MAUSAM, **56**, 1 (January 2005), 169-174

551.526.6 (267.37)

Characteristics of Arabian Sea mini warm pool during May 2003

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सार – इस शोध–पत्र में मई 2003 के महीने में पूर्वी अरब सागर से दूर गहरे सागरीय तथा तटीय क्षेत्रों में लघु उष्ण जल कुँड की विशेषताओं का अध्ययन करने के लिए आरमेक्स के कार्य के रूप में आई. एन. एस. सागर–ध्वनि पर महासागर वैज्ञानिक सर्वेक्षण किए गए। प्रेक्षण की अवधि को कमज़ोर पवनों और साफ आकाश से ज्ञात होने वाली मानसून से पूर्व की विशिष्ट स्थितियों से विशेषीकृत किया गया। टी. एम. आई. एस. एस. टी आँकड़े ग्राउंड ट्रूथ प्रेक्षण (~ 0.2° सें. के मूल माध्य वर्ग अंतर) के साथ अच्छा तालमेल दिखाते हैं। उपग्रह और ग्राउंड ट्रूथ दोनों से प्राप्त चित्र पूर्वी अरब सागर की सतह का तापमान (एस. एस. टी.) 31° से. से अधिक दिखाते हैं। केरल में ग्रीष्मकालीन मानूसन के आरंभ से ~ 8 दिन पहले लघु उष्ण जल कुँड अपना अधिकतम आयाम प्राप्त किया तथा आरंभ की तारीख से पहले समाप्त हो गया। ग्रीष्मकालीन मानसून ऋतु के आरंभ का पूर्वानुमान करने के लिए इस सूचना का उपयोग इंडेक्स के रूप में किया जा सकता है। ग्राउंड ट्रूथ और उपग्रह दानों के चित्रों में चक्रवात और प्रतिचक्रवात परिसंचरण पैटर्न के वैकल्पिक बैंड सुस्पष्ट थे। 31° सें. से अधिक के समुद्र सतह तापमान के क्षेत्रों में सतह की लवणता 34.75 पी. एस. यू. से कम पाई गई और इसकी गहराई पतली सतह तक सीमित था जिसके परिणामस्वरूप परत अधिक स्तरीय रही। भूमध्यरेखीय हिंद महासागर के उत्तराभिमुखी/उत्तर पश्चिमाभिमुखी अभिवहन के कारण तथा शीत ऋतु में वृत्ताकार परिसंचरण के दौरान मध्य अरब सागर के बीच में बंगाल की खाड़ी की जल राशि के पुनः परिसंचरण के दौरान मध्य अरब सागर के बीच में बंगाल की खाड़ी की जल राशि के पुनः परिसंचरण के कारण इस क्षेत्र में जल में लवणता कम पाई गई है।

ABSTRACT. Oceanographic surveys were carried out onboard INS Sagardhwani as a part of ARMEX in the deep and coastal regions of the eastern Arabian Sea during May 2003 to study the mini warm pool characteristics. The observational period was characterized by typical pre-monsoon conditions, as indicated by weak winds and clear skies. TMI SST data showed very good agreement with the ground truth observations (root mean square departure of ~0.2°C). Both the satellite imagery and ground truth showed surface temperature (SST) in excess of 31° C in the eastern Arabian Sea. This mini warm pool attained its maximum dimension ~8 days prior to the onset of summer monsoon over Kerala and the dissipated stated prior to the onset date. This information can be used as an index for the prediction of summer monsoon onset. Alternate bands of cyclonic and anti-cyclonic circulation pattern were evident both in the ground truth and satellite imagery. In the regions of SST more than 31° C, surface salinity was found to be less than 34.75 PSU and its depth extent was limited to thin surface layer resulting highly stratified layer. The low saline water present in this region was due to the northward / northwestward advection of low saline waters of equatorial Indian Ocean origin and the re-circulation of Bay of Bengal water mass trapped in the central Arabian Sea during winter by the eddy type of circulation.

Key words – ARMEX, Arabian Sea mini warm pool, TMI SST, Cyclonic and anti-cyclonic circulation, Low saline water.

1. Introduction

Studies based on sea surface temperature (SST) climatology (Hastenrath and Lamb, 1979; Rao *et al.*, 1991) and thermal structure (Hastenrath and Greischar, 1989; Levitus and Boyer, 1994) indicated a zone of warm waters (SST > 28° C) in the western tropical Pacific Ocean and central and eastern Indian Ocean, which is generally known as Indo-Pacific warm pool. This warm pool extends almost half way around the globe, stretching along the equator south of India, through the waters off Sumatra, Java, Borneo, and New Guinea, and into the central Pacific Ocean. The western Pacific Ocean warm pool is more extensive compared to the Indian Ocean warm pool whereas the core temperature of the Indian Ocean warm pool is much higher than in the Pacific Ocean (Vinayachandran and Shetye, 1991). More over, some studies (Bruce *et al.*, 1994, 1998 ; Shankar & Shetye 1997; Shenoi *et al.*, 1999) has linked the formation of this warm pool to the Laccadive High formation and its westward movement associated with the radiated Rossby waves.

Prior to the onset of summer monsoon, Seetharamayya and Master (1984) reported a pool of warm water with temperature in excess of 30.8° C in the southeastern Arabian Sea. This zone, which is a part of the Indian Ocean warm pool, is later known as the Arabian

Sea mini warm pool. Recently, Sanilkumar *et al*., 2004, reported temperature in excess of 31° C at the core prior to the onset of summer monsoon. Rao and Sivakumar (1999), documented various factors that contributed to the formation of this mini warm pool. The numerical simulation by Durand *et al*. (2004); Hastenrath and Greischar (1989) have shown that the heat trapped within a temperature inversion makes significant contribution to formation of warm pool in the south-eastern Arabian Sea.

The waters of the mini warm pool are warmer than any other open ocean on Earth and hence it has a large effect on the climate of surrounding lands. It was found that the onset vortex during the summer monsoon form in the southeastern Arabian Sea, which is one of the warmest regions of the Indian Ocean (Joseph 1990). Anjaneyulu (1980) pointed out that higher the difference of maximum SST during the pre-monsoon and minimum during the monsoon season, greater the possibility for a good monsoon and *vice versa*. Joseph (1990) found that warm SST anomaly in north Indian Ocean or cold SST anomaly in west Pacific Ocean is favourable for good monsoon rainfall over India.

In spite of all these significance not many scientific missions were conducted in the Arabian Sea mini warm pool region. Recently the national program, ARMEX phase II program (Department of Science and Technology, 2003) was launched to study the characteristics of the warm pool in detail. INS Sagardhwani of Defence Research and Development Organization also participated in this program in May 2003 and concentrated in the coastal and deep waters of the eastern Arabian Sea.

2. Data

INS Sagardhwani carried out an oceanographic survey in the eastern Arabian Sea during the pre-onset phase of the summer monsoon 2003. In this mission, stations were occupied at 3 km intervals in the coastal (20 stations, between 75.71° & 75.85° E and 9.73° & 9.84° N on 8 May 2003) and 30 km intervals in the deep waters (12 stations along 9.75° N and between 70° & 75.5° E during 23 - 26 May 2003) of the eastern Arabian Sea. Temperature and salinity data (using Mini CTD system, accuracy: $\pm$0.01° C, $\pm$ 0.02 PSU) were collected from all the stations. In addition, SST measured by the Microwave Imager onboard TRMM satellite (TMI) at 0.25° × 0.25° grids corresponding to the observational period was also utilized. TMI data and images are produced by remote sensing systems and sponsored by NASA’s Earth Science Information Partnership (ESIP) and TRMM Science team.

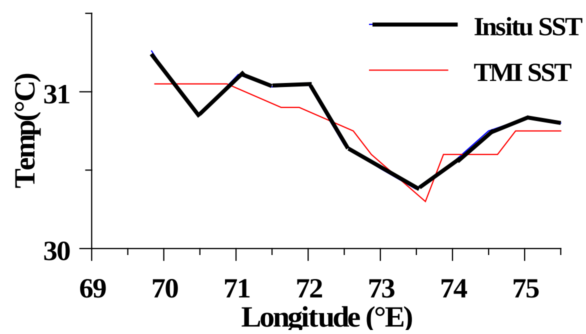


Fig. 1. Comparison of sea truth SST and TMI SST

3. Results and discussion

3.1. *Comparison of TMI SST with sea truth SST*

Studies (Wentz *et al*., 2000) have suggested that the retrieval of TMI SST was not affected by the clouds, aerosols, and atmospheric water vapor. Moreover, this data was available at three day interval at 0.25° × 0.25° grids resolution. Hence, the TMI SST data was utilized to study the evolution of the warm pool during May 2003. Prior to the analysis, the satellite SST data was compared with the simultaneous sea truth SST measurements (1m value from Mini CTD) made during May 2003 (Fig. 1). Comparison with sea truth observations showed that the TMI SST captures most of the variability as observed in the sea truth. The small root-mean-square differences between the satellite and sea truth (~0.2° C) also indicated very good agreement between the two. It is to be noted that the satellite measures the skin temperature whereas the sea truth measurement was from 1m depths, which might have resulted in the slight departure noticed between these two observations.

3.2. *TMI SST measurements*

Typical snapshots of TMI SST during May 2003 were presented to show the evolution of warm pool (Fig. 2). On 10 May, temperature in the Arabian Sea and Bay of Bengal was more than 30.25° C, except north of 18° N and close to the equator, where temperature was less than 30° C. On closer examination, it can be seen that a tongue with temperature in excess of 30.25° C extended from the west coast of India to the south Arabian coast, across the central Arabian Sea. Across this region, three pockets (west of 55° E, ~60° E and east of 71° E), where temperature was more than 30.75° C was clearly seen. Out of these three pockets, maximum temperature (>31° C) are noticed in the eastern Arabian Sea and off the south Arabian coast. However, the one in the eastern Arabian

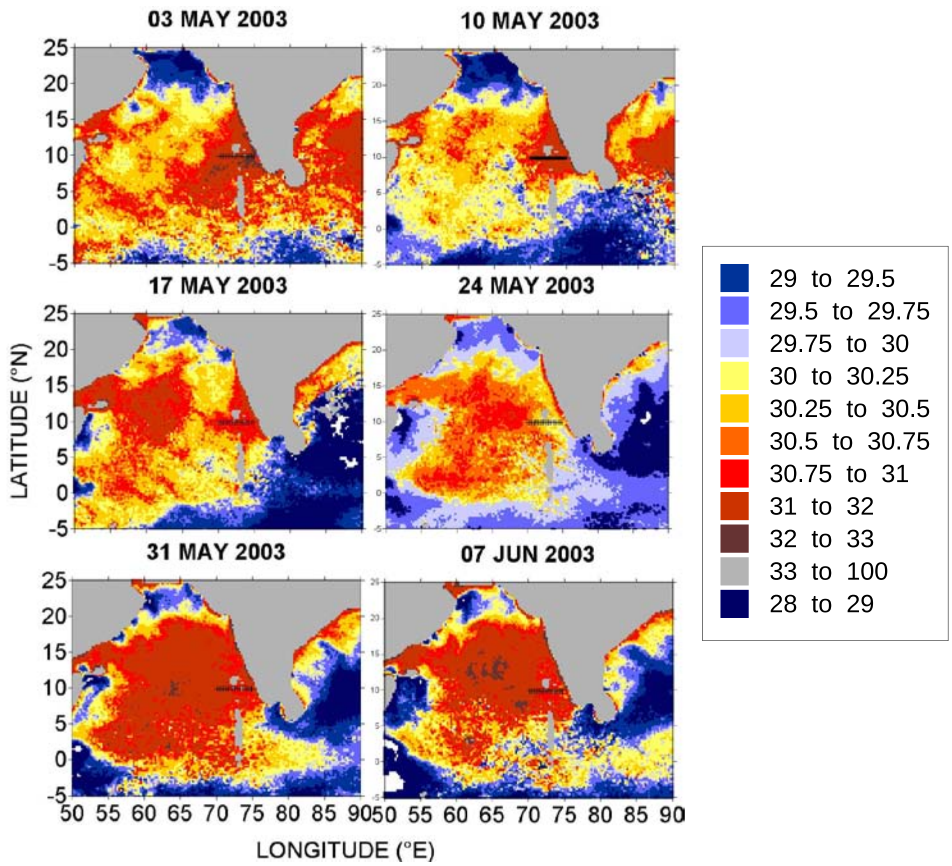


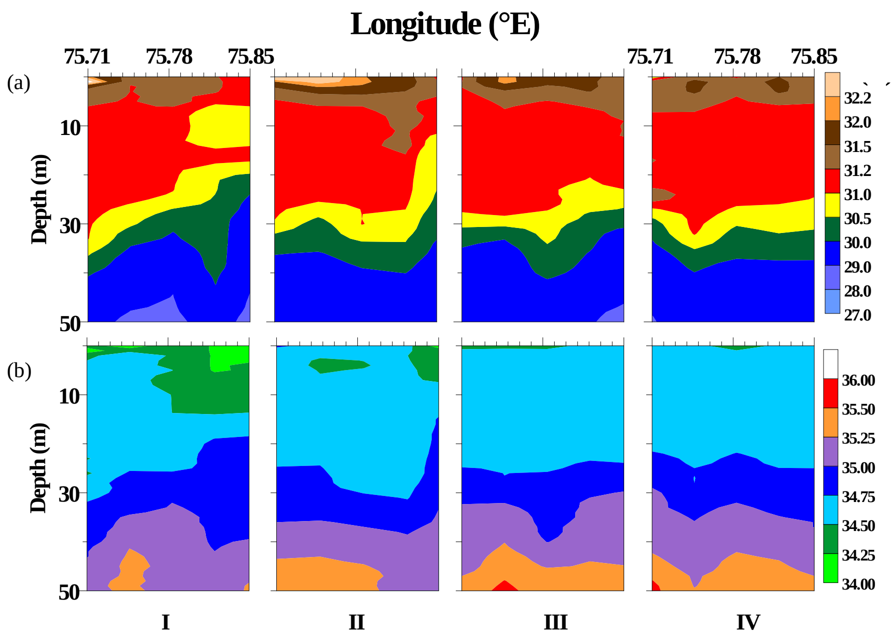
Fig. 2. Weekly TMI SST from 10^{th} to 31^{st} May. Black line indicated the track (9.75° N) of sea truth measurements

Sea was found occupy larger area (8° - 14° N and east of 70° E). Such regions of high temperature (> 31° C) are quite unusual in the other parts of the world oceans. This zone of anomalous water, which is observed in the eastern Arabian Sea prior to the onset of summer monsoon and part of the Indian Ocean warm pool, is known as the Arabian Sea mini warm pool (Seetharamayya *et al*., 1984; Durand *et al*., 2004).

A notable observation was the presence of alternate bands of warm (>30.5° C) and comparatively cold waters (< 30.25° C) along 9.75° N, *i.e.*, along the track of sea truth measurement. The cold water bands (< 30.25° C) were noticed between 52.5° - 54.5° E and 65.5° - 67.5° E (horizontal dimension of ~220 km), while the warm bands (> 30.75° C) were noticed between 54.5° - 65.5° E (horizontal dimension of ~330 km) and east of 67.5° E. This type of alternate warm and cold bands suggests eddy type of circulation, *i.e.*, clockwise and anti-clockwise flow pattern.

Another important point to be noted was the intrusion of water with temperature less than 30.25° C from the equatorial region towards the central (65.5° E and 67.5° E) and western Arabian Sea on 10 May. As these waters from the equatorial region, they are typically low saline compared to that of the Arabian Sea.

The scenario completely changed by 24 May. The regions of warm pool (> 31° C) shifted further offshore and temperature in the central Arabian Sea and equatorial regions (between 55° and 70° E) became more than 30.75° C. However, along the coastal belts off Somalia (~2° C) and southwest coast of India (~1.5° C), significant cooling was observed. It is to be noted that the comparatively low temperature water (~30.25° C), noticed in the southeastern Arabian Sea on 10 May, protruded along the west coast of India, and resulted in the offshore shifting of the mini warm pool. Moreover, on both side of this water (~30.25° C), comparatively higher temperature (> 30.75° C) was noticed. The alternate bands of low and



Figs. 3(a&b). Depth-space sections of (a) temperature and (b) salinity in the coastal waters (8 May 2003)

high temperature observed on 10 May, were evident during 24 May also, but slightly shifted southward. The intrusion of low temperature water from the equatorial region towards central Arabian Sea was evident on 24 May also.

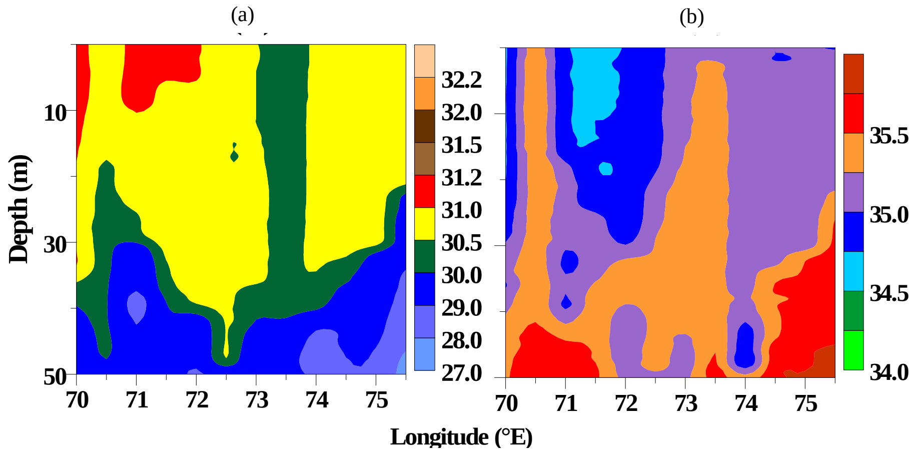
This mini warm pool attained its maximum area by 31 May, when temperature in excess of 31° C was noticed south of 18° N up to the equator. From the weather chart issued by Indian Meteorological Department, it was found that the onset of summer monsoon over Kerala was on 8 June. The analysis of TMI SST data concretely established the presence of Arabian Sea mini warm pool in the eastern Arabian Sea with temperature in excess of 31° C and attained its maximum dimension ~8 days prior to the onset date. Moreover, the warm pool started dissipating by 7 June, which was one day prior to the onset of summer monsoon over Kerala (8 June).

The TMI SST data also showed the northward intrusion of comparatively cold water (< 30.5° C) off the west coast of India, sandwiched between water with temperature in excess of 30.75° C close to the coast and in the deep waters. It is well known that these regions are famous for coastal upwelling. If the cooling was due to upwelling, the cold water has to be concentrated along the coast. The intrusion of this water resulted in the offshore shifting of the warm pool. The ground truth data sets collected in the eastern Arabian Sea during ARMEX gave an opportunity to further verify this phenomenon.

3.3. *Ground truth measurements*

The ground truth measurements were carried out in two phases. First survey was carried out in the coastal regions between 75.71° to 75.85° E and 9.73° to 9.84° N (on 8 May). The second survey was along 9.75° N between 70° and 75.5° E (during 23 - 26 May) covering the deep waters. In both the surveys, the observational period was characterized by typical pre-monsoon conditions, as indicated by weak winds and clear skies. In the coastal regions [Fig. 3(a)], surface temperature was in excess of 31.2° C, and occasionally exceeded 32° C. The same was noticed in the TMI SST data also (Fig. 2). The 31.2° C isotherm extended up to 8 m. The 31° C and 30° C isotherms were noticed up to depths of 30 m and 45 m respectively, suggesting large amount of heat stored in this region. Low saline waters (< 34.75 PSU) were found to occupy the water column [Fig. 3(b)] corresponding to the depth of 31° C. The T-S characteristics suggested that it is of equatorial Indian Ocean type.

In the deep waters Figs. 4(a&b), *i.e.*, along 9.75° N track, the surface temperature was of the order of 30.5° C, except west of 72° E, where pockets of warm waters with temperature more than 31° C were observed. The TMI SST imagery (Fig. 2) also indicated comparatively warmer waters west of 72° E. In these warm pockets (between 71° and 72° E), surface salinity was less than 34.75 PSU and mostly confined to the upper few meters. Similar to that of in the coastal waters, in the deep-water



Figs. 4(a&b). Depth-space sections of (a) temperature and (b) salinity along 9.75°N track (23rd to 26th May 2003)

regions also water column above 31° C was occupied by waters with salinity less than 34.75 PSU [Fig. 4(b)]. Presence of this low saline waters (< 34.75 PSU) increased the vertical salinity gradients to more than 0.06 PSU/m in the upper layers. The resulting strong vertical salinity gradients can inhibit vertical mixing, concentrating the insolation in the near-surface layers, which can lead to higher temperature (> 31° C) in the convergence zones compared to other regions. Moreover, the low saline waters in the upper layers and the comparatively high saline water below also result in a modification of vertical mixing which feeds back onto the heat budget of these warm pockets.

A notable feature in both temperature and salinity section along 9.75° N Figs. 4(a&b) is the alternate bands of troughs (convergence) and ridges (divergence) of isotherms/iso-halines, indicating eddy type of circulation pattern. Three bands of convergence (west of 70.5° E, between 71° E and 73° E, east of 74° E) and two bands of divergence (centered at 70.5° E and 73.5° E) were observed, suggesting anti-cyclonic and cyclonic circulation respectively. Similar features were observed in the TMI SST imageries also (Fig. 2). Various researchers (Bruce *et al.*, 1998; Bruce *et al.*, 1994; Shankar and Shetye, 1997) also reported the occurrence of such eddy type of circulation in the eastern Arabian Sea during the northeast monsoon period. At the anti-cyclonic zones, warm (> 30.5° C) and low saline (< 35.25 PSU) waters and in the cyclonic zone comparatively cold (< 30.5° C) and high saline (> 35.25 PSU) waters were observed. Associated with these cyclonic and anti-cyclonic flow patterns, thickness of the 30.5° C isotherm varied from less than 20 m to more than 30 m respectively. The anti-cyclonic flow region between 71° and 73° E has a horizontal dimension of more than 220 km in the upper layers.

An important question to be answered is how the low saline waters appear in the convergence zones, especially during May, when the circulation was clockwise in the Arabian Sea. Recently, Sanilkumar *et al.* (2004) also observed the same feature along 9° N. Studies by Shankar *et al.* (2004) and Shenoi *et al.* (2004) noticed low-salinity waters from the Bay of Bengal off the southwest coast of India in early December which propagate westward along with the down-welling Rossby waves that constitute the Lakshadweep sea-level high. Recirculation of this water mass due to the eddy type of circulation can be one of the factors for the presence of the low salinity water in the warm pool region.

The TMI SST imageries (Fig. 2) indicated the intrusion of comparatively low temperature water from the equatorial region in to the western and central Arabian Sea during 10th and 24th May. As this water was from the equatorial region, it is of equatorial Indian Ocean origin, which is typically low saline. Moreover, the alternate bands of clockwise and anti-clockwise circulation pattern in the Arabian Sea can also re-circulate this low saline water. The TMI SST also showed evidence of the intrusion of low saline equatorial water towards the central, though weak, and off the west coast of India, even during 24 May. The northward advection of low saline waters of equatorial Indian Ocean origin and its re-circulation by eddy type of circulation can also lead to the presence of low saline water in the warm pool region.

Acknowledgements

Authors are grateful to Director, NPOL for providing the support and encouragement for this study.

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