Spatio-temporal variations of convection and rainfall over Indian Ocean warm pool

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An attempt has been made to examine the spatio-temporal variability of rainfall and cloud cover in relation to the sea surface temperature distribution over the Indian Ocean warm pool (IOWP: 10°N-15°S; 60°-100°E) based on the NOAA Polar Orbiting Satellite outgoing longwave radiation (OLR) and WMO/WCRP Global Precipitation Climatological Project (GPCP) precipitation data at 2.5°latitude/longitude grid for the period 1979-1990 and 1986-1993, respectively. The above data were subjected to empirical orthogonal functions (EOFs) analysis and it was found that the first four modes (EOF 1-4) show strong variability in both the above parameters in the region. In general, the isolophets patterns of the EOF-1 for both the elements show more or less similar trend of fairliness of positive maximum loading in relation to warm pool area and, generally, oriented in an east-west direction depending upon the orientation of the warm sea surface temperature isotherms. The other three modes (EOF 2-4) showed distribution slightly different from first mode (EOF-1). The isolophets of these later three modes showed an inclination from the isolophets of EOF-1 in the region, which implies that the processes which are operating during these modes differ from those of EOF-1.

1 Introduction

It is well known that the eastern equatorial Indian Ocean (10°N-15°S, 60°-100°E) is identified as one of the highly energetically active zones of the Indian Ocean, the others being the eastern Arabian Sea, head Bay of Bengal, the Somali Basin and the Mascarene High region of the southern Indian Ocean. The reason for this activity is that, this part of the ocean surface-water maintains warm temperatures with an order of 28°C and on some occasions 29°C throughout the year (Fig. 1, 28°C isotherm). However, the seasonal variations are part of the anomalies from this value. This region is termed as an Indian Ocean warm pool (IOWP) by Vinayachandran and Shetye1 due to its warmth of about 28°C, which is a minimum SST required for an active convection to occur over open oceans.2,3 Convections in the geophysical fluids (ocean and atmosphere) necessarily involve in a hierarchy of structures and length scales.4 Over a warm ocean surface, small scale turbulence, longitudinal roles and other boundary layer structures tend to increase buoyancy within the confined thickness of the marine Planetary Boundary Layer (PBL). Similar processes convert an upward surface buoyancy flux into a mean density increase of the oceanic mixed layer. Together with the concomitant thickening of PBL and the entrainment, they cause a gradual increase of convection instability at its other boundary. The buoyancy anomaly is advected by low-level winds into areas of convergence over the warm sea surface areas. Within the ocean, dense surface water is similarly advected towards the most strongly cooled regions. The accumulated convective instability can be realized by random fluctuations, by the effect of boundary irregularities, or by synoptic-scale perturbations that cause additional convergent Ekman transports. The resulting deep convection can take the form of relatively large fluid particles or of more persistent plumes, which “cream off” the buoyancy and transport it vertically away from the boundary layers. These convective elements tend to become organized in large rotating structure. Further, it has been observed that the

Fig. 1—Counter of 28°C isotherm
organized convective activity over the IOWP has a large seasonal variation in surface area as covered by the pool and, hence, it is known for the area of active zone of ocean-atmosphere coupling. A quantitative picture of the causes behind this variation is not yet available. However, they speculated that the interaction with the Asian monsoons is important. The factors that control the variability of IOWP, i.e., the fluxes of heat and momentum and ocean currents are noisy processes with the fluctuations spread over a wide range of spatial and temporal scales. Improvement in our ability to observe this process is likely to be slow. Generally, 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 south Indian coastline during April in the Bay of Bengal and during May in the Arabian Sea. The first signal of cooling is observed in the southern Indian Ocean during May. The summer monsoon 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 side of the IOWP, surface temperature does not fall below 28°C during the summer. After the withdrawal of 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 of the southern Indian Ocean and a warm pool in the Bay of Bengal part of the IOWP recedes during October-November. The above changes in the surface temperature may be seen in a recent Atlas. Further, it is seen by Bal Krishnan et al. that there is a formation of warm pool over equatorial Indian Ocean in May which is more marked in June with its intensity being higher during the years of good monsoon activity. In good monsoon years the warm pool over the equator extends from 60°E to 80°E longitude, while during poor monsoon years it lies only between 60°E and 75°E longitude.

Saha has examined the existence of cloud clusters and bands in relation to warm water temperatures of the tropical oceans. He found that over the IOWP, cloud clusters appear to be randomly distributed in convergence zones where they are organized in bands. Further, he found that the cyclonic circulation and convergence zones appear over warm ocean, and anticyclonic circulation and divergent flow over cold subtropical ocean. Again, he showed that the inter-tropical convergence zones (ITCZ) appears in almost the same location at the near equatorial ridge of the surface temperatures. This is certainly as it should be, for convergence zones are the regions of ascending air motion and hence conversion of latent heat of water vapour into sensible heat energy takes place by way of condensation. Indeed, he noticed double cloud band systems that are associated with the double ITCZ, one on each side of the equator, and they form fairly frequently in the Indian Ocean in the vicinity of IOWP. Hastenrath and Lamb also noticed similar features.

The role of equatorial trough zones in the heat balance of tropical atmosphere has been emphasized by Richl and Malkus who pointed out that although the tropics, as a whole, serve as a heat source for the general circulation of the atmosphere, it is mainly through the equatorial trough zone that both sensible and latent heat energies are transmitted upward for eventual transfer to higher latitudes. Cloud distributions are thus visible manifestation of this important process of energy transfer and the bulk of this transfer takes place through ITCZ. The surface trough which forms south of the equator in Asian monsoon regions is, generally, known as 'southern hemispheric equatorial trough (SHET)’, while its counterpart in the northern hemisphere as ‘northern hemispheric equatorial trough (NHET)’. During northern summer monsoon season NHET moves northward and merges with the heat low over central India, which is generally known as monsoon trough during the same period. It is interesting to note that the number of days of occurrence of double cloud bands during the period July-September 1966 (which was a drought year in India) is much greater than those occurring during corresponding periods in other years (which were all good monsoon years), i.e., they had normal or more than normal amounts of rainfall. This life period of double cloud bands appears to be highly variable with an average period of about 5-6 days and 1-2 days in extreme cases. Srinivasan studied some of the aspects of broad-scale cloud distribution using satellite data over Indian Ocean during Indian southwest monsoon season. His study revealed that SHET is often located in between the two near-equatorial cloud bands on either side of the equator. Cloudiness increases in the region of the axis of SHET only when the distribution forms and moves along the trough line. This study further concludes that the basic configuration in the cloud field is the characteristic feature of the monsoon circulation over the Indian Ocean and is independent of the monsoon rainfall over the Indian main land, although there are changes in the intensities of the cloud belts and slight shifts in their locations. Recently, Prasad has also found an inverse relationship between the convective
cloudiness in SHET and south-west monsoon activity over India. The existence of an inverse relationship between the activity of SHET and south-west monsoon rainfall was first reported by Prasad 12 in 1981. This appears promising in fore-shadowing the rain spell with a lead-time of 2-3 days. However, at north of 20°N, the contribution of synoptic scale systems developing north of 15°N becomes equally important. The spells of increased cloudiness (SICs) in the SHET are mainly confined to zones east of 70°E to 75°E. The existence of east-west oriented double convergence zones in the equatorial Indian Ocean during the south-west monsoon season over south Asia has been reported by several workers. 

While examining the mean rainfall distribution over the oceans, Saha 7 commented briefly on the distribution of mean annual rainfall over tropical oceans in relation to mean ocean surface temperatures. Although clouds are essential for rainfall, mere presence of clouds may give no indication of the distribution of rain. However, Sadler 13 compared two-year average cloud distributions as revealed by satellite with normal rainfall distribution over equatorial and southern Africa during February 1966-67 and found a surprisingly close correlation between the two. In a numerical study by Pike 14, it has been shown that a rainfall peak appears over equatorial oceans when it is warm, and a rainfall minimum when it is cold. The cold oceans of the sub-tropical belts are generally dry; almost desert conditions prevail in the equatorial Atlantic, where the Benguela current keeps a minimum surface temperature. The equatorial Indian Ocean lying west of about 60°E, including the Arabian Sea, is affected by the cold Somali currents and is partially dry. The equatorial belt comprising eastern Indian Ocean and western Pacific Ocean is the wettest region of the tropical oceans. 9 In south Pacific and south Atlantic Oceans the locations of cloud bands associated with ridge of ocean surface temperature discussed in the preceding section, appears to be marked by high precipitation. 9 In short, the distribution of mean annual rainfall appear to be related to mean ocean surface temperature in much the same way as the mean cloud distribution 8.

Further, Pai 15 has studied the inter-annual variability of Indian summer monsoon using OLR data for the period 1979-92. The data are derived from polar orbiting satellites digitized in a global grid 2.5°x2.5°. This study has also revealed that there exists a negative relationship between Indian rainfall and cloud cover in SHET. This study has also revealed that during 1979 (weak monsoon) the negative anomalies over IOWP were indicating strong oceanic tropical convergence zone and depressed convective activity over Indian continental region. During good monsoon years (1983 and 1988) continental tropical convergence zone over Indian region was active as inferred from prevailing negative OLR anomalies. 20

Kondragunta 20 has studied the intra-seasonal variations of the Asian summer monsoon using OLR data from NOAA polar orbiting satellites, covering the summers (1 May-30 September) for the period 1975-83. He identified two regions of high standard deviations of OLR, one in the equatorial Indian Ocean (lat.5°S-10°N; long.65°E-95°E) and the other over north-west Pacific (lat.10°N-25°N; long. 110°E-140°E) and also subjected the OLR to spectral analysis. This study clearly indicated that the 40-day mode is the dominant mode in the equatorial Indian Ocean. Kondragunta has further subjected the OLR data to EOF analysis over the Asiatic monsoon region in order to see whether some of these oscillations are of local or global nature. The first four eigen-vectors account for 5.0, 3.6, 3.4 and 3.0 of the total variance in order. The first eigen-vector clearly shows two centres of action with out-of-phase relationship—one centre located over the IOWP around 90°E and the other is located over north-west Pacific around 140°E. This feature is similar to east-west dipole pattern noticed by Lau and Chan 22. They suggested that the east-west dipole patterns near the equator propagate from the Indian Ocean towards western central Pacific. This feature indicates that when the equatorial Indian Ocean is at its dry phase, the north-west Pacific is at its wet phase and vice-versa.

A review of all the above studies has clearly revealed that there exists always a relationship between the processes that take place on IOWP and the rainfall distribution in situ and over the Indian subcontinent. Further, none of the above studies has brought out any coherent relationship among the three parameters, namely SST, rainfall and cloud cover/OLR over the IOWP. However, in the present study, an attempt has been made, in a rather constructive way, to find a relationship between the above three parameters. This study would help us in understanding the ocean-atmosphere interface processes in the range of pentad (five-day mean) to climatological time scale range.

2 Data

The features of spatio-temporal variability generally depend on the season, domain of analysis, the variable
and its time of averaging. In order to understand the seasonal variability over the equatorial zone (IOWP) the following variables are considered in the present study. Both the variables are derived from polar orbiting satellite digitized in a global grid of $2.5^\circ \times 2.5^\circ$ (latitude by longitude).

(i) A 5-day mean OLR for the period 1979-1990 in the domain ($10^\circ N-15^\circ S; 60^\circ-100^\circ E$).

(ii) A 5-day mean GPCP rainfall for the period 1986-1993, in the domain ($11.25^\circ N-16.25^\circ S; 61.25^\circ-101.25^\circ E$).

The seasonal climatological SST atlas by Reddy and Kumari is consulted to understand and evaluate the possible links between the GPCP rainfall and OLR distribution with the seasonal SST distribution.

3 Methodology

Empirical orthogonal function (EOF) is same as the principal component analysis in statistics. This technique is basically used to reduce mathematically the dimension of data. If we have $n$ variables, $X_1, X_2, \ldots, X_n$ then EOF gives us some linear combinations of these variables and, then for further analysis, these linear functions are used. Thus the dimension $n$ is reduced to some $m$ linear functions ($m<n$) and these functions explain maximum variation in the data. These linear functions are the characteristic vectors of variance – covariance or correlation matrix of $X$ and are orthogonal to each other.

If $A_{i;j}$ is correlation matrix, then

$$|A - \lambda I| = 0$$

where, $\lambda_i (i=1, \ldots, n)$ are characteristic roots and $AX = \lambda X$ gives characteristic vectors, which are called EOF loading in meteorology. The EOF technique is also applied in meteorological studies to study joint spatio-temporal variability in the data. They give most dominant recurring patterns in the data. The detailed procedure for determining these functions is available elsewhere. It consists of two basic steps:

**Step 1**—From the $n$ maps each having $m$ points, prepare symmetrical correlation/covariance matrix of order $m \times m$.

**Step 2**—Determine the eigen-values and eigen-vectors from this symmetrical matrix. The spatial distribution of the elements of the eigen-vectors gives the desired empirical functions and the eigen-values are the measure of the variance explained by each function.

To determine eigen-values and eigen-vectors we have used the software package of the Numerical Algorithm Group (UK) Fortran Library installed on the Norsk Data computer system at the Indian Institute of Tropical Meteorology, Pune.

In the present study, the variability explained by only ten EOFs for pentad GPCP and OLR in the IOWP region is considered and given in Tables 1 and 2.

A dipole type of structure in the EOF pattern, i.e., one region of concentrated negative loading and other region of the positive loadings, implies that the variation over these two localized regions is out of phase. If the variation over one region is more, then the variation over other region is less with the same sign, which implies the dominance of one over the other. Negative loadings do not necessarily convey less variability.

| Table 1—Variance-explained ($V$) and cumulative explained (CV) in percentage for pentad GPCP rainfall for winter, spring, summer and monsoon over the equatorial Indian Ocean |
|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| EOF   | Winter (DIF) | Spring (MAM) | Summer (JJA) | Monsoon (SON) |
|       | $V$    | $CV$     | $V$    | $CV$     | $V$    | $CV$     | $V$    | $CV$     |
| 1     | 29.32  | 29.32   | 21.57  | 21.57   | 22.79  | 22.79   | 17.83  | 17.83   |
| 2     | 11.52  | 40.83   | 15.66  | 37.23   | 11.42  | 34.21   | 10.18  | 28.01   |
| 3     | 10.20  | 51.03   | 9.99   | 47.22   | 9.24   | 43.45   | 6.64   | 34.65   |
| 4     | 7.43   | 58.46   | 6.29   | 53.51   | 7.35   | 50.8*   | 7.71   | 42.36*  |
| 5     | 5.46   | 63.92   | 5.92   | 59.43   | 4.89   | 55.69   | 7.00   | 49.36   |
| 6     | 4.64   | 68.56   | 4.76   | 64.19   | 4.21   | 59.9    | 5.53   | 54.89   |
| 7     | 3.50   | 72.06   | 4.01   | 68.2    | 4.15   | 64.05   | 4.63   | 59.52   |
| 8     | 2.93   | 74.99   | 3.48   | 71.68   | 3.57   | 67.62   | 3.89   | 63.41   |
| 9     | 2.38   | 77.37   | 2.94   | 74.62   | 3.05   | 70.67   | 3.08   | 66.49   |
| 10    | 2.21   | 79.58   | 2.71   | 77.33   | 2.65   | 73.32   | 2.92   | 69.4    |

Note: *% Variance explained by first four EOFs: DIF (Dec., Jan., Feb.), MAM (Mar., Apr., May), JJA (June, July, Aug.), SON (Sep., Oct., Nov.).
4 Results and discussion

The results of the present study are described here. Table 1 illustrates the variance-explained (V) and the cumulative variance-explained (CV) GPCP rainfall, in percentage for the four seasons (winter, spring, summer and monsoon). The CV for the 10 EOFs are, respectively, 79.6, 77.3, 73.3 and 69.4, whereas for the 4 EOFs, they are only 58.5, 53.5, 50.8 and 42.4, respectively. The V for EOF-1 are, respectively, 29.3, 21.6, 22.8 and 17.8 for winter, spring, summer and monsoon. Values of V for 10 EOFs are, respectively, 22.2, 2.7 and 2.9. Similarly, Table 2 shows the V for OLR, similar to the GPCP rainfall. Here, the V values for the 10 EOFs are, respectively, 76.0, 76.9, 68.5 and 71.8 for winter, spring, summer and monsoon. Whereas the CV values for 4 EOFs are, respectively, 56.1, 57.2, 46.5 and 49.3. The values for EOF-1 are respectively, 27.85, 26.45, 18.62 and 22.5 for winter, spring, summer and monsoon and for 10th EOF they are, respectively, 2.2, 1.9, 2.5 and 2.2. The distribution in V between EOF-1 and EOF-10 shows the proportionate distribution variance. On comparison of Tables 1 and 2, it is found that, in general, variance-explained for GPCP rainfall is slightly higher than those explained for OLR. The variance explained for GPCP rainfall has gradually decreased from winter to monsoon except during spring. In spring, the V and CV are slightly lower than those in summer. The variance explained for OLR also showed a similar tendency as for GPCP rainfall, but V and CV in summer are slightly less than the monsoon values. We know that the GPCP rainfall is derived from the OLR data. So the variance explained for both the parameters seems to be more or less the same. But in the present case, it is found that the variance explained for OLR is slightly lower than that of GPCP in some seasons and this could be due to disparity in time between the data sets that are considered for analysis.

Figures 2-5 show the distribution of the loadings of EOF-1 to EOF-4 for all four seasons for the GPCP rainfall, while Figs 6-9 show the same for OLR. The isopleth patterns show zonal orientation in EOF-1, EOF-2 (except during monsoon) and EOF-4 in both GPCP rainfall and OLR. Whereas, the EOF-3 patterns show meridional orientation except for monsoon in GPCP rainfall. Figures 2 and 6 (EOF-1) show the isopleth patterns (contours) for both GPCP and OLR from winter to monsoon. It is seen from Figs 2 and 6 that both the elements show positive loading in all the seasons with a plain flat maximum loading (from 100 to 120) along and near the equatorial Indian Ocean, but the centres of maximum loading differ from each other. These discrepancies may be partially due to the difference in the sample size and period between GPCP rainfall (8 years) and OLR (12 years). The latitude of highest loading is located in somewhat southern latitudes as expected. The longitude of highest loading is between 80°E and 85°E during all seasons except in spring during which, it is near 70°E. The elongated band of loading in south of the equator shows predominance of southern hemispheric equatorial zone. Similarly, Figs 3 and 7 show the contour patterns of EOF-2 (dipole mode). The zero isopleths coincide with axis of maximum loadings in EOF-1. The isopleths of dipole modes of both the GPCP rainfall and OLR show more or less similar features in distribution in the study area from winter to monsoon. Both the parameters show strong north-south gradients in the western sector and relatively weak gradients in the

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Note: * % Variance explained by first four EOFs: DJF (Dec., Jan., Feb.), MAM (Mar., Apr., May), JJA (June, July, Aug.), SON (Sep., Oct., Nov.)
eastern sector from winter to summer. However, these gradients differ in monsoon. In monsoon the isopleths have oriented meridionally with strong east-west gradients to the south and weak gradients to north of the equator. In general, both the winter and summer GPCP rainfall modes showed a ridge of maximum positive loading (>80) around 8°-9°N, and a trough of minimum loading (<-80) around 4°-9°S (precisely, at 9°N in winter and 5°N in summer). Exactly opposite features are observed in case of OLR.

In spring, the GPCP rainfall dipole mode shows a trough of minimum loading at 9°N and a ridge of maximum loading at 8°S. The spring OLR is just vice-versa to the above features. The monsoon GPCP rainfall dipole shows large fluctuations in the domain of study with almost negative modes to the west and positive modes to the east of 82°E. The dipole mode event of summer OLR distribution shows a strong positive loading (>100) between 5°S and 10°S and east of 90°E. This value is observed to have coincided with the underlying cold waters [27.5°C, Figure 10(c)], whereas a reversal dipole mode [negative loading (-40)] is observed between 5°N and 10°N and from 65°E to 75°E, an area having very high warm waters (28.5-29°C). At the same places the GPCP rainfall shows an opposite trend to the north and near-similar trend south of the equator.

Figures 4 and 8 show EOF-3 contour distributions. This mode shows an independent distribution in isopleth pattern from season to season and from GPCP rainfall to OLR. In winter and spring, the zero isopleths of GPCP orient in a north-south direction along 75°E, keeping negative loading to its west and positive loading to its east. This mode shows a high positive loading between equator and 8°S and east of 90°E. An opposite polarity of maximum negative loading is observed between equator and 4°N and west of 71°E. In spring, high absolute values of both the modes lie in the southern hemisphere at the opposite rims between 4°S and 10°S. In summer and monsoon the zero isopleth
splits into two and loitering separately in both the hemispheres. In monsoon there exists a well-defined trough line in the southern hemisphere which, from equator, 100°E to 5°S, 61°E, is enclosed by the zero isopleths on either side. The OLR also shows more or less similar features in both the seasons of winter and spring. However, the highest positive loading is even extended to north of equator along the eastern rim. The features of the summer mode of positive and negative signs are in opposite phase to winter mode. However, the mode exhibits fairly larger north-south gradients in the south-west sector between 10°S and 16°S and west of 81°E, whereas the summer OLR shows high positive loading between the equator and 12°S and west of 80°E and opposite polarity is seen near 9°N between 83° and 93°E. During monsoon, a ridge of high positive (125) loading lies around 9°S and a trough of minimum loading is seen north of equator from 3°N, 95°E to 6°N, 61°E. This type of distribution is out of phase with OLR distribution in monsoon.

Figures 5 and 9 show the distribution of EOF-4 from winter to fall. The isopleths are generally oriented in east-west direction except some distortion in the pattern of GPCP rainfall in summer and monsoon. In winter, the maximum positive loading (120) lies along 2°S and between 63°E and 80°E. A ridge through this maximum extends from 4°S, 61°E to equator, 95°E. The opposite polarity is seen in the northern hemisphere around 8°N. These features are in opposite phase to OLR distribution. However, there exists a very high positive OLR loading (140) between 85°E and 90°E, i.e., at southern rim of the domain in winter. For spring GPCP rainfall, there is loading at the south Indian coast and another in the south around 8°S and between 82°E and 85°E. These two positive loadings are separated by a trough of minimum loading near equator. An absolute maximum (negative) loading is seen close to the equator along Indonesian coast and another at 8°S on the western rim. The spring OLR shows an opposite phase distribution with respect to spring GPCP. There
exists a ridge of high positive values close to the equator just south of the equator in summer both for GPCP and OLR. A trough of minimum (negative) loading in GPCP lies around 9°S between 72°E and 95°E. In the northern hemisphere, GPCP shows positive loading, whereas the summer OLR shows a trough of minimum loading along 14°S with high magnitude of negative loading between 72°E and 85°E. Similarly, there is small patch of negative loading in the north surrounding the south Indian coast. During monsoon, in GPCP, the trough of negative loading lies north of equator, i.e. from equator, 61°E to 10°N, 93°E. High positive loading lies in the southern hemisphere around 82°E between latitudes 5°S and 8°S. The OLR, in contrast to this, shows a trough of negative loading south of the equator around 2°S with high positive loading at the extreme boundaries on either side of the trough line. The maximum positive loadings are seen near 15°S, 78°E and 10°N, 80°E.

In order to examine the seasonal variation of SST distribution over the study area, a recent climatological atlas is consulted, and the patterns are shown in Fig. 10. Figure 10(b) shows the winter SST distribution. The 28°C isotherm seems to cover a vast area in both the hemispheres, right from 14°S to 10°N. This isotherm represents the extent of warm pool over this region. There exists two high warm pool islands at Indonesian coast at 8°S between 65°E and 70°E and are embedded with a relatively low warm water pool (28.5°C). The colder water (less than 27°C) is found to lie close to the southern rim of the grid with a maximum cooling (26.5°C) in the south-east corner of the grid. In spring [Fig. 10(b)] the equatorial Indian Ocean further warmed up very rapidly and attained maximum temperature of the order of 30°C in the north-west Indian Ocean. The highest temperature (30.5°C) is seen over eastern equatorial (equator 5°S, 95°E) Indian Ocean where the winter maximum is found. In summer, the ocean surface has cooled down relatively by about 1°C. The warm waters of the spring are now decentralized and pool up into eddies covering a small area. The equatorial region between 3°S and 5°N seems to be the warmest (29°C)
part of the ocean. Coldest temperatures of the order of 25°-25.5°C are now seen along the southern rim of the grid. North-south temperature gradient is strong over the southern hemisphere and weak in northern hemisphere. In monsoon (post-south-west monsoon), the temperature distribution is more or less similar to that of winter, but the central equatorial Indian Ocean between 75°E and 80°E seems to be colder (28°C) than in the summer. Two pools of warm water (29°C) are seen near equator between 60°E and 65°E and between 90°E and 100°E. The southern hemisphere water temperatures are now slightly improved, as 25.5°C isotherm disappeared from the region, except over a small region in south-west corner of the area between 60°E and 65°E. North-south gradients of temperatures are maintained in this season in the way similar to that in the south-west monsoon seasons (summer). Saji et al. have demonstrated that the area through which the 28.5°C isotherm passes is the area where most convective activity takes place. In the Indian Ocean this isotherm is always continued to confine to the equator and marching north-south direction depending on the season by transferring convective activity across the equator.

Figure 11 shows the sea-surface temperature distribution of (a) annual mean and (b) August month mean. It is seen from Fig. 11 that the temperature distribution is more or less similar in both annual and August month. The main features of August month are reflected in the annual mean, except over an area between 80°-87°E and 4°S-1°N, where the SSTs in August are warmer (29°C). This warm core appears to have shifted to the east along the equator in the annual mean. The fairly well mixed warm waters enclosed by the 28.5°C isotherm are confined to the equator in both annual mean chart and August mean month chart. The double broken lines seen in Figure 11(b) represent the mean positions of the SHET south of the equator and NHET north of the equator orienting in an east-west direction. It is interesting to note that these two lines (double broken lines) more or less coincide with the

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**Fig. 5—Distribution patterns for GPCP rainfall, EOF-4**
alignment of the 28.5°C isotherm in the month of August. The existence of these SHETs during the month of August are reported elsewhere\textsuperscript{11,12}. Figure 11 [(a) and (b)] is reproduced here to show the concurrent relationship between SST (28.5°C isotherm) and the meteorological weather systems SHET and NHET and the related cloud and rainfall distributions.

Figure 10 shows the seasonal distribution of SST over the study area. Figures 2-9 show the distribution of EOFs of the pentad GPCP rainfall and OLR. Assuming the steady/quasi-steady state distribution of the above parameters with season, one can clearly bring out a close relationship between SST and the rainfall and between SST and OLR. Of course, a close examination of the contribution of $V$ of each EOF of GPCP rainfall and OLR in each season has revealed that the contributions of the EOF-1 for both the above parameters appear to be substantially higher than the remaining three EOFs. This implies that the major seasonal weather pattern at each grid point is related to each neighbouring grid point that would come under the grip of the seasonal weather change.

Figure 12 shows the seasonal mean OLR distribution over the study area for the seasons (a) winter, (b) spring, (c) summer and (d) monsoon. The OLR can be used as a proxy for rainfall. It is interesting to note that the eastern equatorial Indian Ocean seems to be highly convective during all the seasons as compared to western equatorial Indian Ocean. The distribution of the contours (10 units interval of OLR) varies from 210 W/m\textsuperscript{2} to 270 W/m\textsuperscript{2}, the lowest value being the representative for the region of maximum cloud cover and the highest value for cloud-free region. Further, in southern Indian Ocean, it is to be noted that the isopleths of OLR always run east-west direction and show a strong north-south gradient in all the seasons. Whereas, in the northern Indian Ocean, depending on the north-south moment of the sun across the equator, they organised into a variety of shapes according to the advancement of season. The isopleths are always making an angle with the equator implying the movement of clouds across the equator. Kripalani \textit{et al.}\textsuperscript{20} by analysing the OLR fields, have brought out the importance of the oceanic cloudiness zones that form...
near the equatorial latitudes. They further found that the rainfall (2.5 mm/day) probability exceeds 0.9 mm/day when OLR is less than 180 W/m² and is very low (0.0 mm/day) when OLR is greater than 280 W/m².

In winter [Fig. 12(a)], the area of lowest values of OLR (210 W/m²) is close to 100°E and in between equator and 6°S. An axis of a trough of minimum of OLR runs from north-east to south-west in southern hemisphere from 3°S, 100°E to 9°S, 60°E. This trough line appears to coincide with the ridge warm SST [Fig. 10(a)]. There are three areas of very high values of OLR (260-270 W/m²) along the northern rim of the Arabian Sea and the Bay of Bengal and the south-east corner of the south Indian Ocean where relatively colder water is present. Two ridges of maximum OLR are found in the Arabian Sea and Bay of Bengal. Further, the area of lowest OLR and the axis of the OLR trough line appear to have coincided with a ridge of warm water (29°C) during this period in the southern Indian Ocean. The ridges of OLR coincide with relatively low values of SST [28°C, Fig. 11(a)]. In spring [Fig. 12(b)], the contours of OLR are organized in parabolic form, symmetrical about the equator, and oriented in an east-west direction on either side of the equator. The low values of OLR (210 W/m²) that were found along 100°E and around 3°S in winter are now appear to have moved northward and lie around 2°N. The winter trough axis which was found in the southern hemisphere is now bifurcated into two branches. One branch remains in the same position in the southwestern Indian Ocean 60°E and 90°E south of 5°S, whereas the second part of the trough has shifted to north and now lies along 2°N in the north Indian Ocean. Very high values of OLR (270 W/m²) are now seen along the north-west corner of the grid in the Arabian Sea. A strong ridge of OLR that runs east-west approximately along 3°S separates the above two trough lines. In summer [Fig. 12(c)], the isopleths have further re-organized and dislocated from the spring structure. A flat plain area of OLR is seen near the equator between 4°S and 5°N, 68°E-82°E that covers a low OLR (220-230 W/m²). These are of low OLR and appeared to have coincided with the August warm pool in [Fig. 11(b)]. The area of lowest value of OLR
Fig. 8.—Distribution patterns for OLR, EOF-3

Fig. 9.—Distribution patterns for OLR, EOF-4
(200 W/m²) is further moved northward along the eastern rim up to the northern rim in the Bay of Bengal and now lying around 10°N, 95°E. The trough axes found in spring are now split into multiple trough lines and lie randomly in both the hemispheres. The prominent among these lines in eastern equatorial Indian Ocean lie in a north-east to south-west direction. The area of higher OLR (260 W/m²) is now seen in the south-west corner of the grid and a secondary area of high values of OLR (250 W/m²) in the north-west corner of the grid over the Arabian Sea. During this period, one feeble ridge of OLR is seen in the Arabian Sea near 5°N and between 60°E and 70°E. All the trough lines seen in this area during this period are very well-aligned with areas of warm water pools (29°C). The ridge in the Arabian Sea has coincided with cold water [27.5°C-29°C; Fig. 12(c)]. In [Fig. 12(d)], the isopleths of OLR of monsoon appear to have resembled to those observed in spring. The area of low values of OLR (190 W/m²) of this season is approximately coincided with the area of low OLR during spring. A trough line of OLR lies in the southern hemisphere running in a north-east to south-west direction from equator, 90°E to 5°S, 60°E. A secondary feeble trough line is also seen in the northern hemisphere between
equator and 5°N and east of 90°E. A strong ridge appears to have laid down around 4°N between 70°E and 90°E. Two prominent areas of high values of OLR (260 W/m²) are noted in both the hemispheres along 60°E on either extreme-end rims. The trough line is now coinciding with axis of warm surface waters (28°-29°C) in the south Indian Ocean [Fig. 12(d)]. Examination of the seasonal distribution of SST and the small modes of EOF-3 and EOF-4 have revealed that the small scale changes in convection of shorter duration, i.e., diurnal and synoptic basis, appear to be operating independently, irrespective of warm or cold core water masses.

5 Summary

In this study we have addressed the issue of the structure of tropical convection over the equatorial Indian Ocean warm pool (10°W-15°S; 60°-100°E), by using the satellite derived fields of OLR and GPCP rainfall. The technique known as the EOF analyses, that derive the predominant structure from the data itself, is used. The analyses of the results have revealed the following features:

(i) The first four EOFs (1-4) for pentad OLR and GPCP rainfall explained more than 50% of variance, in which the EOF-1 itself explains about 20% of variance.

(ii) The distribution of loading on the leading EOFs (1-4) showed an elongated structure indicating the predominance of the east-west oriented cloudiness bands in the wake of SHET and its changing latitudinal positions.

(iii) A comparison of the maximum and minimum loadings of the GPCP rainfall and OLR with the seasonal distribution of SST over the study area has revealed that SST (28°C) and minimum loadings coincide with cold SST (28.0°C).

(iv) The dipole mode of the summer OLR showed a strong positive loading (100) between 5°S and 10°S and east of 90°E. The value is observed to have coincided with the underlying cold water [27.5°C, Fig. 10(c)], whereas a reversal dipole mode (negative loading -140) is observed between 5°N and 10°N and 65°E-75°E over very high warm waters (28.5°C-29°C).

Fig. 12—Seasonal mean OLR distribution for (a) Winter, (b) Spring, (c) Summer, (d) Monsoon

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PANCHAWAGH & SEETARAMAYYA: SPATIO-TEMPORAL VARIATIONS OF CONVECTION & RAINFALL
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