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Evolutions of sea level high and warm pool in the southeastern Arabian Sea and their association with Asian monsoons : A study on cause-and-effect relationships

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सार – इस शोध पत्र का उददेश्य ग्रीष्म मानसून ऋतु के आरंभ होने से पहले दक्षिणी पूर्वी अरब सागर में उष्णकुंड के बनने तथा संबद्ध समुद्र सतह उभार के विषय में और अधिक जानकारी प्राप्त करना है। इनसे प्राप्त हुए परिणामों से पता चलता है कि अप्रैल के महीने में भारत के दक्षिणी पष्चिमी तट के समीप उष्णकुंड वाले क्षेत्रों में समुद्र सतह तापमान सबसे अधिक पाया जाता है। दिसंबर के महीने में उसी क्षेत्र में समुद्र सतह तापमान सबसे अधिक रिकार्ड किया गया है। समुद्र सतह उभार में क्षय पूर्व मानसून ऋतु से काफी पहले ही होना आरंभ हो जाता है जबकि उष्णकुंड का क्षय जून के महीने में ग्रीष्म मानसून ऋतु के आरंभ होने के बाद होता है। इसलिए समुद्र सतह की ऊँचाई और उष्णकुंड के क्षयों कें बीच लगभग तीन चार महीनों का अंतराल होता है। सितंबर के महीने से समुद्र सतह तापमान में एकाएक वृद्धि और अक्तूबर के महीने से समुद्र सतह की ऊँचाई में वृद्धि एक दिलचस्प पहलू है जो कि मानसूनोत्तर ऋतु (अक्तूबर – दिसंबर) के दौरान लगातार विद्यमान रहता है। अतः मानसून ऋतु से पहले और बाद में उष्णकुंड के क्षय होने और विकसित होने की प्रकिया आकस्मिक घटनाएं हैं।

अतः वार्षिक पैमाने पर उष्णकुंड की तीव्रता और समुद्र सतह की गोलाकृति की ऊँचाई में पर्याप्त विभिन्नताएं हैं। 1987–88 की अवधि के एलनीनों/दक्षिणी दोलन (ई.एन.एस.ओ.) की परिवर्तनषीलता में कई दिलचस्प विषेषताएं सामने आई हैं। 1987 के एलनीनो वर्ष के दौरान उष्णकुंड तीव्रता जून के महीने में अपने चरम पर थी जबकि 1988 के ला नीना के दौरान उष्णकुंड में काफी पहले अर्थात अप्रैल माह में अधिकतम तीव्रता आई है।

ABSTRACT. The present study aims at gaining more insight into the evolution of warm pool and associated sea level dome in the southeastern Arabian Sea before the summer monsoon onset. The results show that the Sea Surface Temperature (SST) maximum in the warm pool region is found during April close to the southwest coast of India. The Sea Surface Height (SSH) maximum over the same region is observed during December. The collapse of sea level dome begins well in advance during the pre-monsoon whereas the warm pool collapses after the onset of summer monsoon during June. Therefore, there is a lag of about three to four months between the collapses of the sea level high and the warm pool. Most interesting aspect is the dramatic increase of SST from September and SSH from October which is continued throughout the post monsoon season (October - December). Therefore, both the collapse and evolution of warm pool are dramatic events before and after the summer monsoon.

There are considerable variations in the intensity of warm pool and the height of sea level dome on interannual scale. The variation during El-Nino Southern Oscillation (ENSO) epoch of 1987-88 has revealed many interesting features. During El-Nino year 1987 the warm pool intensity reached its peak in June whereas during La Nina year 1988 the warm pool attained its maximum intensity much earlier, *i.e*., in April.

Key words – Sea level high, Warm pool, Sea surface height (SSH), Sea surface temperature (SST), Mean tidal level (MTL), Salinity, Standardized anomaly.

1. Introduction

The warm pool region in the southeastern Arabian sea is associated with intense convection during the onset phase of the summer monsoon. The convection over this region is manifested as a trough of low pressure, low pressure area, depression or cyclonic storm in different events. In several years the onset o f summer monsoon

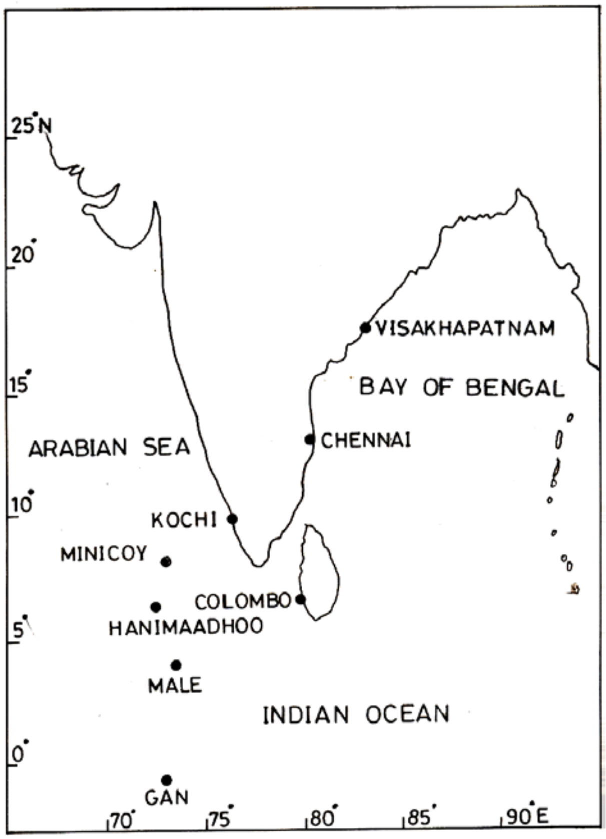

Fig. 1. Locations of stations

over the southeastern Arabian Sea and adjoining southwestern coast of India (Kerala coast) is accompanied with the formation of an onset vortex (Krishnamurti *et al.*, 1981). As the area of formation of onset vortex is usually located in the warm pool region in the southeastern Arabian Sea (Kershaw, 1985), the Arabian Sea warm pool seems to play an important role in the monsoon onset process and the genesis of the onset vortex.

It is believed that the east India coastal current during October - December is responsible for the transport of low-salinity water from the north Bay of Bengal to the southeastern Arabian Sea and subsequent formation of sea level high, called the Lakshadweep high (Bruce *et al.*, 1994; Shankar and Shetye, 1997; Shankar, 1998). The transport of low-salinity water from the Bay of Bengal leads to the formation of a stable layer near the surface waters which in turn initiates the development of the sea level high over the southeastern Arabian Sea. The enhanced heating of this stratified region during summer (pre-monsoon) months leads to the formation of the Arabian Sea warm pool. The exact pathway of low-salinity water from the Bay of Bengal to southeastern Arabian Sea is not known (Han and McCreary, 2001; Shankar *et al.*, 2002; Shenoi *et al.*, 2005). Similarly, the time-lag between the development of sea level high and the warm pool and the causes of large interannual variabilities are also not fully understood.

The monsoon experiments, MONEX-79 & ARMEX-2003 conducted over the Arabian Sea have shown that there is a sudden decrease of SST in the warm pool region during the onset phase of summer monsoon (Rao, 1990; Sikka, 2005; Singh and Hatwar, 2005; Hareesh Kumar *et al.*, 2005; Gnanaseelam *et al.*, 2005; Rao and Sikka, 2005). At the peak of summer monsoon the warm pool region is characterized by the lowest SSTs.

The present work aims at detailed investigations of the comprehensive process of evolution, maintenance and collapse of sea level high and the warm pool in the southeastern Arabian Sea in association with the monsoons. The roles of monsoons both summer and winter in the genesis of warm pool have been looked into. The impacts of El-Nino Southern Oscillation (ENSO) on the warm pool and Lakshadweep high have also been investigated in order to ascertain the probable causes of large interannual variability in the two phenomena. On the other hand, the influence of warm pool intensity in the determination of the nature of subsequent summer monsoon has also been studied for two contrasting monsoons of 1987 and 1988.

2. Data and methodology

The satellite based SST climatology for the warm pool region has been prepared from the NOAA-AVHRR gridded SST data (1985-98) obtained from the NASA Physical Oceanography Distributed Active Archive Centre at the Jet Propulsion Laboratory, California, U.S.A. This gridded satellite SST data is very reliable as it has been validated by various *in-situ* climatologies. The details have been discussed by Casey and Cornillon (1998). It was possible to determine the SSTs very close to the coast due to very high resolution of data (~9.28 km). The satellite SST climatology is highly suitable for the study of SST variability over a localized zone such as Arabian Sea warm pool region due to paucity of conventional SST observations from the ships of opportunity. The sources of monthly values of Mean Tidal Level (MTL) are : Survey of India, the Permanent Service of Mean Sea Level (PSMSL), U.K. and the University of Hawaii, U.S.A. The lengths of historical records of MTL vary for different stations depending upon the commencement of the observations. For Cochin (Kochi) we have considered the MTL data for 53 years whereas the lengths of MTL time-series for Maldives stations are less as the observations started much later in that country. However, the MTL time-series is sufficiently long to bring out the evolution process of sea level high.

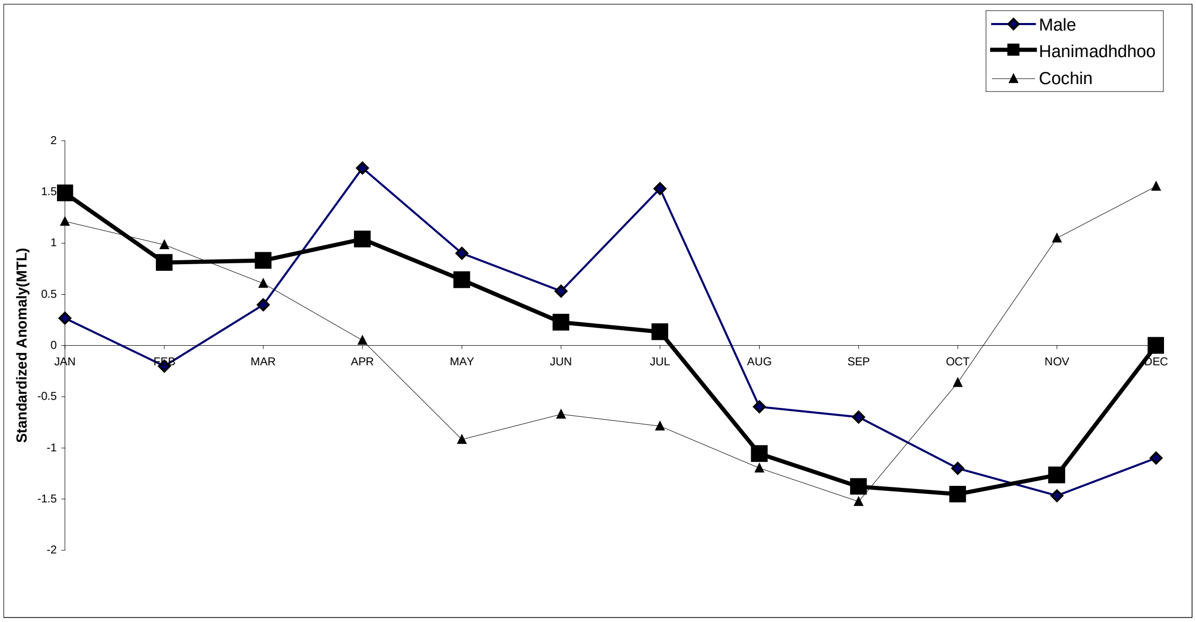

Fig. 2. Annual variation of Mean Tidal Level (MTL) in the warm pool region in the southeastern Arabian Sea

Standardized Anomalies (SA) of MTL for each month from January-December have been computed to facilitate comparison at different stations.

The sources of data on Southern Oscillation Index (SOI) and Multivariate ENSO Index (MEI) are : the U.S Climate Prediction Centre, Washington, D.C., Australian Bureau of Meteorology and the NOAA-CIRES Climate Diagnostic Centre at the University of Colorado in Boulder, U.S.A.

3. Results and discussion

To facilitate the discussion the locations of relevant stations have been depicted in Fig. 1.

3.1. *Evolution of sea level high*

The annual variation of sea level in the southeastern Arabian Sea has been presented in Fig. 2. The stations in the warm pool region have been appropriately chosen so that the spatial variabilities could be determined alongwith the temporal changes. It is seen from Fig. 2 that at Cochin, after the collapse of summer monsoon in September, sea level height abruptly increases from October and a maximum is reached in December. Therefore, the annual variation of sea level at Cochin is associated with the onset of northeasterly winds over the Bay of Bengal which cause the equatorward transport of Bay of Bengal water from October onwards along the east coast of India. Thus, the collapse of southwest monsoon and the onset of northeast (winter) monsoon seem to be responsible for the transport of low-salinity water from the Bay of Bengal to the southeastern Arabian Sea initiating the evolution process of the sea level high, as has been suggested in earlier studies referred to in section 1. After the peak of northeast monsoon, the sea level begins to fall in the southeastern Arabian Sea from January onwards. The sea level high develops due to trapping of low-density water in the surface layer over the southeastern Arabian Sea. Fig. 2 clearly brings out that the evolution process of sea level high begins close to the southern coast of India (near Cochin) first. At Hanimaadhoo the sea level height is maximum during January, a month later than the observed sea level maximum at Cochin in December. At Male which is just below 5° N the sea level variability is entirely different from those observed at Cochin or Hanimaadhoo. Therefore, it could be stated that the sea level high does not extend south of 5° N and Male may be located just at the periphery of sea level high region. The sea level variation at Male is characterized by an absolute maximum in April which is four months later than the sea level maximum at Cochin. Further, there is no sudden rise in sea level at Male during the northeast monsoon season except a slight increase from November-December. However, from December-January the sea level at Male does show a significant rise which is indicative of a delayed and short-lived impact of the evolution process of

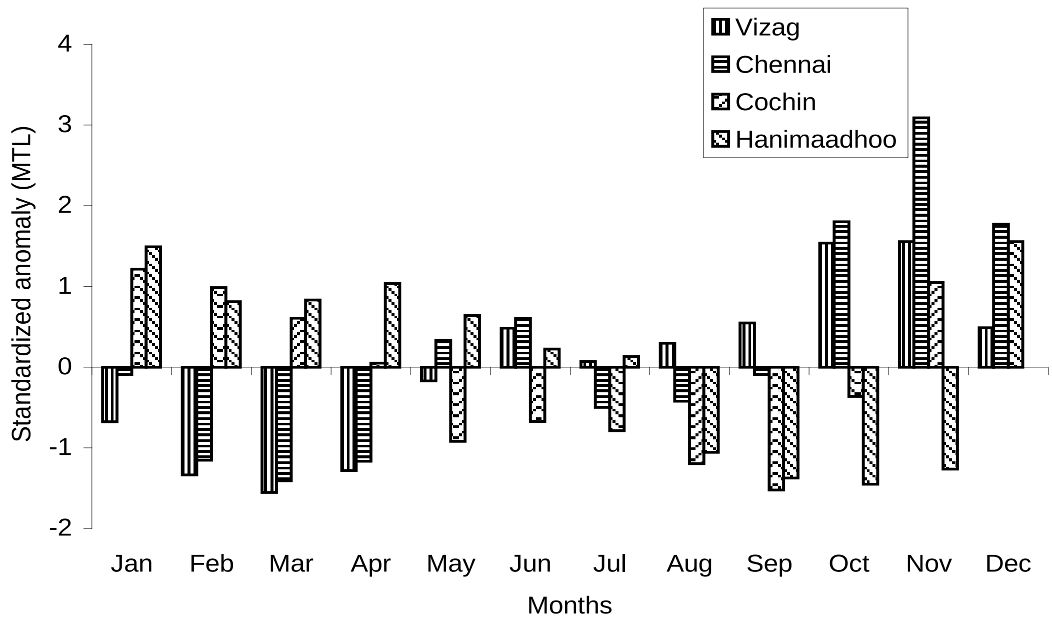

Fig. 3. Evolution of sea level high in the southeastern Arabian Sea

Arabian Sea high at Male. The annual variations of sea level from Cochin to Male presented in Fig. 2 show that the horizontal extent of sea level high is confined to about 400-600 sq. km. with peak of the dome located close to Kerala coast.

In order to determine the pathway of low-salinity water from the Bay of Bengal and to ascertain the reasons for this type of transport, the standardized anomalies of mean monthly sea levels at Vizag, Chennai, Cochin and Hanimaadhoo have been plotted in Fig. 3. As discussed in Section 2 these anomalies have been computed on the basis of respective annual means. It is revealed by Fig. 3 that in the ending phase of summer monsoon in September higher (positive) anomaly of sea level prevails at Vizag only which may be attributed to the large influx of fresh water brought by the Brahmaputra-Ganges and Krishna-Tapi river systems into the Bay of Bengal. The anomalies on the southern side of east Indian coast (Chennai) and also in the southeastern Arabian Sea (Cochin and Hanimaadhoo) are negative (lower) in September. But the scenario changes with the commencement of northeast monsoon in October.

The significant change that takes place in October is the appearance of large positive sea level anomalies on the entire east coast of India from Vizag to Chennai which lies in the northeast monsoon zone. It is not difficult to ascertain the reason for this dramatic sea level rise over the east coast from September to October keeping in view the reversal of surface winds over the Bay of Bengal between two monsoons and increase of SSTs after withdrawal of southwest monsoon. The evolution process of sea level high is very systematic as the low-salinity water from the Bay of Bengal starts reaching Cochin in October where the large negative anomaly of September is replaced by a large positive anomaly in November. However, the sea level at Hanimaadhoo in southeastern Arabian Sea remains little impacted by this type of water transport till November showing that the pathway of low-salinity water from the Bay of Bengal may not be *via* Hanimaadhoo or the latitudinal belt below 7° N. By December the sea level at Cochin reaches its peak and the sea levels at Vizag and Chennai fall substantially compared to the respective levels of November. Though the peak in sea level at Cochin is observed in December, the sea level high in the southeastern Arabian Sea reaches its peak in January in terms of horizontal extent and height when large sea level anomalies prevail from Cochin to Hanimaadhoo. Even at Male positive sea level anomaly appears in January. Therefore, it could be concluded that the Lakshadweep high starts developing near Kerala coast in November but till December its horizontal extent is confined to only a limited region near Kerala coast. By January it expands southwestward into the Lakshadweep Sea and extends upto Male.

3.2. *Evolution of warm pool*

Annual cycle of SST in the warm pool region obtained from the 14-year satellite-based SST climatology is presented in Fig. 4. Near Kerala coast (Cochin)

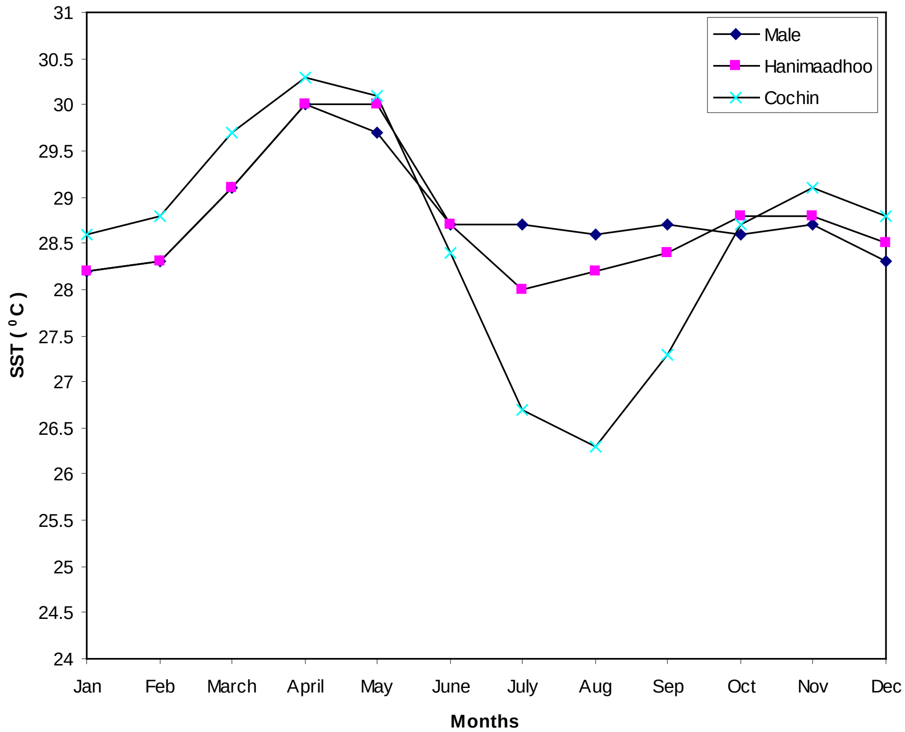

Fig. 4. Annual variation of Sea Surface Temperature (SST) in the warm pool region in the southeastern Arabian Sea

maximum mean monthly SST occurs in April and minimum is observed during the peak phase of summer monsoon in August. The average SST during April is very high near Cochin which is 30.3° C. The warm pool is at its peak intensity during April, not only in terms of warmest surface waters, but also in terms of the largest horizontal extent. As revealed by Fig. 4 the entire region of southeastern Arabian Sea from Cochin to Male registers average SSTs of 30° C or more in April. From May onwards the horizontal extent and intensity of warm pool decrease but over the sea area from Hanimaadhoo to Cochin average SSTs of 30° C or more prevail.

Warming of the surface layer near Kerala coast commences dramatically in the withdrawal phase of the summer monsoon. This is perhaps due to cessation of coastal upwelling off southwest coast of India after the collapse of summer monsoon. The SSTs rise steeply over the sea area between Cochin and Minicoy with the onset of northeast monsoon in October which exceed 29° C by November. The SST gradient in the warm pool region is from southwest to northeast due to which SSTs near Hanimaadhoo and Male are less than 29° C in November. Near Kerala coast surface waters warm by 0.4° C from October to November whereas at Minicoy, Hanimaadhoo and Male the corresponding warmings are much less. This shows that the evolution process of Arabian Sea warm pool begins near Kerala coast (upwelling region during southwest monsoon) and it coincides with the commencement of the northeast monsoon in October. As the evolution of sea level high also commences off Kerala coast during the northeast monsoon the role of northeast monsoon in the entire process of evolution of sea level high and subsequent formation of warm pool in the southeastern Arabian Sea is very important. The evolution processes of sea level high and warm pool during pre-monsoon (March-May) are entirely different. Fig. 2 shows that the sea levels off Kerala coast start falling continuously from December onwards and reach much below annual average by May. Thus, the beginning of pre-monsoon season marks the rapid decay of sea level high. This may be due to cut in the inflow of low-salinity water from the Bay of Bengal after the collapse of northeast monsoon in December. By May clouding due to convection appears which causes fall in SSTs. This facilitates the collapse of sea level high further. The sea level dome, therefore begins to collapse and the low-salinity water begins to expand into the Arabian Sea. During the summer season (pre-monsoon) the increased insolation continues to warm the expanded surface layer of low-salinity water over the southeastern Arabian Sea. This is reflected in Fig. 4 which shows that the entire sea

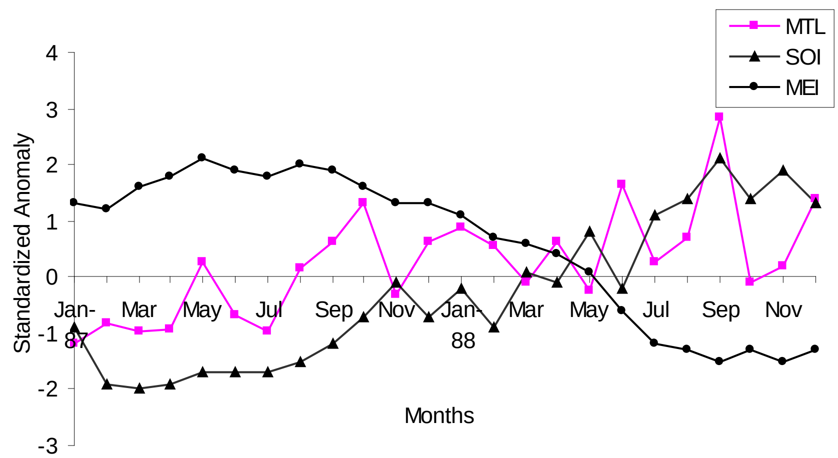

Fig. 5. MTL variation near Cochin during EL Nino/La Nina epochs of 1987-88. Corresponding values of Multivariate ENSO Index (MEI) and Southern Oscillation Index (SOI) are also plotted

area from Male to Cochin warms very rapidly during the period from March to May. As discussed above, there are three important factors involved in the genesis of Arabian Sea warm pool during the pre-monsoon, namely, the formation of sea level high during the northeast monsoon, increased warming of stratified surface layer due to enhanced insolation during summer (March-May), and the absence of any large-scale convection over the southeastern Arabian Sea during March-April. The studies conducted by Gopala Reddy *et al.*, 2005 on the variation of surface heat fluxes utilizing the data of ARMEX 2002 and 2003 confirm the role played by net positive heat flux. The third factor, *viz*., the absence of a large-scale convection over the warm pool region during March-April also plays a significant role in the genesis of warm pool. The stratified surface layer continues to warm for about two to three months without any significant loss of latent heat in absence of active convection or strong surface winds over the southeastern Arabian Sea. The active convection over the southeastern Arabian Sea generally commences in the second half of May just before the summer monsoon onset which is manifested in Fig. 4 in the form of a fall in mean monthly SSTs during May at Cochin and Male. Interestingly, there is no fall in SST at Hanimaadhoo between April and May. This may be due to the combined effect of an overlain stable atmospheric layer (like low level inversion) throughout the pre-monsoon season (March-May) and the seat of convective development to stay north of Hanimaadhoo latitude between Male and Cochin. Further detailed study is required to assign the exact cause.

3.3. *Collapses of sea level high and warm pool*

The withdrawal of northeast monsoon in December seems to be responsible for initiating the decay of the sea level dome near Kerala coast. However, the expanded low-salinity water causes higher sea levels towards southwest in the Arabian Sea for another 2-3 months. The sea levels in the Lakshadweep high region are lowest in the month of September. This is mainly due to continued coastal upwelling during southwest monsoon (June-September) that brings up dense water from lower layers. Fig. 2 shows that near Kerala coast, which is the location of sea level dome, sea level starts falling much before the summer monsoon onset. This implies that the summer monsoon onset has no role in the collapse of Lakshadweep high which takes place a month before the onset. Fig. 3 further substantiates this conclusion and clearly brings out that nothing dramatic occurs in the SSH variation in the sea level high region during the onset phase of summer monsoon between May to June. The lowest sea levels along the southwestern coast of India during southwest monsoon result from the coastal upwelling. On the contrary as shown by Fig. 4, the summer monsoon onset in June is responsible for demolishing the warm pool. SSTs fall steeply throughout the warm pool region from May to June with Cochin registering the maximum fall of 1.7° C in the mean monthly SST in this period. The collapse of warm pool is very rapid near Kerala coast. This could be due to beginning of the coastal upwelling prior to the onset of monsoon as well as build-up of coastal convection. The SSTs near Kerala coast continue to fall rapidly during the active phase of summer monsoon in July-August but in the open sea region of the warm pool the big fall is after the onset phase and minor episodic fall and rise occur thereafter as the monsoon strengthens and weakens over the area. This is also associated to the monsoonal upwelling near Kerala coast. The upwelling may increase as the monsoon westerly wind weakens and increases in northerly component with reverse happening when the monsoon strengthens over the

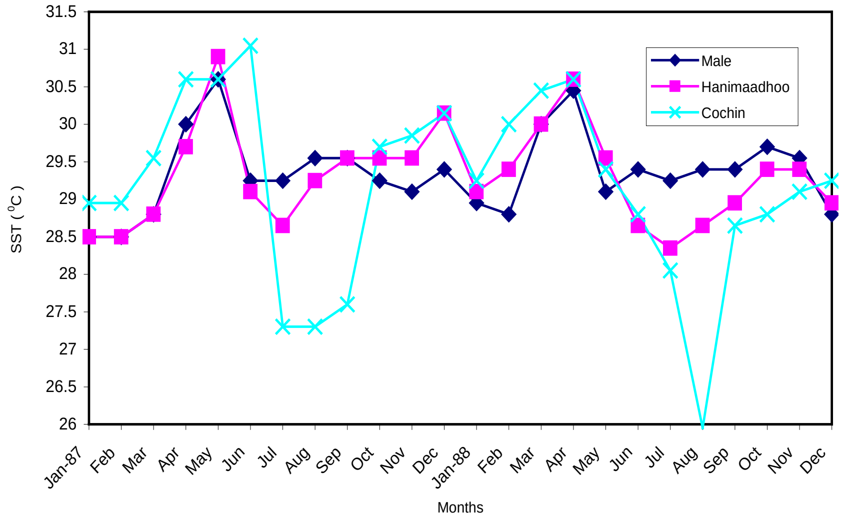

Fig. 6. SST variation in the Warm Pool region during El Nino/La Nina epochs of 1987-1988

SE Arabian Sea. This aspect, however, needs further study to confirm.

3.4. *Interannual variabilities of sea level height and the intensity of warm pool*

Figs. 5 and 6 depict the SSH and SST variations in the southeastern Arabian Sea during two contrasting summer monsoon years 1987 and 1988. There was a major monsoon failure in India during 1987 which happened to be a strong El-Nino year. On the contrary 1988 was an excess monsoon rainfall year and it was also a strong La Nina year. Therefore, 1987 and 1988 were contrasting years in terms of ENSO conditions and the summer monsoon rainfall. These two years were contrasting in terms of northeast monsoon also. During 1987 the northeast monsoon (October - December) was active whereas, during 1988 it was subdued (Singh, 1995).

The sea level variation in the dome region (Cochin) alongwith two ENSO indices, *i.e.*, SOI and MEI during the period January 1987 to December 1988 has been presented in Fig. 5 which covers both El Nino and La Nina epochs. MEI is a comprehensive ENSO index which integrates complete information on ENSO by considering several meteorological and oceanographic parameters like, sea level pressure, *u* and *v* components of wind, SST and cloud cover etc. whereas SOI represents only sea level pressure. The details about MEI are given by Singh, 2001. Positive/negative MEI/SOI correspond to El-Nino and negative/positive MEI/SOI corresponded to La Nina. It is clear from Fig. 5 that El-Nino conditions prevailed right from the beginning of 1987 which continued throughout 1987. Fig. 5 shows that the sea level anomalies in the Lakshadweep high region were negative during January-April, 1987 indicative of weak development of the dome. From Fig. 6 it is evident that the peak intensity of warm pool was observed in June at Cochin and in May at Hanimaadhoo during 1987. Thus there was a delay of about 1-2 months in the attainment of peak intensity of warm pool which normally occurs in April. Therefore, a delay in the attainment of peak intensity of warm pool associated with lower sea levels (weaker development of the dome) during January-April preceded the deficient monsoon rainfall year 1987 which was also an El-Nino year. On the contrary, as revealed by Fig. 5, positive SSH anomalies prevailed off Kerala coast during January-April, 1988 and the attainment of peak intensity of warm pool was normal, *i.e.*, during April (Fig. 6). Not only this, good correlation exists between the sea surface height in the southeastern Arabian Sea and the ENSO indices. Negative phase of ENSO (El-Nino; SOI-negative; MEI; positive) is characterized by the lower sea levels and La Nina epoch is dominated by higher sea levels in the warm pool region. More cases of ENSO years are needed to be examined to establish these relationships firmly.

4. Conclusions

The study has brought out some interesting features of genesis, maintenance and the decay of sea level high and the warm pool in the southeastern Arabian Sea and their associations with summer and winter monsoons. Some important results are:

(*i*) There is a lag of about four months between the peak height of sea level dome and the peak intensity of the warm pool. The peak height is observed in December whereas maximum warming of sea water occurs in April.

(*ii*) The evolutions of the sea level high and the warm pool begin close to Kerala coast and the maximum height of sea level and maximum SSTs are also observed there. Therefore, the core of sea level high and the warm pool is located very close to Kerala coast.

(*iii*) The northeasterly wind over the Bay of Bengal during winter monsoon is the main forcing for the genesis of sea level high in the southeastern Arabian Sea. The withdrawal of winter monsoon initiates the process of decay of sea level high.

(*iv*) The sea level high acts as a catalyst in the genesis of the Arabian Sea warm pool. Other causative factors are the increased warming of sea water during the summer (March-May) and the absence of any active convection over the warm pool region which does not allow the release of latent heat through evaporative cooling. The onset of summer monsoon destroys the warm pool through the evaporative cooling and the coastal upwelling.

(*v*) El-Nino and deficient summer monsoon year 1987 witnessed the prevalence of lower sea level anomalies in the southeastern Arabian Sea during January-April. Also, the warm pool attained its peak intensity very late (in June) during 1987. On the contrary during 1988 (La-Nina and excess summer monsoon year) generally higher sea level anomalies prevailed in the southeastern Arabian Sea during January-April and the warm pool reached its peak intensity on time (in April).

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