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The warm pool in the Indian Ocean

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Abstract. The structure of the warm pool (region with temperature greater than 28°C) in the equatorial Indian Ocean is examined and compared with its counterpart in the Pacific Ocean using the climatology of Levitus. Though the Pacific warm pool is larger and warmer, a peculiarity of the pool in the Indian Ocean is its seasonal variation. The surface area of the pool changes from 24 x $10^6 km^2$ in April to 8 x $10^6 km^2$ in September due to interaction with the southwest monsoon. The annual cycles of sea surface temperature at locations covered by the pool during at least a part of the year show the following modes: (i) a cycle with no significant variation (observed in the western equatorial Pacific and central and eastern equatorial Indian Ocean), (ii) a single maximum/minimum (northern and southern part of the Pacific warm pool and the south Indian Ocean), (iii) two maxima/minima (Arabian Sea, western equatorial Indian Ocean and southern Bay of Bengal), and (iv) a rapid rise, a steady phase and a rapid fall (northern Bay of Bengal).

Keywords. Warm pool; equatorial Pacific Ocean; equatorial Indian Ocean; sea surface temperature; annual cycle.

1. Introduction

Over tropical oceans, the regions with sea surface temperature (SST) above 28°C, referred to here as a "warm pool", has important implications to atmospheric processes. It has been shown that the minimum SST required for active convection is 28°C (Gadgil *et al* 1984; Graham and Barnet 1987). It has also been found that regions with annual mean SST above 28°C are prone to tropical cyclones (Gray 1975).

The most extensive and the best known warm pool of world oceans is in the western Pacific. Lukas and Webster (1989) have summarized its importance. It is a region of deep convection (Lau and Chan 1986; Ardanuy *et al* 1987), convergence of surface winds (Rasmusson and Carpenter 1982), and high precipitation (Taylor 1973; Weare *et al* 1981). The ascending branch of the Walker circulation is located above this pool, and the latent heat released during the ascent supplies energy for the circulation (Bjerknes 1969). It has been found that during an El Nino event the warm pool and the region of deep convection migrates eastward (Gill and Rasmusson 1983; Donguy *et al* 1984) by about 4000 km which is a fourth of the total length of the equatorial Pacific. The Western Pacific Warm Pool (WPWP) may also have implications for the Indian summer monsoon. The SST over the area 120–160°E; 5–15°S was found to be positively correlated to the Indian summer monsoon rainfall (Nicholls 1983).

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A considerable area of the tropical Indian Ocean too has SST higher than 28°C. The Indian Ocean warm pool (IOWP) can cover the equatorial region east of about 50°E, the Bay of Bengal and the eastern Arabian Sea. The importance of this pool for atmospheric processes over the Indian Ocean has been recognized. Joseph (1990) found that onset vortices of the Indian summer monsoon form over the warmest regions of the Indian Ocean. A good part of the IOWP has outgoing longwave radiation below $240\,\mathrm{W\,m^{-2}}$ (Lukas 1988) indicating that it is a region of deep convection. IOWP is expected to play a role in the development of cyclones over the Bay of Bengal, some of which have been amongst the most destructive.

The El Nino and associated atmospheric phenomena provided an impetus to study the WPWP. Significant progress has since been achieved (Donguy 1987). By comparison, the dynamics and the thermodynamics of IOWP are little understood. In this study, we have attempted a synthesis of available climatology to describe the structure of IOWP and to compare it with WPWP. Our intention is to identify the main features of the annual cycle of IOWP. The data set used to describe IOWP and WPWP is the monthly-mean temperature at standard oceanic depths on a 1° x 1° horizontal grid covering the world oceans, compiled by Sydney Levitus (Levitus 1982).

2. Annual cycle of the horizontal and vertical spread of the IOWP and the WPWP

Only in the Pacific and the Indian Ocean there exist regions with SST greater than 28°C throughout the year (figure 1). In the Pacific the area which satisfies this criterion is about $10 \times 10^6\,\mathrm{km^2}$, and in the Indian Ocean it is about $2{\cdot}8 \times 10^6\,\mathrm{km^2}$. In the Pacific, over an area of about $0{\cdot}9 \times 10^6\,\mathrm{km^2}$, the monthly-mean SST throughout the year exceeds 29°C. There is no comparable region in the Indian Ocean. Though the contribution of the Indian Ocean to the total area of the world ocean where the SST exceeds 28°C throughout the year is only about a fourth, during a given month the Indian Ocean's contribution is often much higher. As seen from figure 2, in April the areas with SST larger than 28°C in the Indian and Pacific Oceans are 24×10^6 and $27 \times 10^6\,\mathrm{km^2}$ respectively. The area of IOWP change three-fold during a year from a minimum of $8 \times 10^6\,\mathrm{km^2}$ during September to a maximum of $24 \times 10^6\,\mathrm{km^2}$ during April. The minimum and maximum areas of the western Pacific warm pool are 24×10^6 and $33 \times 10^6\,\mathrm{km^2}$ respectively.

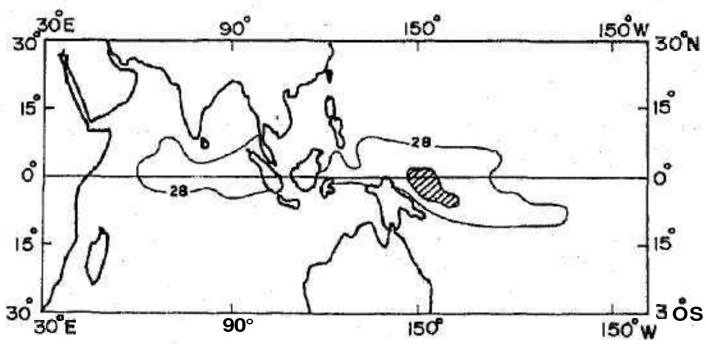

Figure 1. Regions with SST above 28°C throughout the year. The SST over the shaded area exceeds 29°C.

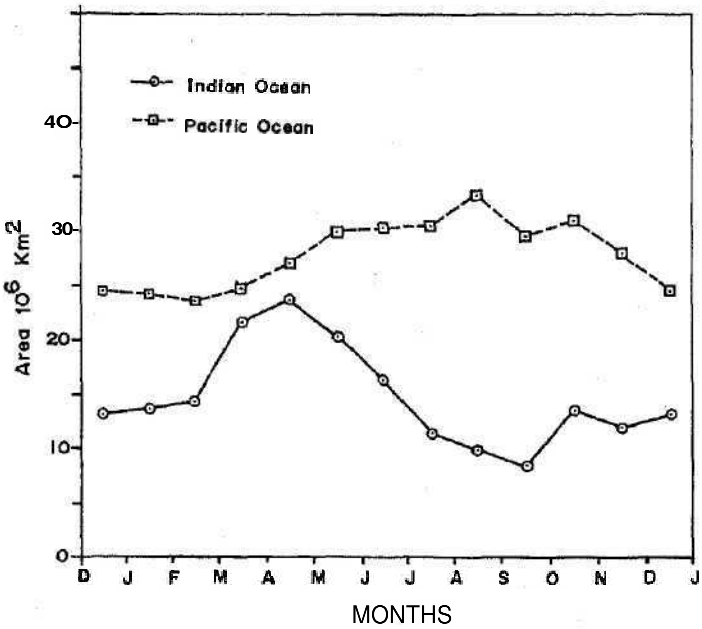

Figure 2. Variation of the monthly-mean area of the warm pool in the Indian and Pacific Oceans.

The warming phase of the nothern WPWP starts in April and continues till August, by which time the pool spreads to about 30°N (figure 3). With the onset of the northern winter the pool starts moving southward. This phase lasts till March, but is most noticeable during September-January. The pool recedes during March-August. The main difference between the WPWP north of the equator and that south of the equator is that the southward spreading of the pool during the southern summer is small in comparison to that to the north during the northern summer.

The warming phase of the IOWP begins in February, when the pool begins to spread on both sides of the equator. This continues through April. The northern boundary of the pool merges with the coastline during April in the Bay of Bengal (figure 3a) and in May in the Arabian Sea (figure 3b). The first signals of cooling are observed in the southern Indian Ocean during May. The summer monsoonal cooling begins during June in the western equatorial Indian Ocean and during July in the Arabian Sea and continues through September. In the Bay of Bengal, the SST does not fall below 28°C during the summer. After the withdrawal of the monsoon a secondary warming takes place in the Arabian Sea during October. This is followed by winter cooling of the Indian Ocean north of the equator, and summer warming in the southern Indian Ocean. The warm pool in the Bay of Bengal recedes during October-November.

Except in January and July, the warm pool in the western Pacific reaches a depth of 125 m (figure 4). The maximum depth of the 28°C isotherm in the Indian Ocean is 100m during March, May, June and October. Table 1 shows that the western Pacific warm pool is in general deeper than the Indian Ocean warm pool. The total volume of the western Pacific warm pool is on an average three times that in the Indian Ocean warm pool. The maximum volume of the Indian Ocean warm pool is 9×10^5 km^3, which is three times its minimum value (figure *5)*. The maximum and minimum values of the western Pacific warm pool are 20×10^5 and 14×10^5 km^3

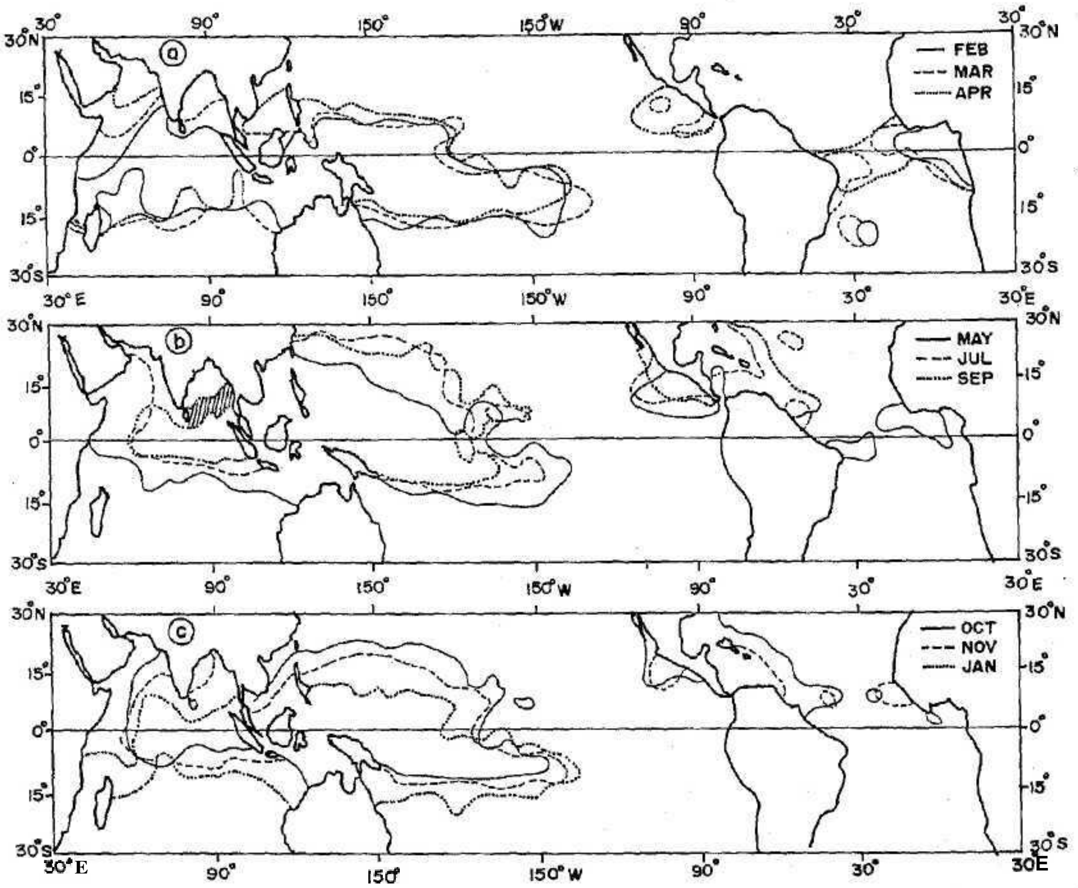

Figure *3.* Annual evolution of the tropical warm pool. The contours show 28°C isotherm during (a) February (———), March (----) and April (.....); (b) May (———), July (----) and September (.....); (c) October (———), November (----) and January (.....). During September the warm pool in the Bay of Bengal is split into two parts separated by the shaded portion which is cooler.

Table 1. Summary of the annual cycle of the maximum depth (m) of 28°C isotherm in the IOWP and the WPWP; (--) means the SST is less than 28°C.

	Arabian Sea	Bay of Bengal	Equatorial Indian Ocean East	Equatorial Indian Ocean West	South Indian Ocean	Pacific Ocean North	Pacific Ocean South
Jan	—	—	50		25	75	100
Feb	50	—	50	—	25	75	125
Mar	50	25	100	25	25	75	125
Apr	50	50	50	50	25	100	125
May	50	50	100	50	25	100	125
Jun	50	50	100	25	—	75	125
Jul	50	50	75	—	—	75	100
Aug	75	25	75	—	—	75	125
Sep	75	25	50	—	—	75	125
Oct	50	50	50	—	—	100	125
Nov	25	50	50	—	25	75	125
Dec	25	—	75	—	—	75	125

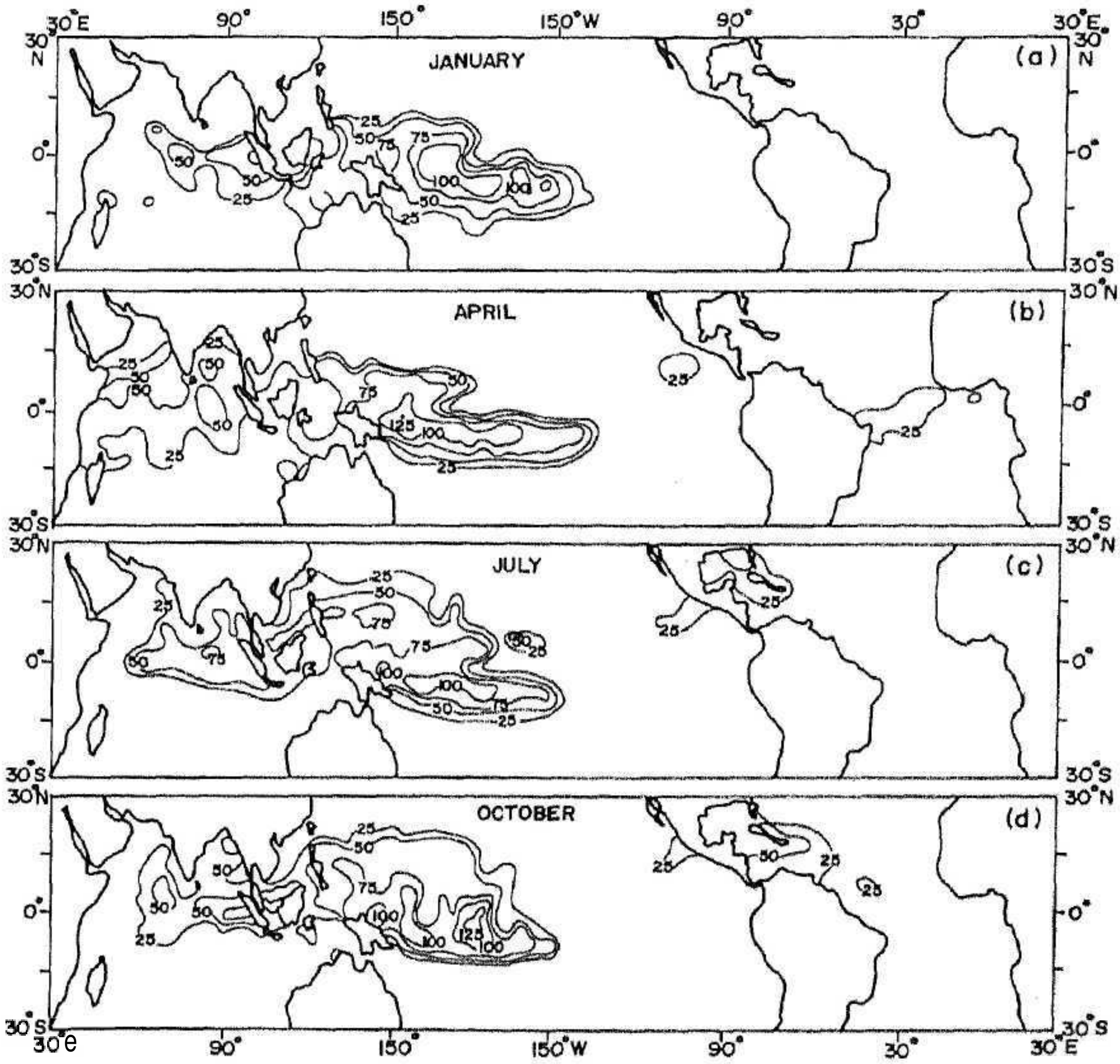

Figure 4. Depth (m) of 28°C isotherm during the months of (**a**) January, (**b**) April, (**c**) July and (**d**) October.

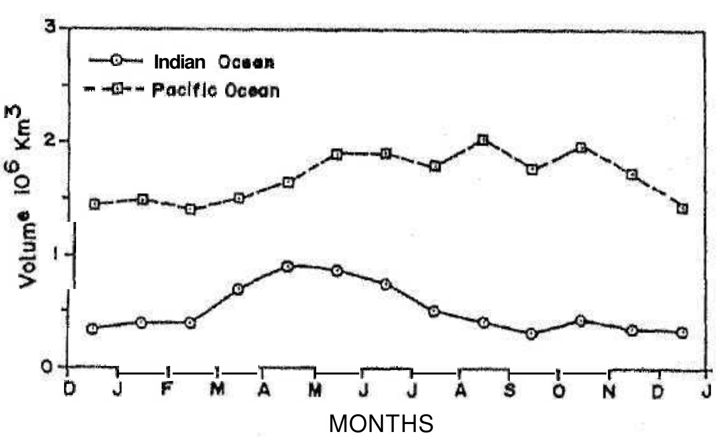

Figure 5. Variation of the monthly-mean volume of the warm pool in the Indian and Pacific Oceans.

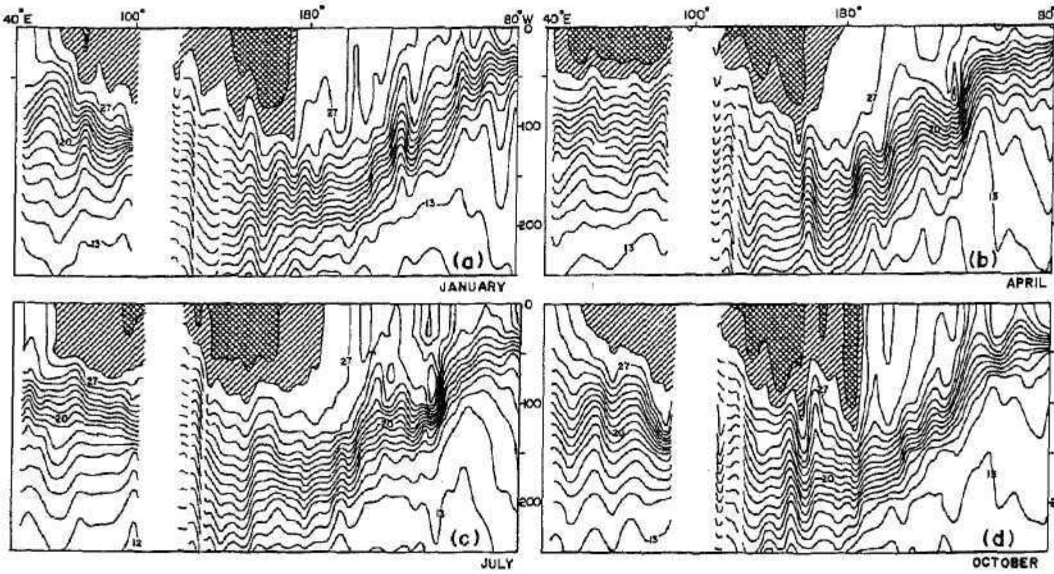

Figure 6. Vertical section of temperature along the equator from the east coast of Africa to Central America during (a) January, (b) April, (c) July, and (d) October. In the hatched, cross-hatched and shaded areas the temperature exceeds 28°C, 29°C and 30°C respectively. Vertical scale is in m.

respectively. The segregation of the warm pool to the western Pacific and to the eastern Indian Ocean (figures 6a-d) suggests that though separated by a narrow strip of land, IOWP and WPWP form a single large mass of warm water which floats amidst the cooler waters to the east in the Pacific and to the west in the Indian Ocean.

3. Factors controlling the annual cycle of the warm pool

The North Equatorial Current (between 8° and 20°N) and South Equatorial Current (between 10°S and 3°N) flow westward in the Pacific. The resulting convergence of mass leads to accumulation of warm water in the western Pacific which continues till an El Nino resets the cycle (Wyrtki 1985). The upwelling on the eastern boundary of the equatorial Pacific cools the eastern part of the ocean. By way of contrast to the other two oceans, the warmest region in the Indian Ocean occurs on the eastern side of the basin. The main reason for this appears to be upwelling along the African coast, which cools the western Indian Ocean during the southwest monsoon. The effects persist during the rest of the year. In the Indian Ocean the surface currents near the equator are on an average towards the east (McPhaden 1982; Cutler and Swallow 1984). On the eastern boundary of IOWP, there is no wind-induced upwelling and there appears to be no poleward transport of the heat accumulated due to surface heat fluxes. Though this explanation for the occurrence of IOWP on the eastern side of the ocean seems reasonable in view of the present meagre evidence, additional studies are needed to ascertain its validity. Such an exercise could also bring out the role of throughflow from the Pacific (Fine 1985) to maintain a warm eastern Indian Ocean.

Had the advective influence been absent, the SST would be controlled solely by mixed-layer dynamics. In this case, the annual cycle of SST and that of the heat content of the water column would depend only on the local air-sea heat fluxes. To what extent does such a balance hold in the warm pool? To address this question we examined the annual cycles of SST, vertical thermal structure in the upper 250 m, net surface heat flux, and, net heat gain in the upper 50 m. Values of net surface heat flux were taken from Hastenrath and Lamb (1979). The heat content (H) per unit surface area was calculated using the relation

$$H = \int \rho C_p T \, dz,$$

where p is the density of water, C_p the specific heat, and T the temperature at depth z. The rate of change of H determines heat gain. The annual cycle of SSTs revealed four distinct modes of behaviour. These are described below together with the cycles of thermal structure and surface heat flux.

3.1 *Cycle without significant annual variation*

The western equatorial Pacific and the eastern and central sectors of the equatorial Indian Ocean exhibit this type of annual cycle (figure 7h, i and g). The surface heat flux at these locations is mainly derived from insolation, and there is no significant correlation between the monthly-mean heat flux through the surface and heat gain in the upper 50 m (figures 9h, i and g). The thermal structure of the upper 250 m (figures 8h, i and g) shows a mixed layer, which on an average is 75 m, and a thermocline which is best developed in the eastern equatorial Indian Ocean. Strong eastward equatorial surface jets occur in the Indian Ocean during the transition period between the monsoons (Wyrtki 1973). Their role in controlling IOWP is not known. Consequently, at present it is not possible to compare the roles of advection and air-sea fluxes in controlling the spread of IOWP along the equator. The apparent lack of correlation between the two curves in figures 9h, i and g suggests that advection plays an important role. In the western equatorial Pacific, Donguy *et al* (1984J have argued that horizontal advection as well as surface heat fluxes influence the heat budget. Complicating the issue further is the suggestion by Godfrey and Lindstrom (1989) that there are serious uncertainties with the estimates of air-sea fluxes over this region.

3.2 *Cycle with a single maximum/minimum*

Observed in the northern and southern part of WPWP and in the south Indian Ocean (figures 7e, f and j), the SST here follows the annual march of the sun. The similarity between the cycles of the heat content of the upper 50m and that of air-sea fluxes (figures 9e, f and j) is closer in the north and south Pacific than in the Indian Ocean, where the South Equatorial Current flows westward.

3.3 *Cycle with two maxima/minima*

This "bimodal" structure is best developed in the Arabian Sea (figure 7a). Though it is also seen in the western equatorial Indian Ocean and the southern Bay of Bengal, the post-southwest monsoon secondary warming at these locations is small in

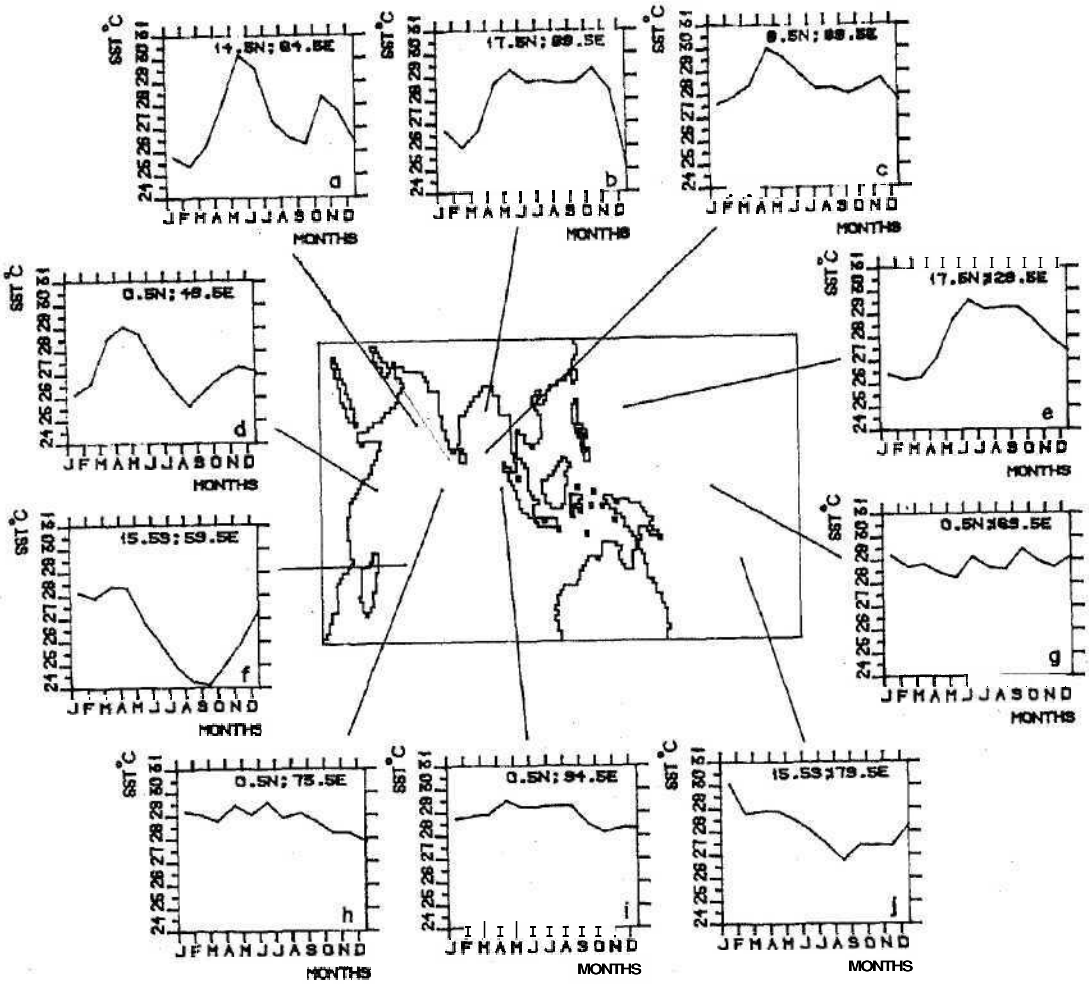

Figure 7. Annual cycle of SST at ten selected locations in the tropical Indian and Pacific oceans.

comparison to that in the Arabian Sea. It has been shown earlier that in the Arabian Sea the air-sea fluxes alone can explain the annual cycle of SST except during the southwest monsoon when advection is important (Shetye 1986). This is reflected in figure 9a. The same may well be applicable to the southern Bay of Bengal.

3.4 *Cycle with a rapid rise, a steady phase and a rapid fall*

This "plateau-like" structure is observed only in the Bay of Bengal (figure 7b). Very little is known about the factors controlling it. Figure 9b suggests that the air-sea fluxes play a dominant role during the phase of steady SST. Colborn (1975) attributed the sharp rise in SST during the pre-monsoon season to increased solar radiation and the subsequent mild cooling to wind mixing. The shaded portion in figure 3b shows a belt of water with SST below 28°C separating warmer regions on either side. The belt of cooler water is very likely caused by the eastward moving southwest monsoon current which carries cooler Arabian Sea surface water. The belt probably indicates the extent to which the current influences the Bay. The process by which the Bay cools during the winter are not known. Colborn (1975) suggested that the advection

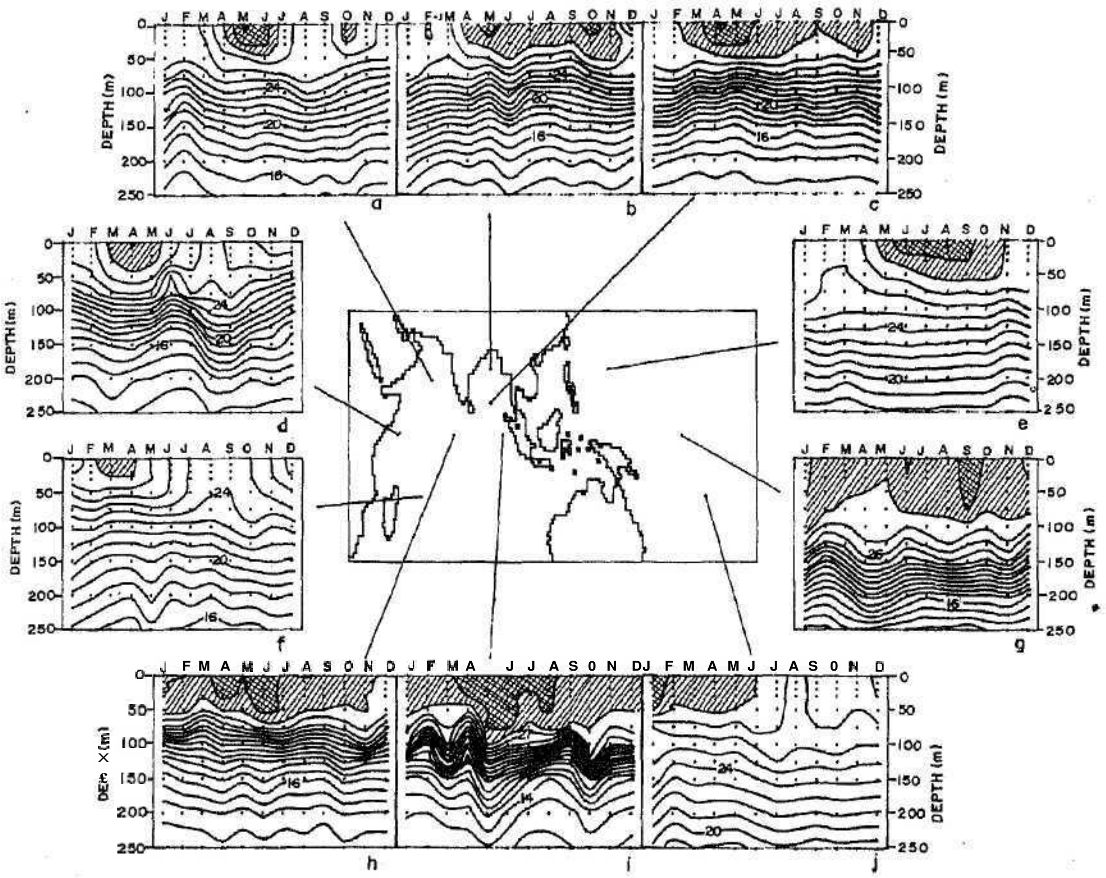

Figure 8. Annual cycle of thermal structure of the upper 250 m at selected locations. In the hatched, cross-hatched and shaded areas the temperature exceeds 28°C, 29°C and 30°C respectively.

from Malaca strait could be an important mechanism. The similarity between the monthly heat gain and the surface heat fluxes (figure 9b) implies that the role of air-sea fluxes is also important.

On the whole, it is not possible at present to quantify the role of advection and that of air-sea fluxes in controlling the SST cycles identified above. In the immediate vicinity of the equator (figure 9h) which is known to have strong jet-like eastward current (Wyrtki 1973), and in the region of the South Equatorial Current (figure 9g) advection plays an important role. Elsewhere (figures 9a, b, c, e and f) the air-sea fluxes appear to dominate most of the year.

4. Concluding remarks

An important feature of IOWP is the large seasonal variation in the surface area covered by the pool, and hence in the area of active zone of ocean-atmosphere coupling. A quantitative picture of the causes behind this variation is not available. However, interaction with the monsoons is expected to be important. The factors that control the variability of the pool, i.e., the fluxes of heat and momentum and ocean currents are noisy processes with fluctuations spread over a wide range of spatial and temporal

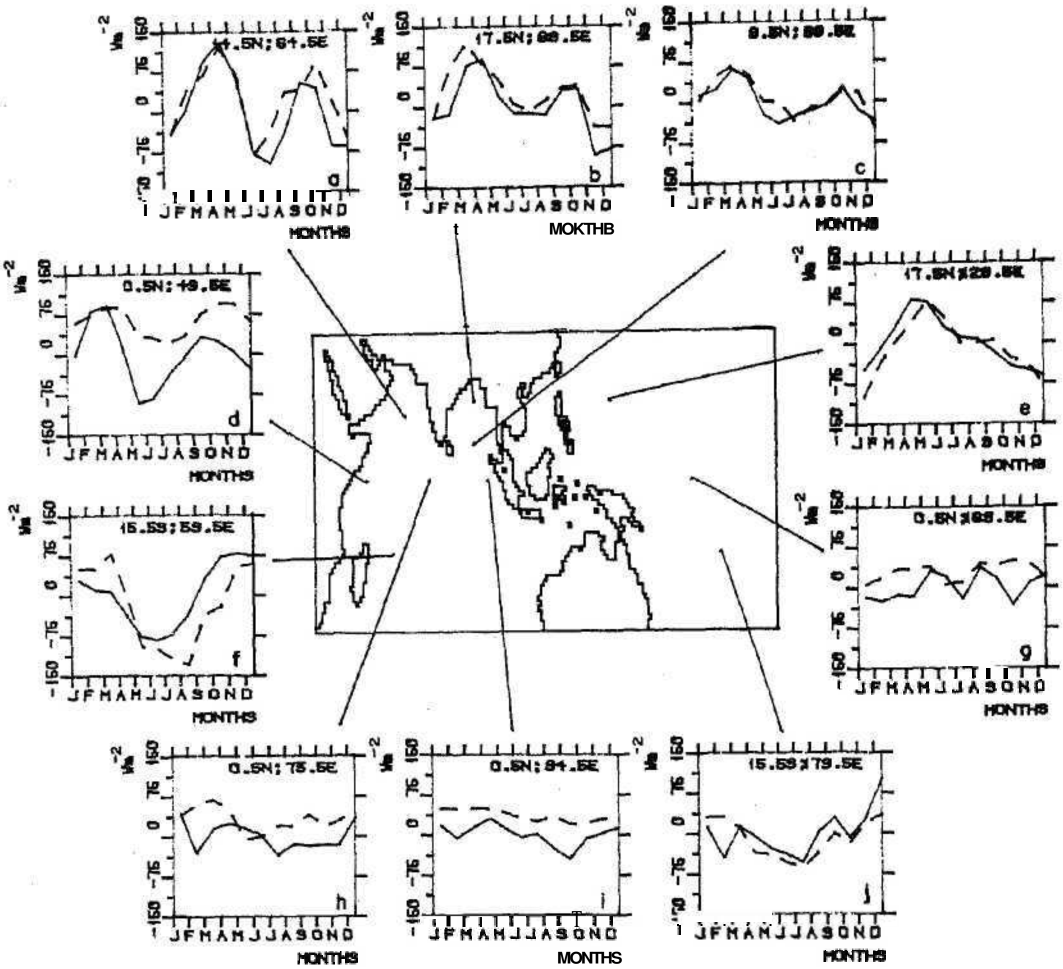

Figure 9. Annual cycle of net heat gain at the sea surface (——) and rate of change of heat content of the upper 50m (———) at selected locations.

scales. Improvement in our ability to observe these processes is likely to be slow. Meanwhile, a pertinent question from the point of view of ocean-atmosphere coupled models to study the monsoons concerns the feasibility of linking the SST variability to local air-sea fluxes alone. This can be done when the contribution of the ocean currents is small. The relationship between the cycles of rate of change of heat in the upper 50 m and the air-sea heat fluxes (figure 9) could be used as a guide in deciding the extent to which SSTs can be treated as a function of air-sea fluxes alone. An important point to note is that the IOWP is a region of net annual heat gain by the ocean. Hence to maintain an annual cycle, it is necessary to remove this heat by transporting it away. At present we have little idea of how and when this occurs. A better understanding of the seasonal and annual heat budgets of IOWP is clearly desirable. Another factor, important from the point of view of air-sea coupling, but not considered here, is the interannual variability of IOWP. Currently, there are no estimates on what this might be.

References

Ardanuy P, Cuddapah P and Kyle H L 1987 Remote sensing of water vapor convergence, deep convection and precipitation over the tropical Pacific Ocean during 1982-83 El Nino; *J. Geophys. Res.* 92 14204–14216

Bjerknes J 1969 Atmospheric teleconnections from the equatorial Pacific; *Mon. Weath. Rev.* 97 163-172

Colborn J 1975 *The thermal structure of the Indian Ocean* (Hawaii; The University Press) 173 pp

Cutler A N and Swallow J C 1984 Surface currents of the Indian Ocean (to 25°S, 100°E): compiled from historical data archieved by the meteorological office, Bracknell, UK. Institute of Oceanographic Sciences, Rep. No. 187, 8 pp & 36 charts.

Donguy J-R 1987 Recent advances in the knowledge of the climatic variations in the tropical Pacific Ocean; *Prog. Oceanogr.* 19 49-85

Donguy J-R, Dessier A, Eldin G, Morliere A and Meyers G 1984 Wind and thermal conditions along the equatorial Pacific; *J. Mar. Res. 42* 103-121

Fine R A 1985 Direct evidence using tritium data for throughflow from the Pacific to the Indian Ocean; *Nature (London)* 315 475-480

Gadgil S, Joshi N V and Joseph P V 1984 Ocean-atmosphere coupling over monsoon regimes; *Nature (London)* 312 141-143

Gill A E and Rasmusson E M 1983 The 1982-83 climatic anomaly in the equatorial Pacific; *Nature (London)* 306 229-234

Godfrey J S and Lindstrom 1989 The heat budget of equatorial western Pacific surface mixed layer; *J. Geophys. Res.* 94 8007-8017

Graham N E and Barnet T P 1987 Sea surface temperature, surface wind divergence and convection over tropical oceans; *Science* 238 657-659

Gray W M 1975 Tropical cyclone genesis. Dept. Atmos. Sci., Paper. 232, Colorado State University, Ft. Colins, Co, 121 pp

Hastenrath S and Lamb P 1979 *Climatic atlas of the Indian Ocean Part II: Heat budget* (Madison; The University of Wisconsin Press)

Joseph P V 1990 Warm pool in the Indian Ocean and monsoon onset; *Trop. Ocean-atmos. Newsl.* 53 1-5

Lau K-M and Chan P H 1986 the 40-50 day oscillation and ENSO: a new perspective; *Bull. Am. Meteorol. Soc.* 67 533-534

Levitus S 1982 Climatological atlas of the world oceans; NOAA Prof. Paper. 13, 173 pp, US Government printing office, Washington, D.C.

Lukas R 1988 On the role of western Pacific air-sea interaction in the El Nino/Southern Oscillation phenomenon. *Proc. US TOGA western Pacific air-sea interaction workshop,* Honolulu, 16-18 Sept. 1987 (eds) R Lukas and P Webster, US TOGA Rep. USTOGA-8 U. Corp. Atmos. Res., 43-69

Lukas R and Webster P 1989 TOGA–COARE: a coupled ocean-atmospheric response experiment for the warm pool regions of the western Pacific. Scientific plan compiled by R Lukas and P Webster

McPhaden J 1982 Variability in the central equatorial Indian Ocean Part I: Ocean dynamics; *J. Mar. Res.* 40 157-176

Nicholls N 1983 Predicting Indian summer monsoon rainfall from sea-surface temperature in the Indonesia-north Australia area; *Nature (London)* 306 576-577

Rasmusson E M and Carpenter T H 1982 Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Nino; *Mon. Weath. Rev.* 110 354–384

Shetye S R 1986 A model study of the seasonal cycle of the Arabian Sea surface temperature; *J. Mar. Res.* 44 521-542

Taylor R C 1973 *An atlas of Pacific island rainfall*; Hawaii Institute of Geophysics Report No. 25

Weare B C, Strub P T and Samuel M D 1981 Annual mean surface heat fluxes in the tropical Pacific Ocean: *J. Phys. Oceanogr.* 11 705-717

Wyrtki K 1973 An equatorial jet in the Indian Ocean *Science* 181 262-264

Wyrtki K 1985 Water displacements in the Pacific and the genesis of El Nino cycles; *J. Geophys. Res.* 90 7129-7132