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Moored buoy observations in Arabian Sea warm pool

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सार – इस शोध पत्र में उष्ण जल कुँड की विशेषताओं का अध्ययन करने के लिए चार माह (मार्च–जून 2003) की अवधि के दक्षिणी पूर्वी अरब सागर में चार स्थिर आँकड़ा प्लवों से लिए गए समयबद्ध श्रृंखलाओं के प्रेक्षणों का उपयोग किया गया है । मानसून–पूर्व की अवधि में स्थिर प्लव प्रेक्षणों से कमज़ोर भिन्न पवनों और शांत समुद्री अवस्थाओं सहित सही मानसून की स्थितियों का पता चलता है । मानसून पूर्व की उष्णता के चरण के दौरान समुद्र सतह तापमान अधिक पाए गए हैं । इस क्षेत्र में सतह मौसम विज्ञान प्रेक्षण से अप्रैल 2003 के अंतिम सप्ताह से लेकर दो सप्ताहों की अवधि में अपेक्षाकृत निम्न अवदाब का पता चला है । इस अवधि में पवन की दिशा में दक्षिणावर्त्त घूर्णन सहित संबधित पवन गति और तरंग की ऊँचाई तथा अनियमित वर्षा का पता चला है । इस प्रेक्षण की रोचक बात बंगाल की खाड़ी में मई 2003 को आए चक्रवात के कारण एस. एस. टी. का शीतलन होना है । इसकी अन्य विशेषता उष्णता की अवस्था के दौरान समुद्र सतह तापमान के प्रेक्षित किए गए 14 दिनों के क्रम में दोलन हैं । मार्च माह में लवणता के समयबद्ध प्रेक्षणों से उष्ण जल कुंड में लवणीय जल की कमी का पता चला है । 2 अप्रैल को धरातलीय लवणता में अचानक 0.4 पी.. एस. यू. की कमी देखी गई जो संभवतः उष्ण जल कुंड क्षेत्र में कम लवणीय पिच्छ के अभिवहन के कारण/अथवा स्थानीय मानसून पूर्व की बौछारों के कारण हो सकती है । दक्षिणी पश्चिमी मानसून के आरम्भ होने और संबद्ध मानसून की धाराओं से उष्ण जल कुंड समाप्त हो गए तत्पश्चात् उस क्षेत्र में उच्च पवनों, समुद्र की खराब स्थितियों और लगातार वर्षा के साथ मानसून की स्थितियाँ प्रबल हो गई ।

ABSTRACT. Time series observations from four moored data buoys in the south eastern Arabian Sea for a period of four months (March - June 2003) are utilized to study the characteristics of warm pool. The moored buoy observations show fair weather conditions in the pre-monsoon period with weak variable winds and calm sea conditions. High SST has been observed during the pre-monsoon warming phase. Surface met observation shows comparatively low-pressure in the region for a period of two weeks starting from the last week of April 2003. Increased wind speed and wave height with a clockwise rotation in wind direction and occasional rains are reported during that period. An interesting observation is the cooling of SST in response to the May 2003 cyclone in Bay of Bengal. Another feature during the warming phase is an oscillation of the order of 14 days observed in SST. Time series observations of salinity in the month of March show the presence of low saline water in the warm pool. A sudden drop of 0.4 psu in surface salinity was observed on 2nd April, which may be due to the advection of low saline plumes in the warm pool region and/or the local pre-monsoon showers. The onset of southwest monsoon and the associated monsoon currents dissipated the warm pool and thereafter the monsoon conditions with high winds, rough sea and frequent rains prevailed in the region.

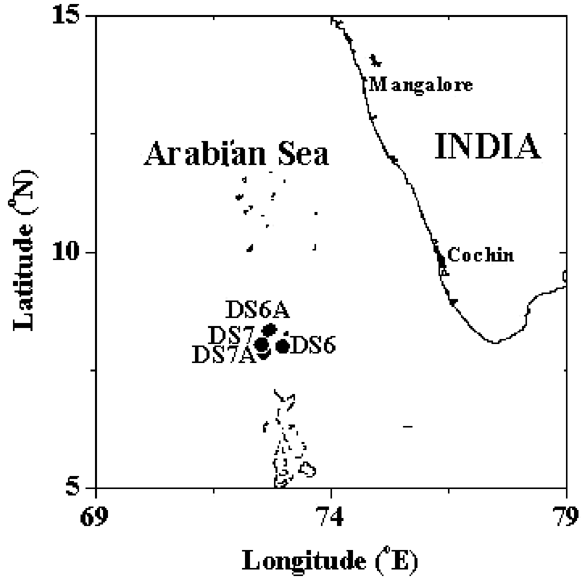
Key words – ARMEX, Warm pool, Arabian Sea, Cyclone, Southwest monsoon, Moored data buoy.

1. Introduction

Arabian Sea warm pool is a unique phenomenon of anomalous warm surface water in the South Eastern Arabian Sea (SEAS), which collapses with the onset of southwest monsoon (Seetaramayya and Master, 1984). Studies by Joseph (1990) and Rao & Sivakumar (1999) highlighted the link between the warm pool and the southwest monsoon. Arabian Sea warm pool is the long-lasting warmest water in the world ocean (Shenoi *et al.* 1999), which accumulates heat in the shallow mixed layer. Weak winds and clear skies during the pre-monsoon period over this region favours the formation of a shallow mixed layer which in turn accumulates heat. Sengupta *et al.* (2002) and Weller *et al.* (2002) pointed out the significance of surface heat flux in the warming of mixed layer. The net heat gain into the sea in a thin surface layer leads to an anomalous rise in Sea Surface Temperature (SST). However the forcing mechanism behind the formation and its association with the southwest monsoon is not fully understood. Hence an observational campaign, "Arabian Sea Monsoon Experiment (ARMEX)" was organized under Indian Climate Research Programme (ICRP) and its phase II was dedicated to study the characteristics of the warm pool in the SEAS.

2. Data and method

Under the ARMEX Phase II programme, four moored data buoys were deployed in the SEAS



Buoy-Id	*Lat (°N)*	*Long (°E)*	*Depth (m)*
DS6	8.30	72.76	1900
DS6A	8.350	72.720	2120
DS7	8.315	72.664	2000
DS7A	8.310	72.650	2000

Fig. 1. Data buoy locations in the SEAS deployed for warm pool study

exclusively to study the evolution and collapse of the warm pool. These buoys were equipped with meteorological and oceanographic sensors to measure air pressure, air temperature, wind, SST, current and wave parameters. The data buoys record and transmit the data at synoptic hours (every three hour) through INMARSAT-C satellite to the shore station established at National Institute of Ocean Technology (NIOT) Chennai. Time series observations of surface met. and oceanographic parameters for a period of four months during March - June 2003 are utilized for this study.

A close network of four data buoys are deployed off Minicoy Island at an average depth of 2000 m. The data buoys DS7 & DS7A were deployed very close to each other (1 nm apart). DS6 is deployed 4 nm east and DS6A at a distance of 4.5 nm north of DS7 (Fig. 1). The observations made by these buoys during ARMEX–II are compared with each other and shows good correlation. The surface wind observations were made at a height of 3 m above the sea surface and are extrapolated to 10 m height using the power law (Panofsky and Dutton, 1984). Water temperature and salinity observations are made at a depth of 3m below the sea surface.

There are data gaps in SST and salinity during the observational period due to stoppage of buoy and bio fouling of the sensor. Salinity observations are available only for a period of one month from 4th March to 7th April 2003. SST data is not available from 16th May 2003 due to the stoppage of DS7A and a new buoy (DS6A) was deployed on 27th May 2003.

3. Results and discussion

The moored buoy observations in the SEAS show fair weather conditions in the pre-monsoon period with weak variable winds and calm sea conditions. Surface met observations show the existence of a comparatively low-pressure in the region for a period of two weeks starting from the last week of April 2003. Rapid increase in wind speed, wave height and a clockwise rotation in wind direction are observed in that period. Associated rain events have caused sudden fluctuations in air temperature and SST in the region. Time series observations suggest that the onset of monsoon over the warm pool region was on 6th June 2003, two days before the onset in Kerala coast. After the monsoon onset, high winds, rough sea and frequent rains prevailed in the region.

3.1. *Surface Met. observations*

The time series observations of wind exhibit the transition of wind pattern with the march of seasons. The initial period of observation shows light winds (~5 m/s), which slowly changes the direction from north-northeasterly to north-northwesterly (Fig. 2). The rapid increase in wind speed and a clockwise rotation in wind direction during the first week of May are due to the low pressure system prevailed in the region. An increase in wind speed (> 6 m/s) in a steady northwesterly direction is observed for a period of two weeks starting from 10th May, which may be the response to the cyclone passage in Bay of Bengal (BoB). There is a sharp increase in wind speed (~10 m/s) after the onset of monsoon and the wind direction changed to west-southwesterly.

The air temperature was around 29° C in the beginning of March, which steadily increased to more than 32° C by the second week of April (Fig. 3). Lower values in air temperature during the pre-monsoon season

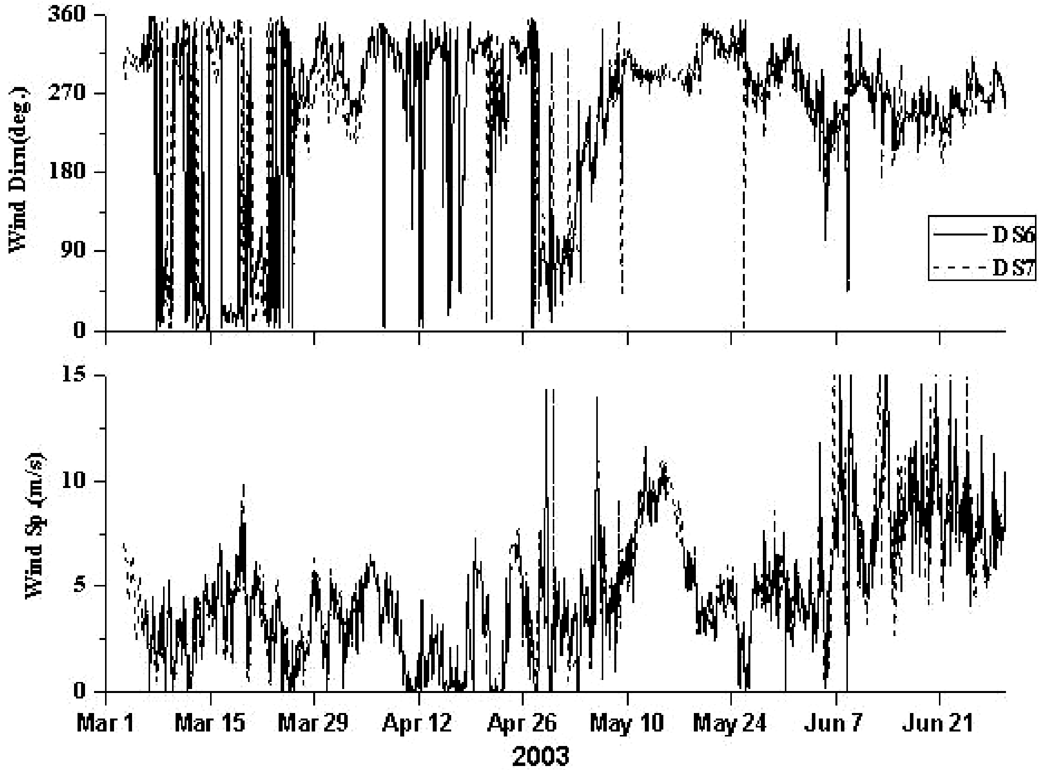


Fig. 2. Time series observations of wind speed and direction in the warm pool

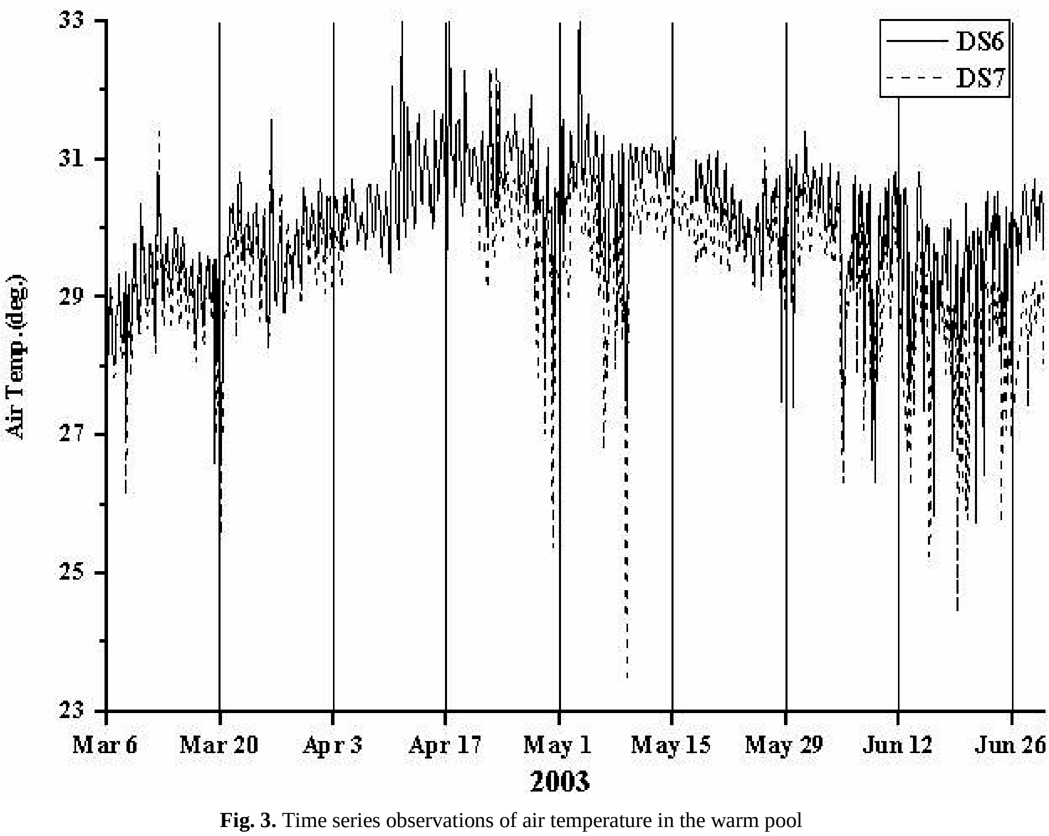


Fig. 3. Time series observations of air temperature in the warm pool

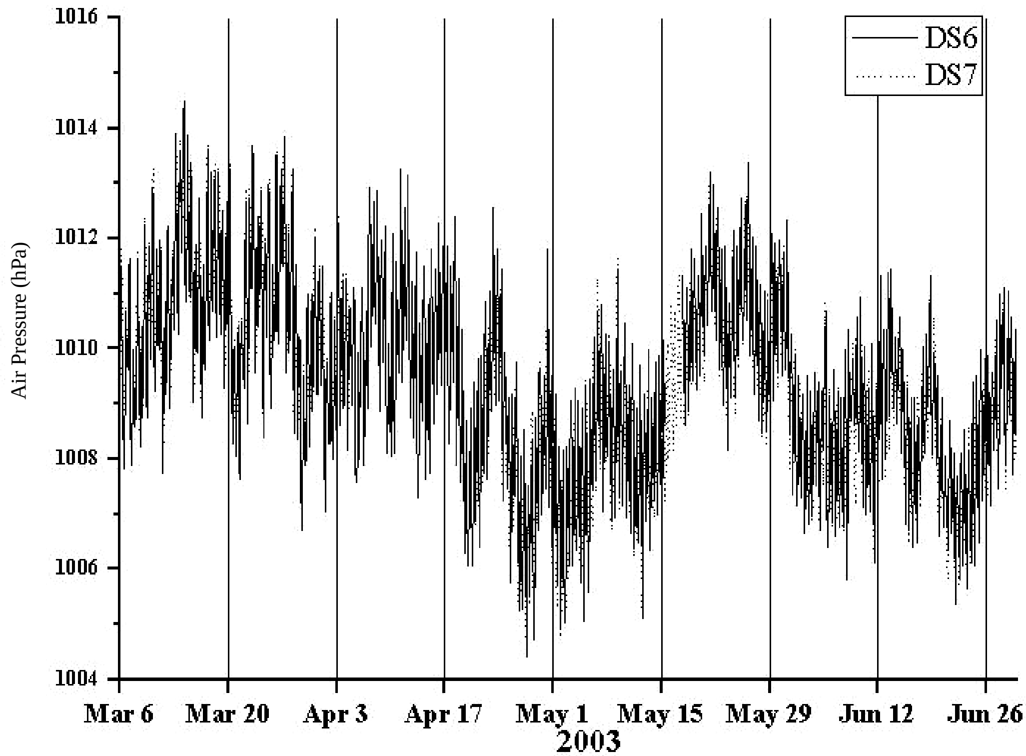


Fig. 4. Time series observations of air pressure in the warm pool

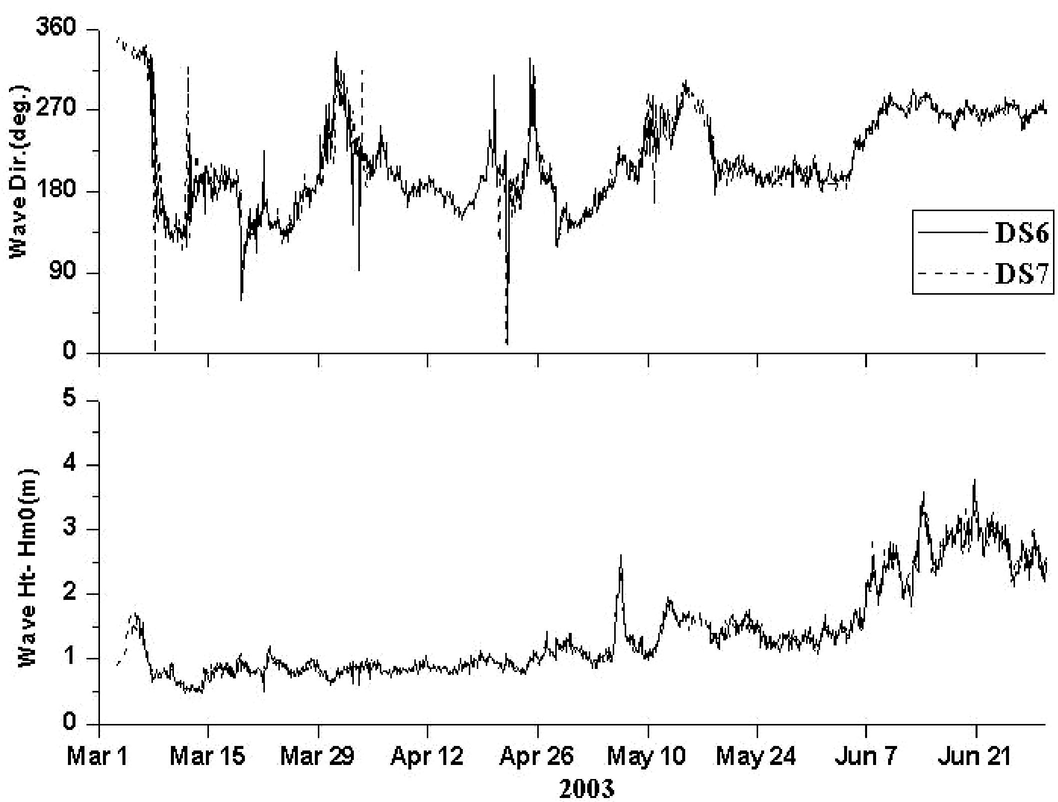


Fig. 5. Time series observations of wave height and direction in the warm pool

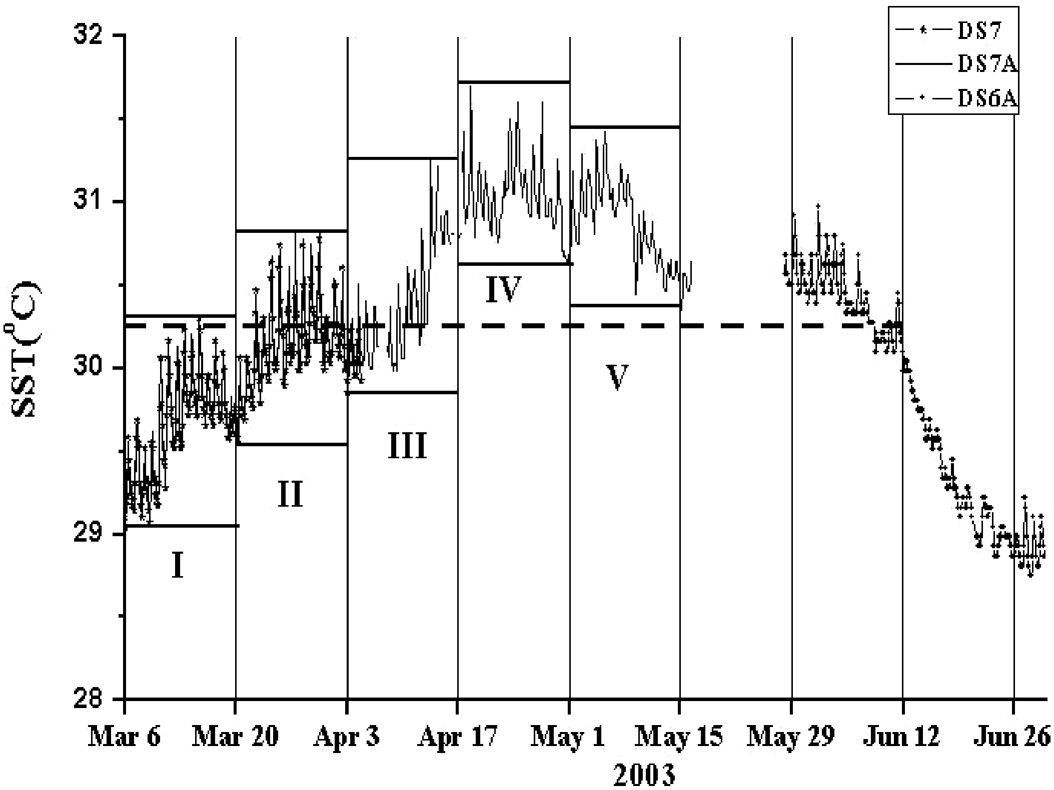


Fig. 6. SST observations in the warm pool region and its biweekly oscillations. The dashed line represents 30.25° C SST

are associated with local showers. The air temperature started decreasing from the beginning of May and continued till the end of observation. Biweekly oscillation of air temperature is observed in the initial period, but overshadowed due to the occasional rains. The sudden fluctuations in air temperature after the monsoon onset is due to the intense rainfall received in this region.

The air pressure observations showed an average value of 1010 hPa during the initial period (Fig. 4). Comparatively lower air pressure prevailed in the region for a period of two weeks from 25th April to 12th May 2003. Minimum air pressure of 1004.4 hPa is observed at DS6 location on 27th April 2003. There is a sudden drop in air pressure on 31st May and continued during the remaining period of observation. Biweekly oscillation observed in air temperature and SST is not evident in air pressure observations. However large intra-seasonal variability can be seen in the surface pressure.

3.2. *Wave observation in the warm pool*

The wave observation in the pre-monsoon period shows the calm sea conditions with an average wave height of 1m (Fig. 5). The waves are variable in direction, predominantly southerly during this transition period. The sudden increase in wave height in the first week of May (2.62 m) is the impact of high wind speed associated with the low pressure in the region. An average wave height of 1.5 m is observed during the second week of May, due to the increased wind speed. Steady southerly swell waves dominated wave conditions during this period whereas the wind direction is west-northwesterly. After the onset of monsoon the wave height has increased with an average value of 3 m in a steady southwesterly direction.

3.3. *SST in the warm pool*

Time series observations of SST exhibit the warming of surface water during the pre-monsoon period and the collapse of the warm pool by the onset of monsoon (Fig. 6). The maximum SST observed was 31.71° C at DS7A on 18th April 2003 and remains warmer with an average of 30.93° C till second week of May. Such a high surface temperature is unique in the world ocean. A recent study by Sanilkumar *et al.* (2004) defined an Arabian Sea mini warm pool as the region where SST is more than 30.25° C. According to the

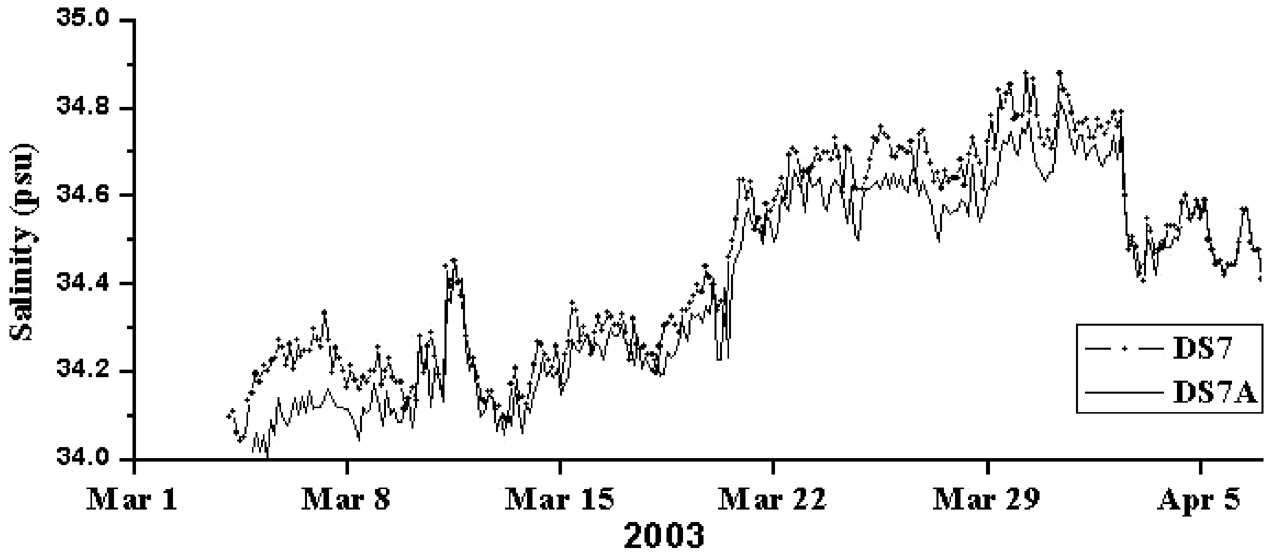


Fig. 7. Time series observations of salinity in the warm pool

definition, during 2003 warm pool in the SEAS exist for a period of ~2½ months from 22nd March till the onset of monsoon (Fig. 6). A sharp decrease in SST followed by the monsoon onset is observed at the buoy site.

An interesting feature during the warming phase is an oscillation of the order of ~14 days in SST (Fig. 6). Five biweekly cycles are recorded from 6th March to 15th May in the observations. The first two cycles show a steady increase in SST whereas the third cycle shows a rapid increase of 1.4° C (Table 1). The fourth and fifth cycles retain the oscillations without much variation in SST, which shows that warm pool attains the mature stage much before the monsoon onset. The sudden fluctuations in SST during the 4th and 5th cycle are the impact of local pre-monsoon showers in the warm pool region.

In the first cycle SST was varying between 29.1° C & 30.3° C. In the second cycle it was between 29.6° C and 30.8° C. However in the third cycle SST attained about 31.5° C and found to be varying between 29.8° C and31.5° C. Maximum SST of 31.71° C on 18th April was observed in the fourth cycle. However the fifth cycle shows a decrease in SST by 1.08° C, which varies from 31.45° C to 30.37° C (Table 1). The maximum rise in SST (1.4° C) is observed in the third cycle and the minimum (1.08° C) in fourth (Table 1). Similar oscillation is observed in air temperature also. The uniform oscillation in SST and air temperature supports the influence of net surface heat flux in warming the mixed layer of the SEAS (Sengupta *et al.* 2002).

TABLE 1

Maximum, minimum and increase in SST in the five cycles observed during the warming phase of warm pool

Cycle	Minimum SST (°C)	Maximum SST (°C)	Increase in SST (°C)
I	29.09	30.31	1.22
II	29.57	30.82	1.25
III	29.86	31.26	1.4
IV	30.63	31.71	1.08
V	30.37	31.45	-1.08

The decrease in SST in the end of fifth cycle may be due to the effect of BoB cyclone, this supports the role of remote forcing (McCreary *et al*. 1993) in controlling SST over SEAS. More detailed model study is however required to understand the processes in detail. There is a considerable decrease in SST and could not regain the pre-cyclone condition. Due to the gap in SST exact effect and the response time is not clear. The SST observations exhibit high amplitude diurnal oscillations during the warming phase of the order of 0.5° C. So the observation reveals the considerable diurnal variation in SST during the pre-monsoon (Weller *et al.* 2002). These oscillations disappeared once the monsoon conditions set in. It shows the intensity of mixing, the dissipation of the thin warm surface layer and the lack of insolation due to cloud cover.

3.4. *Sea surface salinity variation in the warm pool*

The role of salinity in accumulating heat in surface waters of the warm pool region is not well established. However the studies by Shenoi *et al.* (1999) and Rao & Sivakumar (1999 & 2003) have provided an insight into this phenomena. The presence of low saline water in the upper layers of warm pool region that was brought by the coastal currents from the BoB (Shenoi *et al*. 1999) forms a thin surface layer and favours relative warming. The buoy data in the beginning of March 2003 shows the existence of low saline water (~34.2 psu) in the warm pool region (Fig. 7). The presence of barrier layer (Shenoi *et al*. 2004) in the warm pool region prohibits dissipation of heat into deeper layers. The observations show a steady increase in salinity as summer progresses till the end of March with a maximum of 34.88 psu on 31st March. It shows that the low saline water in warm pool region is systematically replaced by the Arabian Sea high saline water. A sudden drop in salinity (~0.4) on 2nd April is observed at both buoy locations. Similar drop in salinity due to advection of low salinity plume is reported by Shenoi *et al*. (2004) during ARMEX cruise in warm pool region.

4. Conclusion

The result of the time series observations are summarized as follows :

(*i*) The moored buoy observations in the SEAS show fair weather conditions in the pre-monsoon period with weak variable winds and calm sea conditions.

(*ii*) Surface met. observations show the existence of a comparatively low-pressure in the region for a period of two weeks starting from last week of April 2003. Increased wind speed and wave height with a clockwise rotation in wind direction and occasional rains are recorded during that period.

(*iii*) Response of SEAS to the BoB cyclone in May 2003 is captured in time series observations. Increased wind speed, wave height and drop in SST without much pressure drop are observed in the second week of May simultaneous to the cyclone occurrence in BoB.

(*iv*) A pronounced pre-monsoon warming of SST over a period of two months is observed in the warm pool, with a maximum value of 31.71° C on 18th April 2003. SST observations show that warm pool attains the mature stage much before the monsoon onset.

(*v*) The SST observations exhibit high amplitude diurnal oscillations (0.5° C) during the warming phase.

(*vi*) Biweekly oscillation in SST is observed in the warm pool region during the pre-monsoon warming phase. The similar oscillations are reported in air temperature, which supports the role of net surface heat flux in warming up the warm pool region.

(*vii*) The salinity observations in the beginning of March 2003 show the existence of low saline water (~34.2 psu) in the warm pool region. The salinity has increased slowly as summer progressed till the end of observation (7th April 2003) and reached a maximum of 34.88 psu on 31st March.

(*viii*) There is a sudden drop in salinity (~0.4 psu) in the first week of April, which could be due to advection of low salinity plume in the warm pool region.

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