

On some aspects of Indian Ocean Warm Pool

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Annual and interannual variation of Indian Ocean Warm Pool (IOWP) was studied using satellite and *in situ* ocean temperature data. IOWP surface area undergoes a strong annual cycle attaining a maximum of $24 \times 10^6 \text{ km}^2$ during April and minimum of $10 \times 10^6 \text{ km}^2$ in August. Unlike surface area, warm pool was deeper (90m) during August than in April. Higher vertical extent was found both at eastern equatorial Indian Ocean and south-eastern Arabian Sea. Frequency distribution of temperatures at one degree interval (28-29, 29-30, 30-31) exhibited independent seasonal variations. The interannual variation of IOWP was found to be associated with ENSO events.

[Keywords: Warm Pool; Sea Surface Temperature; Indian Ocean; IOWP]

Introduction

Warm oceanic waters are often called as warm pools¹. Researchers have used different criteria to define warm pool based on the lower limit of temperature. For example, Wyrтки¹ had used 28°C as the lower limit whereas Chacko et al² used 30°C. The selection of lower temperature limit depends on the spatial scale of the warm pool of interest. For the study of warm pools on a larger scale, 28°C was considered as a better choice whereas for small scale warm pools ('mini warm pool'), higher cut off values can be adopted. Since the focus of our study is on a basin scale warm pool of Indian Ocean, we follow Wyrтки's criteria of 28°C to define the warm pool.

Warm pools are features of tropical oceans and are an important entity for the climate³⁻⁸. Warm pools are identified as areas of strong atmospheric convection, convergence of surface wind, and high precipitation⁹⁻¹⁶. Among the warm pools, Pacific warm pool has been studied extensively over the last two decades due to its close association with the formation of El Nino. Recent studies on IOWP now confirm its role on the climate of Indian Ocean and Indian monsoon rainfall. Vinayachandran and Shetye¹⁷ studied the climatological aspect of IOWP. Joseph¹⁸ found that the monsoon vortex which is essential for the onset of summer monsoon rainfall over India, forms over the warmest part of IOWP in Arabian Sea. Zhang et al¹⁹ identified the role of Indian Ocean Dipole on IOWP variability.

Present study consists the evolution and features of IOWP on seasonal and interannual time scales. Climatological evolution of IOWP studied earlier used Levitus data which had a spatial resolution of $1^\circ \times 1^\circ$. In this study, we also use satellite data which had a better resolution and accuracy than Levitus data.

Material and Methods

The data used in this study consist of Sea Surface Temperature (SST) data (monthly and climatology) from Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) and Levitus World Ocean Atlas subsurface temperature data²⁰. TMI SST has a spatial resolution of $0.25^\circ \times 0.25^\circ$. Climatological version of this data was used to study the annual evolution of IOWP. IOWP surface area for a month was obtained by computing the number of grids having SST greater than 28°C and then multiplying it with unit grid area ($27.5 \times 27.5 \text{ km}^2$). Levitus climatology was used to estimate the depth of warm pool by locating the 28°C isotherm (D28) in the vertical. Monthly TMI SST data for the period 1998 to 2009 was used to study the interannual variations in IOWP surface area.

Result and Discussions

Climatological variability

Figure 1 shows the climatological variation of IOWP surface area. It showed a simple annual cycle with one minimum and one maximum.

Minimum area ($10 \times 10^6 \text{ km}^2$) was observed during the month of August and the maximum ($24 \times 10^6 \text{ km}^2$) during April. Maximum IOWP surface area observed was in agreement with that computed by Vinayachandran and Shetye¹⁷ who used Levitus data but was slightly higher in the case of minimum IOWP area. It is interesting to note that IOWP do not show a bi modal variability in an year in response to the individual hemispheric summer warming but rather showed only a single peak which occurs during the northern summer. Warm pool of Pacific Ocean also had a similar behavior¹⁷.

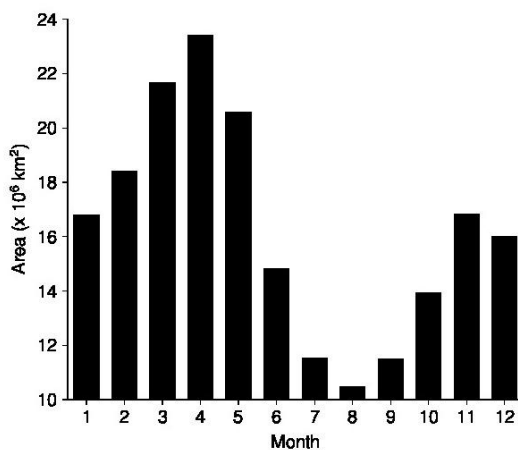


Fig. 1—Annual variation of warm pool surface area.

The climatological evolution of IOWP SST is shown in figure 2. Contours with SST greater than 28°C are only shown. During January, IOWP appears as a zonal band inclined to the equator. Its western end extended more towards south whereas the eastern end extended towards north indicating zonal in-homogeneity in warming. Warming begins to appear at western and eastern extremities of IOWP. Also IOWP had a discontinuity in the south-eastern Arabian Sea with an increased warming feature. This feature was considered as a ‘mini warm pool’ and was an active area of study recently^{18,21-24}. The warm pool core temperature during January was $29.0\text{--}29.5^\circ\text{C}$ (figure 2). IOWP intensified in February, increased warming taking place on the eastern end. Warm pool core temperature now stands enhanced to $29.5\text{--}30.0^\circ\text{C}$. During March, warm pool expansion continued and the core spread across the entire width of the Indian Ocean. During April, IOWP attains the maximum area as well as intensity; warm pool core temperature was $30.0 - 30.5^\circ\text{C}$. Concurrently, warm pool was developing in Bay of Bengal than in Arabian Sea. During May, the warm pool area expanded further north and spreads across the entire north Indian Ocean. With the onset of summer monsoon, the

feature begins to weaken by June both in its area and intensity. Strong winds and upwelling in the western Indian Ocean are the reason for IOWP weakening. As the monsoon progresses, IOWP weakens further and attain its lowest area and intensity by August. Notably, there are large differences in IOWP aerial distribution between Arabian Sea and Bay of Bengal. Warm pool fills the entire Bay throughout the monsoon season (June to September) whereas it stands withdrawn almost completely from Arabian Sea due to strong upwelling in the west. As the monsoon further withdraws by September, IOWP begins to re-develop and continues through the next cycle.

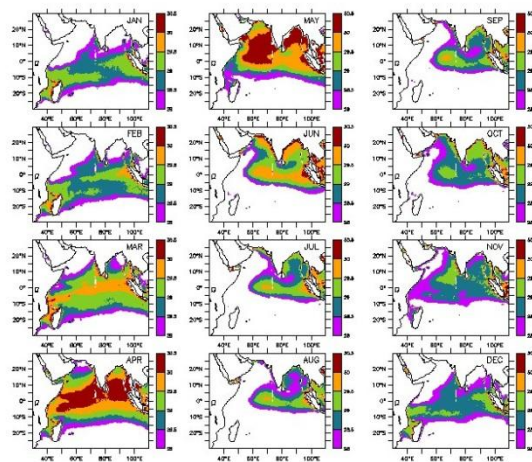


Fig. 2—Climatological evolution of IOWP

Like the variation in its surface area, IOWP volume also undergoes seasonal variations. The depth of IOWP was estimated by locating the depth of 28°C isotherm (D28) using Levitus data. Figure 3 shows the distribution of D28 during selected months. Higher D28 values were found to occur at the eastern equatorial regions. However, high D28 do not occur in areas of high SST. Highest D28 (90m) was observed during pre-monsoon season (May) (figure 3). High values were also observed in the southeastern Arabian Sea (the ‘mini warm pool’ region) during March. The high SST and high warm pool vertical extent is suggestive of its role in the formation of monsoon vortex. Higher D28 (70-80m) was noted during August though it was a weak period in IOWP surface area.

One of the characteristics of the warm pool is in its relatively homogenous distribution of temperature. This is usually studied with the help of frequency distribution of SST25. Homogeneity of warm pool SST is due to the feedback process operating in the warm pool that helps to maintain similar temperatures²⁵. Frequency distributions

of three one-degree SST bands (28-29, 29-30 and 30-31°C) were studied in detail (figure 4).

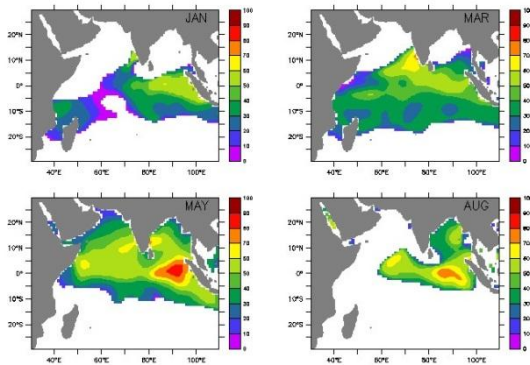


Fig. 3—Vertical extent of IOWP represented as the depth of 28°C isotherm

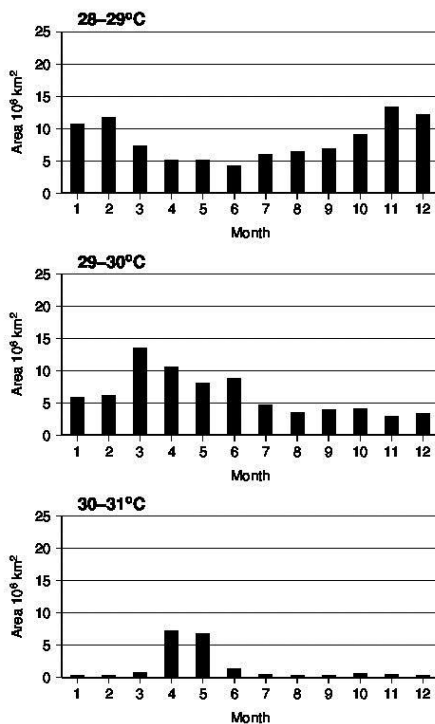


Fig. 4—Frequency distribution of one-degree warm pool temperature bands.

The figure shows distinct type of variation for each temperature band. Lower temperature band of 28-29°C had two peaks during the year; one in February and the other in November. Minimum area for this temperature band was observed during August. The mid-temperature band of 29-30°C was having only one peak which occurred during the peak IOWP months of April and May. Highest temperature band of 30-31°C was significant only during April and May and was almost absent during other months. Total

percentage of area for the temperature bands 28-29, 29-30, 30-31 and 31-32°C was obtained as 50%, 39%, 10% and 1% respectively. Lowest two bands together contribute 89% of warm pool area and hence show its homogeneity.

Interannual Variations

Figure 5 shows the monthly variation of warm pool area during the period 1998 to 2009. IOWP recorded the largest surface area ($29 \times 10^6 \text{ km}^2$) in April 1998. It has been already confirmed that Indian Ocean experienced warming during the El Niño events²⁶. The strongest El Niño of last century had occurred in the year 1997 and it can be concluded that the anomalous increase in warm pool area during 1998 was due to the 1997-98 El Niño. After the El Niño event, IOWP area decreased sharply by about $3 \times 10^6 \text{ km}^2$. Warm pool area then indicated a gradual increase up to the year 2004 and then followed a smooth decrease to 2008. A warming tendency again evolved in 2008 which could be due to the El Niño of 2009-10. Hence the interannual variability in warm pool area was found to be associated with the El Niño events.

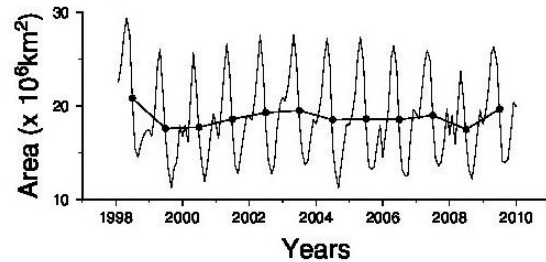


Fig. 5—Interannual variation of warm pool surface area during the period 1998 to 2009. Solid line represents monthly variations and dotted line represents the annual mean.

Increase in the warm pool area occurs when warm pool expands; obviously expansion of warm pool occurs towards south and west¹⁹. This feature was studied by observing the north-south (east-west) displacement of 28°C isotherm at the southern (western) boundaries of the warm pool at a given longitude. Figure 6 shows the interannual variation in the north-south displacement of southern edge of IOWP observed at 60°E longitude.

IOWP had an anomalous southward shift (20°S) during 1998. This was consistent with the anomalous increase in its area during the same period (figure 5). Consistent with the smooth variation in its surface area during the period 2000 to 2008 (figure 5), the southern edge also indicated a similar variation. The anomalous

expansion of warm pool during 2008-09 was also correlated well with the anomalous southward displacement of the southern edge.

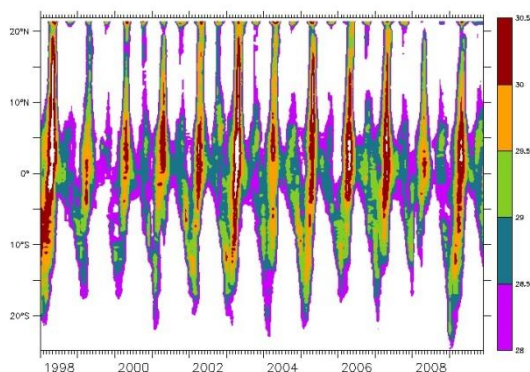


Fig. 6—Interannual variation in the north-south movement of IOWP.

Conclusion

In this paper, we report on some of the salient features of IOWP. Basically, on a seasonal scale, warm pool responds well to the seasonal forcing from atmosphere (heating) and ocean (advection). The combined effects of these forcing create a maximum warm pool area during the months of April and May and a minimum during August. Single-mode annual cycle of warm pool area indicates a marked response to northern hemispheric summer heating. Increased warming found in the southeastern Arabian Sea during the pre-monsoon months favors the formation of monsoon vortex. Further, deepening of warm pool was found to occur usually on the eastern equatorial areas and interestingly, do not coincide with the high SST areas. About 90% of warm pool surface area is occupied by waters in the temperature interval of 28-30°C and this indicates homogeneity in warm pool. Interannual variation of warm pool was found to be associated with El Nino events too.

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