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A study of the air and sea surface temperatures over the Indian Ocean

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ABSTRACT. Several studies on the air and sea surface temperatures over Indian Ocean particularly over west Arabian Sea have been reported (Verploegh 1960; Colon 1964; Bunker 1965; 1970, 1974; Shukla 1975, 1977).

The present paper is a study of the air and sea surface temperatures over the Arabian Sea and Bay of Bengal during the seven year period 1961 to 1967. Its purpose is to demarcate, with the recent date, Indian Ocean into separate zones each of a particular character with reference to the variation of the air and sea surface temperatures through the year as also the warmer than air-sea and colder than air-sea conditions during the southwest monsoon season. An attempt to examine the association of the anomalies of sea surface temperatures over the Arabian Sea to the variation in the activity of monsoon over India in the respective years has also been made.

1. Introduction

Considerable work has been reported on the meteorological aspects of southwest Arabian Sea being particularly so over west Arabian Sea [Verploegh (1960), Colon (1964), Bunker (1965) and Findlater (1971)]. The extensive study of Verploegh based on data of air and sea surface temperatures over the Indian Ocean recorded during 1952-1956 brought out the variation through the year of the above factors and the cold upwelling off Somalian and Arabian coasts during the southwest monsoon season. Rao *et al.* (1976) examined the oceanographic parameters over the area and enumerated the various causes for upwelling. Findlater studied the structure of the wind field in the lower troposphere over Kenya and adjoining Indian Ocean (Somali Jet) and attempted to relate the fluctuations in the strength of the wind to the variation in the subsequent activity of the monsoon (rainfall) along the west coast of Indian and adjoining land areas.

The present study utilizes the monthly mean data of air (T_A) and sea surface temperatures (T_S) at 16 representative areas over Arabian Sea and Bay of Bengal to examine their variation through each year over a seven year period. Further the anomalies of sea surface temperatures during pre-monsoon season and southwest monsoon have also been examined during the good and bad monsoon years to find their association, if any, with subsequent activity of the monsoon (rainfall) over India in the respective years.

2. Data used

The study utilises the data of mean monthly air and sea surface temperature during 1961 to 1967 at representative areas (WMO) over the Indian Ocean shown in Fig. 1 (Zone 4 is in Red Sea—not shown in the figure) for which Marine Climatological Summaries are prepared by India. These data are available on a large number of punched cards. Data for area 4 have not been examined because of large gradients of temperature in that area due to its being surrounded by land on all sides.

3. Monthly means of air and sea surface temperatures

Monthly means of air (T_A) and sea surface temperature (T_S) for the seven year periods 1961—1967 for the areas shown in Fig. 1 have been worked out and are given in Tables 1 and 2 respectively. The highest, lowest and the mean

TABLE 1

Monthly means of air temperatures (1961-1967)

Area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	22.7	23.5	25.1	26.8	28.7	28.9	27.6	26.5	27.5	27.4	26.0	23.3
2	23.1	23.9	24.7	27.0	28.2	27.1	24.9	23.8	52.0	26.7	26.0	23.5
3	25.5	25.6	26.1	27.6	29.2	29.1	28.0	27.2	27.3	27.9	27.4	25.6
5	25.5	26.0	27.5	28.9	30.1	29.2	28.4	28.5	28.8	28.5	27.4	26.0
6	27.1	27.4	27.9	28.8	28.9	28.7	27.6	27.6	27.6	28.3	28.3	27.6
7	25.8	25.9	26.7	28.2	28.9	28.3	26.8	26.3	26.7	27.2	27.2	26.2
8	25.3	25.7	26.7	28.2	28.2	25.2	24.4	23.9	24.8	26.4	26.6	25. 8
9	27.4	27.1	28.2	29.1	29.2	28.5	28.2	28.0	27.7	27.8	27.8	27.6
10	27.0	27.6	28.2	28.8	28.7	28.4	28.1	27.9	29.8	27.3	27.5	27.2
11	26.3	26.9	28.0	28.6	28.6	26.9	26.0	25.6	26.4	26.9	27.3	27.0
12	27.4	27.8	28.3	28.6	28.6	28.6	28.2	28.1	28.0	28.0	27.7	27.2
13	27.5	27.7	28.2	28.5	28.4	28.2	27.9	27.9	27.5	27.3	27.5	27.1
14	27.4	27.7	27.8	28.1	27.7	27.0	27.0	27.9	27.1	27.4	27.4	27.3
15	27.7	28.3	28.8	28.4	27.1	26.0	24.8	24.9	25.8	27.2	27.2	28.1
16	28.0	27.6	28.0	28.1	27.4	26.2	25.5	25.4	25.5	26.1	27.0	27.5
17	26.7	27.0	28.1	29.4	30.0	29.0	28.8	28.6	28.6	28.2	28.0	27.2

TABLE 2

Monthly means of sea surface temperatures (1961-1967)

Area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	23.4	24.0	25.2	26.9	28.7	29.0	27.7	26.6	27.0	28.0	26.9	24.9
2	24.2	24.4	25.5	26.8	28.0	*26.3*	*23.5*	*22.6*	*24.6*	27.1	26.7	25.0
3	25.5	25.6	26.6	28.0	29.3	29.0	28.0	27.2	27.5	28.2	27.6	26.0
5	25.9	26.3	27.4	30.0	30.1	29.1	28.3	28.4	28.8	28.7	27.4	26.5
6	27.6	27.5	28.3	29.3	30.0	29.2	28.1	27.7	27.9	28.8	28.5	28.2
7	26.2	26.4	27.3	28.7	29.6	28.2	26.8	25.8	26.3	27.6	27.5	26.8
8	25.5	25.9	27.1	28.6	27.9	*24.2*	*22.8*	*22.3*	*23.3*	26.2	27.0	26.1
9	27.9	28.1	28.7	29.8	29.9	28.8	28.2	27.9	28.1	28.2	28.3	28.2
10	27.8	28.1	28.5	29.5	29.4	28.4	28.3	28.0	28.0	28.1	28.3	28.0
11	26.5	27.0	28.2	29.5	28.6	27.0	26.0	26.2	26.4	27.2	28.1	27.2
12	28.2	28.3	28.6	29.0	29.0	28.6	28.5	28.5	28.5	28.4	28.1	28.1
13	28.2	28.3	28.6	29.0	29.0	28.6	28.5	28.0	28.0	28.1	28.1	28.3
14	27.7	28.2	28.4	28.5	28.1	27.8	27.8	27.4	27.7	27.7	27.8	28.1
15	28.9	29.3	29.2	29.1	27.7	26.3	25.2	24.8	25.0	25.9	27.5	28.7
16	27.8	28.1	28.2	28.5	27.7	26.7	25.8	25.6	25.5	26.2	27.2	28.0
17	26.7	26.9	28.2	29.5	30.0	28.9	28.8	28.4	28.5	28.6	28.1	27.4

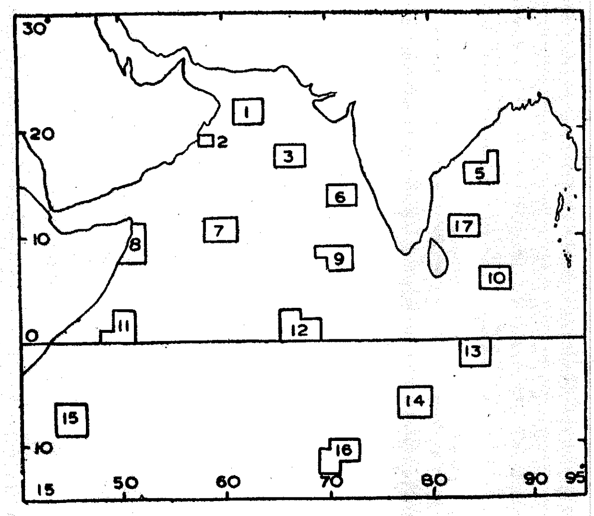

Fig. 1. Selected representative areas over the Indian Ocean for which *Annual Climatological Summaries* are prepared by India

TABLE 3

Difference between the sea surface temperature (T_S) and air temperature

(Negative values in italics)

Area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.7	0.5	0.1	0.1	0.1	0.1	0.1	0.1	*0.5*	0.6	0.9	1.6
2	1.1	0.5	0.8	*0.2*	*0.2*	*0.8*	*1.4*	*1.2*	*0.4*	0.4	0.7	1.5
3	0.0	0.0	0.5	0.4	0.1	*0.1*	0.0	0.0	0.2	0.3	0.2	0.4
5	0.4	0.3	*0.1*	1.1	0.0	*0.1*	*0.1*	*0.1*	0.0	0.2	0.0	0.5
6	0.5	0.1	0.4	0.5	1.1	0.5	0.5	0.1	0.3	0.5	0.2	0.6
7	0.4	0.5	0.6	0.5	0.7	*0.1*	0.0	*0.5*	*0.4*	0.4	0.3	0.6
8	0.2	0.2	0.5	0.4	*0.3*	*1.0*	*1.6*	*1.6*	*1.5*	*0.2*	*0.2*	*0.1*
9	0.5	1.0	0.5	0.7	0.7	0.3	0.0	*0.1*	*0.4*	0.4	0.5	0.6
10	0.8	0.5	0.3	0.7	0.7	0.1	0.2	0.0	0.3	0.3	0.5	0.8
11	0.2	0.1	0.2	0.9	0.0	0.1	0.0	0.6	0.0	0.3	0.8	0.0
12	0.8	0.5	0.3	0.4	0.4	0.0	0.3	0.4	0.5	0.1	0.4	1.1
13	0.7	0.6	0.4	0.5	0.6	0.4	0.6	0.1	0.5	0.8	0.6	1.2
14	0.3	0.5	0.6	0.4	0.4	0.8	0.8	0.4	0.6	0.3	0.4	0.8
15	1.2	1.0	0.4	0.7	0.6	0.3	0.4	*0.1*	*0.8*	*1.2*	0.3	0.6
16	0.2	0.5	0.2	0.4	0.3	0.5	0.5	0.2	0.0	0.1	0.2	0.5
17	0.0	*0.1*	0.1	0.1	0.0	0.1	0.0	0.2	0.1	0.4	0.1	0.2

values of sea surface temperatures (T_S) for each month for the 7 year period have been plotted for each of the areas separately and are shown in Fig. 2. The equatorial stations show the smallest annual veriation in sea surface temperature. Table 1 shows that this is also true with air temperatures. The variation increases towards higher latitudes.

The profiles vary from area to area. Very low sea surface temperatures are noticed during the southwest monsoon period, in areas 2 and 8.

Shown in Table 3 is the annual variation of the difference between mean sea surface and mean air temperatures for the different areas. The negative values are italics.

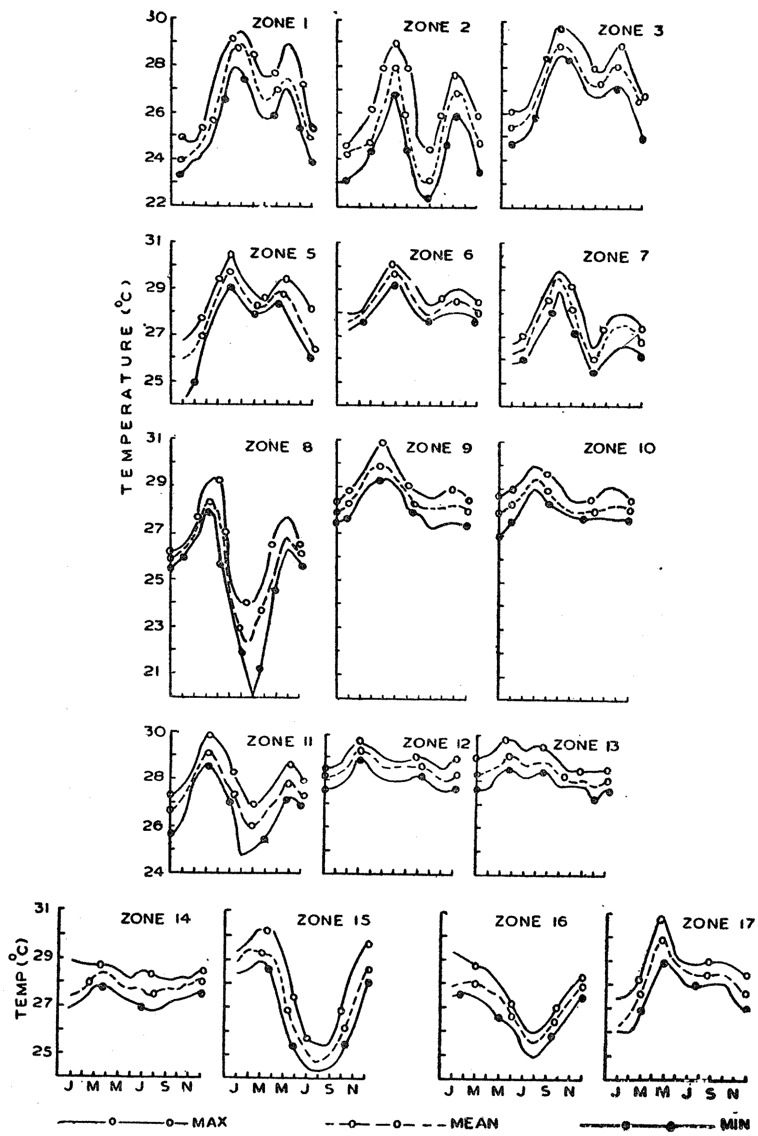

Fig. 2. Annual variation of highest, lowest and mean monthly sea surface temperatures (T_S) at the representative areas

While during NE monsoon $T_S > T_A$ both over the Arabian Sea and Bay of Bengal this feature is reversed with the reversal of the monsoon circulation T_S becoming lower than T_A in certain areas in the Arabian Sea; both the air and sea surface temperatures, however, falling from April/May and reaching the lowest value during July-August the peak period of SW monsoon. This

TABLE 4

Zones	Areas	Type	Temperature character annual variation T_S	(T_S—T_A)	Remarks
I	1, 2, 7, 8	Northern hemispheric (Monsoon) type—Sea colder than air during SW monsoon	*Double Max.* Summer Max. (May) and second Max. (Oct) *Double Min.* Winter Min. (Jan) Monsoon Min. (Aug)	Negative during SW monsoon season.	T_S predominantly lower than T_A during SW monsoon in areas 2 & 8
II	3, 5, 6, 9	Northern hemispheric (Monsoon) type—Sea warmer than air during SW monsoon	As above	Positive through the year	May *minus* Aug. values of T_A and T_S small
III	10, 11, 12, 13, 14	Equatorial type	Little change in both T_A & T_S through the year	Do.	*Area 11 only behaving like northern hemispheric type (Double maximum, Double minimum) however with sea warmer than air through the SW monsoon season also
IV	15, 16	Southern hemispheric type	Summer (Feb) Max. Winter (Aug) Min.		

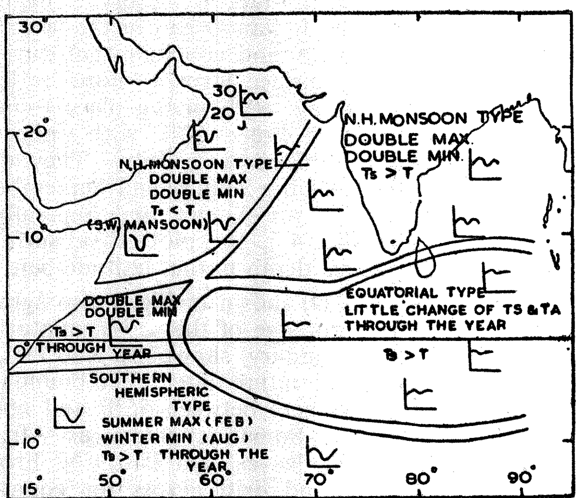

Fig. 3. Annual variation of sea surface temperature in different areas of Indian Ocean and boundaries separating zones of different characteristic features

is also probably so in the lower troposphere (Verploegh 1960). It may be seen that sea is predominantly colder than air in areas 2 and 8 during the southwest monsoon season.

4. Division of areas

Utilising the information from Tables 1, 2 and 3 and Fig. 2 the Indian Ocean is grouped into four zones each having particular characteristics. The grouping of the areas is given in Table 4.

Area 11 marks the transition between the northern hemispheric (monsoon) type and southern hemispheric type. Slightly to its north lies the boundary between cooler than air sea to the north and warmer than air sea to the south during the SW monsoon.

Area 17 marks the transition between equatorial and northern hemispheric (monsoon) type with little change in temperature after June.

Areas 2 and 8 show the most conspicuous fall in temperature after April/May and this fall continues till the middle of August. They show largest temperature difference between pre-monsoon maximum and monsoon minimum with predominantly colder sea. Area 11, however, shows sea warmer than air even during the monsoon season.

The above features, namely, the profile of variation of SST through the year and the sign of magnitude of difference of T_S and T_A enable us to mark the boundary between west Arabian Sea, the region of cold upwelled water and the east Arabian Sea, shown in Fig. 3 is the annual variation of T_S at different areas and the boundary

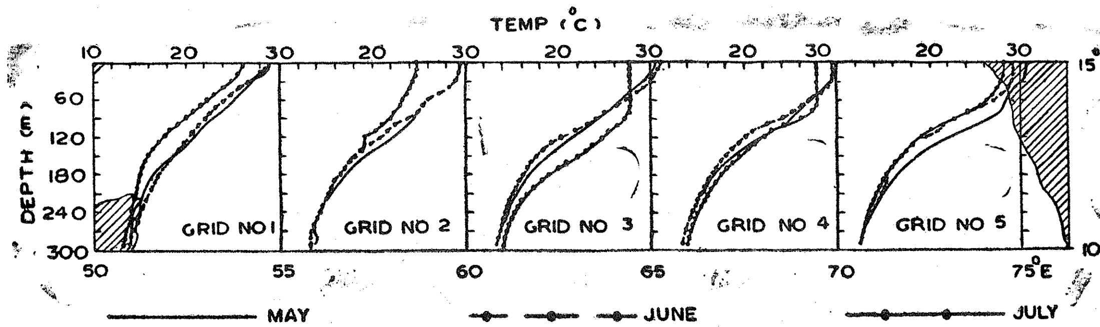

Fig. 4. Mean depth-temperature profiles (Rao *et al.* 1976)

between colder than air-sea and warmer-than air-sea southwest monsoon over the Arabian Sea. It also shows the boundary between areas 11 and 12, area 11 showing considerable fall of T_S from May to August, the temperatures reaching lowest values in August and area 12 showing no perceptible change in T_S during the period.

Bunker (1965) on the basis of the study of the lower layers of the atmosphere over the Arabian Sea make a mention of the inversion over the west Arabian Sea which gets progressively lifted up eastward being altogether broken up some hundreds of kilometres off west coast of India. The boundary AB shown in Fig. 3 also marks the separation of the region of inversion in the very low levels above the sea surface, CD marks the eastern boundary of marked equatorial crossing of the southern hemispheric air. The air over the sea off the coast of Somalia is cooled by cold upwelled water. Heat is brought down from the upper layers and is again transported upward from the sea surface so the air at the lower level is warmed during its passage over the Arabian Sea. This warming decreases the horizontal temperature gradient and, in turn, results in decrease of wind speed and consequent streamline convergence toward the eastern half of the Arabian Sea. Bunker noted that while sensible heat is transported downward west of Long. 60°E, it is transported upward to the east of Long. 70°E. But water vapour is transported upwards over both the areas. Therefore, the boundary AB also separates zones of downward transport of sensible heat (to the west) and the upward transport of sensible heat (to the west). This boundary AB also agrees with the zones of separation between warm continental airmass and cool maritime airmass at 850 mb over the Arabian Sea (Saha 1974), XC makes the boundary between the northern hemispheric (monsoon) type (double maximum and double minimum) and southern hemispheric type (single maximum and single minimum).

Findlater (1971) made detailed analysis of the relatively narrow band of high speed transequatorial current over Kenya and adjoining Indian Ocean. Daniel Cadet *et al.* (1976) constructed the low level air flow from the data of satellite tracked superpressure balloon trajectories during the summer of 1975 and conclude that air reaching west coast of India cross the equator west of Long. 55°E. Rao *et al.* (1976) examined the bathythermograph data for every 5 degree square grid over the Indian Ocean in the latitude belt of 10°N and 15°N and conclude that during May and July the surface layer is more or less uniform west of Long. 60°E giving place to isothermal layer east of Long. 60°E with a phenomenal increase in thickness in July. They did not examine the data for August and September. This is probably so for August and September also. Shown in Fig. 4 is the plot of subsurface temperatures against depth in that latitude belt.

The boundary (CD) shown in Fig. 3 also agrees well with the eastern edge of the cross-equatorial flow as also the boundary shown by Rao *et al.* with subsurface temperature date. The boundary probably lies somewhere between 55°E and 60°E *say*, Long, 57°E. The Somali jet enters east Africa around Lat. 3°S and leaves it at Lat. 9°N. From considerations of wind drift across the equator and subsurface balance of vorticity there should be considerable divergence and hence upwelling to the immediate south of the equator [Yoshida & Mao (1957)], Verploegh (1960).] However it is seen that the sea surface temperatures are lowest north of Lat. 10°N and extend upto 22°N (zones 2 & 8). This is probably due to large evaporative cooling north of 10°N where the Somali jet comes out of land causing considerable air sea coupling. This may also be due to spread of cold upwelled water [Swallow & Bruce (1964 1966)].

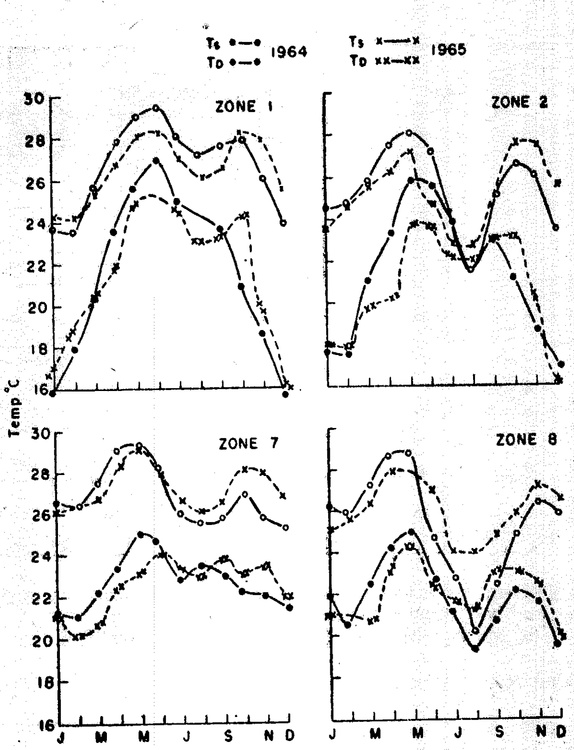

Fig. 5. Annual variation of sea surface temperature (T_S) and dew point temperature (T_D) at selected areas

T_S *minus* T_A is markedly negative in zones 2 and 8 throughout the monsoon season and slightly negative at zones 1 and 7 for some period during the monsoon season. To determine the relative importance of wind and saturation deficit in causing evaporation these areas T_S and T_D (dew point temperature) have been examined during 1964 and 1965, the years for which mean T_D data are available. Shown in Fig. 5 are the plots of T_S and T_D against the month during the years 1964 for areas 1, 2, 7 & 8.

It may be seen that a areas 2 and 8 during 1964 (good monsoon year) T_S, though higher than T_D is nearly equal to it indicating that the strength of the wind factor is primarily responsible for evaporation over this area. The importance of stronger wind over the Arabian Sea for good monsoon rainfall over India is well known to monsoon meteorologists.

5. Distribution of the difference between the highest sea surface temperature during the premonsoon and the lowest sea surface temperatures during the monsoon season

Shown in Fig. 6 is the distribution of difference between the highest sea surface temperature during the pre-monsoon season and the lowest sea surface temperature during the monsoon season during two good monsoon years (1963, 1964) and two poor monsoon years (1965, 1966) and the mean difference over the 7 year period 1961-67. It may be seen that the difference is large in years when the monsoon was good and small during the years when the monsoon was poor. Shown in Table 5 is the above difference in sea surface temperature and the percentage number of subdivisions of India, having normal/excess rainfall during June to September from 1963-1966.

TABLE 5

Year	Pre-monsoon max. *minus* Monsoon min. of sea surface temp. (°C)		Percentage number of subdivisions having normal/excess
	Area 2	Area 8	
1963	7.1	8.2	94
1964	6.4	8.5	97
1965	4.6	4.1	55
1966	4.4	4.2	64

The large difference may be either due to low minimum in August or high maximum in April/may. It is seen that this is largely due to lower sea surface temperature in August. This aspect is further elaborated in the next section.

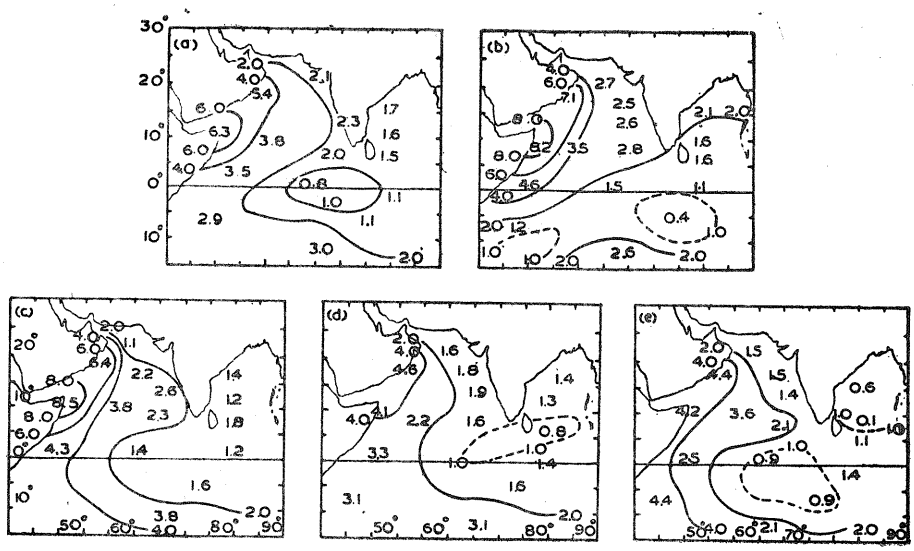

Fig. 6. Distribution of pre-monsoon (highest) *minus* monsoon (lowest) sea surface temperature during good and bad monsoon years
(a) Mean, (b) 1963, (c) 1964, (d) 1965, (e) 1966

6. Utility of SST anomalies in Long Range Forecasting

Monsoon meteorologists are aware of the association of the activity of the monsoon with westerly waves of either hemisphere and the movement of low pressure system over west Pacific Ocean. These are, however, more or less concurrent relationships and are, therefore, not of much practical utility in issuing seasonal forecasts.

Considerable attention is being paid in the recent years to relate the anomalies of sea surface temperature to anomalies of sea level pressure and other parameters. Bjerknes (1966, 1969), Sutcliffe & Murray (1970), Roger (1976), Namias (1978) related the anomalies of sea surface temperatures over oceanic areas to anomalies of sea level pressure/1000-500 mb thickness/700 contour over adjoining land masses. Saha (1970, 1974) suggests a possible relationship between observed variation in west coast rainfall in July and August and advection of cold water across central Arabian Sea. Shukla (1975, 1977) in a numerical experiment finds lag relationship between sea surface temperature over the west Arabian Sea and monsoon rainfall over India.

Sea surface temperatures are quasi-steady because of the heat storage factor in the ocean and could, therefore, have lag relationship with monsoon activity. Heat sinks in the ocean can be identified by the rate of fall of temperature from highest pre-monsoon value to the lowest value in the monsoon as well as the mean maximum temperature in pre-monsoon season (Verploegh 1960). If an area is to be considered as a heat sink the lowering in temperature of the sea surface should commence earlier over there than over the surroundings. The distribution of sea surface temperature in March/April/May gives the area of lowering of temperature earlier. Such sink regions are also the regions where maximum evaporation occurs. With the above reasoning west Arabian Sea is a sink. It may also be seen from Table 2 that the highest sea temperature during the monsoon season over west Arabian Sea occurs in the month of April/May and falls thereafter, whereas it occurs in May/June in other zones. Shown in Table 6 are the month of occurrence of the highest temperature during the pre-monsoon season and the lowest temperature during the monsoon season and the mean rate of all of temperature (°C/month) for the selected zones where the maximum sea surface temperature occurs in either May or earlier and the rate of all of temperature is large.

TABLE 6

Area		Highest (°C)		Lowest (°C)		Mean rate of fall of temp. (°C)
1	T_A	28.9	Jun	26.5	Aug	1.2
	T_S	29.0	Jun	26.5	Aug	1.2
2	T_A	28.2	May	23.8	Aug	1.5
	T_S	28.0	May	22.6	Aug	1.8
3	T_A	29.2	May	27.2	Aug	0.7
	T_S	29.3	May	27.2	Aug	0.7
7	T_A	28.9	May	26.3	Aug	0.9
	T_S	29.6	May	25.8	Aug	1.3
8	T_A	28.2	Apr/May	23.9	Aug	1.5
	T_S	28.6	Apr	22.3	Aug	2.1
11	T_A	28.6	Apr/May	25.6	Aug	1.0
	T_S	29.5	Apr	26.0	July	1.2
12	T_A	28.6	Apr/May	28.0	Aug	0.2
	T_S	29.2	Apr/May	28.5	Jul/Aug/Sep	0.2
15	T_A	28.8	Mar	24.6	Aug	0.8
	T_S	29.2	Mar	24.8	Aug	0.8
16	T_S	28.1	Apr	25.4	Aug	0.7
	T_S	28.5	Apr	25.5	Sep	0.6

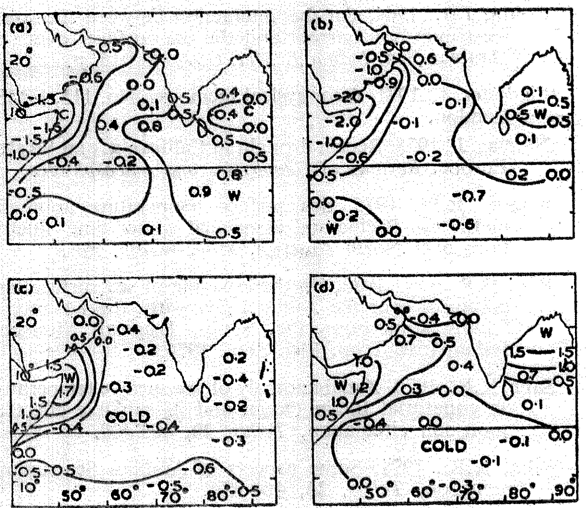

Fig. 7. Anomalies of sea surface temperatures during August in good and poor monsoon years (a) 1963 (good monsoon), (b) 1964 (good monsoon), (c) 1965 (poor monsoon) and (d) 1966 (poor monsoon)

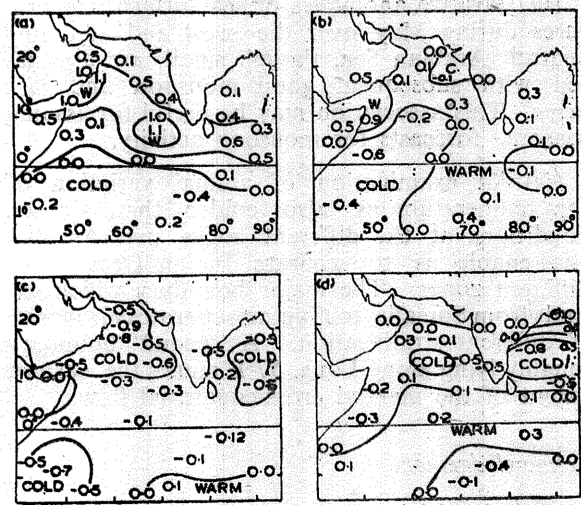

Fig. 8. Anomalies of sea surface temperatures during May (a) 1963, (b) 1964, (c) 1965 and (d) 1966

The marked sink areas can be seen to be 2, 8 and 11 considering both the early fall in temperature and large rate of fall of temperature from maximum to minimum. Area 15 is also a subsidiary sink.

For relating the sea surface temperatures to the subsequent activity of the southwest monsoon, August and May anomalies of sea surface temperatures for 1963, 1964 (good monsoon years) and 1965, 1966, (poor monsoon years) have been worked out on the basis of 7 years (1961-67) means and the same are shown in Figs. 7 and 8.

The sink zones 2 and 8 seem to be important. The anomalies are large in August and small in May. Anomalies of August are negative during good monsoon years and positive during poor monsoon years. The anomalies of May, though small, are positive over west Arabian Sea and adjoining central Arabian Sea during good monsoon years and negative during poor monsoon years.

Thus, the sign of anomalies during May over west and central Arabian Sea appears to be an useful indicator of the likely activity of the monsoon during the year. However the above tentative conclusion may have to be further verified and confirmed for some more good and poor monsoon years. Then only it may be possible to correlate the magnitude of positive or negative anomaly to the departure of monsoon rainfall over India.

7. Limitation

The study is limited by the non-availability of mean monthly sea surface temperature data for each degree square. The data are available only at the 17 representative areas. Only air and sea surface temperature data are available for all the 7 years (1961—67). The data of new point temperature and wind are processed only for 1961, 1964 and 1965. For want of mean monthly resultant wind data, computation of fluxes of sensible heat and water vapour could not be undertaken. No correlation could be attempted between the anomalies of rainfall and the anomalies of sea surface temperature because of the short series of data that is available.

8. Conclusions

The above study reveals that :

(*i*) In the good monsoon years the difference between highest sea temperature during the pre-monsoon season and the lowest sea temperature during the monsoon season in areas 2 and 8 is large. The difference is small in the poor monsoon years.

(*ii*) Negative anomalies of sea surface temperature during August over west Arabian Sea and adjoining central Arabian Sea are associated with good monsoon and *vice-versa*.

(*iii*) Positive anomalies of sea surface temperatures during May over the west and adjoining central Arabian Sea, though small, are associated with subsequent good monsoon and *vice versa*. This association may be useful for issuing seasonal forecasts for monsoon activity.

(*iv*) An examination of annual variation of sea temperature as also colder than air sea conditions at the different zones over Arabian Sea enable us to separate Indian Ocean into different zones. The major boundary which extends from Somalia to Gujarat separates air masses of different stratification. A second boundary roughly lying along Long. 57°E marks the eastern extent of the marked cross-equatorial flow.

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