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Principal component analysis of monthly mean sea surface temperature over the Arabian Sea, Bay of Bengal and north Indian Ocean for two contrasting sets of monsoon years

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सार – 1961 से 80 तक की अवधि में अरब सागर, बंगाल की खाड़ी और उत्तर हिन्द सागर में समुद्र सतह ताप का मासिक मान एवं क्षेत्रीय बंटन और सामयिक परिवर्तिता, विभिन्न मानसून वर्षों का अप्रैल माह से जुलाई तक, आनुभविक सांविक फलन तकनीक द्वारा उन क्षेत्रों को, जो विशेषतया मानसून वर्षा से सम्बन्धित है, अंवेषण किया गया है। कुल परिवर्तिता के 75% को प्रथम बहुलक ई. ओ. एफ. में वर्णित किया है। समुद्र सतह तापमान के विश्लेषण द्वारा उत्तर और उत्तरपूर्व अरब सागर में मानसून के पूर्व महीनों में मानसून प्रक्रियाओं की सुनिश्चितता के सूक्ष्म संकेत मिलते हैं। मई में उत्तरपूर्व अरब सागर पर उच्च अभिलक्षणिक सदिशों से अच्छे मानसून के संकेत मिलते हैं। जून में अरब सागर में समुद्र सतहीय तापमान का बंटन वर्षों के दो समुच्चयों में उल्लेखनीय विविधता पाई गई है, कम वर्षा के वर्षों में पूर्व अरब सागर गर्म होता है जबकि अच्छे मानसून वर्षों में सुदूर उत्तर अरब सागर के अतिरिक्त अरब सागर ठंडा रहता है। मई में इंडोनेशिया द्वीप के पास भूमध्य हिन्द सागर क्षेत्र पर समुद्र सतहीय तापमान प्रतिचक्रवात बन जाता है जोकि विशेषतया जून में अधिक स्पष्ट रूप से दृष्टि-गोचर होता है और भारत के ऊपर होने वाली वर्षा की सक्रियता के साथ सकारात्मक रूप में सम्बन्धित होता है।

ABSTRACT. The spatial distribution and temporal variation of the monthly mean SSTA over the Arabian Sea, Bay of Bengal and the north Indian Ocean were investigated for a set of contrasting years of monsoon over the period 1961-80 for months April through July using Empirical Orthogonal Function (EOF) technique with a view to identify regions that are significantly related to the monsoon rainfall. Over 75% of the total variance is explained by the first mode EOF. SSTA over the north and northeast Arabian Sea during pre-monsoon months were found to be possible indicators of the ensuing monsoon activity. The higher eigen vectors in May over northeast Arabian Sea may signal good monsoon and *vice versa*. In June there is a marked contrast in the distribution of SST over the Arabian Sea between the two sets of the years, the eastern Arabian Sea is warmer for the deficient monsoon years while the entire Arabian Sea except over the extreme north Arabian Sea is cool during good monsoon years. There is formation of SSTA over the equatorial Indian Ocean area close to Indonesian island commencing from May which is more marked in June and is positively correlated with seasonal rainfall activity over India.

Key words — Sea surface temperature anomaly, Spatial distribution of sea surface temperature differences.

1. Introduction

The contribution of the oceanic bodies to the variation of climate and weather over the globe arising from large area and thermal capacity and long time scale of the oceans is considerable but complex. Among the oceanic parameters, SST plays a pivotol role on the variation of atmospheric circulation. SST is known to be controlled by a variety of atmospheric and oceanic processes such as the incident solar radiation, net longwave radiation, sensible and latent heat fluxes, coastal and mid oceanic upwelling, advection of warm and cold water, lateral diffusion, entrainment of cold water from below and thickness of mixed layer; the relative importance of these processes vary both in time and space. The factors that determine the influence of the SSTA on the atmospheric circulation are rather complex; the immediate effect being change of sensible heat flux and evaporation which are confined only over the oceanic surface may not produce significant changes in the atmospheric circulation. For an SSTA to affect the atmospheric circulation, it should be able to produce a deep heat source in the atmosphere. Numerical model experiments have suggested that deep heat source associated with SSTA depends upon the structure and magnitude of the SST and their anomaly fields, basic flow in the atmosphere, the latitude of anomaly and the atmospheric instability mechanisms in the region. As tropical region is dominated by Hadley, Walker and monsoon circulations, changes in the boundary conditions can alter the location and intensity of these systems. The heat released by oceans to the overlying atmosphere is a function of air-sea temperature difference, vapour pressure difference, wind velocity and radiation which again is a function of clouds and moisture in the atmosphere.

Several observational and numerical modelling studies have been made correlating SST over the Arabian Sea, Bay of Bengal and monsoon rainfall of India. Shukla and Mishra (1977) with the Geophysical Fluid Dynamics Laboratory (GFDL), GCM found that SST over western and central Arabian Sea is negatively correlated with rainfall over India. Washington *et al.* (1977) using National Centre for Atmospheric Research (NCAR) model found local responses to anomalies over the Arabian Sea and remote response for anomalies over central Indian Ocean while Weare (1979) found negative

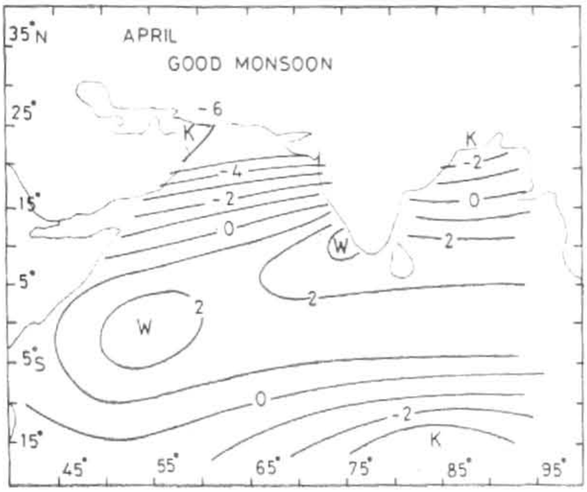

Fig. 1. Eigen indices of mean SST for April based upon six good monsoon years

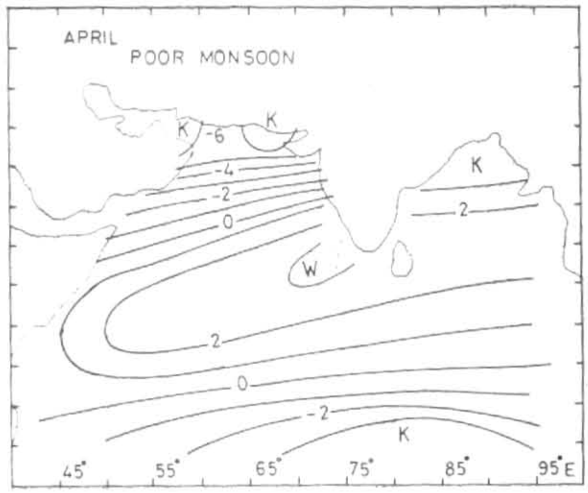

Fig. 2. Eigen indices of mean SST for April based upon six poor monsoon years

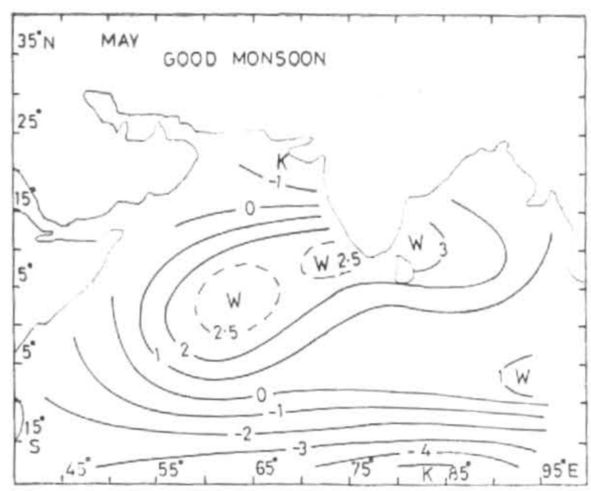

Fig. 3. Eigen indices of mean SST for May based upon six good monsoon years

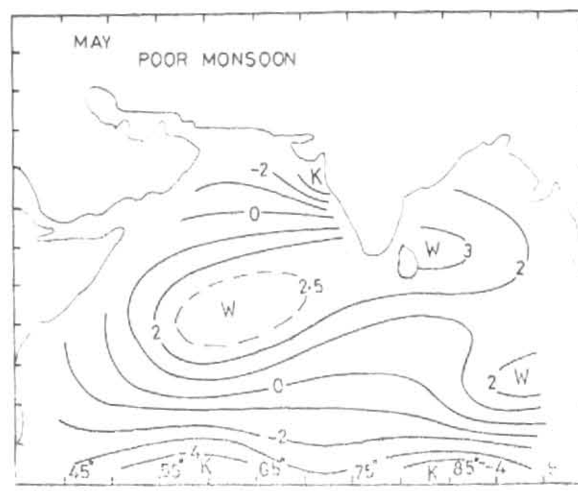

Fig. 4. Eigen indices of mean SST for May based upon six poor monsoon years

correlation between SST and rainfall. Shukla and Mishra (1977) obtained positive correlation between SSTA in central Arabian Sea and rainfall over west and central India. Joseph and Pillai (1986) based on data of a few years concluded that for good monsoon, the warm pool over the Arabian Sea and Bay of Bengal during pre-monsoon months were having higher magnitudes and were over more northerly latitudes. Sadhuram *et al.* (1990) obtained negative correlation between SST over southeast Arabian Sea and rainfall over west coast of India. Shukla (1987) based on a composite SSTA both for heavy rainfall and drought years came to the conclusion that pre-monsoon SSTA is negative for both the cases. Rao and Goswamy (1988) from a similar study obtained that SSTA over southeast Arabian Sea in March and April is positively correlated with rainfall over India. Ray (1991) observes that SST over southeast Arabian Sea has to be more than 30°C for occurrence of good monsoon. Most of the observational studies reported above were based on sparse data sets. Some of the studies have mixed space and time variation of SST. It is well known that SST over the Arabian Sea and the Bay of Bengal increases during pre-monsoon months and falls after the onset of monsoon. The magnitude of this rise or fall considerably varies from one location to another even over the Arabian Sea itself and hence mixing of space and time may not yield the desired results. Keeping in view the above, an attempt has been made in this paper to utilise maximum possible data set over the Indian Ocean area and prepare monthly mean values of SST for every 5° square based on the principal components analysis (PCA) for a period of 20 years from 1961.

2. Data used

India is holding responsibility for the collection, processing and publication of ships data of the Arabian Sea, Bay of Bengal and north Indian Ocean, north of 15° S latitude between 20° E and 100°E longitudes. On an average nearly 1.5 lakh observations per year are on our archives which is the optimum number of

TABLE 1

Variance of first eigen indices of mean SST for good and poor monsoon years

Month	Good monsoon	Bad monsoon
April	75.17	85.57
May	79.02	81.93
June	83.78	87.75
July	86.62	86.83

records possible. As the incoming data are heterogeneous, since they are coded and recorded by several nations, they have been converted to a homogeneous data set by a set of computer programs. These data are then subjected to electronic quality control checks and observations for the 4 months April through July are extracted. Monthly means of SST were calculated for every 5° Lat./Long. square over this area. The seasonal rainfall departures over the country for individual years over this period were scrutinized and set of six years 1961, 1964, 1970, 1973, 1975 and 1978 having rainfall departures (percentage) +22, +10, +12, +8, +15 and +9 respectively and set of six deficient monsoon years 1965, 1966, 1968, 1972, 1974 and 1979 having rainfall departures (percentage) —18, —13, —10, —24, —12 and—19 respectively were identified. The means of six good and six poor monsoon years were then computed for these 5° square and these are subjected to EOF analysis.

3. Method of analysis

The principal component analysis provides a simple means due to its restrictions to linear functions of the original variables expressing a linear function of the p variable of the form given by :

$$z = a_1 x_1 + a_2 x_2 + \ldots\ldots\ldots\ldots + a_p x_p$$

where, $a_1, a_2, \ldots\ldots a_p$ are constants. As we change $a_1, a_2, \ldots\ldots a_p$ we get different linear functions and we can calculate the variance of any such linear function. The first principal component (PC) is that linear function which has the maximum possible variance; the second PC is the linear function with maximum possible variance subject to being uncorrelated with the first PC; the third PC is the linear function which maximises variance subject to being uncorrelated with the first and second PCs, and so on. Thus, it is easy to construct p principal components providing optimal m-dimensional representation of the data for each $m=1, 2\ldots\ldots, p$ for various different definitions of optimality. In particular, at each stage the sum of the variances of the PCs is as large as possible. In other words, with PCA we get for each $m=1, 2, \ldots, p$ the m linear functions $x_1, x_2 \ldots\ldots, x_p$ which account for the maximum possible proportion of the original variations. Expressing in more general terms, the kth principal component is given by :

$$z = a_{k1} x_1 + a_{k2} x_2 \ldots\ldots\ldots + a_{kp} x_p$$
$$= \mathbf{a}'_k . \mathbf{x}$$

for $k=1, 2, \ldots, p$. Here $\mathbf{a}'_k$ are vectors consisting of the weights to different variables. We compute eigen vectors of the $(p \times p)$ co-variance matrix.

Thus the empirical orthogonal function (EOF) is the set of coefficients a_{11}, a_{1p} appearing in the first PC. Similarly subsequent EOF consist of coefficients of $x_1, x_2, \ldots\ldots x_p$ in each successive PC. The first eigen value is the variance of the first PC and so on. To define the principal components uniquely the normalisation constant is imposed. Method of normalisation used in this paper is given by :

$$\sum a^2_{kl} = \frac{1}{\lambda_l}$$

which gives Var $(z_k)=1$ for all $k=1, 2, \ldots\ldots p$.

The primary advantage of the principal component solution is its ability to compress the complicated variability of the original data set into a relatively few temporally uncorrelated components. However, the spatial orthogonality of the eigen vectors is a strong and often undesirable constraint imposed on the principal component solution. While the first principal component and its eigen vectors are not influenced by this constraint, the remaining eigen vectors often bear predictable geometric relationship to the first eigen vector.

4. Results and discussion

4.1. *April*

Figs. 1 and 2 represent the eigen values of first EOF mode for good and poor monsoon years respectively for the month of April. For the good years, the first EOF is having a variance of 75% and for poor monsoon years the variance is nearly 80% of the total variance as can be seen from Table 1. The region of positive maximum corresponds to warm area. Comparing the two sets of years, it is seen that the region of warm pool over the Arabian Sea extends to a more northerly location in this month. Their average magnitude is higher for poor monsoon years and not for good monsoon years as reported by Joseph and Pillai (1986) and Singh (1980). Rao and Goswamy (1988) studied the interannual variation of monthly mean SSTA over the north Indian Ocean for the months of March and April with the seasonal rainfall over India. They obtained positive correlation between mean SST of March and April on an area over the Arabian Sea between 5°N-10°N Lat. and 60°E-70°E Long. From the present study, it is clear that the mean eigen values over this area for April is 1.86 for good monsoon years while it is 2.86 for poor monsoon years. Since monsoon is the result of large scale thermal gradient from heat low over northwest India to further south over extreme north Arabian Sea it is logical to assume that the response of the oceans lying close to the heat low to the incident solar radiation during pre-monsoon months of good monsoon years has to be higher than that for poor monsoon years. The north Bay of Bengal presents a striking contrast between the two sets of years. For the good monsoon years the value of the eigen vectors is —2.11 over the extreme north Bay of Bengal while it is +0.25 for deficient monsoon years implying that north Bay of Bengal is considerably cooler during good monsoon years as against deficient monsoon years.

4.2. *May*

Figs. 3 and 4 represent eigen values for the month of May for good and deficient monsoon years respectively May is the peak summer month when SSTs attain

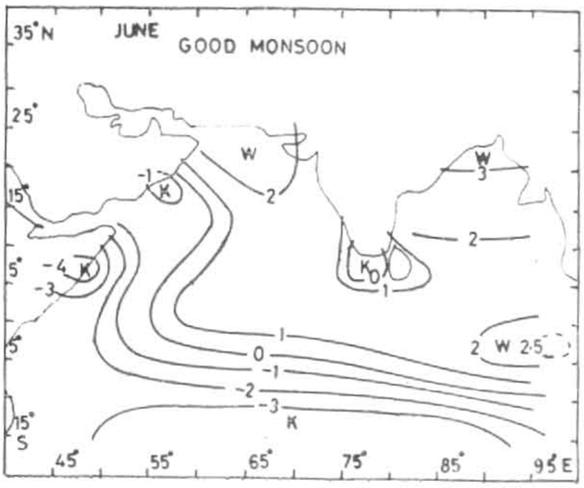

Fig. 5. Eigen indices of mean SST for June based upon six good monsoon years

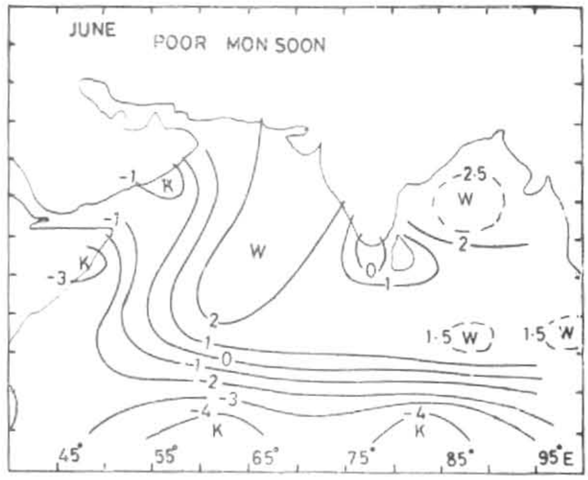

Fig. 6. Eigen indices of mean SST for June based upon six poor monsoon years

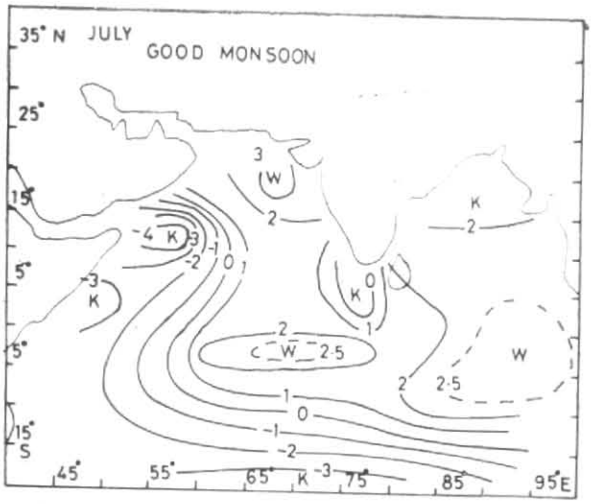

Fig. 7. Eigen indices of mean SST for July based upon six good monsoon years

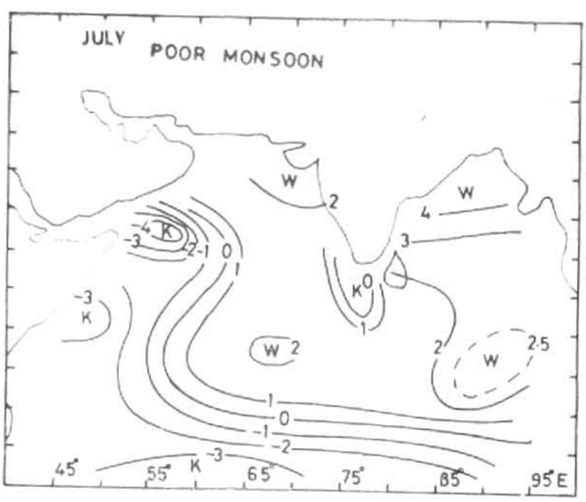

Fig. 8. Eigen indices of mean SST for July based upon six poor monsoon years

maximum amplitude over the Arabian Sea and the Bay of Bengal. In both the sets of years the eigen values are positive over the entire Bay of Bengal and the Arabian Sea excepting the extreme north Arabian Sea and the east African coasts. The contrasting features between good and poor monsoon years are the large difference in the eigen vectors over the extreme north Arabian Sea. The anomaly is maximum over northeast Arabian Sea in the area bounded between 70°-75°E Long. and 15°N-25°N Lat. where the mean difference in the eigen values between good and poor monsoon years is +1.90. It decreases both towards south and west and becomes negative south of 10°N. Over the latitude belts between 15° and 25°N the magnitude difference decreases westwards excepting over the Persian Gulf area where there is a marginal increase which may be due to flow of warm water from the Persian Gulf. The eigen values over the southeast Arabian Sea is higher for poor monsoon years. Over the extreme north Bay of Bengal, the change over from April to May is more marked during good monsoon years where there is reversal of phase from negative to positive. Though the north Arabian Sea and north Bay of Bengal lie over the same latitude circle, the eigen vectors are having opposite sign signify that different processes assume differential importance at different geographical locations. Over the Bay of Bengal the position of warm pool is roughly along 15°N latitude in both the sets of years. South of the equator the western parts of the Indian Ocean is warmer than the eastern portion for good monsoon years. This clearly brings out the fact that the contribution of the western Indian Ocean towards the Indian southwest monsoon is higher by way of generation of large flux of moisture. Another feature is the presence of a trough along 85°E longitude south of 10°S latitude in Fig. 3 while in Fig. 4 besides the trough along 80°E there is another trough along 60°E longitude as revealed by low eigen vectors, implying weaker Mascarine High.

Another significant feature observed in both the sets of years is the warm SSTA over the equatorial east Indian Ocean which is marginally higher during poor mon-

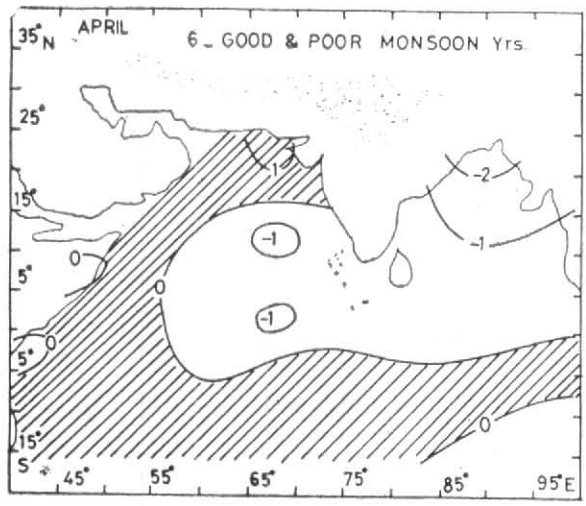

Fig. 9. Difference in eigen values between sets of six good and six poor monsoon years for the month of April

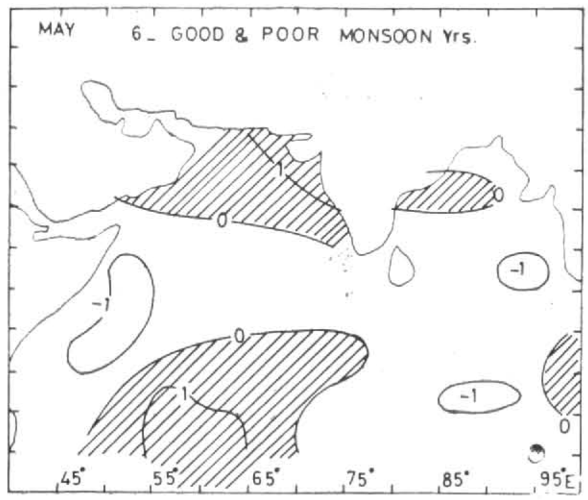

Fig. 10. Difference in eigen values between sets of six good and six poor monsoon years for the month of May

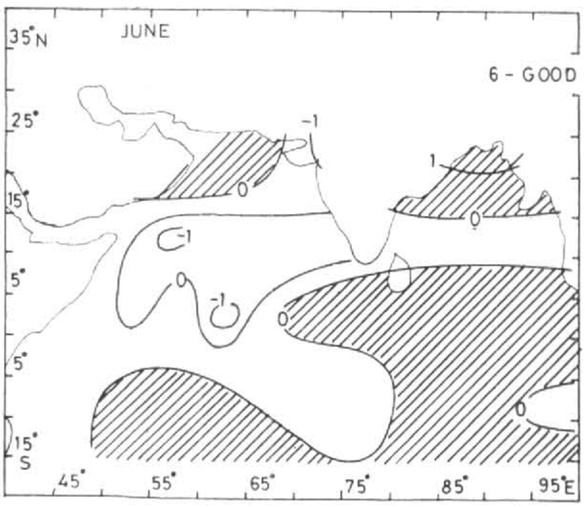

Fig. 11. Difference in eigen values between sets of six good and six poor monsoon years for the month of June

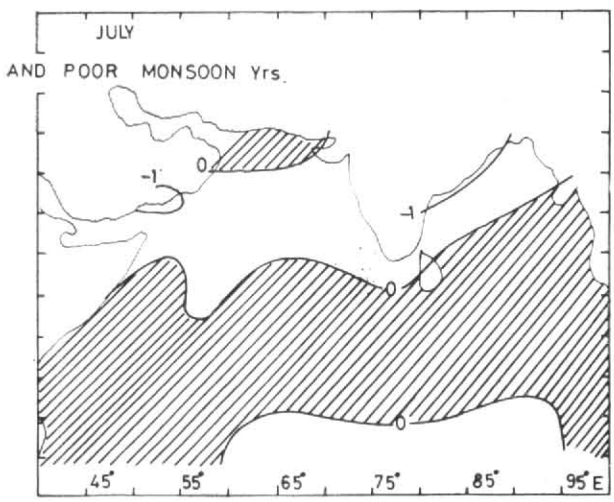

Fig. 12. Difference in eigen values between sets of six good and six poor monsoon years for the month of July

soon years. Indonesian region is one of the continental areas where much heating over the tropical region is found to occur (Ramage 1968, Krueger and Winston 1974). In the case of ocean-land proximity the response is rather complex (Webster 1987). However, it is logical to assume that the oceanic bodies lying close to the land heat lows, get warmed up, their intensity decides the strength of the monsoon flow. In other words since northwest India is the region of heat low, the SSTA over north Arabian Sea has to be larger for occurrence of good monsoon. Also since the maximum, accumulated summer heating is observed in May, it is logical to look for this anomaly in this month. Hence the finding that SSTA over the extreme north Arabian Sea in May is larger for good monsoon years than for deficient monsoon years is well substantiated by the above physical reasoning.

4.3. *June*

Figs. 5 and 6 show the distribution of eigen vectors for the month of June for excess and deficient monsoon years respectively. For both the sets of years the eigen vectors are positive over the Bay of Bengal and the Arabian Sea except over the east African/Arabian coasts and the west coast of south Peninsula. The Arabian Sea presents a contrasting picture between the two sets of years as reflected in the eigen vectors. For good monsoon years the warm pool is confined only over the extreme north Arabian Sea while for deficient monsoon years a tongue of warm water extends from northeast Arabian Sea, southwestwards up to the equator. During pre-monsoon months transfer of energy and momentum is from oceans to the atmosphere while with the commencement of the monsoon the feedback from atmosphere to the ocean caused by large wind stress associated with the monsoon flow which results in fall of SST. Larger is the drop over the Arabian Sea, greater is the intensity of the monsoon. From Fig. 6, which is for poor monsoon years, it is clear that cooling associated with the wind stress is observed only over the western Arabian Sea which does not reach the Indian region as seen from the persistence of warm SSTs over the east Arabian Sea. In Fig. 5, which is for good monsoon years on the other hand the entire Arabian Sea is cool except the extreme north Arabian Sea where the monsoonal effects are not felt.

Somali current system plays a major role in the heat budget of the Arabian Sea through a combination of upwelling and offshore advection of cold water. The intense cooling associated with Somali current system with embedded vortices corresponding to gyre systems, one over the Somali coast and another over the Arabia coast is seen in both the figures. The contrast between the two sets of years is that in the good monsoon case the intensity of cooling associated with the southern gyre is marginally higher than for bad monsoon years. There is large eastward extension of cooling associated with these current systems during good monsoon years than over poor monsoon years. It may be noted that the intensity of cooling associated with the Somali current system is not greatly different between the two sets of the years. The cooling over the west coast of south Peninsula is observed for both the sets of the years, the magnitude of eigen vectors being smaller during poor monsoon years. Towards north, *i.e.*, over the Karnataka-Goa coasts there is reversal of phase as seen from the eigen vectors, the magnitude being smaller during good monsoon years. The cooling over the west coast of India can be attributed to the development of current parallel to the coast which undergoes variation during its north-south flow along the west coast. Recent studies (Kesava Das and Desai 1990) have revealed that there is an equatorward surface current and a poleward under current along the continental slope, whose intensity was found to decrease northwards. Duing and Leetmaa (1980) from heat budget calculations of the Arabian Sea postulated that the western boundary current may balance the accumulation of heat over the Arabian Sea. During good monsoon years the north Bay is the region of highest SST with gradual fall of temperature from north Bay to south Bay while for deficient monsoon years the warm pool is over the central Bay with fall in temperature both northwards and southwards. The north Bay of Bengal is the region of cyclogenis and presence of warm pool creates conditions conducive for the formation of monsoon depressions.

The warm pool over the equatorial east Indian Ocean that appeared in May persists during June also but differs from May in that the intensity is higher for good monsoon years than over poor monsoon years. It is generally known that the anomalies in the flow pattern especially over the upper troposphere caused by heating over the equatorial regions is different for different longitudes which assumes special significance over the Indian Ocean area during summer. The monsoon cell which spans the entire Indian Ocean longitudes is having large zonal asymmetry. The equatorial heating over the Indonesian area in conjunction with heating over the monsoon trough region generates the monsoon flow. However, the effect of the westward shift of these anomalies together with the heating at mid-latitude on the circulation pattern has not been studied by numerical methods.

4.4. *July*

Figs. 7 and 8 depict the pattern for the month of July for good and bad monsoon years respectively. This month corresponds to the period when the monsoon is fully established over the entire country for most of the years. Similar to June, the phase of eigen vectors is positive over the Bay of Bengal and east Arabian Sea except over the extreme south Peninsula where it is negative. The chief features of this month are the intensification of the Socotra eddy from the previous month in both the sets of the years as reflected in the lowest eigen values over this region, the magnitude being —4.47 for good and —4.0 for poor monsoon years. The intensity of the 'Great Whirl' over the Somali coast is less pronounced in comparison to May values as well as in comparison to Socotra eddy. Another significant feature of this month is the presence of warm pool over the equatorial region of the central and west Indian Ocean extending from 60°E to 80°E during good monsoon years, while it is only between the 65°E & 70°E during poor monsoon years. The existence of the warm pool near the equator over the western Indian Ocean is very significant. There is also a northward displacement of this warm pool by 5° from the previous month. This warm pool may be due to the movement of anomalies over the equatorial east Indian Ocean towards the west which are reflected before reaching the east African coast due to current shear associated with strong cross equatorial flow. Another possible explanation may be that due to strong wind stress, evaporation, advection of water and clouding, the Arabian Sea does not attain the temperature that it should have attained but for monsoonal effects. Equatorial region is, however, least influenced by these effects which results in comparatively higher temperatures. Another reason for the extended eastward temperature anomalies over the equatorial west Indian Ocean may be that cross equatorial flow which occurs during the monsoon priod is most intense near the east African coast during years of good monsoon giving rise to concentrated jet while during poor monsoon years, cross equatorial flow spread over large longitudinal area and is weak. The cool southern hemispheric waters while being advected towards north, lowers the temperature over the equatorial regions.

4.5. *Difference between active and weak monsoon*

For April, May, June and July the difference in eigen indices between good and poor monsoons were plotted (Figs. 9-12). It may be noted that the differences are generally less as compared to the composite maps for good and poor monsoon years. However, the location of warm and cool pool over the seas remains in general unchanged. For example, in April the differences are positive over the north Arabian Sea and south Indian Ocean and the east coast of Africa and negative elsewhere. In May, the north Arabian Sea is positive and the magnitude is quite significant (>1.0°C). The southwest Indian Ocean area is another sensitive region where also the difference is positive. In the month of June/July the difference is negative and of magnitude larger than 0.5°C over the Arabian Sea and western parts of Bay of Bengal. Over the east African coast the difference is negligible confirming the finding that the drop in SST over the Somali coast is not very much different between contrasting monsoon years.

5. Conclusions

(*i*) The eigen values over the extreme north Arabian Sea during pre-monsoon months may be related with the following monsoon rainfall; higher values over the north Arabian Sea in May may indicate good monsoon and *vice versa*.

(*ii*) The establishment of the Somali current system with the associated cooling over the Arabian Sea is observed during the month of June. During the poor monsoon years the western half of the Arabian Sea is cool while the eastern half is comparatively warmer while during good monsoon years the entire Arabian Sea is cool.

(*iii*) There is a formation of warm pool over the equatorial east Indian Ocean in May which is more marked in June with its intensity being higher during years of good monsoon activity. During July, the warm pool extends northward up to 10°N latitude. There is also formation of warm pool over the equatorial west Indian Ocean with marked contrast between good and poor monsoon years. During good monsoon years the warm pool over the equator extends from 60°E to 80°E longitudes while during poor monsoon years, it is only between 65°E & 70°E longitudes.

(*iv*) The western part of the Indian Ocean south of the equator is warmer during good monsoon years as compared to poor monsoon years.

(*v*) The distribution of eigen values over the southern hemisphere support the earlier results about Mascarine High : weaker during poor monsoon years and *vice versa*.

(*vi*) The temperature gradient over the Bay of Bengal also shows contrast between good and poor monsoon years. In June the north Bay is warmer during good monsoon years while the warm region is over the central Bay during poor monsoon years. During July the north Bay is cooler during good monsoon years and warm during poor monsoon years.

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