796680
2008	7602	442231
2009	14050	817331
2010	17155	997959
2011	12340	717855
2012	10483	609828
2013	14193	825650
2014	14219	827162
2015	18079	1051711
2016	19823	1153164

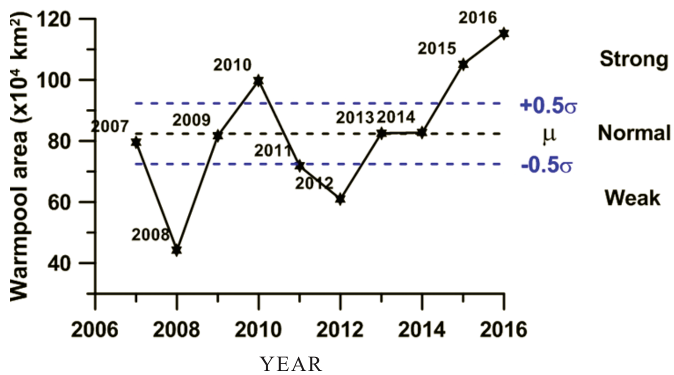

Figure 4. Surface area of warm pool during the decade 2007-2016 with its statistical estimates.

2007, 2009, 2011, 2013, and 2014 fall under 'normal' and the year 2010, 2015, and 2016 fall under 'strong' warm pool year. The year 2008, 2009 and 2016 representing 'weak', 'normal' and 'strong' warm pool years are used for further analysis.

4.3 Vertical Profile

The depth profile of the temperature for each considered warm pool type was taken into account for analysing the impact of warm pool across the ocean depth. The bunch plots of the vertical temperature profiles limited up to 100 m from the surface for the two longitudinal transects (9 °N and 10.5 °N) for the years 2008, 2009 and 2016 are as shown in Fig. 5. Robust *in-situ* observations in 2009 are not available to clearly represent the mixed layer.

It can be seen that the mixed layer depth (MLD) is relatively deep (~50 m) in May 2016 as compared to that in May 2008 (~38 m). It is also noted that the mixed layer temperature in the year 2008 is well within 30 °C whereas it is more pronounced during 2016 (>30 °C). It can be inferred that the vertical extent of the mixed layer has a great influence on the evaporative heat flux and hence the heat content is calculated based on the depth of MLD i.e. up to a depth of 50 m. The influence of warm pool on acoustic propagation was also studied using range dependent Parabolic Equation model[15]

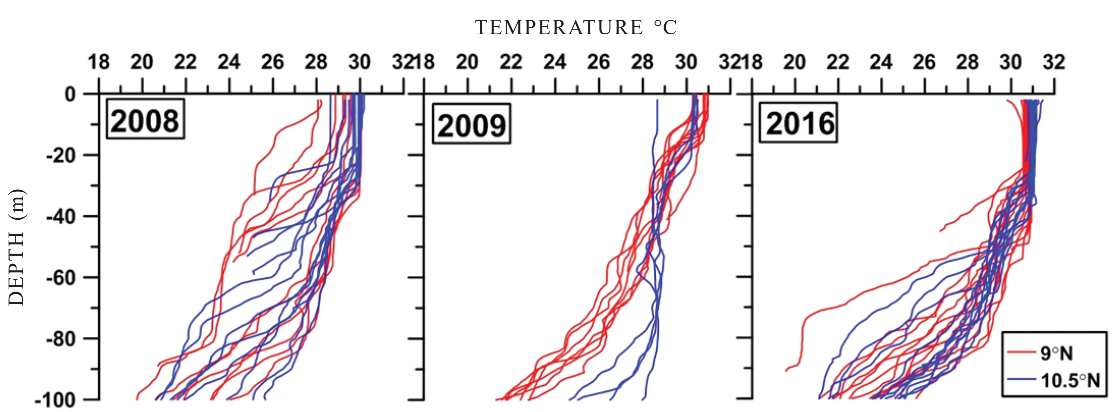

Figure 5. Vertical profile of temperature.

in the frequency range of 1 kHz - 1.5 kHz. It was found that the warm pool favours the ducted propagation within the MLD. However the results are not included in this study.

4.4 Heat Content

To quantify the warm pool events, heat content was calculated using *in-situ* temperature data. The heat content was calculated as integrated vertical temperature from the sea surface to 50 m depth following[16] and is as shown in Fig. 6.

$$HC = \rho C_P \int_0^{50} (T - 26) dz \qquad (1)$$

ρ = Seawater density (kg/m^3)
C_P = Specific heat capacity at constant pressure
T = Ocean temperature (°C)
ρC_P = 0.409 x 10^7 J/m^3/°C

The heat content was calculated along the two latitudinal transects viz. 9 °N and 10.5 °N. The heat content offshore of 73.5 °E could not be calculated for 2008 and 2009 due to the non-availability of the *in-situ* observations. It can be inferred from the figure that the heat content in 2016 is higher than the 2008 and 2009. It can also be seen that the heat content in the latitude 10.5 °N is more than that of 9 °N which can be attributed to the fact that the latitude 10.5 °N is in close proximity to the core of warm pool.

4.5 Atmospheric Water Vapour

To understand the impact of the warm pool on the atmosphere, Wind and Atmospheric Water Vapour (AWV) were considered. The longitudinal variation of AWV content (mm) for 2 latitudinal transects is as shown in Fig. 7. From the figure, it can be seen that as we move closer to the shore the AWV increases for both the latitudinal transects for the 3 year considered in the study. To justify this steady increase in AWV towards shore, wind data were taken from satellite as shown in Fig. 8. As expected the direction of the wind was from south west, which causes the piling up of the AWV near the shore. From the heat content and AWV graphs, a common pattern is that the warm pool behaviour for 2008 and 2009 overlap each other as against to consistent increase as observed in 2016. It was observed that the wind is west to SW in 2008 and in 2016, whereas in 2009, the wind pattern is inconsistent. This is primarily because of depression formed in 2009. Unlike heat content, the latitudinal variation was very minimal in the case of AWV whereas it was found to be maximum for 2016 similar to heat content which helps in confirming that 2016 as warmest. The piling of the AWV near the coast can also be attributed to the orographic effect due to the presence of Western Ghats.

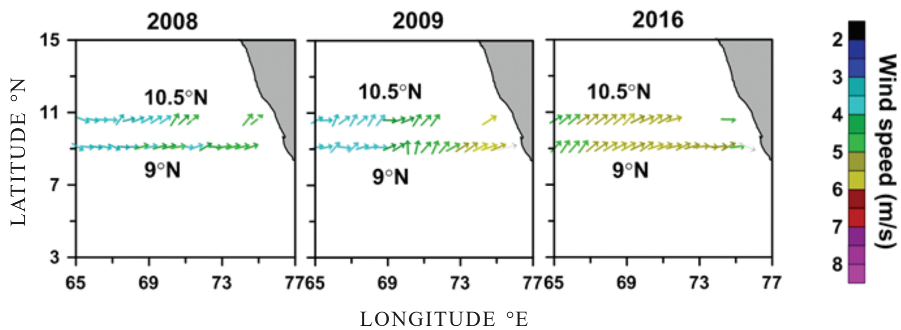

Figure 8. Wind speed and direction.

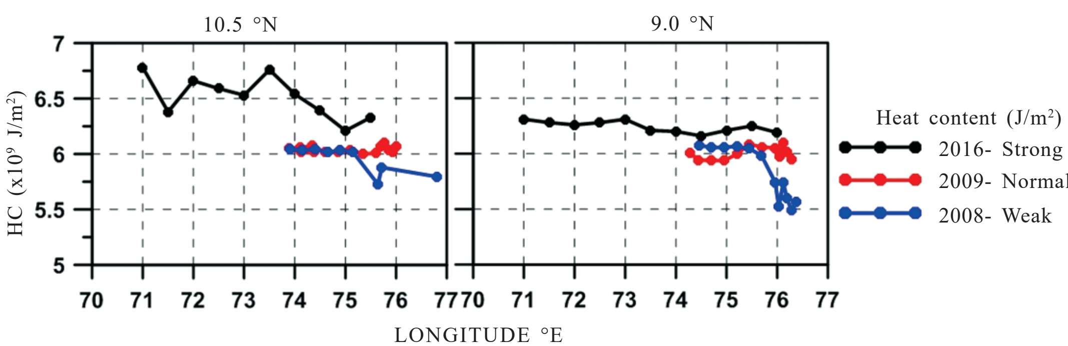

Figure 6. Heat content.

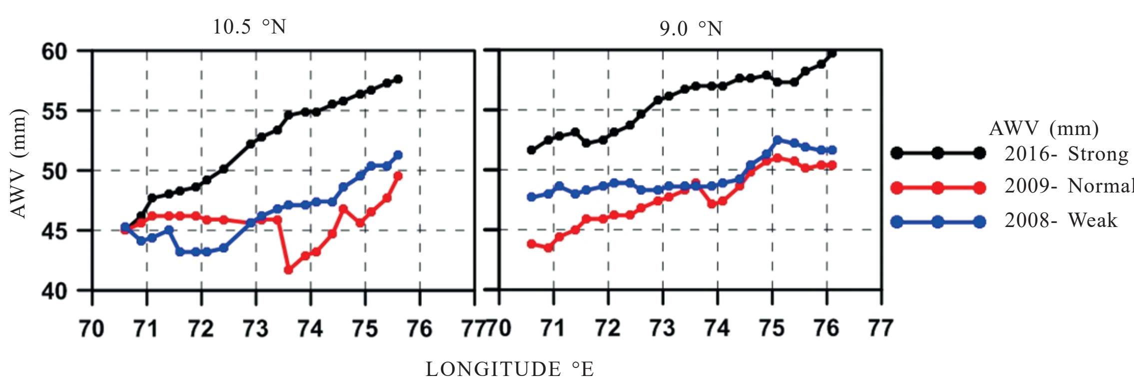

Figure 7. Atmospheric water vapour content.

5. CONCLUSIONS

Satellite data on the SST during the pre-monsoon months (March-May) were analysed for a period of 10 year (2007-2016) to find the inter-annual variability in ASMWP and to identify the warmest year of the decade. The impact of warm pool was analysed at 3 level viz., sea surface, ocean depth and atmosphere. A statistical analysis was done and 3 classifications such as 'weak', 'normal' and 'strong' warm pool years were made. The Heat content was calculated using temperature data measured from *INS Sagardhwani* for the representative years to analyse the vertical distribution of heat and to find the influence of warm pool towards deeper layers. The analysis of SST and heat content for the period 2007-2016 shows substantial warming of SEAS in 2016. The year 2016 was identified as the warmest year of the decade as per the satellite observations and also the *in-situ* observations. The heat content and AWV helped in confirming that 2016 as the warmest event in the decade.

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